

Internet of Things

Abdul Salam

Internet of Things for Sustainable Community Development

Wireless Communications, Sensing, and
Systems

Second Edition

 Springer

Internet of Things

Technology, Communications and Computing

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The series Internet of Things - Technologies, Communications and Computing publishes new developments and advances in the various areas of the different facets of the Internet of Things. The intent is to cover technology (smart devices, wireless sensors, systems), communications (networks and protocols) and computing (theory, middleware and applications) of the Internet of Things, as embedded in the fields of engineering, computer science, life sciences, as well as the methodologies behind them. The series contains monographs, lecture notes and edited volumes in the Internet of Things research and development area, spanning the areas of wireless sensor networks, autonomic networking, network protocol, agent-based computing, artificial intelligence, self organizing systems, multi-sensor data fusion, smart objects, and hybrid intelligent systems.

Indexing: *Internet of Things* is covered by Scopus and Ei-Compendex **

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Computer and Information Technology
Purdue University
West Lafayette, IN, USA

ISSN 2199-1073

Internet of Things

ISBN 978-3-031-62161-1

<https://doi.org/10.1007/978-3-031-62162-8>

ISSN 2199-1081 (electronic)

ISBN 978-3-031-62162-8 (eBook)

1st edition: © Springer Nature Switzerland AG 2020

2nd edition: © The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

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*This book is dedicated to Umbreen, Alizay,
Anzalna, Naba, and Mohammad.*

Preface

Fires in Amazon rainforest, Hurricane Dorian in Bahamas, and wildfires in California are among some of the recent events related to the climate change. The rising sea levels, higher temperatures, and extreme precipitation are some of the causation of climate change. The communities around the world are coping with these changes now. In this regard, an untypical effort from all sectors of community is needed to address critical problems of adapting to climate change and feeding 7.7 billion people.

The *Internet of Things for Sustainable Community Development* addresses the key inter-related environmental, climate change, energy, water, health, mining, agro-economic, and cybersecurity challenges that limit the development of sustainable and resilient society. The aim of this book is to present an integrated depiction of how the Internet of Things (IoT) can stimulate the sustainable community development. The expertise across multiple domains including engineering and technology, ecosystems and natural resource management, environmental toxicology, human health, agriculture, mining, and urban underground infrastructure monitoring is introduced to examine important environmental challenges that can be solved with applications of recent advancements in Internet of Things.

In these domains, the sensing data is generated by a wide range of sensors, from point-based direct in situ measurements to airborne and remote sensing for global coverage through satellites. In each domain, the sensing requirements change considerably, stretching from plant-level water status to field-level soil moisture, and regional-level cloud hydrometer to global-scale climate crises and greenhouse gases. The integration of huge volumes of data being generated across these spatial-temporal scales is a major challenge. Moreover, the transmission and processing of this data in decision support systems to address sustainability challenges requires cross-disciplinary endeavors with expertise in sensing, wireless communications, systems science, and modeling, in addition to the specific domain knowledge. The Internet of Things has strong potential to foster the creation of these cross-disciplinary next-generation sensing and communication systems using IoT. These IoT systems for data gathering, wireless communications, processing, and presentation of sensing data are vital to get insights into the biological, physical, and

chemical processes in the environment, and forecasting the prospective advancement of ecosystems sustainability. Such forecasts are also required to support policy and regulation decisions.

The *Internet of Things for Sustainable Community Development* presents a portfolio of cutting-edge, interdisciplinary research developments and challenges in IoT sensing, communications, and systems. It provides a well-founded coverage of these technologies with rigorous focus on scientific concepts, evolution, and applications to sustainability. The comprehensive contents are arranged systemically to provide the scientific foundations of Internet of Things for sustainable community development. The book covers research and innovation ecosystem of the Internet of Things for sustainability in the following major areas that are explored in this book. These areas highlight converging activities that enable the main cohesive objective of sustainable community development.

- Climate Change
- Sustainable Energy Systems
- Sustainable Water
- Human Health
- Sustainable Mining
- Decision Agriculture
- Storm and Wastewater
- Sustainable Forestry

Each of these areas emphasizes core IoT research challenges and solutions while leveraging their shared traits, interdependencies, and expertise to converge on applications of IoT to sustainability challenges. These sections of our community do not exist in segregation. The energy and water are fully intertwined because the water is used to produce energy, and the energy is needed to drain, remedy, and transport water, which underscores the connection between the water-dependent crop growers and city dwellers. Moreover, the human health is impacted by water availability and quality, energy availability, cultivation, mining, and waste management, inter alia, impacting patients, diseases spread, and outbreak. Furthermore, forestry and watershed are impacted by water availability, energy supply, climate crisis, and biodiversity.

In that regard, the book emphasizes IoT paradigm's sensing, wireless communications, monitoring, actuation, and real-time decision capabilities for sustainability "things." Thus, proper focus is also given to systems, standards, and tools that have tremendous potential to achieve United Nations Sustainable Development Goals. It provides a comprehensive reference to all these aspects in an easy language that is understandable by a wide audience. It also includes advanced treatment of sustainability IoT technology applications and provides in-depth coverage of research developments and open research challenges.

While intended primarily for sustainable engineering and technology professionals, researchers, and students, this book is also beneficial to policy makers, city planners and managers, technicians, and industry professionals. The research in Internet of Things for sustainability has a vital role to play in shaping the future of

our community as they must create a research and education ecosystem promoting impactful solutions-oriented science to help citizenry, government, industry, and other stakeholders work collaboratively to make informed, socially responsible, science-based decisions. The socio-technical analysis presented in this monograph together with application of the latest innovations in IoT sensing, systems, and wireless communications technologies allows for a deeper understanding and management of these complex interconnected human-socio-environmental challenges.

West Lafayette, IN, USA
May, 2024

Abdul Salam

Acknowledgments

I could never be grateful enough to my wife *Umbreen Abdul Salam* and my children *Alizay Meerub Bilal*, *Anzalna Akhtar Sajid*, *Naba Salam*, and *Mohammad Yahya Hassan* for their unqualified encouragement that has meant so much to me.

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Chapter 1

Internet of Things for Sustainable Community Development: Introduction and Overview



1.1 Introduction

Sustainability is one of the vital factors in the realization of the digital future. The Internet of Things (IoT) is envisaged as one of the enabling paradigms of this sustainable digital transformation and community development. In this book, community is referred to as any geographical zones that function under some sort of structure and resources at its disposal to meet their current and future needs. Community sustainability depends on risk tolerance. The combined economic value of the industrial IoT along with public and consumer sector is likely to be more than \$15 trillion by 2030 [28, 67, 71]. Moreover, the convergence of the IoT with other technologies (e.g., artificial intelligence (AI), technological revolution, blockchain, cluster, and cloud computing) presents a tremendous potential for sustainable community development.

1.1.1 *Global Efforts to Address Sustainability*

A United Nations conference on the human environment was held in Stockholm, Sweden, in 1992. It was the first conference to discuss environmental issues. A report titled “Our Common Future” (also referred to as the Brundtland Report [38]) published by the World Commission on Environment and Development defined sustainability as:

“development that meets the needs of the present without compromising the ability of future generations to meet their own needs”

This report played an important role in increasing the awareness of environmental sustainable development. It identified many issues and changed our thinking toward sustainability. Accordingly, the United Nations started developing indicators and systems for sustainable development. Since then, many conferences are held for sustainable development. The progress made by these conferences is outlined below:

- In 1983, the General Assembly (resolution 38/161) established a special commission to report on strategies for sustainable development, environment, and the global problems by 2000. The commission was later renamed to World Commission on Environment and Development.
- Earth Summit, United Nations Conference on Environment and Development (UNCED), June 1992. Approximately, 100 heads of state met in this Earth Summit to discuss pressing problems in environmental protection and socioeconomic sustainable development.
- Barbados Programme of Action (BPOA). UN General Assembly resolution 47/189. UN Global Conference on the Sustainable Development of SIDS, Barbados, 1994. A 14-point program identified priority areas' recommended actions.
- A UN General Assembly review session was held to review progress of sustainable development in New York, USA, in 1997.
- World Summit on Sustainable Development (WSSD). The Johannesburg Summit was held in 2002 to address challenges in improving human lives, natural resource conservation, increasing water, sanitation, energy, food, shelter, and health.
- Mauritius Strategy of Implementation (MSI 2005). It was held in Port Louis, Mauritius, to review sustainability progress in 2005.
- MSI+5. It was held in New York, USA, in 2010 to review the Mauritius Strategy of Implementation.
- The UN Conference on Sustainable Development (Rio+20) in Rio de Janeiro, Brazil, in June 2012. It was decided to develop a set of Sustainable Development Goals (SDGs) on top of the Millennium Development Goals (MDGs).

1.1.2 Sustainable Development Goals (SDGs)

In 2015, the UN General Assembly set forth the Sustainable Development Goals (SDGs) in its resolution 70/1 with 2030 [71] as the target year [66]. These goals have been developed with the community involvement including academia, governments, and private sector. It encompasses three major sustainable community development dimensions (e.g., protection of the environment, social diversity and inclusions, and economic growth). The SDGs have become the widely accepted and adopted standard system to attain the aim of sustainable community development. These goals are important in the entire IoT paradigm to increase the sustainability and social impact. The UN Sustainable Development Goals are shown in Fig. 1.1.



Fig. 1.1 The UN Sustainable Development Goals [41]

The IoT with its ability to sense and communicate through interconnection of things and systems in different environments has the great benefit of achieving these sustainable development goals. In the sustainability area, the IoT along with technology is going to be a huge game changer in the near future. It is a comprehensive, commercially viable, widely available, and accepted technology to achieve these goals with many social and economic benefits at the regional and national level to broader community.

1.1.3 Sustainability Indicators

The indicators of sustainability are useful to describe minimum and contemporary requirements for sustainability. Accordingly, management policies and actions can be evaluated to make a reliable forecast of future changes.

“indicators must provide information relevant to specific assessment questions, which are developed to focus monitoring data on environmental management issues.”—Evaluation Guidelines for Ecological Indicators [37].

The sustainability indicators alone cannot help to achieve sustainable goals. More detailed actions are required at appropriate levels coupled with policy decisions. For example, surface water quality indicators only provide information about issues only at a small spatial and temporal scale requiring extrapolation for decision-making. Accordingly, the sustainable development guides policies considering all these factors. In the next section, the potential of the IoT as a comprehensive enabling paradigm to achieve SDGs is discussed.

1.2 IoT as Enabling Paradigm for Sustainability

The Internet of Things (IoT) for sustainable community development is envisaged to develop the engineered systems that enable sustainability by protecting the natural and environmental systems [14, 16]. Through interconnection of systems, sensing, and communication technologies, IoT for sustainability aims to provide a paradigm that balances community's need to provide ecological and environmental protection and maintains secure economic society.

The strong relationship between the Internet of Things and sustainability cannot be overemphasized [9, 25, 32, 35, 59, 60, 65, 67, 68, 72]. For example, a flood, sewerage, and storm overflow monitoring [53] Internet of Things solution based on sensing and communications supports sustainable communities (SDG 11) by reducing water-related disasters and economic losses. An IoT for condition-based maintenance of smart grid supports infrastructure (SDG 9). A city-scale smart lighting IoT supports improvements in energy efficiency (SDG 7). The next-generation wireless IoT has the potential of advancements in multiple fronts to accommodate the ever-increasing demands of commercial applications, scientific infrastructures, governmental agencies, and the public, in general for better and larger-scale connectivity (SDG 9). In the area of human health (SDG 3), instead of a single major technological breakthrough, the community can rely on the culmination of several key enabling IoT technologies. The wireless data harvesting IoT technologies can provide managers and users real-time access to crop and soil moisture data, which supports effective water management decision-making (SDGs 2 and 12). In digital forest management, the early warning system for drought stress can help to initiate and prioritize actions (SDG 13). The forest soil moisture detection can guide restoration decisions. These examples clearly show that sustainable community development is the mainstream benefit of Internet of Things.

In a study [28], the relationship between the Internet of Things and sustainability has been explored. Particularly, the 640 different Internet of Things projects were compared with the 17 SDGs in order to analyze the relationship between sustainability and Internet of Things. It has been shown that 84% of the analyzed IoT projects exhibited stronger potential to attain these goals. The five SDGs (SDG# 3, 7, 9, 11, and 12) were emphasized by 75% of the projects. The IoT supports sustainable development in the following areas:

- **Ecological Engineering.** The IoT enables sustainable development in the area of ecological engineering (e.g., rehabilitating and enhancement of ecological functions to natural systems and natural capital) [60].
- **Earth Systems Engineering.** The sustainable development of IoT supports monitoring of earth systems (e.g., greenhouse gas emissions). It has strong potential to guide adaption to varying climate, forestry, mining, energy systems, and related global-scale concerns through development of decision support systems [42].
- **Industrial Ecology.** The IoT fosters advancements and innovations in the area of industrial ecology, including evolution of life cycle assessment and economic models and measurements for sustainable systems [84].

- **Environmental Sustainability and Green Engineering.** The IoT paradigm has great potential to advance the sustainability of infrastructures (e.g., water; recycling and reuse of drinking water, stormwater, and wastewater; and climate assessment) [47]. Accordingly, the IoT guides innovations and growth strategies in distribution and collection systems based on its sensing and monitoring paradigm.

1.3 SDG Goals and Sustainable IoT Systems

The examples of the sustainable IoT systems in developing and developed countries are explained in the following.

1.4 Examples from Developing Countries

In developing and emerging countries, the IoT paradigm has the strong potentials to make big improvements in sustainability and human life [28]. With the increasing coverage of wireless networks in developing countries, it has become easier to form IoT networks with interconnection of “things.” The second-/third-generation wireless/cellular networking infrastructure in emerging countries surpasses electricity, water, and sewage infrastructure. The adaption of modern technology, such as technological innovations in the field of digital agriculture, health, environmental monitoring, energy systems, water resource monitoring, and livestock, is lacking due to the lack of basic resources and supporting infrastructure required for technology operation in developed countries. Consequently, the IoT monitoring systems either are in their infancy or do not exist. Scarce connectivity and spectrum availability are some of the other limiting factors. Therefore, there is need for ubiquitous connectivity with energy-efficient, low-cost wireless, machine-to-machine (M2M), and sensing technologies. Moreover, great potential exists for sustainable community development using IoT in various areas. The prospects for a variety of sustainable IoT use cases are very high. Higher level of efficiency can be achieved by using meaningful IoT paradigm and implementation. Accordingly, SDGs can be monitored for achieving sustainability goals.

There are many examples of IoT deployments around the globe which highlight sustainable community development. In the following, some examples from developing countries are presented [28]:

- **SDGs 10 and 16:** Secured biometric cash is being provided to refugees in Jordan by using the retina scan connected to financial IoT.
- **SDGs 7, 9, and 11:** Fire and smoke detection IoT with alarms is being used in highly dense urban settlements in Kenya and South Africa.
- **In the Indian Ocean,** the buoy IoT supports an early warning tsunami monitoring system.

- In East Africa and India, the low-income households are being powered by micro solar electricity off-grid IoT.
- Black carbon sensing IoT supports cooking stove monitoring in Sudan.
- Public transportation-connected mini bus IoT in Kenya is being used to monitor acceleration, speed, and braking to control risky driving.
- SDGs 12, 13, 14, and 15: In East Timor, cloud-based IoT supports monitoring the illegal fishing activity.
- Air pollution monitoring IoT to sense outdoor air pollution in Benin.
- Acoustic-based sensing IoT are being used to monitor sea bird migration patterns and population count.
- In Africa, animal tracking IoT supports game park management.
- In UAE, drone and ground camera monitoring IoT is being used by national park service.
- In Indonesia, digital forestry IoT supports monitoring of illegal logging activity.
- SDG 4: In South Africa, school attendance IoT has interconnected the students and faculty with the automated attendance system using biometric features.
- SDGs 1, 2, and 8: In Kenya, a weather monitoring IoT supports accurate weather forecasting.
- In India, pumps are interconnected using irrigation IoT for mobile-based irrigation management.
- Agriculture IoT based on soil moisture sensing to tea crop in Sri Lanka and Rwanda.
- Herd IoT in Namibia, Senegal, and Botswana, for animal tracking, keeping health records, and theft control.
- SDGs 3 and 6: In Rwanda and Kenya, SMS and sensor-enabled water pumps to support villagers.
- Cellular-connected cool chain IoT is being used for refrigerated delivery of vaccines.
- In West Africa, the medical IoT supports pulse, oxygen, and temperature monitoring.
- River monitoring IoT to sense river depth and rate of flow in Honduras.

1.4.1 Examples from Advanced Countries

Examples of the sustainable IoT systems toward achieving SDGs are discussed below:

- Internet of Things in Transportation and Logistics (IoTTL) [15]
- Agricultural IoT (Ag-IoT) [77]
- Internet of Battlefield Things [5]
- Wearable IoT [75]
- Internet of Body Things [20]
- Internet of Things in Smart Lighting and Heating [13]
- School bus transportation and tracking IoT [26]

- IoT of autonomous vehicle and unmanned aerial systems [18]
- Payment facilitator [39]
- Micro-transit IoT [10]
- Truck fleet IoT with charging stations [30]
- Multi-model transportation and logistics IoT [30]
- Garbage monitoring IoT [29]
- Waste and storm overflow monitoring IoT [53]
- Energy, smart meter, and renewable energy system IoT [45]
- Urban parking IoT [4]
- Mobility modeling and management IoT [63]
- Traffic counting IoT [62]
- City utility IoT [61]

1.5 IoT Challenges for Sustainability

Since the IoT market is still in infancy, there is a need for comprehensive business models and proof-of-concept implementation. Employing the sustainability goals during the design phase of the IoT is required to attain its full potential and economic benefit. Regulations, governmental incentives, monetary benefits, tax credits, and industry goodwill are some of the methods to encourage consideration of the sustainability goals at the system analysis and design of the IoT projects. An efficient business model is vital for sustainable IoT development. Introduction of accreditation programs to certify sustainability goals of the IoT is needed.

The management of a huge amount of data being generated through connected ubiquitous IoT projects is a major challenge because of its competitive and analytical value. The collection, ownership, and storage of data and its usage and sharing and sensitivity and privacy are some of the contentious issues that need to be solved.

The emergence of multitude of IoT platform providers has caused fragmentation which is hindering the critically desired consensus for standard development in the area of sensors, interfaces, and radios. The interoperability issues limit the choice of available hardware for IoT projects, and inter-system integration also suffers because of the closed standards. Collaboration among different stake holders particularly the standardization efforts can help to reduce the impact of fragmentation. Opening up the data will also lead to development of cross-industry systems. These technical partnerships can also be used to integrate different technologies together to provide a unified front end.

The lack of large-scale IoT infrastructure due to low interest from investments from public and private sectors is also hindering sustainability goals. The utilization of existing infrastructure and encouraging investors for IoT infrastructure through policy incentive and simplified legal and regulatory frameworks will help in the development of IoT infrastructures at a scale. A joint symposium of governments, academia, and industry leaders should be organized to discuss the sustainability promise of IoT in water, energy, urban environment, and transportation areas.

1.6 IoT Definitions

In this section, the IoT definitions as conceived by different standard bodies are presented.

1.6.1 *Institute of Electrical and Electronics Engineers*

A network of items, each embedded with sensors that are connected to the Internet [1].

1.6.2 *International Telecommunication Union*

The International Telecommunication Union Telecommunication Standardization Sector (ITU-T) has defined IoT as a vision with technological and societal implications:

Internet of Things (IoT) is a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies [36].¹

According to this recommendation, the IoT, by using sensing and communication capabilities, utilizes things to serve different types of application needs while ensuring security and privacy. The elements (terms) of the IoT paradigm are given below [36]:

- **Device.** A piece of equipment with the mandatory capabilities of communication and the optional capabilities of sensing, actuation, data capture, data storage, and data processing.
- **Things.** An object of the physical world (physical things) or the information world (virtual thing).

¹ ITU-T Rec. Y.2060 (06/2012) Overview of the Internet of things.

An infrastructure of interconnected objects, people, systems, and information resources together with the intelligent services allow them to process information of the physical and the virtual world and react—[79].²

1.6.3 Internet Engineering Task Force

The Internet Engineering Task Force (IETF) excludes TCP-/IP-based Internet from the IoT domain because of private networks. To be considered an IoT, it has to contain both IP and other protocols. IETF defines IoT as:

The Internet of Things is the network of physical objects or “things”: embedded with electronics, software, sensors, and connectivity to enable objects to exchange data with the manufacturer, operator, and/or other connected devices [34].³

IETF definition of “things”:

In the vision of IoT, “things” are very various such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, mobile phones, clothes, food, medicines, and books. These things are classified as three scopes: people, machine (e.g., sensor and actuator), and information (e.g., clothes, food, medicine, and books). These “things” should be identified at least by one unique way of identification for the capability of addressing and communicating with each other and verifying their identities. In here, if the “thing” is identified, we call it the “object.” [34]

1.6.4 National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST) defines IoT as:

² IT4IT References Architecture—ISO/IEC JTC1 WG10.

³ IETF.

Internet of Things (IoT)—involves connecting smart devices and systems in diverse sectors such as transportation, energy, manufacturing, and healthcare in fundamentally new ways. Smart cities/communities are increasingly adopting CPS/IoT technologies to enhance the efficiency and sustainability of their operation and improve the quality of life [48].⁴

Internet of Things Architecture (IoTIA) describes IoT in the following manner:

It can be seen as an umbrella term for interconnected technologies, devices, objects, and services [8, 33].

1.7 Architecture of IoT Paradigm for Sustainability

The Internet of Things (IoT) for sustainability concept is based on the defining network of things and people in various environmental and natural setting goals to achieve sustainable goals. This pertains to application of IoT concepts to these settings using sensing and communication technologies and systems and tools tailored to various application domains and for different use cases. The sensing elements provide the interface to the physical world and are linked through communication technologies.

1.7.1 *IoT Elements*

The Internet of Things for sustainability consists of the following elements:

- **Sustainability Things.** It is an integral part of the IoT paradigm with the ability to have physical or virtual connection to the IoT system.
- **Sensors/Actuators.** An instrument/equipment for environmental, climate, forestry, water, and energy sensing. It consists of an interface for networking and communications and may have on-unit processing and data storage capabilities.
- **Networking and Communications.** To support interconnection of sustainability things and sensor/actuator components.
- **Sustainability IoT System.** It consists of interconnection of different elements such as things, sensors, and communication components integrated together to perform certain unique functions.

⁴ NIST.

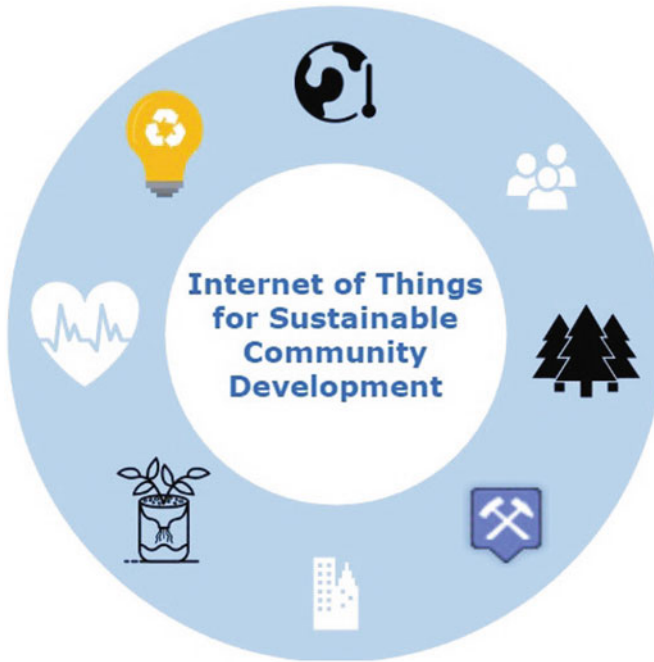


Fig. 1.2 The Internet of Things (IoT) for sustainable community development

- **Holistic Sustainability IoT Paradigm.** It is the paradigm in which different IoT systems work together in order to achieve sustainability goals for a particular environment. These environments are shown in Fig. 1.2.

1.7.2 IoT Functions

The proper functionality of these sustainability IoT components is vital to meet requirements and achieve sustainability goals. A clear description of these sustainability goals coupled with requirements is needed for integration into the holistic sustainability IoT paradigm for various applications. A detailed list of these functions along with examples is given in the following:

- In IoT, the sensing function is used to sense physical, logical, and biological properties of different environments in the physical world in the analog and digital domains. Accordingly, this data becomes an input to subsequent functions of the IoT which can be used by data collection, networking, data storage, processing, and decision-making functions. Examples include cloud sensing, soil sensing, and water sensing. Different examples of sensing mechanisms in various sustainability IoT sensing phenomena are discussed in detail in this book in subsequent chapters.

- The data collection is a major function of the IoT in which data is gathered, combined, and processed for a particular environment that provides the ability to combine and process some data of interest within a given IoT system.
- The networking function of the IoT is used to transport sensed data from different locations to storage location and cloud for subsequent decision-making function. These could function in delay-tolerant and delay-sensitive fashion depending on the latency requirement of a particular sustainability paradigm. In the IoT for sustainability paradigm, the networking tiers contain many layers including satellite, aerial, terrestrial, underwater, and underground networks. These network tier functions are discussed in the next section. The network interface cards are used to implement the networking and communication functions in the IoT paradigm and provide connection between links. The Ethernet adapter (IEEE 802 Standard), long-term evolution (LTE) Bluetooth, and Zigbee are some examples of these networking interface cards.
- The data storage and cloud function of the IoT are related to storing the data and information over the spatial and temporal variation. The examples of data storage functions include precipitation data, soil moisture data, hydrometer data, air temperature, wind speed and direction, water flow in different water bodies, nutrients and ion concentrations, and forest inventory.
- The processing function of the IoT converts raw sensed data to the useful information and provide it to decision-making function, where it can be utilized by managers and policy makers. The center pivot control algorithms of actuator units in the sensor-guided irrigation management systems are one example of the processing function where data is fed from underground sensors in the field of digital agriculture. Feedback control is another example.
- Decision-making. In this IoT function, a decision is made based on the data collection and processing, and accordingly, appropriate actions are taken which results into corresponding changes in the physical world to achieve the desired sustainability goal. Some of the examples of these functions include flow control based on flow nutrient sensing, correct application of water treatment based on contaminant sensing, proper irrigation based on soil moisture sensing, cardiac treatment based on hear conditions, and fertilizer application based on the crop needs. It also includes functionality related to the human interaction with the IoT systems using graphical user interfaces, touch displays, and voice interfaces. The cybersecurity, encryption, and authentication are other functionalities.

1.8 Networking for Sustainability IoT Paradigm

The IoT for sustainable development will be deployed at large scales by using networking and advanced 5G/6G communication architectures to serve a wide variety of applications in different areas. These communication networks are discussed below.

1.8.1 *Five-Tier Network*

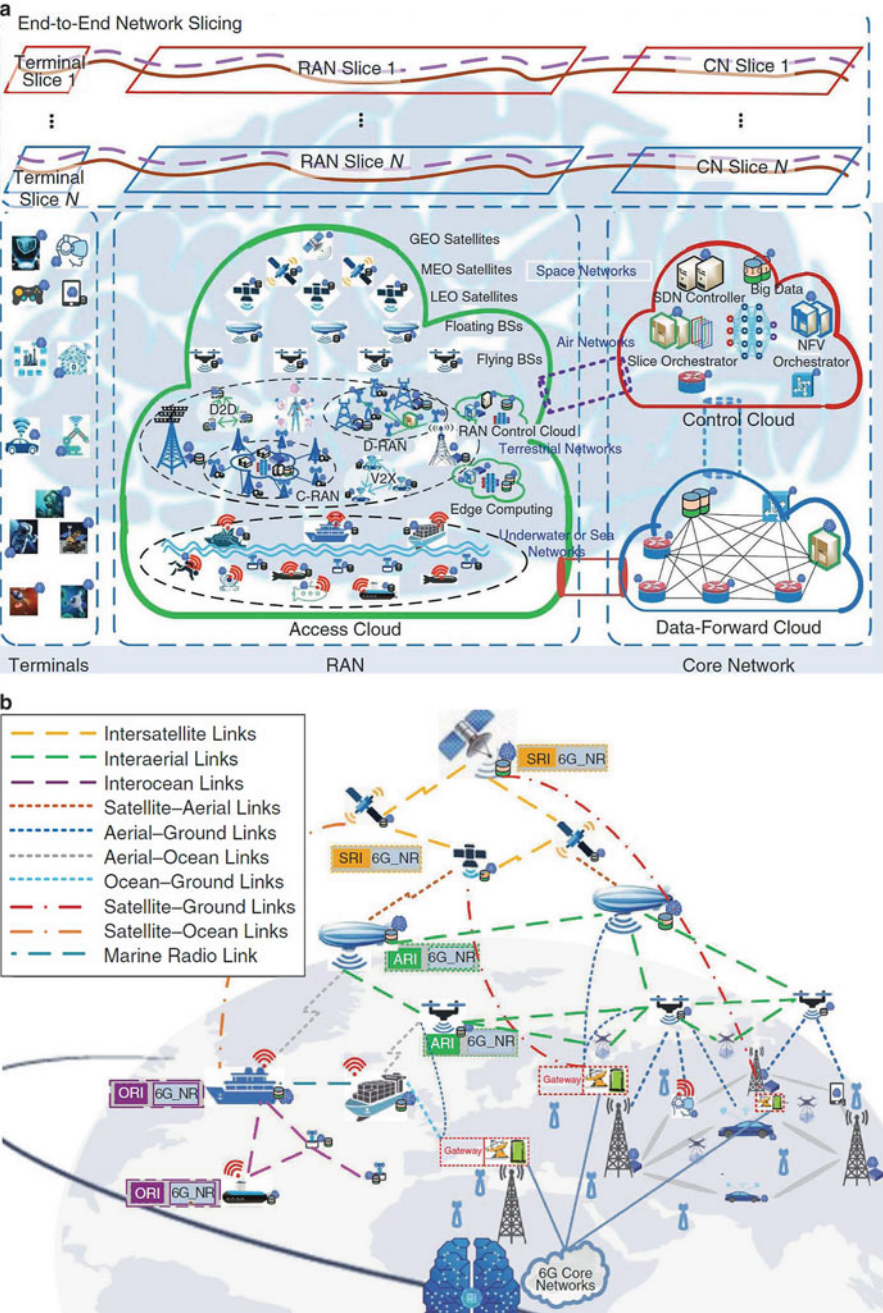
The potential of current terrestrial networks is too less to support ubiquitous coverage connectivity requirement of sustainable IoT in climate, water, ocean, and energy areas. Therefore, to support these IoT paradigms, a multidimensional network with capability to integrate terrestrial and non-terrestrial systems is required. A five-tier network can support this integration and consists of five different tiers including space, ground, air, underwater, and underground. In Fig. 1.3, a design of multitier network is shown [83]. The sixth-generation (6G) networks will have this capability to integrate multiple tiers which are explained below.

1.8.1.1 Terrestrial Network Tier

The terrestrial networks are the main tool to provide wireless connectivity for most of the sustainability IoT paradigms discussed in this book. Terrestrial networks will have the capability to operate in low frequencies, microwave spectrum, mm-wave, and THz bands. To support higher data rate (e.g., Tb/s), such as sustainable water and climate measurements, the THz band can be utilized. Energy-efficient mm-wave communication devices based on a hybrid beamforming approach can also support real-time high data rate communication needs. These networks will have high-density deployments because of the higher attenuation in mm-wave and THz. An optical fiber is needed as a backbone of these networks. The important technologies for the terrestrial networks are shown below [82]:

- The millimeter-wave, terahertz communications, and full-duplex communication
- Multiple-input, multiple-output (MIMO), distributed antenna arrays, and DMIMO
- Interference cancellation, cognitive radio networks, and NB-LPWAN
- Underwater/underground, large-scale network design, and sensor networks
- Cellular networks, device-to-device, and cyberphysical systems
- Vehicular networks, UAV connectivity, safe UAV operation, and green cellular networks
- Cyber threat defense, mobile computing, network estimation, and content delivery networks
- Statistical signal processing, multimedia networking, security, and privacy
- Smart grid, cloud-fog platforms, software-defined networking, and mobile edge networking

Moreover, the conventional SDRs with novel mm-wave radio can be used to create unique solutions by combine beam agility for highly directional communication in mobile environments with ultralow-power characteristics. The design of novel low-loss hybrid electronically scanned arrays (ESA) capable of beamforming at millimeter-wave (mmW) frequencies for next-generation high data rate communication systems will be central for sustainable IoT realization.



1.8.1.2 Space-Based Wireless Network Tier

The wireless coverage requirements of the IoT for sustainability can be supported by space network by using satellites [6]. The future space network can utilize densely deployed low-medium-geostationary Earth orbit satellites to provide connectivity uncovered and undeserved area (e.g., IoT for sustainable digital agriculture). In agriculture, the irrigation and water management community has measured soil moisture to inform water management and irrigation decisions for decades. Automated technologies have largely replaced the use of handheld/manual soil moisture technologies because of difficulties associated with taking manual soil moisture readings in production fields in remote locations.

In the last decade, wireless data harvesting technologies have developed that provide managers and users real-time access to soil moisture data, which has resulted in more effective water management decision-making. Unfortunately, advanced automated and wireless soil moisture measurement technologies still face practical application challenges. One challenge is a lack of consistent and robust wireless service in rural communities that prevent immediate access to soil moisture data. Another is the difficulty of installing soil moisture sensors early in the growing season and removing them at the end of the season. Currently, users must drive long distances to install and remove sensors in different locations during the growing season, which creates problems in deploying advanced technologies in production fields.

Therefore, wireless underground soil moisture devices imbedded permanently in the soil, coupled with robust, reliable, and continuous wireless network services through satellites in rural agricultural communities, will significantly contribute to the adoption of technology and sustainable practices in production fields. For long-range, high data rate satellite to field communications in sustainable digital agriculture, the satellites with mm-wave communications can be deployed.

1.8.1.3 Aerial Network Tier

The recent advancements in technology have made possible to deploy air networks in low-frequency bands, microwave spectrum, and mm-wave bands using aerial base stations mounted on unmanned aerial vehicles complemented by space networks. The aerial networks can enable IoT paradigms in the harsh areas where terrestrial networks are unable to provide coverage [12]. One application of aerial networks is in IoT for sustainable water where pollution-level monitoring and advanced nutrient measurements are used in water bodies to assess water quality to assist regulators for pollution policy making.

Currently, the UAV potential in sustainability IoT is limited in part by their ability to navigate spaces precisely and in a cost-effective manner. The existing mechanisms to support localization are often hampered by cost (e.g., GPS-RTK), service gaps (cell towers), or crowded environments (e.g., Global Positioning System (GPS)).

1.8.1.4 Underwater Network Tier

The underwater networks will enable sustainable IoT monitoring applications in oceans, estuaries, rivers, lakes, streams, canals, and wetlands [7, 17, 64, 78]. Due to different wave propagation characteristics in the water medium from over-the-air (OTA), the acoustics and laser propagation can be utilized to attain higher data rates for underwater communication and networking. It has applications in sustainable climate IoT in tsunami and undersea earthquake monitoring.

1.8.1.5 Underground Network Tier

In a new type of wireless communications (wireless underground (UG) communications) [2, 76], radios are buried underground and communication is conducted partly through the earth. The underground communication (UG) solutions are in their infancy and depend on off-the-shelf radios, which are not designed for the medium. For example, the maximum attainable communication ranges for underground-to-underground links are limited to a few meters, which prohibits the establishment of multi-hop underground networks. On the other hand, UG radios can establish communication with aboveground devices at distances over 200 m. While promising, these distances are still limited for some applications, e.g., agricultural automation where large fields need monitoring with a limited network architecture to mobile data harvesting components [19]. In addition, the data rates attained by commercial off-the-shelf (COTS) solutions are limited to tens of kbps, which prohibits data-hungry applications, including real-time control and navigation components.

To enhance wireless UG communication ranges, a novel theoretical framework for UG beamforming using adaptive antenna arrays to improve wireless underground communication performance [55] has been devised. A soil moisture adaptive beamforming (SMABF) algorithm was developed for planar array structures, and simulations show, with different optimization approaches, that the range can be significantly improved. Similarly, multi-carrier underground communication through soil-adaptive sub-carrier and system bandwidth operation can significantly improve data rates [54, 57]. Currently, practical *and large-scale* evaluations of these techniques are cost prohibitive, limiting rapid commercialization for practical applications.

Underground networks support many unique applications in sustainability IoT by using wireless UG communications (e.g., stormwater and wastewater monitoring IoT and agricultural IoT). Existing over-the-air (OTA) wireless communication solutions face significant challenges in meeting the unique requirements of Ag-IoT applications. Therefore, these IoT paradigms for sustainability can use a diverse set of UG communication requirements and realistic scenarios to implement the communication range- and capacity-enhancing solutions in large scales. The integration of UG communications with Ag-IoT will help conserve water resources and improve crop yields [24, 27, 70, 74]; advances in Ag-IoT will benefit underground

infrastructure and landslide monitoring, pipeline assessment, underground mining, and border patrol [3, 19, 54, 56–58, 76].

1.9 Wireless Communications for Sustainability IoT

In the following section, the key wireless communication technologies and drivers are discussed for the sustainability IoT.

1.9.1 *Key Drivers for Next-Generation Wireless Systems in Sustainability IoT*

- The operation frequency in the spectrum is moving from the radio bands to sub-terahertz (THz) bands and visible spectrum (e.g., visible light communications).
- The drive for automation and intelligence in wireless networks is relying on use of advanced technologies such as artificial intelligence (AI) and machine learning.
- More robust and dynamic networking architectures to meet goals of sustainable development.
- These innovations will also drive development in novel applications based on networking architectures.

1.9.2 *Wireless Requirements for Sustainability IoT*

The wireless communications and networking requirements for sustainability IoT require innovation to increase data rates, capacity, connectivity, spectrum usage, energy efficiency, and mobility [23]. The key requirements are listed in the following:

- **Peak Data Rates.** The current peak data rates of 5G are around 10 gigabits per second (Gbps), whereas to meet sustainability IoT demands, the data rates of 1 Tb/s are required. This hundred times higher data rates demand that the current can be met by the next-generation technologies such as 6G, where the peak back-haul and front-haul data rates of 10 Tb/S can be achieved.
- Due to multitude of technology operators vying for the scarce spectrum, spectrum-efficient communications are vital for sustainability IoT. Particularity, in multitier networks, the same connectivity zones will be covered by multiple access network tiers, causing severe interference among tiers within the paradigm. Therefore, advancement in interference mitigation, suppression, and cancellation techniques is required. Integration of licensed and unlicensed technologies (e.g., short-range Wi-Fi and long-range cellular) is also necessary to connect all sustainability things in different IoT applications.

- **Application-Specific Data Rates.** For some scenarios, such as hyper-spectral mineralogy sensing techniques, application-specific data rates of 1–10 10Gb/s rates are required.
- **Extreme energy-efficient technology and devices** are required to support prolonged uninterrupted operation in some of the sustainability IoT scenarios such as urban underground infrastructure monitoring, storm and sewer overflow monitoring, and underground soil sensing. For example, IoT devices can awake from the sleep mode for data reception after periods of longer duration to extend battery life.
- **Latency and Mobility.** To archive quality of service (QOS), an OTA latency of 0.01–0.1 ms and extremely high mobility (621 miles/h) is required for sustainability IoT paradigm. More, low-latency space-to-air and space-to-ground links are needed.
- **Novel gateways, protocols, and standards** are required to integrate different network tiers. One example of this link is interconnection between IoT devices in aerial networks and sensors in underground and underwater networks. Other examples include aerial to ground and space to aerial to ground stations. Things to people interaction gateways can utilize computer vision, always-on discovery and awareness, and machine learning. Moreover, advancements in Things-to-Things (T2T) communication technologies are needed.
- **Connectivity Density.** For water climate monitoring IoT applications, a very high density of approximately 145 devices/ mi^2 and with subnetwork capacity of more than 1 Gb per second per square mile. This will help to attain interoperability across multiple sustainability paradigms.
- **Cybersecurity.** It is discussed in detail in Chap. 10.

1.9.3 Wireless Standard Applications to Sustainability IoT

1.9.3.1 RF Wireless Modem Chipset

The chipset with ability to support multiple wireless and cellular standards will play a critical role to achieve the regional and local connectivity in different applications in sustainability IoT paradigm (e.g., health, security, and energy). In this regard, innovations are needed to produce cost-effective and scalable RF wireless modem chipset design [52]. Any such chipset will support multiple bands and modes with power saving, battery life for up to a decade through advanced power saving with Bluetooth, voice, and Wi-Fi interfaces with backward compatibility. Other important wireless interfaces include GSM, LTE FDD and TDD, EDGE/EGPRS, DC-HSPA, LR-WPAN, and TD-SCDMA. AllJoyn Open Connectivity Foundation (OCF) is an open-source framework interface-/device-/application-secure communication protocol that supports discovery of devices manufactured by different vendors.

1.9.4 Standardization for Sustainability IoT

1.9.4.1 Long-Term Evolution (LTE) IoT

The long-term evolution (LTE) is an enabler for high-performance and scalable sustainability IoT services that can provide high data rate (gigabit) [46]. It has high energy and power efficiency to address sustainability IoT needs. It combines improved machine-type communication (eMTC Cat-M1) and the narrowband IoT (NB-IoT) for narrowband applications (Cat-NB1) and supports grant-free uplink and multi-hop mesh. The low-complexity, long-range, and low-power communications in sustainability IoT can be supported by using NB-IoT and eMTC (e.g., agriculture, wearable, health, smart meters, and climate). The LTE Direct is a device-to-device (D2D) protocol that uses LTE user authentication, resource allocation and timing features to provide neighbor discover, and connectivity to mobile nodes in the node proximity.

1.9.4.2 802 Wi-Fi Standards

Wi-Fi has a great potential to provide connectivity to many IoT devices and things to achieve sustainability. These 802.11 Wi-Fi standards that can be utilized for sustainability IoT are shown below [31]:

- 802.11ah for low-power operation in the 902–928 MHz frequency bands
- 802.11ac for 5 GHz spectrum unlicensed uses
- 802.11ad for WiGig networking
- 802.11ay for 60 GHz unlicensed uses
- 802.11ax for dense networking environment

Many important alliances include HomePlug Powerline Alliance [49], Bluetooth Special Interest Group (Bluetooth SIG) [11], Open Connectivity Foundation (OCF) [43], the Thread Group [40], the Powerline Technologies, and oneM2M. In a recent trial of high data rate communications, it has been shown that it is possible to achieve 100 Gb/s in microwave spectrum using multiple-input, multiple-output (MIMO) for a communication range of approximately 1 mile. This trial has shown the feasibility of better communications in microwave as compared to the millimeter-wave (mm-wave) communications [81]. The important trial parameters are 8×8 LOS MIMO, and 2.5 GHz channel bandwidth in the 70 and 80 GHz (E band) with high spectrum efficiency of 55.19 b/s/Hz. Recently, an autonomous unmanned broadband smart surface vessel was operated remotely using 4G network for water quality and pollutant sensing.

1.9.4.3 5G and 6G Wireless Communications

Currently, the 5G communications [22] are envisioned as a big technology driver for the Internet of Things, in particular for sustainable community development (e.g., smart cities, public safety, transportation, smart energy usage, connected and autonomous vehicles, and healthcare). Through its better than 4G speeds, energy and spectrum efficiency, low latency, and higher reliability, the 5G wireless networking is vital to realize sustainability IoT and its real-time data-intensive communication needs in applications such as real-time video streaming for police body cams and medical imaging.

Currently, there are many challenges in 5G. Although in 5G the ultrareliable low-latency communications (URLLC) [69] has the potential to support sustainability IoT applications, its performance suffers from the small packet size issue that is a limiting factor for higher data rates. In addition, the support for sensing, communications, things, and system convergence is limited in 5G and more improvements are needed in this area. Another needed feature in regard to IoT is the support for virtualization radio access network (vRAN) due to front-haul challenges. Moreover, in 5G dynamic pricing models are needed based on capacity and usage. The limitations of slow data rates; convergence of IoT sensing, systems, and wireless communication; and open interfacing-related issues can be solved with novel networking architectures of 6G wireless communications which is discussed next (Fig. 1.4).

The road map to 6G wireless communications has already started to take shape. The requirements and trends are being defined with 6G enabling technologies for connected intelligence and things. The prominent 6G goals and desirable features are listed below [83]:

- Support of extremely high data rates (in Tb/S) as compared to current 4G wireless communications
- High-energy efficiency, energy harvesting, and wireless power transfer to support IoT
- The ultralow latency in data and control planes in few microseconds
- Support for a very wide spectrum in GHz and THz bands such as from 72 GHz to 141 GHz and 1000 GHz to 3000 GHz
- Convergence of space- and ground-based wireless networks to provide global connectivity and coverage
- Intelligence built into the network through machine learning, enhanced mobile broadband (eMBB) [44] ultrareliable low-latency communications (URLLC) [69], and massive machine-type communications (mMTC) [50]

1.9.5 Artificial Intelligence and Wireless

Artificial intelligence (AI) will play a key role in optimization and autonomous functionality of the network [80]. A list of AI algorithms in networking is shown

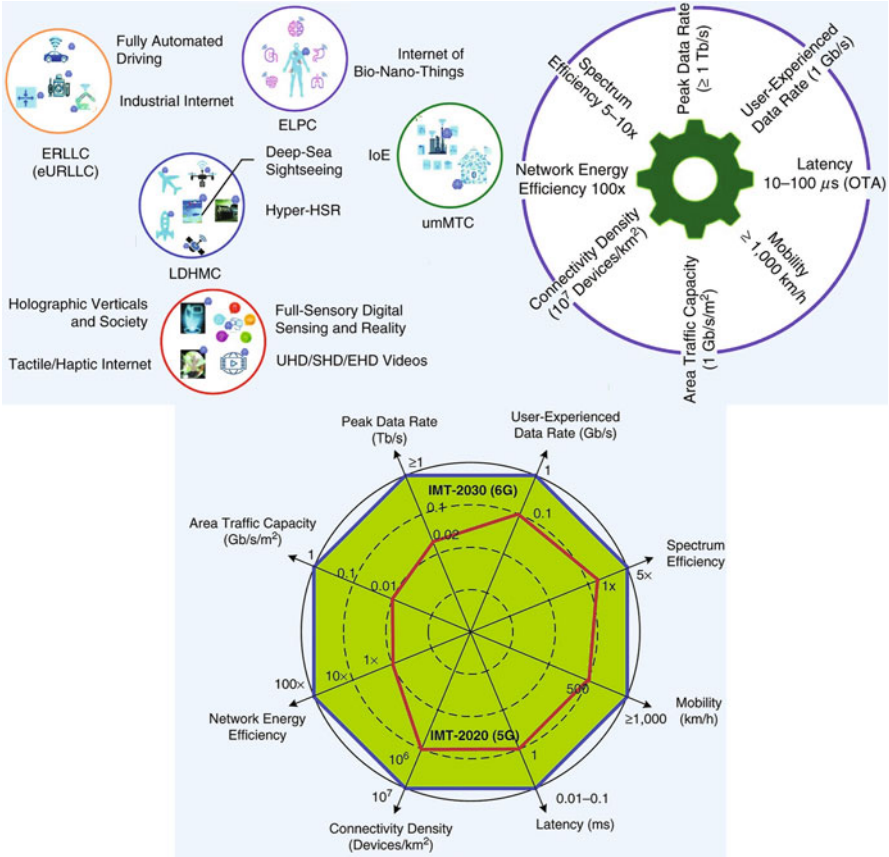


Fig. 1.4 The 6G application scenarios [83]. (a) The 6G application scenarios, (b) typical scenarios, and (c) key capabilities of 6G networks

in Fig. 1.5. The AI enabling technologies in wireless communications are discussed below:

- Application of AI training methods, specifically machine learning, in wireless communications will bring innovation and performance improvements. This can be achieved by intelligence management and autonomous agent.
- The neural network-based deep learning for data-driven approaches in wireless.
- AI applications to address network management, complexity, and QoS issues in next-generation wireless networks.

1.9.6 Wireless Spectrum Paucity

The wireless spectrum scarcity is a major challenge for heterogeneous wireless systems. The demand for wireless spectrum to meet the needs of sustainability IoT

Network Functions		AI Algorithms	Descriptions
Network Architecture			
SDN	Decoupling the control and data-forward function to achieve programmable network management and configuration.		
NFV/ NS	NFV: Decoupling software and hardware and eliminating the dependency of network functions or dedicated hardware		· Achieving dynamic network orchestration and slice management according to real-time network information and service requirements
Cloud/ Fog /Edge Computing	NS: Creating multiple instances of parallel network functions to achieve on-demand network deployments.	· DNN · Enhanced Q-Learning	· Providing on-demand dynamic network configuration and critical network management.
	Cloud Computing: Providing for stocking and accessing data and applications and using networks of shared IT architecture containing large pool of systems and servers.	· Support Vector Machines · Decision Trees · Self-Organizing Maps · Biological Danger Theory · Gradient-Boosted Regression	· Achieving autonomous network management and maintenance to improve network performance and reduce operational expenditures.
	Fog Computing: Extending computing to the edge of the network and facilitating the operation of computing, storage and networking services between end devices and cloud computing data centers.	· Deep Reinforcement Learning	· Achieving optimal multilevel computing resource allocation according to resource state, network load, and computing task profile to improve computing efficiency
PHY Air-Interface Protocol Layers			
Physical Layer	· Providing reliable data transmission, including channel coding, modulation, MIMO precoding, OFDM Modulation, and so on.	· DNN · K-Means · CNNs · CCNNs	· Innovating end-to-end PHY design and reducing the complexity of the MIMO-OFDM receiver.
	· Providing channel estimation	· Autoencoder	· Improving PHY performance, especially for such scenarios as high mobility.
Data Link Layer	· Performing frame flow-related operations, including scheduling (or resource allocation), power control, error control, error correction, flow control, synchronization, data packet queuing, and so on.	· DNNs · Q-Learning · Reinforcement Learning · Supervised Learning · Transfer Learning	· Achieving optimal user scheduling by channel estimation and traffic prediction based on trained models to improve network performance and increase radio-resource efficiency. · Optimizing retransmission redundancy version and reducing transmission overhead.
Network Layer	· Responding for RRC connection management, mobility management, BS association, BS clustering, load management, and routing management.	· DNNs · Q-Learning · Reinforcement Learning · Supervised Learning · Un-supervised Learning · K-Means · Transfer Learning	· Optimizing service cells and data offloading cells by traffic prediction. · Optimizing multiple connectivities · Achieving mobility prediction and hand-over process optimization to improve mobility performance. · Providing optimal path for data transmission by learning routing strategies and extracting useful information from raw network data directly. · Achieving optimal BS lustering and controlling the size of a cluster in a dynamic

Fig. 1.5 AI algorithms in networking [83]

applications is increasing which could be met by the identification and allocation of additional spectrum. Spectrum sharing through cognitive radios is another approach to address the issue of dearth of spectrum where unlicensed users can use the spectrum when the primary user is not present in the licensed spectrum. The efforts of the US Federal Communications Commission (FCC) to address this issue through rulemaking are presented below [21, 73]:

- Use of spectrum bands above 24 GHz for mobile radio services
- Establishing a more flexible framework to facilitate satellite operations in the 27.5–28.35 GHz and 37.5–40 GHz bands

- Petition for rulemaking of the fixed wireless communication coalition to create service rules for the 42–43.5 GHz band
- Petition for rulemaking of the fixed wireless communication coalition to create service rules for the 42–43.5 GHz band
- Allocation and designation of spectrum for fixed-satellite services in the 37.5–38.5 GHz, 40.5–41.5 GHz, and 48.2–50.2 GHz frequency bands
- Allocation of spectrum to upgrade fixed and mobile allocations in the 40.5–42.5 GHz frequency band
- Allocation of spectrum in the 46.9–47.0 GHz frequency band for wireless services
- Allocation of spectrum in the 37.0–38.0 GHz and 40.0–40.5 GHz for government operations

1.9.7 Rural Broadband Telecommunications

The broadband infrastructure is vital for the proper functionality of sustainability IoT. In rural areas, there are many challenges being faced by the service providers (e.g., network extension to under-covered areas and need of infrastructure upgrades to meet increasing demand) [51]. Rural broadband is important to provide connectivity to agricultural users and things.

1.9.8 Satellite Communications

Satellite communications also play an important role to provide connectivity to the sustainability IoT paradigm things. A global low-power wide-area network (LPWAN) to support IoT devices around the world by combining the Inmarsat's global connectivity as backhaul connectivity and Actility's LoRaWAN technology. Various applications are enabled by this network such as cattle tracking systems for remote ranches, water and soil moisture monitoring in agriculture, and remote oil facility monitoring in areas where cellular coverage does not exist. Other sustainability IoT applications that can benefit from satellite communications include smart grid, underground and surface pipeline monitoring, vehicular fleet tracking, water resource management, disaster response, remote and critical infrastructure monitoring, environmental protection, wind turbine monitoring, and border security.

1.10 Organization of the Book

The book covers the research and innovation ecosystem of the sustainable Internet of Things in the following major areas:

- Climate change
- Sustainable energy systems
- Sustainable water
- Human health
- Sustainable mining
- Decision agriculture
- Storm and wastewater
- Sustainable forestry

Each of these areas will emphasize core IoT research challenges and solutions while leveraging their shared traits, interdependencies, and expertise to converge on applications of IoT to sustainability challenges. In the following, we highlight the abovementioned areas, each with a collection of supporting concepts that are developed and explored in this book. Many of these areas emphasize cross-cutting activities that support major cohesive goal of sustainability.

Chapter 2: Internet of Things for Environmental Sustainability and Climate Change Our world is vulnerable to climate change risks such as glacier retreat, rising temperatures, more variable and intense weather events (e.g., floods, droughts, and frosts), deteriorating mountain ecosystems, soil degradation, and increasing water scarcity. However, there are big gaps in our understanding of changes in regional climate and how these changes will impact human and natural systems, making it difficult to anticipate, plan, and adapt to the coming changes. The IoT paradigm in this area can enhance our understanding of regional climate by using technology solutions while providing the dynamic climate elements based on IoT sensing and communications that are necessary to support climate change impact assessments in each of the related areas (e.g., environmental quality and monitoring, sustainable energy, agricultural systems, cultural preservation, and sustainable mining). In the IoT in Environmental Sustainability and Climate Change chapter, a framework for informed creation, interpretation, and use of climate change projections and for continued innovations in climate and environmental science driven by key societal and economic stakeholders is presented.

Chapter 3: Internet of Things in Agricultural Innovation and Security The agricultural Internet of Things (Ag-IoT) paradigm has tremendous potential in transparent integration of underground soil sensing, farm machinery, and sensor-guided irrigation systems with the complex social network of growers, agronomists, crop consultants, and advisors. The aim of the IoT in agricultural innovation and security chapter is to present agricultural IoT research and paradigm to promote sustainable production of safe, healthy, and profitable crop and animal agricultural products. The chapter covers the IoT platform to test optimized management strategies, engage farmer and industry groups, and investigate new and traditional technology drivers that will enhance resilience of the farmers to the socio-environmental changes. A review of state-of-the-art communication architectures and underlying sensing technology and communication mechanisms has been presented with coverage of recent advances in the theory and applications of wireless underground

communication. Major challenges in Ag-IoT design and implementation are also discussed.

Chapter 4: Internet of Things for Water Sustainability Water is a finite resource. The issue of sustainable withdrawal of freshwater is a vital concern being faced by the community. There is a strong connection between energy and water which is referred to as energy-water nexus. The agricultural industry and municipalities are struggling to meet the demand of water supply. This situation is particularly exacerbated in the developing countries. The projected increase in world population requires more freshwater resources. New technologies are being developed to reduce water usage in the field of agriculture (e.g., sensor-guided autonomous irrigation management systems). Agricultural water withdrawal is also impacting ground and surface water resources. Although the importance of reduction in water usage cannot be overemphasized, major efforts for sustainable water are directed toward the novel technology development for cleaning and recycling. Moreover, currently, energy technologies require abundant water for energy production. Therefore, energy sustainability is inextricably linked to water sustainability. The water sustainability IoT has a strong potential to solve many challenges in energy-water nexus. In this chapter, the architecture of IoT for water sustainability is presented. An in-depth coverage of sensing and communication technologies and water systems is also provided.

Chapter 5: Internet of Things for Sustainable Forestry Forests and grasslands play an important role in water and air purification, the prevention of soil erosion, and in the provision of habitat to wildlife. Internet of Things has a tremendous potential to play a vital role in the forest ecosystem management and stability. The conservation of species and habitats, timber production, prevention of forest soil degradation, and forest fire prediction, mitigation, and control can be attained through forest management using Internet of Things. Use and adoption of IoT in forest ecosystem management are challenging due to many factors. Vast geographical areas and limited resources in terms of budget and equipment are some of the limiting factors. In digital forestry, IoT deployment offers effective operations, control, and forecasts for soil erosion, fires, and undesirable depositions. In this chapter, IoT sensing and communication applications are presented for digital forestry systems. Different IoT systems for digital forest monitoring applications are discussed.

Chapter 6: Internet of Things in Sustainable Energy Systems Our planet has abundant renewable and conventional energy resources but technological, capability, and capacity gaps coupled with water-energy needs limit the benefits of these resources to citizens. Through IoT technology solutions and state-of-the-art IoT sensing and communication approaches, the sustainable energy-related research and innovation can bring a revolution in this area. Moreover, by the leveraging current infrastructure, including renewable energy technologies, microgrids, and power to gas (P2G) hydrogen systems, the Internet of Things in sustainable energy systems can improve challenges in energy security to the community with a minimal trade-

off to the environment and culture. In this chapter, the IoT in sustainable energy system approaches, methodologies, scenarios, and tools is presented with a detailed discussion of different sensing and communications techniques. This IoT approach in energy systems is envisioned to enhance the bidirectional interchange of network services in grid by using Internet of Things which will result in enhanced system resilience, reliable data flow, and connectivity optimization. Moreover, sustainable energy IoT research challenges and innovation opportunities are also discussed to address the complex energy needs of our community and promote a strong energy sector economy.

Chapter 7: Internet of Things for Sustainable Human Health The sustainable health IoT has the strong potential to bring tremendous improvements in human health and well-being through sensing and monitoring of health impacts across the whole spectrum of climate change. The sustainable health IoT enables development of a systems approach in the area of human health and ecosystem. It allows integration of broader health sub-areas in a bigger archetype for improving sustainability in health in the realm of social, economic, and environmental sectors. This integration provides a powerful health IoT framework to sustainable health and community goals in the wake of changing climate. In this chapter, a detailed description of climate-related health impacts on human health is provided. The sensing, communications, and monitoring technologies are discussed. The impact of key environmental and human health factors on the development of new IoT technologies is analyzed.

Chapter 8: Internet of Things for Sustainable Mining The sustainable mining Internet of Things deals with the applications of IoT technology to the coupled needs of sustainable recovery of metals and a healthy environment for a thriving planet. In this chapter, the IoT architecture and technology are presented to support development of a digital mining platform emphasizing the exploration of rock-fluid-environment interactions to develop extraction methods with maximum economic benefit while maintaining and preserving both water quantity and quality, soil, and, ultimately, human health. New perspectives are provided for IoT applications in developing new mineral resources, improved management of tailings, monitoring and mitigating contamination from mining, and tools to assess the environmental and social impacts of mining including the demands on dwindling freshwater resources. The cutting-edge technologies that could be leveraged to develop state-of-the-art sustainable mining IoT paradigm are also discussed.

Chapter 9: Internet of Things in Water Management and Treatment The goal of the water security IoT chapter is to present a comprehensive and integrated IoT-based approach to environmental quality and monitoring by generating new knowledge and innovative approaches that focus on sustainable resource management. Mainly, this chapter focuses on IoT applications in sewer and stormwater management and the human and environmental consequences of water contaminants and their treatment. The IoT applications using sensors for sewer and stormwater monitoring across networked landscapes and water quality assessment, treatment,

and sustainable management are presented. The studies of rate limitations in bio-physical and geochemical processes that support the ecosystem services supporting water quality are presented, and the application of IoT solutions based on these discoveries is discussed.

Chapter 10: Internet of Things for Sustainability—Perspectives in Privacy, Cybersecurity, and Future Trends In the sustainability IoT, the cybersecurity risks to things, sensors, and monitoring systems are distinct from the conventional networking systems in many aspects. The interaction of sustainability IoT with the physical world phenomena (e.g., weather, climate, water, and oceans) is mostly not found in the modern information technology systems. Accordingly, the actuation and the ability of these devices to make changes in the real world based on sensing and monitoring require special consideration in terms of privacy and security. Moreover, the energy efficiency, safety, power, and performance requirements of these device distinguish them from conventional computer systems. In this chapter, cybersecurity approaches toward sustainability IoT are discussed in detail. The sustainability IoT risk categorization, risk mitigation goals, and implementation aspects are analyzed. The openness paradox and data dichotomy between privacy and sharing are analyzed. Accordingly, the IoT technology and security standard development activities are highlighted. The perspectives on opportunities and challenges in IoT for sustainability are given. Finally, the chapter is concluded with sustainability IoT cybersecurity case studies.

Chapter 11: Medium Access in Internet of Things In medium access control, the medium access control, connectivity, and diversity reception approaches are discussed for wireless underground communications. The connectivity and interference models are studied for ad hoc and hybrid networks. The topology control mechanisms for maintaining network connectivity are explored for maximizing network capacity under the physical models (e.g., the protocol interference model and the physical interference model). Moreover, the underground diversity is examined for 3W-Rake receiver and coherent detection along with experimental evaluation. Finally, the chapter is concluded with comprehensive analysis of performance of equalization techniques.

In Chap. 12, a system model is presented, whereas Chaps. 12 and 13 discuss the IoT in cyber-physical systems.

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Chapter 2

Internet of Things for Environmental Sustainability and Climate Change



2.1 Introduction

The global climate is changing rapidly mainly because of the human activities over the period of last five decades [76, 133]. This change is projected to continue in the foreseeable future depending on the heat-trapping gas emissions in the environment and sensitivity of the climate of the Earth on these emissions [104]. From 1895 to 2020, an increase of 1.3–1.9 °F in average temperature has been observed in the USA with substantial increase after the year 1970 [7, 25, 106]. The change in global annual mean surface air temperatures (ocean and land combined) is shown in Fig. 2.1. An increase of 8 in. has been observed in global sea levels since 1880 with a projected increase of up to 4 ft by the end of this century. The ice-covered areas (surface extent) in sea, land, and lakes are decreasing with increase in temperature [59, 112]. The warmest month records are being broken consistently, and human-caused global warming combined with natural changes in climate is making too difficult to accurately predict climate variations [8, 75, 113, 115, 120]. Accordingly, due to the interdependence of the growing season on the frost-free period, the length of growing season has been increased and will continue to increase [4, 26, 34, 58, 64, 70, 142, 157, 158, 173]. Moreover, the average precipitation has increased with the corresponding increase in intensity of the extreme downpours and precipitation [7, 90, 124, 135, 151]. Furthermore, more variations are being observed in extreme weather occurrence patterns (e.g., the frequency of the cold waves have decreased but its intensity has increased) [9, 28, 40, 51, 79, 116, 146]. Similarly, the same patterns are being observed for droughts and flooding, where drought intensity has increased [44, 78, 117]. Since 1980, hurricanes have become more frequent and intense spanning over longer duration which is also related to the heavy downpours and intense storms [20, 39, 102]. The frequency and intensity of the winter storms, damaging winds, thunderstorm, and tornadoes are also the subject of climate change investigation [17, 61, 109, 155]. The ocean acidification (the decrease in the pH levels of the oceans) is increasing due to the one-fourth

Fig. 2.1 The change in global annual mean surface air temperatures (ocean and land combined) based on NASA/GISS/GISTEMP data

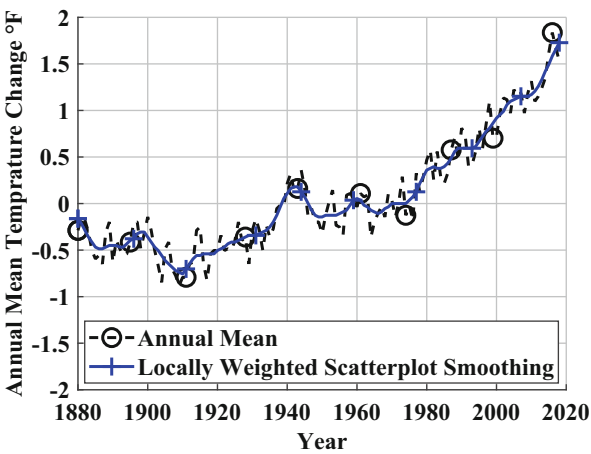
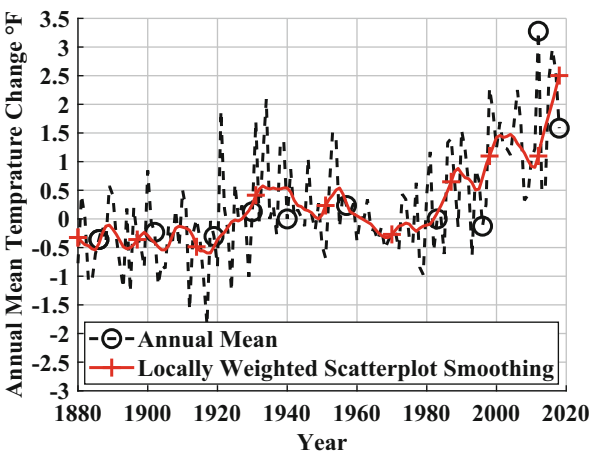


Fig. 2.2 The change in annual mean surface air temperatures in the USA based on NASA/GISS/GISTEMP data



absorption of the atmospheric carbon dioxide emission in oceans which is impacting marine echo system [29]. The change in annual mean surface air temperatures in the USA is shown in Fig. 2.2.

The IoT is being envisioned as an effective tool to combat the climate change [77]. Through its sensing and monitoring capabilities, it provides insights into the root cause of climate change by sensing the amount of CO₂ and different greenhouse gases in our atmosphere [150]. The emissions of greenhouse gases from burning of fossil fuels can be sensed in real time. Accordingly, the carbon sequestration processes and rates can be monitored to increase the storage of carbon captured in forests which helps to offset emissions. Furthermore, the novel atmospheric “things” and technology can be developed to permanently reduce the atmospheric CO₂ with integration into the climate IoT.

The climate IoT is also useful in climate change anticipation and adaption preparation. Its sensing and communication technologies coupled with prediction systems and models clear uncertainty and provide useful insights into the exact nature of the climate changes. The IoT-enabled climate decision-making tools can predict how the climate will change and how the ecosystem is likely to respond to the climate change and other factors affecting it. The IoT technology has enabled empirical investigations on impacts of elevated greenhouse gases [122]. It also supports simulations of ecosystem's response in different climatic conditions (both current and future). With this new knowledge, the environmental and atmospheric management practices are tailored, and accordingly novel management techniques can be developed. By utilizing the contemporary scientific and technological advancements, the climate IoT has the potential to meet immediate and long-term goals and application needs. This architecture provides better understanding and insights into the global ecosystems and supports informed decision-making. This enhanced understanding of the Earth system from universal to regional scales has the potential to enhance our ability to assess water resources, predict weather patterns, forecast climate, and increase understanding of ecosystem health. The impact of these factors on our community determines the need for development of applications utilitarian to the society.

2.2 Climate Change IoT Things for Environmental Sustainability

The worldwide environment consists of the atmosphere, ecosystems, air quality, hydrosphere, lithosphere, atmospheric chemistry, chromosphere, biosphere, land, and ocean biogeochemical processes [73]. The following climate change elements outline main contextual components related to functionalities of the IoT in environmental sustainability and climate change (Fig. 2.3):

- Severe precipitation, hurricane, and heat wave events
- Storm surge, shoreside and in-land flooding, and increase in sea levels
- Ocean acidification and alteration of marine ecosystems
- Decline in water availability and elevated water competition aggravated by increase in population and land-use practices
- Surging carbon dioxide levels
- Rising temperatures, droughts, and warming caused by wildfires
- Enhanced demand of water for energy and water
- Variation in timing of streamflow caused by snow melt
- Shrinking glaciers and permafrost thawing
- Water scarcity and reducing supplies of fresh water

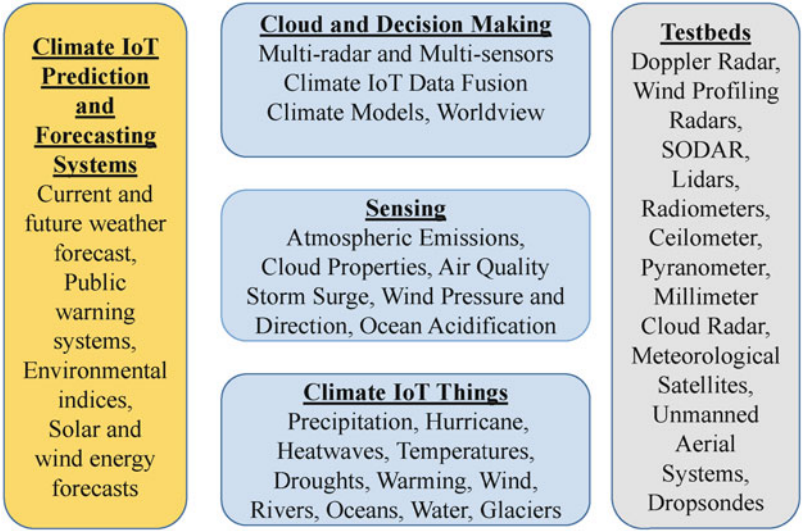


Fig. 2.3 The architecture of environmental sustainability and climate change IoT

2.3 Climate IoT as the Sustainability Enabler Framework

2.3.1 Holistic System

The integration of sensors, communication technologies, reporting, prediction, and forecasting and surface meteorological systems in the environmental sustainability and climate change IoT paradigm has many potential benefits [159]. Novel visualization and decision support tools for changes in ocean temperature, coastal inundation, and sea level at decision-relevant scale can be developed for real-time analysis using multi-radar and multi-sensor IoT elements. These systems will serve as indicators of climate impacts on ocean and coastal resources and other sectors which will aid in enhanced weather forecasting using adaptive atmospheric sensing and sampling and radar technology with resolution of 10,000 m for deterministic forecast and 20,000 m for ensemble forecast.

2.3.2 Novel Sensing Methods

The data from new sensors and robotic floats for biogeochemical, biooptical, and pH measurements can be fused in the cloud for real-time analysis [100]. The multidimensional atmospheric analysis prototypes can be integrated into the system with data assimilated from wide area meteorological zones for providing robust warnings using real-time radar sampling techniques. The environmental

sustainability and climate change IoT paradigm can help prototyping the weather and fire behavior modeling system for local firefighting applications. The climate IoT paradigm brings improvements in accurate understanding and better planning by enabling climate forecasts at multi-time-scales, projections of future climate trends, and change for support policy decisions. It enables integration of the following sensing and monitoring systems.

2.3.3 Solar Radiation and Soil Moisture Data

In environmental sustainability and climate change IoT paradigm, the solar radiation and soil moisture data can be linked for improved insights into the wind, water content, and temperature profiles [33]. The aerial sensing systems composed of different types of sensors (e.g., LiDAR, Doppler radar, spectrometer, dropsondes [126], and radiometer) also provide diverse insights [87, 156]. These observations are useful to fill gaps in measurements of different parameters of water cycle including water vapor transport, precipitation, snow, river flow, sea ice, waves, water level, and surface energy budget terms including evapotranspiration and aerosols. Moreover, the impact of natural changes such as solar and volcanic activities, varying aerosols, and greenhouse gas radiative forcing can be observed at a large scale:

- Tropical and extra tropical oceans and cyclones, ocean basin, and sea levels
- Storm surges, droughts, heat waves, and wildfires
- Land-based ice sheets and hydrologic cycle
- Simulations of ocean, atmosphere, and land surface processes
- Surface albedo, water vapor, clouds, and geomagnetic conditions
- Temperature, precipitation, extreme events, and pollution
- Air quality modeling, wildfires, and dust storms

2.3.4 Forecasting Models

For understanding and predicting the impacts of climate variabilities and extreme and precipitate climate changes, there is a strong need of full range of tools for environmental prediction and projection forecasts on different spatial and temporal scales [11, 119]. The climate IoT paradigm is also useful to ascertain the effects of the slowly changing Arctic Oscillation (AO) weather patterns through simulations [8]. New insights can be gained about the impact of ocean-atmosphere link on weather forecast through interconnection of these currently disjoint systems [36]. Similarly, it enables hurricane inner nest for global forecasting system. The advantages of multi-model, stochastic-, and multi-physics ensemble generation can be realized with novel methods of uncertainty condition representation [2]. Moreover,

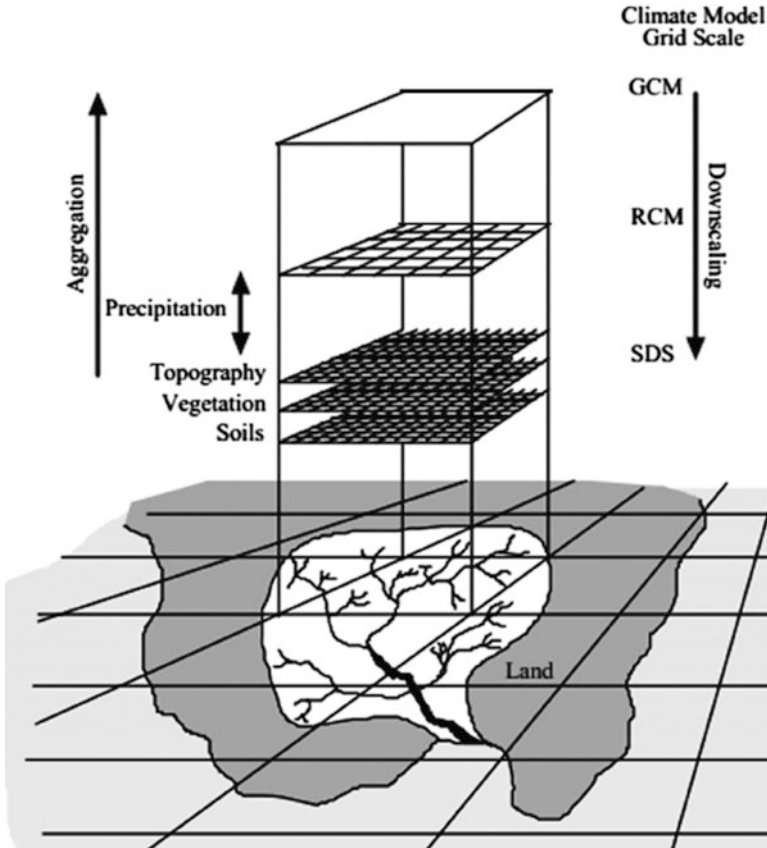


Fig. 2.4 The global climate grid-scale model [132]

with the data obtained from the sensing and monitoring systems, the advanced statistical models can be developed for reliability improvement (e.g., tropical storm and extra-tropical storm inundation model) [55, 108, 114, 143]. It also enables development of new disciplines such as storm behavior climatologies by providing access to data collected over a span of multiple decades. Furthermore, prototypes of high-resolution climate models and prediction systems can be developed including novel downscaling methods for climate systems across different temporal/spatial scales [12, 38, 44, 45, 47, 134]. The data assimilation process in ionosphere and thermosphere in forecast models can provide better insights. A global climate grid-scale model is shown in Fig. 2.4. Other important models are listed below:

- Route inundation storm surge
- Storm scale
- Geospace model in local geomagnetic storm
- Radiation environment at aviation and orbital altitudes

- Assimilative models
- Ionosphere plasmasphere
- Wind energy
- Coupled human and natural systems

2.3.5 Emission Monitoring

Black carbon, methane, and nitrous oxide emissions can be quantified through climate IoT sensing techniques with high certainty [10, 41, 54, 71, 86, 88, 89, 97, 149, 154, 167, 170]. Accordingly, its impact on the environment and clouds can be assessed by developing reliable flux estimates. The impact of four replacement compounds on extremely high ozone layer, surface air quality, and climate can be evaluated for solvents, refrigerants, and other blowing agents [13, 16]. It also enables air chemistry assessment of the effects of urban, gas, and oil development emissions on urban air quality [144]. Moreover, accurate models can be developed to quantify climate sink and forcing for the following:

- Atmospheric aerosols
- Greenhouse gases
- Aerosol interactions
- Stratospheric chemistry

2.4 Climate Communication Technologies and Systems

With the advancement in systems development, many novel atmospheric monitoring and mapping and communication technologies have been developed. These are discussed in the following section.

2.4.1 Doppler Radar

Data about the velocity remote objects can be obtained using a special type of radar that measures the Doppler effects [23, 91]. A microwave EM signal is transmitted from the radar toward the desired target that is in motion [22, 37]. The frequency of returned signal (bounced from the object) is analyzed to get accurate measurement of target speed.

The Doppler effect can be produced using four different methods:

- Coherent pulsed (CP)
- Pulse-Doppler
- Continuous wave (CW)

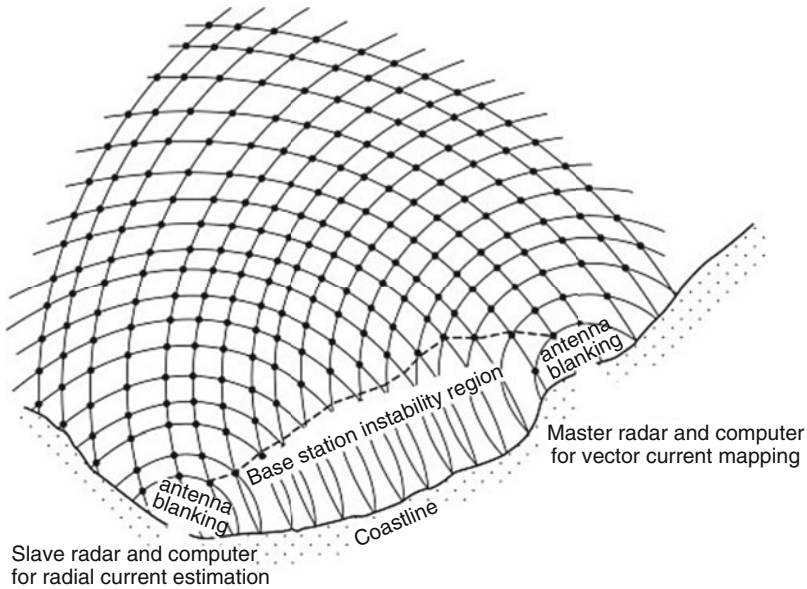


Fig. 2.5 Conceptual rendition of the spatial coverage of dual-site HF/VHF Doppler radar systems using two wide-beam transmit antennas. The dots represent the locations on the sea surface from which radial water current vectors are derived using echoes received at both the radars [74]

- Frequency modulation (FM)

The narrowband filters are employed in Doppler radars to cancel interference from low-speed and immobile objects (e.g., birds, clouds, insects, and wind) (Fig. 2.5).

2.4.2 Wind Profiling Radars

Wind profiling radar (also called wind profiler) [57, 94] is a type of Doppler radar that functions in the VHF frequency band from 30 to 300 MHz and UHF frequency band 300–1000 MHz frequency bands. It operates by directing the beam energy to the normal offset by few degrees. The wind profiling radar differs from the scanning Doppler in their processing and production of Doppler [93]. In the profiler, hundreds of low-intensity pulses are transmitted to create Doppler velocity spectrum with a 30 s of dwell time. However, in Doppler scanning radar, resolved volume moments are produced by a limited number of pulses that are transmitted with dwell time of few milliseconds.

2.4.2.1 Types of Wind Profiling Radars

Different types of wind profiling radars are explained below [147]:

- 404 MHz NOAA profiler network (NPN). The profiler is used for the deepest atmospheric coverage. It uses a coaxial-collinear phased array antenna with a diameter of 13 m and a beamwidth of 4° . It can cover a height of up to 16,000 m with vertical resolution of 900 m. With a peak transmit power of 6000 W, it can attain a temporal resolution of 60 min. Due to its sophisticated hardware, it is considered expensive to fabricate and operate.
- A 915 MHz boundary layer profiler is easy to build and operate, but it has limited height measurement capability beyond the boundary layer. It uses flat rectangular microstrip patch antenna with a diameter of 2 m and a beamwidth of 10° . It can cover a height of up to 4000 m only with a vertical resolution of 106 m. With a peak transmit power of 500 W, it can attain temporal resolution of 60 min.
- A 915 MHz quarter scale profiler is also easy to build, and its height measurement capability is better than the boundary layer profiler. It uses a coaxial-collinear phased array antenna with a diameter of 6 m and a beamwidth of 10° . It can cover a height of up to 8000 m only with a vertical resolution of 212 m. With a peak transmit power of 2000 W, it can attain temporal resolution of 60 min.

The wind profiling radars can operate in two different modes: the Doppler beam swinging (DBS) and radio-acoustic sounding system (RASS) modes. Both modes are not supported simultaneously.

- In Doppler beam swinging (DBS), the beam is steered in three to five different radial directions for Doppler spectral measurements. Accordingly, the motion of the horizontal wind radial component is measured for each direction to determine the horizontal wind profile. The longer-duration high-mode pulses and shorter-duration low-mode pulses are employed for low and high height resolution, respectively.
- In radio-acoustic sounding system (RASS) mode, acoustic waves and radio waves are employed simultaneously to determine. The velocity of sound wave is analyzed as a function of height to determine vertical air motion and temperature.

2.4.2.2 Sonic Detection and Ranging (SODAR)

The sonic detection and ranging (SODAR) is a type of wind profiling radar that is used for meteorological purposes [93, 95, 138]. The sound waves are impacted by turbulence when propagating in the atmosphere. SODAR measures the scattering process to determine the aboveground wind speed at different heights. It is also used to analyze the thermodynamic structure of the low atmospheric region. It is based on the Doppler effect mechanism of the frequency change of sound waves relative to the moving target. It operates in the 4.5 KHz sound wave spectrum. Three different acoustic beams are transmitted. A vertical beam that goes straight upward and two

beams are emitted at 17° normal to the Earth. The reflected signal is received and fast Fourier transform (FFT) operation is performed for frequency domain analysis. Accordingly, the Doppler-shifted frequency is used to determine the wind speed. It works for the height range of up to 200 m.

In bistatic SODARs, the sender and receiver can be located at a distance (usually up to 10 m) instead of being housed in the same unit. In conventional setting, SODARs are only able to get measurements from a fixed height. With electronically scanned array of acoustic microphones, the receiver can get multiple views from different heights with accurate measurements of velocity variations in turbulence.

2.4.2.3 Wind Profiling LiDARs

LiDAR (light detection and ranging) is used to illuminate the target by using laser light and sensing the reflectance by using light sensors [110, 119]. A 3D result can be produced by using the delay in laser arrival time and wavelengths. A wind profiling also works on the Doppler effect principle where the backscattering of light particles from the atmosphere is used to measure the wind turbulence and speed at different heights. The performance can be further improved by using laser beam steering mechanism where interference from the undesired components can be reduced or totally eliminated to produce high-quality results.

2.4.3 Microwave Radiometers

At larger wavelengths in the spectrum, the microwave measurements of the electromagnetic (EM) radiation are used for wavelengths between 1 mm and 1 m [15]. Microwave measurements are classified into the longwave and shortwave measurements. These are explained in the following:

2.4.3.1 Longwave Measurements

The longwave measurements are done using wavelengths that are longer than approximately $4.0\ \mu\text{m}$. These are further classified into three types:

Longwave Broadband The longwave broadband measurements are used for direct radiant energy diffusing in vertical upward and downward direction within the broadband and infrared wavelengths [47].

Longwave Spectral The longwave spectral measurements are employed for radiant energy resolving in spectrum at infrared wavelengths.

Longwave Narrowband It includes radiant energy measurements in the narrow-band infrared wavelengths.

2.4.3.2 Shortwave Measurements

The shortwave measurements are done using wavelengths that are less than $4.0\text{ }\mu\text{m}$. These are further classified into three types:

Shortwave Broadband The shortwave broadband microwave is used to measure the intensity of the radiant flux in the visible spectrum and infrared-approaching spectrum chunks of the shortwave broad-wavelength bands.

Shortwave Narrowband The shortwave narrowband is employed to measure the intensity of the radiant flux in the visible and infrared-approaching spectrum chunks in shortwave narrow-wavelength bands.

Shortwave Spectral The shortwave spectral measurements of radiant energy flux intensity are done at spectrum resolving visible and infrared-approaching wavelengths.

Radiometers are receivers of the frail EM energy which is transmitted from the surface of the earth, whereas the radars transmit their own EM pulses to the surface [15, 92]. The radiometric measurements are done using different methods such as active radar, active LiDAR, passive broadband radiometers, and passive sensors [123]. The measurements are important source atmospheric data which is obtained by measuring the decay of the energy of the electromagnetic waves when traveling through the atmosphere.

2.4.4 Ceilometer

A ceilometer is an aerosol concentration measurement device that operates on the light sources such as by using laser to obtain the cloud heights and base [139]. It is considered as a type of the LiDAR with much less range. There are two different types of ceilometers.

2.4.4.1 Optical-Drum Ceilometer

An optical-drum ceilometer consists of a detector, recorder, and moving projector and works on the triangulation technique to get the height of the cloud-based light spot projection.

2.4.4.2 Laser Ceilometer

A laser ceilometer carries both the laser transmitter and receiver in the same unit and has the capability to transmit very short pulses for few nanosecond duration to the atmosphere. These work on the same principles as the LiDAR and can be used to map atmospheric volcanic ashes and clouds.

2.4.5 Microbarographs

The microbarograph, also named as barograph, is used to measure pressure of the atmosphere in millibars with reference to sea levels. A graph paper, wrapped around the moving cylindrical bar, is used for recording the continuous pressure [60].

2.4.6 Pyranometer

A pyranometer is a device to determine flux density of solar radiation in the hemisphere. It measures solar irradiance by surfaces of planar shapes [103]. The pyranometer is a special type of actinometer with a wavelength range of 0.285–2.8 μm . It is used for measuring solar irradiance on a planar surface, and it is designed to measure the solar radiation flux density from the hemisphere above within a wavelength range of 300–3000 nm. The sun emits solar radiation, which can be harvested for heat and electric energy uses. Many environmental indexes are produced from the data acquired from the pyranometer such as temperature, humidity, sun, and wind (THSW) and ET. Aerosol characteristics (e.g., scattering, phase, and refraction index) can be produced through photometer sky radiance measurement inversion. Sun photometer instrument is used to measure radiance at four frequencies in various scanning scenarios. The aerosol optical depth (AOD) is also measured using this instrument.

2.4.7 Millimeter Cloud Radar

The millimeter cloud radar (MMCR) works on the measurement of vertical speed of the particles, which is also called the Doppler velocity [3, 140]. When clouds are above the radar, the MMCR measures its vertical profile by using the reflectivity which is a measure of the intensity of the returning signal. Accordingly, the size of the cloud particle is determined by using colors. A rising particle is indicated by a warm color and fall particles are specified by cool colors. Similarly, the width of spectrum shows the diversity of the cloud particles (the typical particle size is approximately 0.2 μm .)

2.4.8 Sonic Anemometers

An anemometer is an instrument commonly found in meteorological stations. It is used for rapid three-dimensional wind speed measurements with higher accuracy. It is also used for turbulence measurements [62]. It supports sub-meter (0.01 m/s

resolution) in 6000 cm range with rates of 0.1 KHz which is helpful for detailed turbulence analysis. Sonic anemometers operate by measuring the time taken for a pulse of sound to travel between a pair of acoustic radios (both radios are equipped with transmission and reception facility, which is alternated for bidirectional measurements). Since the velocity of the sound wave is affected by many factors (e.g., fog, dust, temperature, and pressure), accurate measurement requires sensitive anemometer equipment. Moreover, the heavy downpour also affects the measurements and leads to variations in pulse travel time. A similar type of errors is also observed in icy conditions requiring anti-ice warming equipment to be integrated with the equipment. To reduce the effects of the distortions caused by the air flow, calibrations are performed in wind tunnels to correct direction-related errors. The wind angle and direction can be measured by employing more than two radios. It supports operation in 0.02, 0.05, and 0.1 kHz frequency bands.

2.4.9 Environmental and Meteorological Satellites for Remote Sensing

Meteorological satellite plays a vital role in climate change and variability analysis. These are used to obtain the meteorological, oceanographic, and terrestrial data of the Earth [6, 18, 19, 31, 32, 128, 160]. The meteorological and environmental satellites are used for different types of EM wave measurements that are either emitted or reflected from the Earth such as ocean and land surface and from the atmosphere [18, 35, 63, 67]. These satellites have the capability to measure the wide range of EM spectrum including the visible light spectrum, radiations in microwave, and infrared bands [57, 72]. These are explained in the following sections.

2.4.9.1 Geostationary Satellites

Geostationary satellites function in orbits and these spin in the direction of the Earth's rotation [164]. Therefore, with reference to the surface of the Earth, a static position is maintained over the Earth at very high altitude (23,922 miles). Due to this factor, these satellites have the capability to observe the same region of the Earth and are frequently used in weather applications such as cloud property sensing. However, in comparison to the low-altitude satellites, high-resolution analysis cannot be supported. These satellites provide consistent data flow to ground stations about the planet after every half hour. Two main instruments on the GOES satellite are an imaging and a sounding system. The imaging instrument supports are capable of taking measurements at four different frequencies in visible, water vapor infrared and thermal infrared spectrum for cloud water, and surface temperature monitoring.

The Geostationary Operational Environmental Satellite (GOES) East and West are the two examples of the geostationary satellites:

- The Geostationary Operational Environmental Satellite-East is also known as GOES-12. It is located 75° west longitude over the equator at 7. It is used to cover the American continent.
- The Geostationary Operational Environmental Satellite-West, positioned over 135° west longitude, is also called GOES-10. The eastern Pacific region is covered by these satellites. Similar satellites are also being operated to cover and provide coverage at the global scale.
- The Geosynchronous Meteorological Satellite (GMS) is also known as GMS-5. It is used to cover the western Pacific region. It is located over the equator at 140° east longitude. With the exception equipment of sounding hardware, all equipment found on the GOES-West and GOES-East satellites are also present on the GMS with the same imaging capabilities.

2.4.9.2 Polar-Orbiting Satellites

The polar-orbiting satellites generally are in comparatively low-altitude circular orbits in comparison to the geostationary satellites. The typical height is approximately 435–500 miles and it takes 1.6 h to complete the orbit. Moreover, as compared to geostationary satellites, their position is not fixed; rather, they continuously change their position with relative to the surface of the Earth. These can provide high-resolution imaging, but a complete coverage of the Earth takes many days by using multiple satellites.

Examples of the polar-orbiting satellites are given below:

- The Defense Meteorological Satellite Program (DMSP). These are used to provide meteorological coverage on diurnal basis about the oceanographic, meteorological, and terrestrial properties of the planet. DMSP satellites orbit at an altitude of approximately 830 km, collecting images across a 3000 km swath under both daytime and nighttime conditions. Each satellite views any point on the Earth twice a day and completes an orbit in about 101 min. Complete global coverage is provided every 6 h. The measurement instrument on DMSP satellites includes the Special Sensor Microwave Imager (SSM/I) [43, 65, 129, 163] for geophysical parameters, the SSM/T, and the SSM/T2 (atmospheric sounding instruments for microwave temperatures at different heights). These are used to gather data at four different frequencies using two polarization settings. The geophysical data provided by SSM/I consists of wind speed and temperature at ocean surface, land and water precipitation, and atmospheric water vapor.
- The NOAA Polar-orbiting Operational Environmental Satellites (POES) provide daily coverage.
- Landsat satellites. Supports higher resolution and multispectral imaging.
- French SPOT satellites. No daily coverage capability.

2.4.9.3 More Meteorological Satellites

More weather imaging and atmospheric monitoring satellites are also used globally such as Meteosat operated by the European Community, Feng-Yun operated by China, GOMS operated by Russia, and INSAT satellite operated by India. Features of these satellites are explained in the following:

- Meteosat is a type of geostationary satellite. It is operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Meteosat is used to obtain data using visible light, thermal infrared, and water vapor infrared wavelengths.
- Feng-Yun is also operated by a geostationary meteorological satellite. It is located at 105° east longitude. It is equipped with visible wavelength sensor system that senses radiation in one visible frequency and two infrared frequencies. This equipment has the capability of producing visible imaging of the Earth on a particular day.
- GOMS has an infrared equipment and is also Elektro and GOMS-1. It works on the geosynchronous weather imaging technology.
- The Indian INSAT satellite is located above the equator at approximately 90° east longitude. It is used to obtain images of Central Asia and Indian Ocean.

2.4.10 GPS Signals for Remote Sensing

A remote sensing tool has been proposed which uses signals from GPS satellite systems for sensing applications where GPS reflectivity data is utilized for weather forecast [14, 172]. GPS consists of 28 satellites that orbit approximately at an altitude of 12,427 miles. Two different methods are discussed below:

2.4.10.1 GPS Limb Sounding for Atmospheric Reflectivity

In GPS, the position of the receiver is determined by the signal travel time from the satellite to the receiver [83]. GPS signal reaches at the receiver through multiple paths that are reflected from the surrounding objects and surfaces. These multipath signals can cause destructive or constructive interference depending on the location of the object. However, this reflection is being utilized to obtain useful information about the sea ice, ocean state, soil moisture, and snow pack. The GPS-transmitted EM signal wavelength is approximately 0.2 m. The reflections from these environmental parameters are investigated, and novel GPS limb sounding techniques have been developed which are also called the occultation method. This technique produces accurate profiles of reflectivity in atmosphere.

2.4.10.2 GPS for Precipitable Water

GPS signals are also used to monitor the amount of precipitable water which is the entire water vapor in the atmosphere between two points in a column [14]. Due to the complex permittivity of the water vapor, it absorbs and delays the EM waves traveling through the atmosphere. This can be measured by using interferometric instrument and is mapped to water vapor content. Another device, sun photometer, is also used to measure precipitable water by measuring the collimated solar radiation and the columnar aerosol optical depth (AOD).

2.5 Climate IoT Monitoring Systems

2.5.1 Cloud Property Monitoring

The sensing of the vertical and horizontal distribution of macroscopic properties of clouds is done using active and passive remote sensing equipment [42, 145, 161]. The ceilometer is used to produce the vertical backscatter profile for cloud base height measurements. The Cloud, Aerosol Polarization, and Backscatter LiDAR (CAPABL) is another type of cloud property measurement tool. The microphysical cloud properties (e.g., shapes, sizes, water, and ice phases of the cloud particles) are also determined.

Microphysical Properties of Clouds The cloud property sensing also involves microphysical measurements of thorough physical dimensions of the hydrometeor (an atmospheric phenomena related to clouds that involve water, water vapor, rain, and other time-varying characteristics of the clouds) [52, 84, 139, 141]. These measured hydrometeor characteristics are related to its phase, water and ice content, size, optics, and radar recurring properties.

Macrophysical Properties of Clouds The macrophysical properties of clouds involve measurements of cloud-level parameters of clouds, which include their place and position, dimensions, location, type, and the path of water and ice [80, 81, 140].

The cloud profiling instrument (profiler) operates in three different wavelengths. These include 915 MHz ultrahigh-frequency band, 2.835 GHz microwave band, and 50 MHz very-high-frequency band. The radar sends energy and receives the backscattered waves. Two types of turbulence phenomena are observed in these bands: Bragg scattering from reflectivity and Rayleigh scattering from hard objects. In these spectrum bands, the moisture and temperature are the primary sources of Bragg scattering, whereas the organic objects and hydrometers are the main causes of Rayleigh scattering. These instruments are used to observe atmospheric hydrometers.

2.5.2 Atmospheric Emission Monitoring

The emission's scenarios [104] including different radiatively active substances such as greenhouse gases and aerosols are monitored using LiDARs and other equipment that measure optical and scattering properties, size distribution, and aerosol extinction. This includes atmospheric monitoring for vertical and horizontal moisture, thermal and kinetic properties, and concentration of CO₂ and O₃ gases (e.g., radiatively active traces) using airborne and surface-based instruments.

2.5.3 Monitoring of the Surface of the Earth

The monitoring of the surface of the Earth involves measurements taken on, alongside, and underneath (less than 2 m in the subsurface) the Earth's earth-air interface. These observations ascertain characteristics such as soil's temperature and soil's volumetric water content, reflectivity of the Earth's surface, momentum flux, latent and sensible heat, moisture, and CO₂ [30, 68, 96]. The numerical weather prediction models use these observations of earth surface, aboveground and underground temperature, soil moisture, temperature of the radiative Earth skin, and surface reflectivity to provide current and forecasted values of these phenomena.

Surface Meteorology The land-based observations close to the Earth-air interface including precipitation, air temperature and pressure, moist content, and wind speed and direction are done using surface meteorology [66, 69].

Upper Air State Another important element of earth monitoring is the upper air state. The measurement techniques include balloon-borne, areal, and satellite-based observations. Many important parameters of the atmospheric profiles include geopotential height, wind, moisture, temperature, and air pressure to support weather prediction models by providing input of these vital parameters.

2.5.4 Sea State Monitoring

The accurate information about the sea state is vital for weather forecasting and marine traffic [17]. The knowledge of sea state along with heat and moisture fluxes provides useful information at multiple scales. The sea state monitoring is the one using radars and drones. Other important sea state monitoring parameters include status of Arctic changes such as sea ice melting process, decline in sea ice extent and thickness, and wind and ocean circulation in North Atlantic. These are discussed in the next section.

2.5.4.1 OceanSITES

The OceanSITES is a network of global measurement stations for ocean to seafloor and air-sea interaction monitoring [136]. It measures the surface and water column automated using sensors. The observations made using OceanSITES include water transport, ocean acidification, meteorology, bio-geochemistry, carbon cycle, physical oceanography, and geophysics.

2.5.4.2 Air-Sea Heat Fluxes

In the Atlantic observing system, the transport mooring arrays (TMAs) are employed in Atlantic Ocean to acquire long-term data of heat, volume, and freshwater fluxes of significantly strong flows. The air-sea heat flux calculation is important for wave dynamics and kinematic and thermodynamic sensitivity analysis [171].

2.5.5 Arctic Measurements

The increasing temperatures have caused the rapid warming of the Arctic at a large scale, thereby resulting in the reduction of the sea cover. It has also induced the variation in heat reflection and absorption from the ocean. The sunlight scattering, transmission, and absorption mechanisms of ice, snow, and water are different. Arctic measurements will play a vital role to get insights into the changing global weather patterns [24, 27, 49, 53, 81, 82, 111, 121, 148, 152, 156, 161, 169].

2.5.6 Hurricane Monitoring

To predict hurricane path and its intensity [99], reliable weather models are necessary. However, many physical model components that predict severe hurricanes are not understood very well and more measurements are needed. In this regard, the identification and parameterization of heat fluxes and momentum over sea-air interface are required. The extension of similar analysis to the spray-filled transition layer is also needed for better accurate path prediction. The climate IoT with its capabilities of atmospheric observations and empirical measurement in lab settings, coupled with models these parameterizations of sea-air momentum, and the heat flux can be better understood hurricane conditions. Different hurricane models are:

- The Global Forecast System (GFS)
- United Kingdom Meteorology (UKMET)
- Hurricane Weather Forecast Model (HWRf)

- Geophysical Fluid Dynamics Laboratory (GFDL)
- The European Medium Range Forecast Model (ECMWF)
- Navy Operational Global Prediction System (NOGAPS)

2.5.7 Solar Radiation Monitoring

Solar Radiation Network (SolRad-Net) is a network of sensors that provide high-frequency solar flux measurements [131]. The Aerosol Robotic Network (AERONET) is a network of distributed dynamic sun photometers to enable different ocean-related applications [46]. The aerosol optical depth is done using the Maritime Aerosol Network (MAN) element of AERONET. These measurements can be used to validate satellite, ground, and other aerosol-based measurements.

A list of field testbeds with functionality and sensing capabilities for climate IoT integration is shown in Table 2.1.

2.6 Climate Database Integration to IoT and Cloud

Climate IoT is envisioned as a paradigm to manage and leverage the data from sensors and monitoring systems. Through cloud integration, it can handle complex data sets of high volume to support decision support systems designed to address complex environmental problems. Climate IoT also provides the opportunity to design novel tools for searching, sharing, analysis, and visualization of data. A list of such data sets is given in Table 2.2.

2.7 IoT-Enabled Indices

The climate IoT enables integration of the following vital indices:

2.7.1 Air Quality Index (AQI)

AQI is an air quality pollution index [98]. The AQI is determined for various air pollutants including sulfur dioxide, particle pollution, ground-level ozone, and carbon monoxide. For each of these pollutants, the AirNow is used to report current and future pollution forecasts.

Table 2.1 A list of field testbeds with functionality and sensing capabilities for climate IoT integration

Testbed	Description
Arctic clouds in summer experiment	Observation of ice and sea conditions, clouds, atmospheric composition, and energy budget of the Earth’s surface
Boulder atmospheric observatory	Boundary layer analysis and long-term climate baseline measurements using a 300 m meteorological tower for instruments
California nexus	Air quality and climate change airborne measurements using aircraft and surface measurements using mobile platform as well as fixed ground stations
CalWater	Analysis of atmospheric rivers and aerosols in clouds and precipitation using areal, ground, and sea-based measurements
Colorado airborne multiphase study	Cloud and precipitation investigations
Coordinated observations of the lower Arctic atmosphere	Low atmosphere thermodynamic analysis
Denver-Julesburg basin air quality study	Analysis of hydrocarbon emissions from gas and oil to observe methane
Dynamics of the Madden-Julian oscillation	Flux, sonde, and W-band radar measurements for MJO analysis
Front range air pollution and photochemistry testbed	Wind profilers/RASS and surface meteorology sensors for photochemistry, oxidant and aerosol formation, and fate, flow, and recirculation patterns
Discover air quality testbed	Air quality and pollution measurements
High wind gas exchange	Air-sea flux and wave observations
NOAA hydrometeorology testbed	High-impact regional precipitation, weather, and land surface condition analysis
Hurricane and severe storm sentinel	Hurricane formation and intensity change analysis in the Atlantic Ocean basin
Intl Arctic systems for observing the atmosphere	Arctic atmospheric observations of air-sea-ice flux, boundary layer dynamics, and clouds
Integrated characterization of energy, clouds, atmospheric state, and precipitation at summit	The cloud and precipitation analysis over the Greenland ice sheet using radar, LiDAR, precipitation, and radiosonde
Midlatitude continental convective cloud testbed	Cloud and precipitation analysis using radars
RV Mirai Arctic	Surface flux measurements using sonic anemometers and radiometers
Sea state	Wave and energy flux analysis during ice expansion at the boundary layer

(continued)

Table 2.1 (continued)

Testbed	Description
Sensing hazards with operational unmanned technology	High-impact weather prediction using unmanned observations
Storm peak cloud property validation	Mixed-phase cloud and precipitation analysis using aircraft
Swedish-Russian-US Arctic testbed	Cloud and boundary-layer observations with remote sensing equipment
Tropical ocean tropospheric exchange	Air-sea flux measurements of carbon monoxide
Uinta basin winter ozone	Tower-based measurements of surface fluxes, and ground-based measurements of surface, net irradiance, and meteorological variables
Wind forecast improvement testbed	Wind forecasting and wind energy modeling and applications
Hawaii ocean timeseries testbed	The climate observations using flux reference buoy sites
Winter storms and Pacific atmospheric rivers	Dropsonde system operations and data analysis to observe winter storms and Pacific atmospheric rivers
Experimental PBL instrumentation assessment	Remote sensing instrumentation for wind energy
Advanced vertical atmospheric profiling system	Global Hawk dropsonde unmanned aircraft for atmospheric observations

2.7.2 Drought Index (EDDI)

The Evaporative Demand Drought Index (EDDI) [105] is a drought monitoring and early warning tool. It provides early warning of developing drought and status of current droughts. The Standardized Precipitation Index (SPI) is another drought index used to monitor meteorological droughts.

2.7.3 Environmental Sensitivity Index (ESI)

The information about the coastal resources and other hazards such as oil spill and sensitive shorelines can be obtained from ESI [48]. The ESI maps are utilized for hazard planning, to set safety priorities and practices.

Table 2.2 Climate databases

Name	Data set description	Technology used in collection
International surface pressure data bank	The world's largest collection of pressure observations from 1856 to 2012. The ISPDv3 is a blend of many national and international collections of station, marine, and tropical cyclone best track pressure observations	Miscellaneous
Arctic summer cloud ocean cloud database	Cloud macro and microphysical measurements	Ka-band cloud radar, multichannel radiometer, and ceilometer
Arctic summer cloud ocean wind profiler database	Wind profiles and backscatter	449 MHz wind profiler radar
Daily hydrometeorological data set for Mexico, the conterminous USA, and southern Canada: 1950–2013	Hydrologic states, precipitation, maximum and minimum daily temperature, and fluxes	A 6 km gridded product station
Hydrologic rainfall analysis XMRG data set	Four years of the California Nevada River Forecast Center (CNRFC) precipitation and temperature data sets with the XMRG	Miscellaneous
Air-sea flux	Ship-based flux observations	Satellite observations
Global ensemble forecast system reforecast data set	A 150 TB data set of global ensemble forecasts and a wide range of experimental forecast guidance based on these, including week-2 temperature and precipitation forecasts, week +1 precipitation forecasts, weeks +1 to +2 tornado forecasts	Miscellaneous
Worldview	More than 800 global, full-resolution satellite imagery layers for ash plumes, air quality, dust, drought, fires, severe storms, floods, smoke, water and ice, settlements, vegetation, and temperature	Satellite
Web soil survey (WSS)	Source of comprehensive soil-related information	In situ soil moisture measurements
Wave exposure model (WEMo)	Wind wave energy and the movement of seafloor sediment in enclosed water bodies such as lakes, coastal bays, and estuaries	Miscellaneous
Multiscale Integrated Models of Ecosystem Services (MIMES)	Georeferenced data sets as well as knowledge of ecological, economic, and social processes	Miscellaneous

2.7.4 Coastal Drought Index Using Salinity Data

Based on salinity data, a Coastal Salinity Index (CSI) has been developed which provides monthly precipitation along with monthly mean salinity data to ascertain the probability of salinity for a specific month [125].

2.7.5 Wildfire Threat Index (SAWTI)

SAWTI is an index to forecast the fire potential by considering the wind potential. Surface temperature and relative humidity are the vital parameters for these fire-prone wind event monitoring [130].

2.8 Environmental Sensing Systems

In this section, different atmospheric sensing systems are discussed. A detailed list of these systems is given in Table 2.3.

2.8.1 Precipitation Occurrence Sensor System

The Precipitation Occurrence Sensor System (POSS) is a type of Doppler radar that operates in X-band for precipitation sensing. It can sense the type, intensity, and occurrence of precipitation and provides measurements of liquid precipitation and solid precipitation [118].

2.8.2 Radiosonde Temperature and Humidity Sensing

A radiosonde contains atmospheric sensing instrument (e.g., radiometers) installed on a weather balloon to measure different atmospheric parameters and transmission to ground stations. These are generally launched in open seas and oceans for temperature and humidity measurements and provide resolution of up to 10 km depending on the balloon flight altitude and capabilities of the sensing instrument [21].

Table 2.3 Environmental monitoring systems

Tool	Description
Twentieth-century reanalysis	Global reconstruction of weather every 6 h from the surface of the earth to the tropopause back to 1851
Automated frost/heat forecast system	Frost and heat occurrences prediction in vineyards
Atmospheric river water vapor flux tool	Combines observations of wind profiles and integrated water vapor (IWV) to measure the IWV flux in the controlling layer and compares to operational numerical weather prediction prior and future forecasts
Atmospheric river detection tool	Automated objective software package to aid in the identification and characterization of atmospheric rivers to assist forecasters
Fairall-Banner sea-spray flux algorithm	A set of computer codes that allow estimation of air-sea momentum, heat, and moisture fluxes at hurricane wind speeds. Accounts for the effects of sea spray
Forecast reference evapotranspiration (FRET)	Bias correction of FRET
Hydrologic model performance assessment tool	Set of R codes for calculating the performance metrics of hydrologic modeling. The developed metrics include Nash-Sutcliffe efficiency, runoff volume difference, modified correlation coefficient, percent bias, and time to peak. These functions can also automatically detect the miss of the USGS streamflow data to ensure the model assessment being executed on the apple-to-apple basis
Integrated characterization of energy, clouds, atmospheric state, and precipitation	Web page hosting near real-time measurements and data products from a suite of ground-based remote and in situ sensors characterizing the atmosphere, clouds, and precipitation at summit station on top of the Greenland ice sheet
MRMS NetCDF-XMRG format transformation tool	A set of Python codes which can transform the 1 km resolution multi-radar multi-sensor (MRMS) QPEs between the NetCDF and XMRG format. The tool also possesses the capabilities to perform the georeference and aggregation functions
NOAA COARE bulk flux algorithm	A set of computer codes that allow estimation of air-sea or air-ice fluxes using bulk meteorological inputs. Meteorological and numerous trace gas fluxes are available
Snow-level product	A patented method to detect the level of the atmosphere where snow changes into rain

(continued)

Table 2.3 (continued)

Tool	Description
Vertical profile tool	Website allows users to extract different atmospheric products showing the vertical profile of the atmosphere. The products include single or multiple profiles on a date, a vertical transect between 2 points, a skew-T plot, and a time by height plot. Data is extracted from different reanalyses and starts in 1871
Vertically integrated water vapor transport (IVT) GIS tool	A Python-based function that can automatically calculate water vapor transport at each pressure level and take integral of them. The domain covers the Pacific Ocean, Western USA, and Southern Alaska. The tool is suitable for calculating IVTs for the variables extracted from the MERRA and NARR data sets
WRIT: web-based reanalysis intercomparison tools	A set of web tools for plotting maps and time series that allows users to compare reanalysis and observed data sets
Climate registry for the assessment of vulnerability	Assessments of the vulnerability of various natural and human resources to a changing climate
Climate resilience toolkit	Enable decision-makers to take action to boost their climate resilience using data-driven tools, information, and subject-matter expertise to make smarter decisions
Planning framework for a climate-resilient economy	Help communities recognize their economic vulnerabilities
Smart growth fixes for climate adaptation and resilience	Codes and policies for climate change

2.8.3 Cloud, Aerosol Polarization, and Backscatter LiDAR (CAPABL)

The CAPBL is a tool used to measure depolarization, particle orientation, and the backscatter of clouds and aerosols [145].

2.8.4 Operational Bright-Band Snow-Level Sensing

A Doppler effect-based atmospheric profiling radar is employed to sense bright-band snow levels (the heights in atmosphere at which snow becomes rain) from the atmospheric reflectivity and vertical Doppler velocity [162]. Another type, FM-

CW snow-level radar, uses advanced low transmit power frequency modulation of continuous waveform technique, which only uses less than a watt of transmitted power. It operates in 2835 MHz frequency band, which is useful for precipitation property measurements due to very weak attenuation/absorption of radio waves by moisture in this frequency spectrum.

2.8.5 Atmosphere Tomography Using Acoustics

In acoustics, travel time of sound waves is measured using an array of horizontally located (up to 100m high) acoustic tomography transmitters and receivers for temperature and wind velocity analysis [168].

2.8.6 Automated Atmospheric River Detection

Atmospheric river (AR) consists of narrow quills of high water vapor transport that leads to flooding [85, 101, 107, 127, 165, 166]. The identification and characterization of atmospheric river events are done using satellite and CALJET aircraft observations in the areas of integrated water vapor and transport (IWV and IVI) [126, 128, 137, 165]. It is based on integrated water vapor thresholds (e.g., width, length, and core IWV contents of different features). A comparison of different detection criterion is given in [165]. A list of environmental monitoring systems is given in Table 2.3.

2.9 Case Studies

2.9.1 Indian Ocean Tsunami Warning System

In Indian Ocean, tsunami warning system water and wave flow is measured using the kinetic sensors [56]. These sensors are deployed in the ocean bed. These sensors can transmit data from the ocean floor which can be received by disk buoys afloat. The tsunami warnings are issued using these warning systems. The sensors communicate to buoys using acoustic technology for sea floor to surface communications and then use satellite links to warning systems.

2.9.2 Undersea Cables as Seismic Sensors

In an ITU project, sensors are deployed submarine cables to detect earthquakes and seismic events. Moreover, the fiber-optic cables, on the ocean floor, that can also

be used as seismic sensors can predict tsunamis and provide insights into global seismic activity without any disruption to the service [50].

2.9.3 Connected Alarm Systems for Fast-Moving Fires

Due to close proximity of homes, fires can spread quickly in urban slums. A Red Cross project in high-density urban slums is using low-cost, low-energy, solar power sensors that can sense and alert authorities about the emerging fast-moving fires, its location, and threat. It is deployed in Nairobi and Cape Town [153].

2.9.4 Urban Air Quality Sensing

Air quality sensors are employed to sense air in fresh air in Benin urban areas to track quantity and variations of pollutants. These sensors can sense and sense data with duty cycling period of 20 min using 3G wireless technology [5].

2.9.5 Water Flow Sensors

To monitor hydrological data about river levels and flows, water flow sensors are being used in developing countries. These sonar range water stream sensors can determine the distance to water surface [1].

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Chapter 3

Internet of Things in Agricultural Innovation and Security



3.1 Introduction

One of the biggest sustainability challenges of the twenty-first century is to ensure proper food and water to the growing population of the world [140, 182]. Management of these resources is vital in our response to these challenges. Climate change has negatively impacted the agricultural production in the last four decades [6, 12, 35, 87, 110, 127, 127]. Various factors such as stresses related to crops, droughts, weeds, and crop diseases have caused decline in crop production and yields [45, 67, 85, 93, 119, 129]. In particular, the geographic areas and crops that depend on rain and precipitation are impacted the most due to losses in soil- and water-related resources caused by extreme weather patterns [121, 132]. These weather patterns are making it hard to adapt to the climate changes in agriculture and stress on critical threshold is already at maximum [86, 122, 206].

The rapid adoption rate in agriculture will be able to keep pace with climate-related changes [44, 102, 172, 205]. Innovations in the field of decision agriculture (also called digit, smart, and precision agriculture) are needed to ensure global sustainable agriculture and food security [113, 164] through higher crop yields and resource conservation [39, 72, 92]. In the decades to come, sensing and wireless communication in the precision agriculture will play an important role to measure soil moisture accurately over larger landscapes [13, 202]. The accurate soil water content measurements are vital to improve crop yield and to enhance water and irrigation management, hence providing food security to our society [4]. Plant productivity also heavily depends on the soil moisture. From the field level to networked landscapes of farms to the regional level, there is a need to scale point-based measurements to remote sensing measurement [161]. Moreover, the lack of interconnection in these measurement paradigms creates errors in models that propagate all the way up to hydrology, vegetation, soil surface, soil saturation, and runoff models [132] and creates challenges for accurate prediction and sustainability over a scale.

3.1.1 *Decision Agriculture*

The precision agriculture as defined by the International Society of Precision Agriculture (ISPA) is [81]:

a management strategy that gathers, processes, and analyzes temporal, spatial, and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability, and sustainability of agricultural production [81].

Recently, for sustainable agricultural practices, the field of precision agriculture has witnessed a lot of development in the areas of technology and concept [8, 25, 42, 64, 107, 142–151, 154–158, 161, 192]. It is beneficial in terms of reduced cost production with high outputs. It is driving in innovations in different agricultural areas such as farm equipment and machinery, crop, plant, and soil sensing, seeding, and harvesting. These technologies in decision agriculture are being used to make informed decisions for sustainable agriculture in real time which help to reduce input and resource conservation through applications of variable-rate techniques in the field such as variable-rate irrigation. Moreover, pesticide, fertilizer, and nutrient inputs can be tailored accordingly based on the field conditions. Accordingly, accurate applications are done for critical areas which lead to economic benefits (e.g., improved crop yields with low cost). Through sensor-guided decisions, the costs reduce at different stages of the crop growth such as types and density of seeds, inter-plant spacing, and planting depth, rates and schedule of fertilizer, pesticide applications, and customized harvesting. The important precision agriculture technologies are in situ and remote sensing, geo-location, soil mapping, and variable-rate technologies (see Fig. 3.1). The custom application of seeding, fertilizer, herbicides, chemicals, and pesticide technologies are manual control GPS guidance system, automatic control GPS guidance system [50], automatic control of nozzle and sprayer boom [208], sprayer turn compensation [111], and variable-rate prescription maps [141]. Currently, precision agronomist services available to farmers are soil sampling and field mapping. Soil sampling is done using whole field approach-based traditional methods and grid patterns and through management zones. The management zones for soil sampling are determined by electrical conductivity and soil mapping unit. The yield-dependent field mapping is done using GIS and soil EC, pH sensing, chlorophyll sensors for N, and profit/cost analysis.

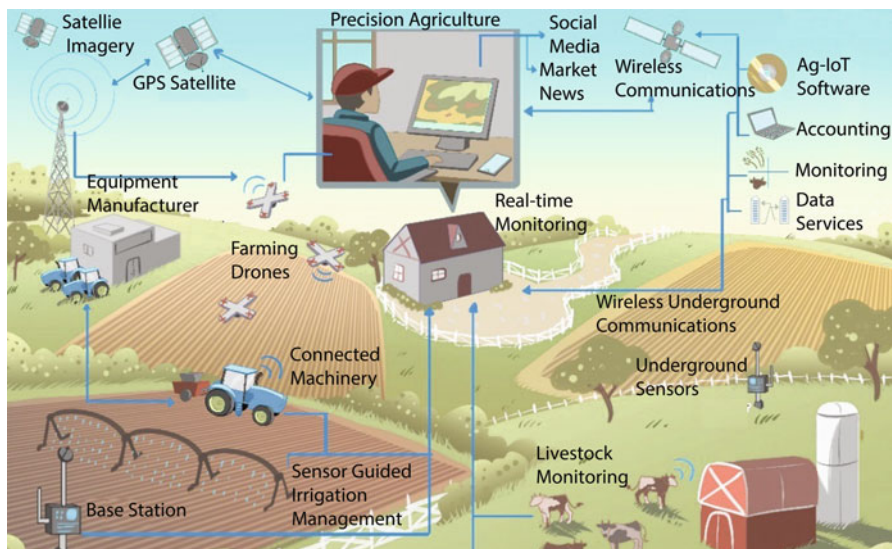


Fig. 3.1 An overview of the precision agriculture technologies

3.1.2 Main Barriers to Digital Agriculture Technology Adoption

There are many barriers to adoption and expansion of digital agriculture technologies. The precision agriculture technology adoption in maize production is shown in Fig. 3.2. The first major issue in adoption is return on investment. Moreover, the cost of digital agriculture equipment and services is higher than the benefits. This also affects the motivation levels of the farmers because there is more emphasis on increasing farm income as compared to adoption of the technology digital agriculture technology business is mostly targeted to big farms and smaller farm owners are left behind. Moreover, the use of digital agricultural technology in diverse topographic and soil texture fields is limited. Due to enormous data being generated from the farm and lack of decision tools, interception and decision-making are very time consuming for farmers. Farmers trust more the educated guess based on experience rather than having confidence on the recommendations made based on the sensing (in situ and remote), yield maps, and soil maps. Because of these barriers, the digital agricultural business is not profitable. The cost and availability of specialists for complex equipment, lack of manufacturer support, difficulty in putting up encompassing high value, and precision portfolios are the limiting factors for precision business.

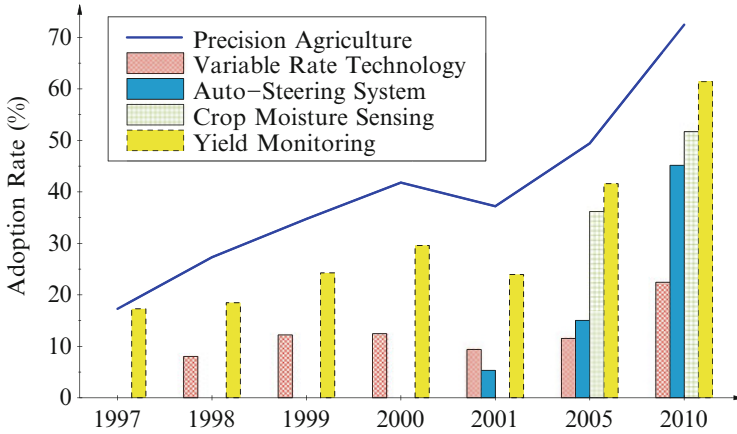


Fig. 3.2 Precision agriculture technology adoption in maize production [202]

3.2 Internet of Things for Sustainable Agriculture

Internet of Underground Things (IOUT) has numerous applications in the field of digital agriculture [8, 25, 42, 64, 107, 142–151, 154–158, 161, 190, 192]. It is a paradigm in which technology is being used to effectively manage agriculture by understanding the temporal and spatial changes in soil, crop, production, and management through innovative techniques. A multitude of wireless devices is employed for sensing and communications on the field [202] in smart farming. With the development of novel soil sensing methods, adaptive input application (e.g., fertilizer and lime), and soil mapping techniques, there is a higher demand for increased data rates and long-range underground communications. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [9, 181]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [64, 179, 180].

The IOUT delivers consistent access to data garnered from the farming areas via underground networking, aboveground networks, and the Internet. The IOUT paradigm in precision agriculture is shown in Fig. 3.3. IOUT incorporates in situ underground sensing [4] of soil physical, chemical, and biological factors which includes water content sensing, salinity sensing, pH and nitrogen sensing, and temperature sensing. It also has the communication capabilities built-in as one of the integral components to provide the sensing data from the plants, roots, and soil. Moreover, it has the ability to include the environmental sensing capability to provide the real-time data pertaining to the diverse environmental phenomena such as wind data, rain information, and solar potential [203]. When integrated with agricultural machinery and farm equipment on the field (e.g., seeding equipment, irrigation controllers, harvesting machines, and combines), the IOUT leads to the

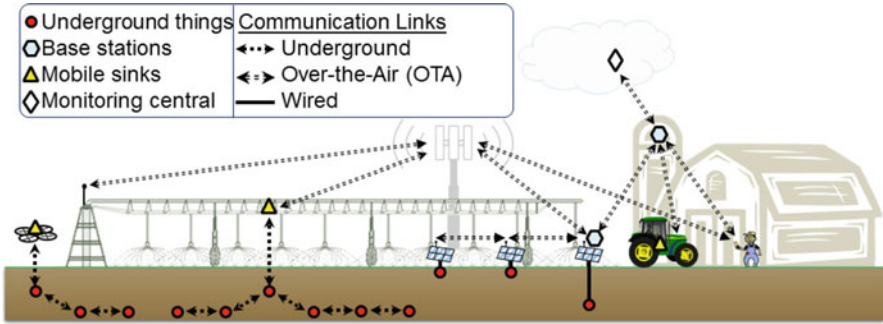


Fig. 3.3 IOUT paradigm in precision agriculture [202]

full self-sufficiency on the smart farming fields and has the strong potential of development of enhanced food production solutions and applications in the area of digital agriculture [202]. The IOUT is also being utilized to provide useful decision-making information to the growers in the field in real time.

The sustainable agricultural IoT in the subsurface environment has the potential to transform soil and natural resource management systems. The improved knowledge gained through development of this underground sensing system will contribute to the development of better management techniques in the field of digital agriculture. Effective and reliable soil moisture sensing and irrigation management techniques will lead to advances in underground sensing and communication technology. To build technology-aware and advanced digital agricultural practices, this innovation and automation in underground sensing and secure communications, data collection, analysis, and visualization will play a vital role. Based on the IoT systems, sensors for soil and water quality across networked landscapes can be developed. Moreover, it will also facilitate integration of advances in digital agricultural data analytics, in situ and remote sensing into working systems, and indigenous and local information.

The development and application of novel sensing and communication techniques for water resource conservation and enhancement of the crop yield is a major area that needs technology innovations. A large-scale field Ag-IoT built using these wired and wireless technologies and sensing solutions will also aid in advancing the fields of subsurface radio wave propagation, underground communications and networking, and digital agricultural data analytics. It enables a novel way of studying soil properties that will facilitate efficient resource usage (e.g., improved water conservation and improved crop yield) leading to healthy and sustainable communities. Creation of networked collection of existing soil type and moisture-related databases will improve access to large-scale consolidated data for decision-making.

3.3 Wireless Underground Communications

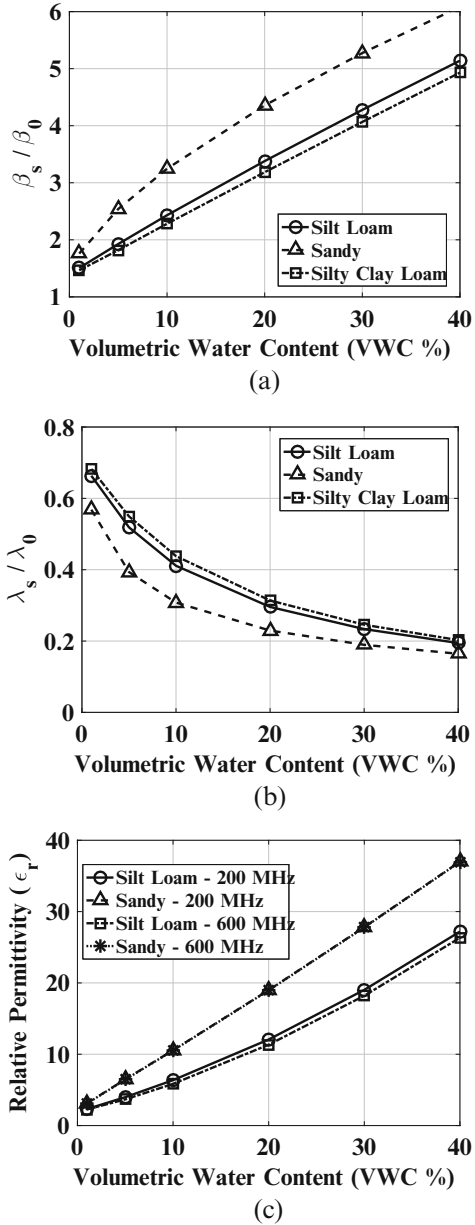
An accurate analysis of wireless underground channel model is vital for any efficient wireless subsurface communication system design. The prospect of completely underground sensing and communication network, without any footprint on the soil surface and support from nodes mounted on aboveground infrastructure, has therefore fueled interest in underground channel propagation measurements. Since many of the smart farming future applications will need high data rate and long-range connectivity between underground and aboveground nodes, a lack of detailed measurements is affecting the design of next-generation soil sensing systems [150, 156, 161].

Not only the subsurface path loss as compared to over-the-air (OTA) is higher in the wireless underground channel [41, 144, 152], but also the underground antenna design is highly sensitive to many soil factors such as soil texture, bulk density, soil moisture, depth, and the air-soil interface [157]. Furthermore, at lower frequencies in the underground channel, the time-domain channel characteristics such as root mean square (RMS) delay spread and coherence bandwidth of the wireless underground channel are of utmost importance. However, the underground communication system design is highly dependent on these characteristics to overcome higher path loss due to complex permittivity of the soil and also to achieve higher data rate underground communications [144, 153].

The development of a wireless underground channel path loss model that accounts for the soil type and moisture impact is important because of many factors such as the operation frequency, communication protocol, modulation scheme, network layout, connectivity, and other important operational parameters that can be ascertained based on the model. Moreover, to evaluate IOUT solutions, a reliable UG channel model is required. Existing over-the-air (OTA) channel models cannot be used in subsurface communications because of the high path loss that is caused by complex permittivity of the soil in the lossy propagation medium. Moreover, spatial and temporal changes in the soil permittivity also lead to path loss variations, a phenomenon not observed in OTA communications.

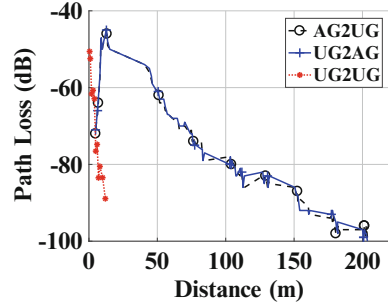
Impact of soil moisture variations on permittivity and wavenumber in soil is analyzed in this section. The β_s and β_0 are the phase constants in soil and air, respectively. The λ_s and λ_0 are wavelengths in soil and air. Effects of the change in β_s/β_0 and λ_s/λ_0 , parameters with change in soil moisture in silt loam, sandy, and silty clay loam soil types, obtained from complex wavenumber $k_s = \beta_s + i\alpha_s$, are shown in Fig. 3.4 (where α_s is the attenuation constant in soil). From Fig. 3.4, it can be observed that β_s/β_0 increases with increase in soil moisture. At 40 % soil moisture level, in silt loam and silty clay loam soil, the phase shift is five times higher as compared to the free space β_0 . This effect is more significant in sandy soil. Effects of change in wavelength, λ_s/λ_0 , as compared to OTA wavelength are shown in Fig. 3.4b. Frequency shift as compared to the OTA is less for lower soil moisture levels, and it increases with increase in the soil moisture level. It can be observed that at higher soil moisture levels, due to higher permittivity of the soil,

Fig. 3.4 (a) Change in β_s/β_0 , (b) λ_s/λ_0 , parameters with change in soil moisture in silt loam, sandy, and silty clay loam soil types, (c) relative permittivity of silt loam and sandy soil with change in soil moisture at 200 and 600 MHz frequency



the difference in frequency shift between different soils is also low. In Fig. 3.4c, the relative permittivity of silt loam and sandy soil with change in soil moisture at 200 and 600 MHz is shown. It can be seen that change in soil moisture affects the relative permittivity of the soil. Sandy soil has larger effect due to the change of soil moisture

Fig. 3.5 The path loss of different wireless channels in underground communications [202]



as compared to silt loam soil. It can be also observed that sandy soil permittivity does not change with frequency. This is caused by two different physical phenomenon, namely, dielectric and conduction losses. Soil moisture variations happen due to dielectric losses in soil as a result of relaxation process of water particles held in the soil medium [40].

There are three different paths that contribute to propagation in wireless underground communications. Through-the-soil paths are direct and reflected. For both components, the wave path remains completely in the soil. The third wave, lateral component, moves along the air-soil interface above the soil surface. The path loss of different wireless channels in underground communications is shown in Fig. 3.5. An in-depth discussion of these components of the UG channel is presented in [41, 159].

3.4 Underground Antennas and Beamforming

In [145], an empirical investigation of propagation path loss variations with frequency in sandy and silty clay loam soils has been done using planar and dipole antennas. The path loss experiments are conducted using a vector network analyzer (VNA) in sandy soil testbed and greenhouse outdoor silty clay loam testbed for different operation frequencies and communication distances. The results show that the planar antenna can be used for subsurface communications in a wide range of operation frequencies. The comparison paves the way for development of sensor-guided irrigation system in the field of digital agriculture. Moreover, a model has been developed to predict the resonant frequency of the underground dipole antenna at different soil moisture levels and depths [157]. The textural triangles containing resonant frequencies for all soil types are shown in Fig. 3.6.

The UG transmit beamforming using array antennas at the transmitter can be employed in the underground (UG) communications to maximize the lateral wave by transmitting energy at a particular angle [154, 159]. By using this approach, the energy wastage by sending signals in isotropic direction can be reduced by forming the narrow-width beam and steering it accordingly [198]. In underground wireless

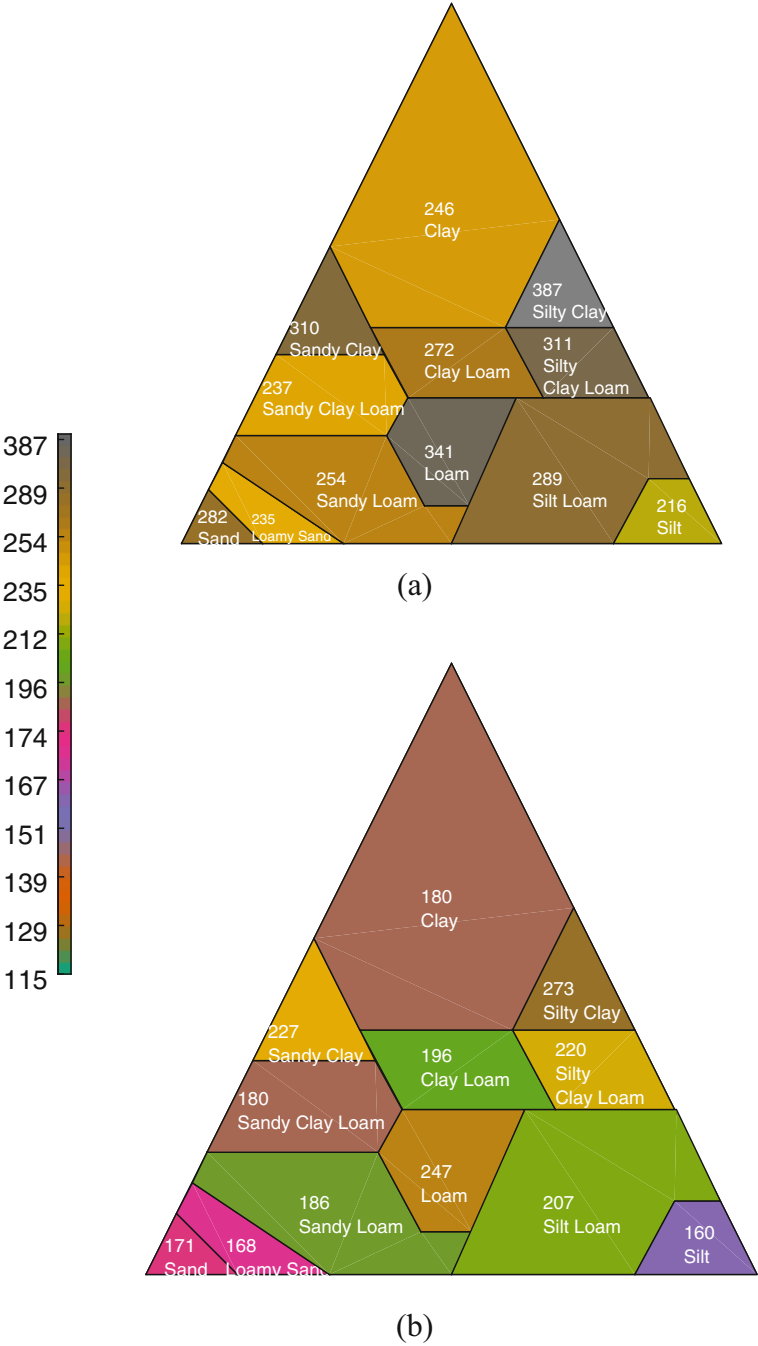


Fig. 3.6 Resonant frequency (MHz) of different soils in textural triangle at different soil moisture levels for a 433 MHz OTA antenna [157]. (a) 10% VWC. (b) 20% VWC. (c) 30% VWC. (d) 40% VWC

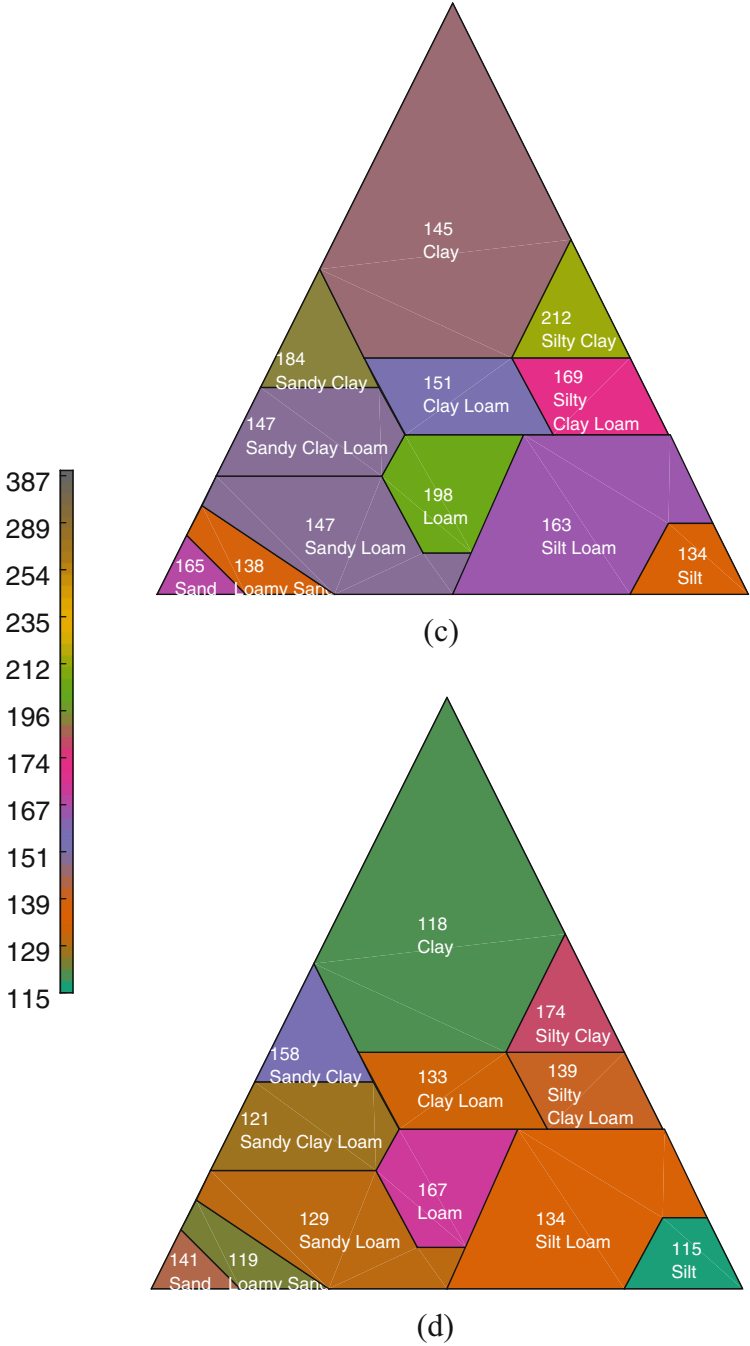


Fig. 3.6 (continued)

communications, the aim is to enhance the received signal strength and reduce the interference at receiver [154]. In underground phased array antennas, the soil moisture adaptive weights, based on soil moisture sensing and feedback signals, are used to adjust the weights by using the array gain feedback loops. This problem is formulated as to maximize the array gain by using the pilot signals. In this method, phased array at the transmitter receives the pilot signal in the receive mode and then accordingly adjusts its parameters for the transmit mode. In the receive mode at the transmitter, scan angles are varied to get the estimate of the channel state. The best SNR statistics are used, and accordingly, with change in soil moisture, parameters are adjusted for optimum performance.

3.5 Soil Sensing for Sustainable Ag-IoT

With change in soil structure and particles over time, the process-based and empirical models are needed to understand the relation of soil texture with its water cycle [48, 117]. The global climate and change in rain patterns, in addition to the lack of crop rotation, microbes, and organic matter, has accelerated the process of changes in pore size, compaction, and structure of soil [131]. The analysis and corresponding analysis will help us to better sensing through the soil communication techniques in response to such biochemical changes in soil [132]. Different factors (e.g., crop and soil type, climate, hydrophilic and biogeochemical properties, and pore size evaluation at the pedon scale) should be considered together for development of such models. The development of these models will also lead to long-term soil sustainability and development of better response to deterioration of soil caused by global climate changes. Currently, there is a dearth of novel soil sensing techniques to measure the chemical, biological, and properties of the soil. Accordingly, novel sensing mechanisms are needed to understand these physical, chemical, and biological phenomena in soil. The soil sensing for sustainable Ag-IoT is discussed in this section.

Soil Sensor Requirements The soil moisture and temperature sensors should have the capability to calibrate itself because currently the major challenge in soil moisture measurements is sensor calibration [36, 221, 223]. Understanding the carbon nutrient cycle, leaching, and uptake process of nitrogen can be improved by development of hydrological flow models. The development of sensors for agricultural purposes should also include to sense salinity and nutrients. The dielectric-based and electrophoretic nitrate-based signal processing approaches [124] are of particular interest to enhance the soil sensing capabilities for agricultural applications. The pH and measurements of dissolved oxygen need to be integrated with low-cost low-power systems and advanced power management on single circuit boards [30, 219].

The energy conservation issues are also important in the development of such sensor systems. For prolonged uninterrupted operation in soil, these sensor systems should have the capability to harvest the energy from the environment as well as able

to wirelessly receive power from the soil surface and other aboveground sources (recharge). This wireless transmission of power to these sensing systems can be achieved through the propagation of subsurface radio frequency transverse magnetic mode (TM) where soil-air interface serves as a waveguide. The performance efficiency of this scheme can be increased twofold by using multiple transmitters on and below the soil-air interface, creating two such modes, hence maximizing transfer using lateral (Zenneck) waves.

Different sensing and modeling approaches (e.g., remote sensing, field-scale tools, in situ sensing, crop models and coefficients, transport models, nutrients and microbes, and subsurface soil data) also need to be integrated in the digital agriculture. It will improve our understanding of the physical, chemical, and biological processes of the soil and will also improve soil-crop management practices and health.

Self-Deploying Sensors There is also a need for further development of sensors with self-boring capability to overcome installation challenges in excavation, penetration, and replacement of sensors in heterogeneous environments [99]. The use of robots is a potential candidate for the development and auto deployment of these with this capability with minimum soil and crop during the growing season aided with GPS technology. The major advantage of this approach is its ability to auto relocate sensors without human intervention for spatial temporal sensing of physical, chemical, and biological properties of the soil. The major challenges in self-deploying and relocating sensors are ability to adjust to varying field terrain, maintaining connectivity within the optimal deployment region, and requirement of different deployment hardware for different types of soil.

Acoustic Soil Sensors Acoustic soil sensors are also being envisioned as the alternative to wire-based sensors [116]. One major limitation of wire-based sensors is the low sensor density per unit in agricultural fields as the limited number of wires can be connected from the underground hole. Because of the changes in the surrounding environment of these sensors, these connections become gradually weak which leads to loss of connectivity due to cable degradation. Moreover, these exposed cables also offer an attractive target to field animals. Acoustic connections offer opportunity to remove these cables completely for underground to aboveground communications. However, the major challenge in this area is higher path loss because of higher soil moisture content. Moreover, currently, only sea-based underwater acoustic and through the animal tissue acoustic communication techniques are being applied, and there is need to tailor these underwater communication techniques to groundwater, soil moisture, pesticide chemicals, agricultural machinery, farm equipment, and foot traffic [23, 173, 186, 201]. Surface acoustic wave sensors can be used to manufacture soil nutrient sensors by using acoustic wave delay lines [103] and polymer-based conductive impedance detectors [168].

Seismometers in Soil A related approach is based upon the use of soundscapes and seismic signals by using seismometers to study the movement of soil particles [137]. The main challenge in this approach is to pick the signal of interest (elastic waves) from the background noise by using state-of-the-art seismic arrays in geological,

ecological, and biological landscapes. These types of measurements because of their high temporal and spatial resolution can provide insights into the different geomorphic bioturbation factors contributing to spoil erosion and landscape changes on the surface (e.g., animals, plants, deposit rocks, and foot and machinery traffic).

Root Sensing New noninvasive soil sensor systems are needed to understand the root chemistry. Using current methods, this information cannot be obtained without disturbing soil. Development of root sensors will make available the real-time information about roots which can be used to model the impacts of soil type and irrigation cycle on the root growth [178]. Current practices for soil root imaging include minirhizotrons [183] and planar optodes [100]. In the former approach, a transparent plastic tube is buried into the soil root growth zone to obtain contusion images of plant roots. The latter approach is based on the use of optical fluorescence sensing mechanism [7]. The big size and high deployment cost of these approaches are major factors limiting the use of these techniques in precision agriculture. Moreover, it can also be used at the small-scale plant-based level. To address these challenges, there is a need for development of EM-based root imaging and growth sensing techniques that can be used at a large scale in a cost-effective way.

On-the-Go Soil Sensors Depending on the soil minerals and texture, there is an emission of gamma radiation based on the radioactive decay in soil. Gamma radiation is the electromagnetic photons in the visible light spectrum. These are also being used at topsoil mapping. However, they cannot be used as real-time on-the-go sensing apparatus in soil because one measurement is not sufficient but multiple measurements are required. The soil pH can also be used for real-time on-the-go soil mapping [4, 5, 171]. A soil pH-based autonomous soil sampling and mapping system has been developed in [171] that used ion-selective electrode technology for pH sensing and soil mapping. The prototype has demonstrated the effectiveness of the system for lime application. A lime is a soil supplement developed from chalk and limestone. There is also a need for sensors to measure mechanical impedance of the soil [5]. This mechanical resistance can be used for selection of no-till or chiseled soil treatment based on the soil impedance measurements.

Topography Soil Sensors There is need for development of topography soil sensors for precision agriculture application. The topography soil sensors in the field can be used to measure slope and corresponding water flow. Currently, GPS and LiDAR technologies are being used for mapping the topography of soil [162].

Microbial Sensors There are many different species of microbes present in the soil ecosystem. These organisms play a vital role in our support system. Development of new sensing approaches can provide us with the better capability into crop growth control cycle and energy influx. In literature, there is no existing work to support the use of microbes as input parameters into major models (e.g., waste management, soil health, and climate); therefore, there is a need for inexpensive, real-time, and highly dense deployment of microbial sensors [26]. Development of new microbial sensing techniques will help in development of better soil models coupled with maximum

entropy production from the thermodynamic perspective. It can also provide much needed insights into the microbe organization and composition changes.

Other major candidates for development of novel microbial sensing approaches are methanogenesis, thermodynamically controlled metabolic sensing approach, chronoamperometry, methanotrophy, and electrochemical and piezoelectric quartz crystal micro-balance (E-QCM) [54]. A network of microbial sensors working together for sensing will improve the reliability and will contribute to decreasing the cost and amount of field inputs in the field of digital agriculture. It can also lead to better crop health. However, currently, excess or improper application of fertilizers in agricultural fields is causing nitrogen runoff, which not only contaminates drinking water but is creating troubles in the commercial sector (e.g., tourism and fishing) [138]. The algal outbreak and reduction of dissolved water oxygen also results from overfertilization [59, 114]. The phosphorous cycle is also important for sustainable agriculture. The increase in human activity in the field leads to development of hazardous phosphorous in the environment. Therefore, growers can benefit through these advanced soil nutrient sensing systems by application of the correct amount of fertilizers.

Soil Nutrient Sensing Soil nitrogen sensing techniques require high field density for correct prediction and development of nitrogen models. Moreover, for better accuracy, these sensors should be buried at different depths in the soil. Development of low-cost sensors to sense the concentration levels of nitrate, heavy metal ions, and ammonium will help to overcome these challenges. Carbon-based low-cost graphene (ionosphere membranes) can be used to fabricate these sensors in a cost-effective way to detect nitrate and ammonium in soil [189]. This knowledge along with NDVI will help in improving crop productivity.

The process of soil erosion can be understood and effective mitigation approaches can be developed by sensing soil iron and oxygen. The erosion of topsoil by physical tillage, wind, climate change, and forces of water is a major issue in agriculture [48, 212]. Better insight into the erosion process can be gained from interaction of soil with iron and oxygen. The information combined with surface water lateral flow models can also illuminate the interaction of microorganisms and resulting seismic change in soil chemistry in managed and unmanaged soil.

Photonic Sensors Macro-fabricated photonic sensors work on the principle of detecting changes to the environmental reflective index and can be used to measure soil nutrients. Photo- or electron-beam lithography-based photonic sensors developed on silicon can be used to detect nitrate and phosphate [10]. This approach has been used in metal sensing but can be tailored to soil nutrient sensing. Zinc oxide nanorods allow spatial high-resolution sensing of soil nutrients. These nanorods when combined with Raman spectroscopy can provide highly reliable soil nutrient sensing for abundant and rare nutrients in soil. The major challenge in this area is the difficulty of developing standard methods for sensing, calibration, and validation across different nutrient types and soils.

Biosensors Another potential approach for sensing the presence of hazardous microorganisms and chemicals is based on engineered bacterial spores (complete cell-sensors) [106]. Traditionally, spores can be used to store biosensors for an extended period of time. These biosensors can sense microbial activity based on bacteria that can be tailored to adopt to the change in the microbial activity in soil. These can be muted (dormant mode) and be reused across different sensing cycles. The self-sustainability of these biosensors is an important challenge to achieve long-term field operation to monitor crop health. Underground microbial fuel cell (MFC) is being used effectively to supply power to these sensors [222]. Impedance spectroscopy sensors (ISS) [94] can also be developed by using the MFCs. The ISS sensors are based on detection of change of permittivity of soil to detect ionic concentrations in soil. Therefore, it can be used to monitor soil nutrients. However, there is a need to develop and validate models to connect these permittivity changes to the microbial activity and changes in soil.

Microelectromechanical System (MEMS) Array The soil health can be better characterized by biochemical processes and volatile organic compounds produced by them. The detection of soil chemical properties is currently restricted to the pH. The microelectromechanical system technology consists of miniature transducers that can be used to sense concentrations of these chemicals at different frequencies. These combined with other sensors can provide a full-spectrum soil health sensing capability in digital agriculture. A schematic of the cantilever-array nutrient sensor is shown in Fig. 3.7.

Soil Organic Matter Sensing The soil organic matter (SOM) constitutes 2% of the soil particles but is not generally accounted as part of the soil texture, which sometimes leads to error in soil models. The sensing of the subsurface biotic

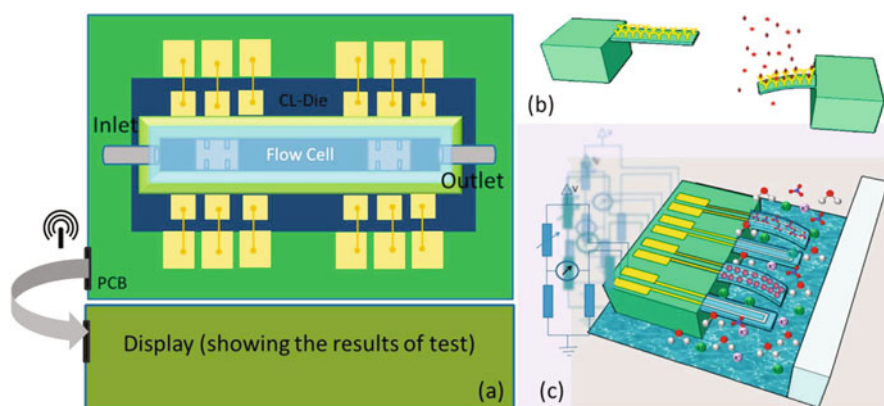


Fig. 3.7 A schematic of the cantilever-array nutrient sensor [125]. (a) A lab-on-a-chip system (LOC), (b) sensing principle of a microcantilever, and (c) microcantilever array depicting the sensing of multiple macronutrients

factors (e.g., plants, algae, animals, bacteria, and fungi) and abiotic factors (e.g., soil type, mineral weathering, temperature, soil water content, sunlight, oxygen present in the soil pore space, wind speed, water flux, carbon nitrogen cycle, carbon dioxide, ammonia, and nutrients) can provide decision-making information in real time. Among these, the soil respiratory quotient (RQ) [29] is a strong indicator of soil metabolism. An understanding of water-gas exchange and diffusion can also provide better information into the gas composition in soil. The pore space sensing for presence of azane, carbon dioxide, and oxygen can be used to assess nitrification process, gas water exchange, and diffusion in different soil textures. Variation in these also needs to be investigated over large spatial and temporal scale in agricultural fields.

Stress Sensing The lack of enough nutrients, water shortage, improper irrigation, crop diseases, and weeds lead to crop stress. Proper identification of factors causing crop stresses is vital for insights into phenology and crop physiology. The multispectral and hyper-spectral sensing approaches can use chlorophyll concentration sensing and biomass estimation. However, systematic research and empirical evaluations in the areas of multiple view plant geometry and RGB are required to show effectiveness of these approaches in crop stress identification.

Weed Sensing Weed sensing is another area of digital agriculture that requires major research because weeds have a significant impact on the crop yield. The satellite-based imaging for weed sensing has not been promising because of low accuracy, reliability, and resolution. Therefore, new techniques need to be developed for GPS-guided high resolution to effectively sense different types of weeds. High-quality weed map can help in the identification, classification, and proper elimination of weeds.

Autonomous Disease Sensing There is almost a total lack of literature on the use of technology in digital agriculture for autonomous disease detection, although the problem of disease sensing has been investigated from the vegetation index perspective by comparing and contrasting the normal and anomalous crop growth pattern. However, models are required which can link these abnormalities to the automatic early stage disease identification.

Plant Temperature and Physiological Property Sensing The vital physiological properties of plants can be estimated through the chlorophyll fluorescence sensing. It requires light-saturating photosystem technology with high beam intensity. Lasers that can produce this high intensity beam cannot be used for plants. Traditionally, satellite imagery has been used for chlorophyll fluorescence sensing but suffers from low-resolution problems. Another alternative is micro-hyperspectral sensing technology. However, it is expensive and it is not possible to be used for large farms. Therefore, novel inexpensive fine resolution chlorophyll fluorescence sensing techniques need to be developed.

Plant temperature sensing via thermal sensing is done to assess water stress. This sensing is important to analyze the important process of photosynthesis. Thermal

sensors offer very low resolutions and have to be placed close to the plant for correct assessment of water stress. Mounting uncooled thermal sensors on mobile farm machinery can lead to this assessment, but it is not possible for all crop types. Moreover, it results in slowing the speed of that particular machinery on which these sensors are mounted, because an instantaneous thermal sensor imagery cannot be used to measure water stress. Rather multiple images are required which are then processed off-line to assess water shortage. Therefore, advanced technology is required for real-time in situ processing of the data and estimation of deficiency of water pressure and CWSI. Moreover, interferences (e.g., the machinery heat generated from the field operation, soil emissions, and plant temperature) are some of challenges that limit applications of this approach to the field of the precision agriculture.

3.6 Aerial Sensing

In digital agriculture, UAVs are becoming ubiquitous as an IoT platform for sensing, data collection, and real-time decision-making. Because of flexible design and lower footprint, these can be adopted for use in different types of fields in different terrains as UAVs are of high quality and inexpensive and higher resolution and high rate data collection as compared to the remote sensing where performance suffers from the bad weather conditions. Other advantages of UAVs in precision agriculture are ability to select and integrate different sensors on UAVs. In terms of modeling, UAVs offer better alternatives to the traditional agricultural modeling processes. Potential applications of UAVs are monitoring the nitrogen status for building nutritional nitrogen index and map and evaluation of crop growth during the growing season using regression for making SAVI, NDVI, and NDRE index indicators of vegetation growth. UAVs in precision agriculture are also being used for plant height and biomass analysis with very higher accuracy using multiple UAV trips in the field in real time. Photogrammetry is very helpful for this types of height analysis. A detailed analysis of this approach has been presented in [70]. A stand count analysis in the crop field via UAV photos combined with proximal soil sensing and satellite photos has been done. Digital agriculture can be benefited from automation of UAV flights for safe operation, integration of different sensors and sensing techniques across disciplines under a standard protocol, and development of business planning models and supervised learning for effective and optimum field operation. Other novel applications of UAVs include disease and water stress and weed detection, biomass and yield prediction, assessment of deficiency of nutrients, and crop modeling and classification.

The crop ripeness and weed analysis using UAVS has been done in [70] for prolonged field operation, and predictive models have been done based on this analysis. In [177], UAVs are utilized, in cotton fields, for canopy response observation and residue management using a thermal camera mounted on the craft. The nitrogen and correlation of LAI and biomass have been analyzed using different

UAVs in [14, 71, 75, 184, 197]. Applications to the effective in-field irrigation management and soil sensing using UAVS are shown in [3, 62]. The idea of multiple micro-UAV platoons has been presented in [62]. The use of UAVs for fertilizer management in the crop field has been done in [76, 118]. The superior capabilities of spatiotemporal sensing of the UAVs as compared to the remote sensing are demonstrated in [20, 22, 165] using thermal and multispectral sensing systems mounted on UAVs. The correlation between the remotely sensed soil moisture and in situ soil moisture measurements is done in [18]. The analysis of plant structure and canopy and plant height was carried out in [11, 95, 218]. In [218], the drainage management has been done using crop scouting. Plant pathogen mapping using UAVs has been done in [120, 188] in a potato field. Applications of UAVs in the area of canopy cover and temperature are tested in [21, 109]. The weed detection and management using UAVs have been explored in [37, 53, 60, 74, 126, 174, 193]. The effectiveness of the crop disease detection using UAVs has been studied in [28, 163, 176]. The characterization of plant growth parameters and yield prediction has been done in [15, 57]. The biological and physical parameters of the soil were estimated using UAVs in [217]. The application of UAVs in the area of vegetation maps and for creating different indices (NDVI, LAI, GAI, GNDVI, CWSSI, PCRI) using UAVs have been carried out in [27, 56, 108, 194, 199]. The use of UAV imaging in precision agriculture has been discussed in great detail in [2, 51, 56, 58, 73, 97, 101, 108, 120, 211]. A detailed analysis of UAV-based pest management has been done in [133].

3.7 Big Data

The decision-making parameters at the farm include nitrogen, P and K, liming, hybrid variety selection, placement in field, crop planting rates, variable seeding rate prescriptions, pesticide selection (e.g., herbicides, insecticides, and fungicides), cropping sequence/rotation, and irrigation. The data is obtained from soil testing, yield and soil maps, and EC at the farm level and through satellites. It can be managed at different levels. At the local level, the data obtained from farmer is restricted to farmer use only at the field level and no data aggregation is done. At the farm level, data is aggregated from different fields within the farm. At the regional level, data collected from the farmers can be combined effectively to get regional insights. These data collected at the regional level can be combined to national level decision-making and can also be used in the analysis of the future trends [19, 169].

3.8 Soil Mapping

Soil mapping holds high promise in the area of digital agriculture for production of high-quality high-resolution soil maps. Through soil mapping, the impact of

different physical, chemical, and biological phenomena on the crop and yield can be assessed [112]. The production potential of the soil can be correlated with plant growth and seeding can be adjusted accordingly. Effects of fertilizer can be assessed using soil maps to make adjustments to inputs accordingly. The loss of nitrogen can be controlled to improve yield. Some basic components of the soil mapping are soil texture (percentage of clay, silt, and sand) mapping, salinity, soil organic matter mapping (OM), curvature, slope, tomography, and TWI.

Currently, electrical conductivity, optical, topography, gamma, and electromechanical sensors are being used for soil mapping [61, 63]. Soil salinity and texture sensors work by measuring the in situ electrical conductivity of the soil and are based on the ability of the soil to conduct electricity. Clay soils have higher conductivity because of the presence of a significant amount of fine clay particles. On the other hand, sandy and silty soils have particles in large size. Therefore, their ability to conduct electricity is low compared to clay soils. Electrical conductivity measurement differences are used to map soil texture. Electromagnetic induction and soil contact are popular EC methods. In soil contact EC measurement method, sensors work in contact with the soil using EM wave, whereas MI sensors work on the principle of induction. Both methods have comparable results.

Soil texture mapping using EC has many advantages: (1) crop growth is directly related to the water-holding capability of soils which also depends on the soil texture. Clay and silty soils have higher water-holding capacity compared to the sandy soil because of the number of the pores and pore size difference [49]. The root depth and other soil properties such as cation exchange capacity (CEC) also depend on the soil texture. Soil mapping is also used to characterize the soil response to the applied herbicides. Soil animal population, transport of nutrients, and buffering capacity are soil factors vital for crop production and growth. The major application of soil maps generated through soil sampling is in demarcation of soils in different zones, variable rate seeding and sowing rates, assessment and management of nitrogen, and yield maps. These maps combined with output of other soil sensing mechanisms lead to creation of a comprehensive real-time decision making tool.

Moreover, the soil EC can also be calibrated with soil type with laser diffraction mechanisms. It also guides soil sensor location and density in the soil for sensor-guided irrigation management in the field, thus leading to optimum operation. In the regions with high soil variability, soil maps are proven useful in development of seeding plans [16].

Organic carbon and matter sensing can be carried out using optical reflectance [209] to distinguish between organic matter and carbon. An agricultural field with darker color soil texture has higher amounts of organic matter compared to lighter color textured soils. This phenomena is caused by the absorption and bonding of light with CH and OH molecules of the soil which leads to darker colored soils with the presence of higher organic level and high soil water content. In soil maps, these areas also appear darker. However, the current ability of these soil mapping systems is milted up to the top inch of organic matter. On the other hand, organic

matter layers can be 2–3 in. deep in some soils. Therefore, development of optical soil sensing techniques with the ability to generate layered soil maps below 2–3 in. is very essential. Soil organic matter improves soil aggregation; helps in mineralization of N, P, and S; expedites the nutrient exchange process; reduces the top soil crusting process; prolongs the soil water content retention in soil; and reduces soil compaction and bulk density. Given this important nature of the organic matter, the OM soil maps can be used as good indicator of the soil health and increase OM understanding. These can also aid in nitrogen management and variable rate seeding. These can also be related to other soil parameters, EC, and nitrogen soil models for informed decision-making.

The results from a multitude of available soil mapping approaches discussed in this section can be used powerfully with fused sensor data using multiple soil layers. These multilayer soil maps are important to understand and get insights about what the change, what caused it, and what is the best course of action to deal with it [17]. In precision farming, existing challenges in adoption of soil mapping approaches and resulting maps are limited motivation to use them because of lack of high-precision maps. Moreover, in practice, fixed application of lime, K, and P is carried out, and the relationship of the insights gained from the yield is not very strong. Now with the availability of high-precision maps, the inputs are indirectly dependent on the soil texture and growers are customizing their application of fertilizer based on the maps which leads to the improvement in crop yield as well. Creating these soil maps is becoming more convenient with improved technology and ubiquitous connectivity. With the success of variable seeding and fertilizer application, there is need for high-precision soil maps to inform these variable technologies.

3.9 Digital Agricultural Education

There are many climate and production differences (e.g., crops, water availability, and irrigation practice terrain) between the different regions of the world. This contrast leads to differences in crop yield and return on investment for the same crop in different regions. Therefore, precision farming education and curriculum should be designed accordingly [151].

3.9.1 Curriculum Development

For precision agriculture curriculum, the online courses should be available to growers, policy makers, farm managers, and workers in order to provide training on latest developments. These training sessions can also be conducted on campus in evening and on Saturdays to attract larger agricultural community. Government

funding can help to start these initiatives to train and certify digital agricultural workforce. Universities in consultation with the industry partners and Ag companies can develop course plans for students. Availability of internships in this area will aid in the creation of skilled workers for jobs. For farm managers, one such sequence of courses can combine latest developments in irrigation management and food sciences, with advanced precision agricultural technology. Other major digital agriculture areas needing attention are integrated management of pests, training in safety, and use of connected heavy machinery and equipment. Although many community colleges in the USA are offering training in these areas, with the rapid developments and advances in technology, the institution of higher education should assume the role of training the next generation of students to adopt digital agricultural careers. Universities can not only conduct research but also transfer it to the community through start-ups and partnering with industry.

These connections can help students to learn the current needs of industry, the direction in which market is proceeding, and current precision agricultural use-case. These partnerships will also help to build focused faculty research groups and labs and will make huge advancements in the field through integration of ideas. The existence of novel challenges and right opportunities will increase the motivation to work together to find solutions and technology transfer. The industry board from the precision agricultural company will help shape the overall curriculum learning objectives through technology updates, discussions, and feedback. Through classroom integration, the curriculum can be enriched with examples and industry-based capstone design projects. Through this hands-on training, students will learn better about new developments in the area. Internships in digital agricultural companies through meaningful projects will also contribute to digital agricultural workforce development and create new employment opportunities at all level for students, industry, and academia. Overall, these university-industry partners can together solve many challenges in the area of silage and grain covers, underslab gas barriers, fumigation, building enclosures, and landfill covers.

The precision agricultural curriculum should be viewed as multidisciplinary tree that has branches in agronomy, computer science and electrical engineering, sensor technology and sensing approaches, and biological science and engineering with one shared goal of increasing crop yield though reducing input cost, better management and informed decision, and sustainable agricultural practices. The proposed digital agricultural curriculum should be able to develop global leaders for solving great changes in the area with a common commitment to the future of the digital agriculture. It will benefit farm managers, software developers, agronomists, engineers, technicians, and educators. It requires dedicated efforts by providing more resources, reducing adoption barriers to precision agriculture technologies, and investing in industry-academia partnerships.

3.9.2 *Work Roles in Digital Agriculture*

The precision agriculture work roles are described below:

- An applicator is the field worker who works to apply fertilizers and pesticides by using the related equipment.
- An agronomist specializes in soil and crop management and provide recommendation to the farmers.
- A precision equipment technician is an expert in digital agricultural equipment installation, trouble shooting, and repair and maintenance on the field.
- A precision sales specialist deals with sales and support of digital agricultural equipment and software. In this role, a precision sales specialist can also provide services remotely.
- A data manager collects and analyzes data from customers, farms, and agricultural businesses.

3.10 Energy Harvesting

For sustainable underground soil sensing and field communication operation, it is highly desirable to transfer wireless power to subsurface radios and sensors. In the agricultural field, ideally, the lifetime all sensing equipment should be greater than 5 years [78]. With the recent developments and improvements in technology and through development of energy-efficient sensor materials, the energy requirements for these sensors are decreasing rapidly. However, underground radios still require power to communicate through the soil to aboveground receivers. There are many intermittent energy harvesting resources available on the field for precision agriculture which include solar, vibration, bacteria as fuel cells, thermal, and underground living plants. However, the literature is scarce on underground wireless RF power transfer. The maintenance, repair, and removal of sensors for battery replacement and re-installation of underground equipment are costly, and access to field equipment not only is sometimes difficult but also causes disturbance to soil and plants. The extended lifetime of digital equipment is a very important adoption of the technology in precision agriculture.

In the digital agriculture, these underground devices can be powered in many different ways. The first method is based on wireless power transfer and is based on EM induction and magnetic resonance [68] and radiation.

Through RF power transfer, the energy can be transferred from the source to the subsurface equipment using the wireless electromagnetic waves. These waves exhibit less deterioration and attenuation as compared to resonance- and induction-based approaches. Therefore, it can be used for long-distance (up to few meters) energy transfer [31]. The normal power consumption of underground devices is few milliwatts, since underground digital agricultural devices can operate with low power using duty cycling. In duty cycling, the sensors and radios are activated only

when sensing data and communication is required. In a large farm, the sleep time can vary from few hours to days depending on the growing season, climate, and irrigation needs. For remaining time, the nodes remain in the sleep mode. Therefore, even few micro-watts power is sufficient for sustainable operation in the agricultural fields [91, 213].

Wireless RF power transfer requires external sources. The power beacons can be developed and utilized for this purpose. However, in the field, it is hard to have fixed aboveground energy sources as power beacons are permanently dedicated to power the sensors and radios. However, these sources can be mounted on pick-up trucks and farm equipment such as tractors. Moreover, the UAVs can be used to install these external power source combined with other data collection and sensing equipment for concurrent information and power transfer. Novel methods need to be developed for external energy transfer. The power transfer through the soil should be investigated. The ideal depth of sensors and distance between different nodes can be modeled by understanding the deterioration of signals in the soil. A detailed survey of power transfer in over-the-air wireless communications and networks has been given in [104, 105]. External power sources can be designed based on a single antenna approach where energy can be transferred to a single node only. However, recently, the idea of using multi-antenna approaches has attracted the attention of the research community, where beamforming can be used to direct energy to multiple nodes.

3.10.1 In Situ Energy Harvesting Methods

This interaction with the external power sources can be avoided with the development of in situ energy harvesting methods. The second method is based on energy harvesting from different sources. The piezoelectric technology has the capability to convert the vibration energy into power. It can be modeled through circuit and mechanical methods (mass, spring, and damper) [89, 216]. However, this technique is required to correct vibration frequency in order for power generation. The operation of diverse equipment and traffic leads to generation of different frequencies in the field. Therefore, either the multiple vibration sensors are tuned to different frequencies or one sensor with broadband spectrum sensing capability is needed [66, 123]. In [89], the applications of vibration energy harvesting have been investigated in a corn field. The piezoelectric energy harvesting technology, where these devices are buried in the field at low depths, has been used to harness the vibration field sources (e.g., the seeders, farm machinery, and harvester and other agricultural equipment). This empirical analysis has shown the viability of this technique for digital agriculture. However, the provision of prolonged sustainable energy to underground sensors is still challenging because this method is not sufficient to provide power to a multitude of devices underground. The burial depth of the equipment is one major issue because at deeper depths attenuation is higher

in the soil. To overcome challenges in the area of energy harvesting in the field, more insights into the vibration propagation in soil are needed. There is also a need for development of new protocols and platforms for subsurface power transfer. The link layer protocols for optimal frequency section and sensor placement should be developed. An in-depth validation of these approaches is required at the field level with consideration of models, nonlinear efficiency, and power consumption of circuits. It should also be combined with novel channel estimation methods in underground communications.

3.10.2 Wireless Subsurface Power Transfer

Generally, agricultural fields do not have enough ambient RF energy (stray EM waves) that can be harvested for self-sustainable operation. Another method is based on the use of energy harvesting for received data communications signals. It is done either through time sharing approach, where some slots are allocated to information transfer and alternative time slots are assigned to RF energy sensors. Other approaches are based on frequency sharing, where the frequency of the information signal is shared with the RF energy harvester. Beam splitting is another method for distribution of energy via energy scheduling approach. These co-channel data and power transfer approaches have been investigated in [31, 32, 135]. However, it leads to information communication performance degradation and requires designing new equipment which increase the cost of deployment, hence increasing the challenges in digital agricultural adoption.

There is also a need for medium access protocol (MAC [52]) for RF energy transfer techniques to work for multiple users in wireless underground network [115]. A rectenna is a type of energy harvesting antenna that is used for collection and rectification of the EM waves [136]. Many technologies are available to manufacture a rectenna for use in digital agricultural applications. These include CMOS, tunnel, Schottky and spin diodes, and active rectification. These rectennas also required matching circuits to match the input impedance of the rectifier to the impedance of the antenna for maximum energy harvesting. The design of such antennas has been explored in [47], which can be tailored for underground RF energy transfer applications. Some field experiments using these antennas in bridge settings are done in [47, 79]. Further investigation of possible distance up to which RF power can be transferred should be investigated as power transfer efficiency is dependent on the distance. There is also a need for development of energy beamforming with adaptive steering toward any underground and aboveground nodes, because with the advancement and adoption of precision agricultural practices, a multitude of sensors will be deployed across the field. Multiple antennas in the aboveground power source can be used to achieve very narrow-width beams with the capability to carry more power compared to traditional single-antenna transmission. For

beamforming with beam steering capability to work, there is a need for accurate channel estimation of underground channel between transmitter-receiver pairs to obtain channel gains. The wireless underground channel impulse response can be utilized for this purpose [160].

Additionally, the traditional receiver-guided [207, 215] and up-link phase estimation approaches can be used. To reduce equipment complexity and to conserve energy, there is a need for development of low complexity channel estimation schemes based on the receive power only (e.g., one bit feedback algorithm) [214]. Moreover, in agricultural Internet of Things (Ag-IoT), an energy neutral operation [175] is desirable to avoid the saved energy from being depleted and also to attain high efficiency of energy transfer and harvesting schemes. Duty cycling of the underground can be utilized as well to conserve energy. This depends on many factors such as requirement of frequency sensing operation, distance from the external power sources, crop, fertilizer inputs, and weather [170, 204]. Duty cycling can be activated based on some threshold of power going below some level, and the system should also have the ability to automatically make changes on the sleep and wake-up duration based on the changes in these field factors. Moreover, the nodes running out of power should be capable of requesting energy on an urgent basis. Further research is also needed to assess the number of external power sources needed based on the fixed sensor density in a typical agricultural field and should also be able to accommodate mobile sensors.

Recently, magnetic near-field inductive power transfer approach has been proposed for magnetic induction-based wireless underground sensor networks [91]. There are many standards available for magnetic near-field inductive power transfer. However, its range is limited to distances less than 1m.

Far-field wireless power transfer (WPT) can be used for long energy transfer. There are many advantages of long-range wireless power transfer approach in the underground sensing and communications in digital agriculture.

- Physical contact with devices and wired connection can be completely removed.
- Mobility can be achieved in energy transfer as external power sources can charge many devices in the field.
- On-demand and reliable delivery can be insured all conditions in contrast to other sources of power which are weather or farm activity dependent.

A concurrent wireless and power wireless network can be effectively used to transmit data and power in full-duplex settings. The first case is aboveground to underground energy transfer in which the solar energy harvested from the aboveground nodes can be transferred to underground nodes. In the second case of underground to aboveground energy transfer, the energy harvested by the underground nodes from the vibration and bacterial sources acting as fuel cells can be transmitted to aboveground nodes. Therefore, both these bidirectional energy transfers will lead to more reliable and sustainable operation for longer periods of time anywhere and anytime.

3.10.3 Solar Power

Solar power transfer through aboveground nodes can also be used in the agricultural fields in the sun belt area to transfer power to underground nodes. The harvested solar energy can be steered to different underground nodes using the soil moisture adaptive beamforming with phased antenna arrays [154]. The Solar Power Radio Integrated Transmitter (SPRITZ) can be developed by combining with solar cells that provide the DC power.

3.10.4 Energy Harvesting Challenges

The design underground energy transfer in digital agriculture should address following major issues:

- Transfer range for fully functional underground energy transfer network, underground-to-underground power transfer range should be 35m, which is the current communication range for the same wireless channel. However, for the transfer link where there are sources available aboveground, the energy transfer range of 100m is desirable to cover a standard 300x300m agricultural field.
- Multipath support. Energy transfer technique should be able to function where direct line of sight is not available. During plant growth in the growing season, many reflections from soil-air interface and multipath can exist which can pose critical challenges to effective energy transfer.
- Efficiency. Highly effective approaches are needed for through-the-soil power transfer. Because of complex permittivity of the soil, high attenuation of wireless signals carrying data and power can reduce the efficiency of these approaches. High RF to DC conversion efficiency of devices is also vital for efficient energy harvesting.
- Mobility. Since a multitude of farm machinery and pickup trucks can function in the field, mobility power transfer will enhance the efficiency compared to the fixed external power sources in the field.
- Accessibility. The wireless power transfer approaches should be resistant to the changing crop pattern, weather, and irrigation conditions. Ubiquitous accessibility will ensure reliable power supply in the wake of changing environmental conditions.
- Standards for in-field power should be developed so that all existing and new digital agricultural devices can be compatible and function in the transfer network.

- Energy consumption storage. There is also a need for development of new methods to store energy at the underground nodes and reduce energy through development of novel adaptive duty cycling approaches.
- Frequency spectrum. Types of uniform power and data transfer in digital agriculture should be used to effectively to utilize the underground frequency spectrum (less than 1 GHz) within the bounds of existing delay spread and coherence bandwidth.

3.10.5 Combined Power and Data Transfer in Digital Agriculture

The different types of uniform power and data transfer in digital agriculture are discussed in the following:

- Concurrent transfer of data and power. The same channel is used for power and data transfer. The power sensor can be integrated in the receiver nodes (co-located) or two separate devices can be used in this type of transfer.
- Unidirectional data and unidirectional power. One line is used for the transfer of power (from transmitter to receiver) and other link is used for data (from receiver to transmitter).
- Time-shared approach. The channel is shared between data and energy by using the time sharing approach depending on the need of the energy and information transfer.

3.11 The Ag-IoT Systems

The academic and commercial IOU systems are given in Tables 3.1 and 3.2, whereas their classification is shown in Fig. 3.8.

Table 3.1 The academic IOUT systems [202]

Architecture	Sensors	Comm. tech.	Node density
Automated irrigation system [65]	DS1822 (temperature) VH400 (soil moisture)	OTA, Zigbee (ISM)	One node per indoor bed
Soil scout [192]	TMP122 (temperature) EC-5 (soil moisture)	UG, custom (ISM)	Eleven scouts on field and a control node
Remote sensing and irrigation sys. [90]	TMP107 (temperature) CS616 (soil moisture) CR10 data logger	OTA, Bluetooth (ISM)	Five field sensing, one weather station
Autonomous precision agriculture [42]	Watermark 200SS-15 (soil moisture) Data logger	UG, custom (ISM)	Up to 20 nodes per field
SoilNet [25]	ECHO TE (soil moisture) EC20 TE (soil conductivity)	OTA, Zigbee (ISM)	150 nodes covering 27 ha
MOLES [187]	Magnetic induction communications	Magnetic induction	Indoor testbed
Irrigation nodes in vineyards [200]	Yield NDVI	Variable rate irrigation	140 irrigation nodes per field
Sensor network for irrigation scheduling [38, 167]	Capacitance (soil moisture) Watermark soil moisture sensors	OTA	6 nodes per acre
Cornell's digital agriculture [33]	E-Synch, touch-sensitive soft robots Vineyard mapping technology, RTK	OTA	Field dependent
Plant water status network [139]	Crop water stress index (CWSI) Modified water stress index (MCWSI)	OTA	Two management zone—two treatments in each zone
Real-time leaf temperature monitor system [98]	Leaf temperature Ambient temperature Relative humidity Incident solar radiation	OTA	Soil and plant water status monitors,
Thoreau [220]	Temperature, soil moisture, electric conductivity, and water potential,	OTA	Based on Sigfox,
FarmBeats [196]	Temperature, soil moisture Orthomosaic and pH	OTA	Field size of 100 acres

(continued)

Table 3.1 (continued)

Architecture	Sensors	Comm. tech.	Node density
Video-surveillance and data-monitoring WUSN [55]	Agricultural data monitoring Motion detection Camera sensor	OTA	In the order of several kilometers
Purdue university’s digital agriculture initiative [134]	Adaptive weather tower PhenoRover sensor vehicle	OTA	Field dependent
Pervasive wireless sensor network [210]	Soil moisture, camera	OTA	Field dependent
Pilot sensor network [96]	Sensirion SHT75	OTA	100 nodes in a field
SoilBED [46]	Contamination detection	UG	Cross-well radar

Table 3.2 The commercial IOUT systems [202]

Architecture	Sensors	Comm. tech.	Node density
IRROmesh [84]	200TS (temperature)	OTA, custom (ISM)	Up to 20-node network mesh
	Watermark 200SS-15 (soil moisture)	OTA, cellular	
Field connect [88]	Leaf wetness	OTA, proprietary	Up to eight nodes per gateway
	Temperature probe	OTA, cellular	
	Pyranometer	OTA, satellite	
	Rain gauge		
	Weather station		
SapIP wireless mesh network [43]	Plant water use	OTA	Up to 25 SapIP nodes with 2 sap flow sensors each
	Measure plant stress		
	Soil moisture profile		
	Weather and ET		
Automated irrigation advisor [195]	Tule actual ET sensor	OTA	Field dependent
Internet of agriculture-biosense [24]	Machinery auto-steering and automation	OTA	Field dependent— Real-time irrigation decision-making
	EC probe & XRF scanner		
	Electrical conductivity map		
	NDVI map		
	Yield map		
	Remote sensing		
	Nano- and micro-electronic sensors		

(continued)

Table 3.2 (continued)

Architecture	Sensors	Comm. tech.	Node density
	Big data, and Internet of Things		
EZ-farm [77]	Water usage	OTA	IBM bluemix and IBM IoT foundation
	Big data and Internet of Things		
	Terrain, soil, weather		
	Genetics		
	Satellite info		
	Sales		
Internet of food and farm (IoF2020) [82]	Soil moisture	OTA	Field dependent
	Soil temperature		
	Electrical conductivity and leaf wetness		
CropX soil monitoring system [34]	Soil moisture	OTA	Field dependent
	Soil temperature and EC		
Plug & sense smart agriculture [128]	Temperature and humidity sensing	OTA	Field dependent
	Rainfall, wind speed, and direction		
	Atmospheric pressure		
	Soil water content and leaf wetness		
Grain monitor-temputech [191]	Grain temperature and humidity	OTA	Multiple depths in grain elevator
365FarmNet [1]	Mobile device visualization tool for IOUT data	OTA	Field dependent
SeNet [166]	Sensing and control architecture	OTA	Field dependent
PrecisionHawk [130]	Drones for sensing	OTA	Field dependent
	Field map generation		
HereLab [69]	Soil moisture	OTA	Field dependent
	Drip line PSI and rain		
IntelliFarms [80]	YieldFax	OTA	Field dependent
	Biological		
	BinManager		
IoT sensor platform [83]	IoT/M2M sensors	OTA	Field dependent
Symphony link [185]	Long-range communications	OTA	Field dependent

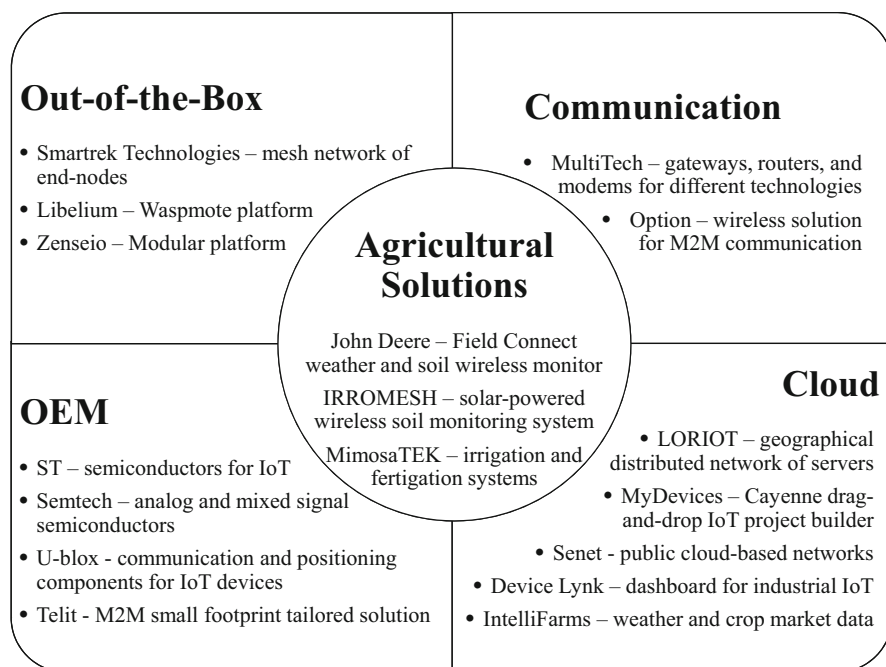


Fig. 3.8 The classification of commercial IOUOT solutions [202]

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Chapter 4

Internet of Things for Water Sustainability



4.1 Introduction

When the well runs dry we know the worth of water.—Benjamin Franklin

The survival of the humanity is contingent upon the availability of water. The aquatic ecosystems that include groundwater, oceans, river, lakes, streams, and estuaries supply a wide range of resources and services to the community [18, 56]. These are important for water storage, regulation of water quality and quantity, food provision, recreation, and transport of water and substances downstream [14, 92]. Droughts and flooding impacts the normal functionality and are the main causes of reduction in its tolerance and diversity, a vital factor for sustainable community [63, 126, 131]. The contents of the chapter are shown in Fig. 4.1.

The water-, energy-, and land-based systems are linked in many different ways [39, 63, 107]. The precipitation patterns are changing rapidly due to the ocean and atmosphere warming [14, 17, 31, 33, 43, 101]. The most visible effects of these phenomena include increase in the duration of dry periods, higher evaporation, and rapid snow melt [46]. These cascading effects propagate to the water cycle, which encompasses complete and dynamic processes of water movement and circulation in the Earth system. Due to global warming effects, these water cycle processes (see Fig. 4.2) are exhibiting unpredictable increase and decrease with abundant (flooding) or little to no water availability (drought) [33]. The decrease in the amount of available water is a major threat to the entire ecosystem. Similarly, flooding poses a major risk to communities and infrastructure.

Significant changes are also being observed in streamflow patterns with peak flows moving to the beginning of the year [111, 133]. The increase in the amount of rain as compared to the snow is also impacting water storage facilities. The rate of evapotranspiration is a major element of the water cycle, which represents the evaporation of water from different sources such as oceans, lakes, plants, soils, and rivers [93]. Its rate is impacted by wind, solar radiation, humidity, and wind.

Fig. 4.1 The internet of things for sustainable water

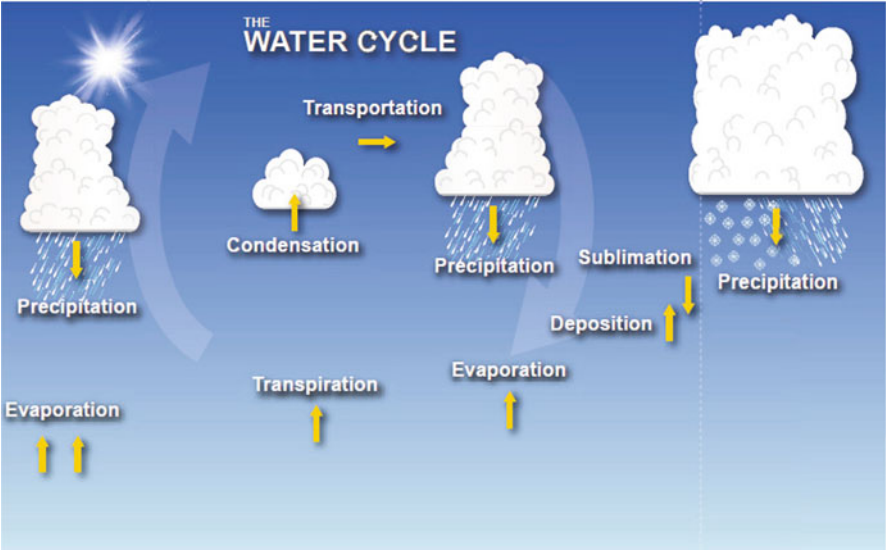


Fig. 4.2 The water cycle

Consequently, the water content of soil, water runoff, and groundwater recharge are impacted by these variations in the rate of evapotranspiration [33, 78]. Among these factors, the soil water content is significant because of its implications in agriculture and air evaporation and temperature. This increase in evaporation is considered to be a big factor contributing to increases in dry periods and shorter

droughts on a seasonal basis [42]. These changes in precipitation patterns are also impacting the municipal water supplies [103]. For a reliable water supply to cities, the utility management companies are facing many challenges in water storage due to the projected decline in supply and increasing population. The world population is expected to reach 9.8 billion people by 2050, with a corresponding increase of 25–70% in food production [129]. The world food production challenges span beyond the UN agenda of eradicating malnutrition and poverty by 2030. According to the WHO, the daily minimum human demand for water is 1.84 gallons per day, whereas the recommended water needed to maintain adequate hygiene is 5.28 gallons [109]. For a total human population of 7.7 billion, the global water need of freshwater is 40.65 billion gallons. The UN Sustainable Development Goal (SDG 6) talks about providing safe water [110].

The crop and landscape irrigation also depends on water, being the largest withdrawal of water. Although three-fourths of our planet is covered with water, but only 2.5% constitutes the freshwater. Approximately 70% of the available freshwater is frozen in glaciers and ice caps. The residual 0.75% of freshwater is in swamps, subsurfaces, lakes and rivers, living organisms, and the atmosphere. The 70% of the remaining 0.75% of freshwater is utilized in irrigation.

Water quality is another major challenge. The high streamflow takes sediments and pollutants to the water, whereas the well below-average rates of streamflow also result in the decrease of water quality. Similarly, heavy precipitation, increased intensity and scale of wildfires, impacts fertilizer usage contributes nutrients, contaminants, and sediments from the surface water downstream [35].

Freshwater aquifers and wetlands are also vital for water sustainability. These are being undermined by many factors including changing sea levels, surface and groundwater usage, and storm surges [16]. The saltwater gets mixed with underground and surface water due to rise in sea levels. The saltwater also flows upstream to make up the deficiency in river flows that are caused by high withdrawals. Moreover, storm surge and rise in sea levels also impact the urban underground infrastructures such as storm drainage and sewer treatment.

In the water-energy nexus, the demand for water for energy production is increasing rapidly. Water is needed in hydroelectric dams for turbine, in thermoelectric power plant for steam, and for cooling of the equipment in nuclear power generation to absorb heat. Likewise, the energy is needed to draw out water from rivers and aquifers, to transport it to storage and treatment facilities, to distribute water supply, and finally, to collect wastewater. Collectively, energy and water need land resources.

4.2 Water Sustainability IoT

The water sustainability IoT contain components such as water things, sensing, water quality measurements, cleaning and treatment technologies, and water resource management. The elements of the water IoT are as follows:

- Groundwater, fresh water, and surface water
- Precipitation, river flow, lakes, and wetlands
- Evapotranspiration, hydrology, and hydraulics
- Aquifer and runoff
- Irrigation, recycling, and cleaning

4.3 IoT as an Enabler for Sustainable Water

In this section, the IoT paradigm is discussed as an enabler of sustainable water.

4.3.1 Advantages of Sustainable Water IoT

The water IoT is envisioned to provide accurate decision support systems to guide technological and societal progress in water use. It enables annual precipitation monitoring and river flow variation observations. Accordingly, very heavy precipitation, dry periods, and seasonal and short- and long-term droughts can be predicted at the spatial and temporal scale. Moreover, based on the IoT sensing technologies for withdrawal of groundwater, and aquifer recharge, the availability of demand can be ascertained. The surface and groundwater supplies are decreasing because of the consumption, withdrawal, precipitation, and runoff, combined with changes in consumption and withdrawal. The determination of variations in surface water and groundwater usage patterns will help to attain substantial freshwater aquifers and wetlands. The total precipitation measurements can be used to forecast potential flooding threats. Therefore, risks to economy, community infrastructure, human health and property, and human safety can be reduced.

The state-of-the-art IoT technology, ecological standards, and indicators are useful in achieving sustainability goals. There are many advantages of the water IoT for sustainable community development. The cumulative water withdrawal scale and impact can be modeled on ecosystem through IoT data collection tools. The development of novel sensing technologies enables monitoring of water IoT such as wetlands and lake inflows. Accordingly, based on the sensing of water IoT, better approaches can be developed for water sustainability indicators which will contribute to the aquatic and terrestrial ecosystem resilience. Other important enabling sensing includes water and air temperatures, runoff, and precipitation.

Using the integrated water IoT paradigm, the connection between ecological parameters and hydrology flow regime and groundwater can be better understood through the identification of impact of flow regime thresholds. One example is flow variations link to invasive species. The water quality can be improved by reduction of pollutants caused by human activities. The IoT paradigm can also inform deployment of new systems for reducing water use. Moreover, the water cleaning and recycling technologies can be developed and integrated into the system

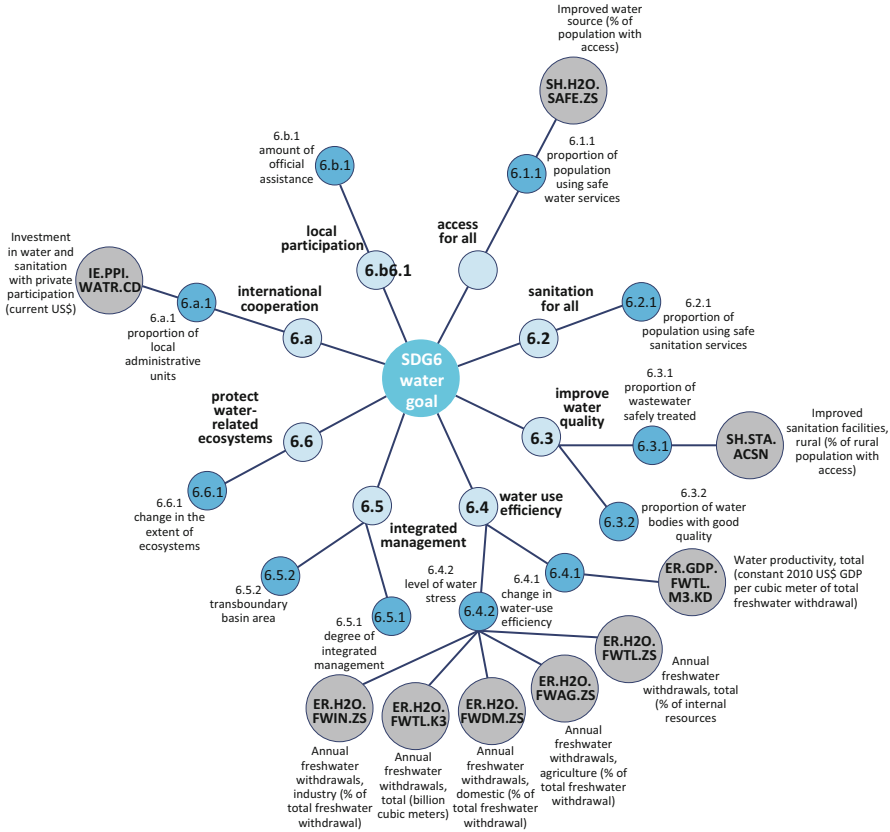


Fig. 4.3 The sustainable development goals related to water sustainability

through sensing of the water pollutants, nitrogen, and sediments. Accordingly, lake and water quality can be improved. Moreover, critical data sets (e.g., data related to stream and river flow, groundwater, waterborne disease, water usage, and paleoclimate reconstruction) can enable advance research and better understand the ecosystem (Fig. 4.3).

4.3.2 Research Challenge Needs in Sustainable Water IoT

In this section, research needs in support of all aspects of the sustainable water ecosystem are discussed.

- Better insights are needed in relationship between groundwater and surface water through improvements in water IoT monitoring tools and infrastructures [34, 48].

- In the ecology domain, a particular emphasis is needed on sensing of ecological parameters and lakes and wetland inflows. The connection between point and nonpoint sources against freshwater supply also needs more investigation [45].
- In urban localities, more advanced real-time pathogens, contaminants, and chemical compound sensing technologies are needed. Novel techniques are needed for nutrient reduction, detection of new types of contaminants, spill detection, and source tracking [60].
- There is need for whole cycle measurement integration into sustainable water IoT with emphasis on communication networks to eliminate dependency on detached measurements to assess the effects of climate change, land use, and water conservation activities including water source and discharge [44].
- Other important technological needs for sustainable water integration are in the area of inexpensive storage and metal removal [22, 127].

4.4 Water Sustainability IoT Monitoring and Applications

Water quality is an indicator of the state of biological, chemical, and physical properties of water [115, 123]. The importance of the water quality for sustainable environment and ecosystem cannot be overemphasized [130]. Water quality measurements in rivers and lakes and other water bodies are important to identify inadequate oxygen supply caused by extra amounts of nutrients and algal blooms. Through monitoring the impact of the climate change, human activities can be better understood [57]. Accordingly, it enables better decision and policy making. Moreover, the impact of the sediment loading can also be analyzed by using the turbidity measurement. Monitoring can be done by using different approaches such as sampling, continual monitoring, and remote sensing which are all used to collect water quality data in estuarine and coastal ecosystems, surface and groundwater, stormwater, and ballast water [57]. In this regard, novel pathogen, nutrient, and chemical contaminant sensing technologies are needed.

Similarly, water monitoring in urban areas includes:

- Accession and transport of rainfall and runoff data for sewage and stormwater networks [105]
- Management of stormwater retention base [122]
- Water supply infrastructure monitoring [95]
- Pipeline system to identify issues related to water supply shortage [54]
- Industrial activities that impacted water quality monitoring [69]

For sustainable water IoT, development of novel monitoring technologies for the entire water cycle is needed. The sustainable water IoT is envisaged to integrate different types of measurements at a large scale. This paradigm removes the issue of single-point failures and insufficient data for decision-making. It also gives insights into the baseline conditions at different spatial and temporal scales (including natural perturbations and industrial impacts). Accordingly, various relevant baseline

indicators can be utilized for policy making and remedial actions by providing accurate and certain data. The sustainable water IoT enables development and integration of different types of systems for robust evaluation of water ecosystems. The predictive models can be developed and integrated into the paradigm for different water use scenarios (e.g., drinking water, discharge, and industrial use).

4.4.1 Applications

The important water monitoring applications are discussed below:

- Potable water monitoring. For chemical properties including pH, nitrates, and dissolved oxygen (DO).
- Chemical leakage monitoring. Extreme pH and low dissolved oxygen levels are used to identify spills because of sewage treatment plant or other pipeline issues in rivers.
- Pollution level monitoring: Temperature, pH, salinity, and nitrate dissolved oxygen monitoring in seawater.
- Corrosion and limescale deposit monitoring: pH, conductivity, calcium (Ca^{+}) temperature, and magnesium (Mg^{2+}) concentration monitoring.
- Aquatic life condition monitoring. Water conditions of aquatic animals such as fish.
- Swimming pool monitoring: pH, oxidation-reduction potential (ORP), and chloride values to assess water quality in swimming pools.

4.4.2 Source Water Monitoring

Source water is impacted by different factors including seasonal weather changes and upstream discharge. The source water quality monitoring enables selection of proper treatment options. Groundwater has low content of natural organic matter (NOM) and therefore can be disinfected by using chlorine disinfection techniques.

4.4.2.1 Surface Water

Surface water comes from rivers, lakes, and other reservoirs. It is the vital source of water production. The groundwater has high content of natural organic matter (NOM) and needs proper disinfection techniques.

The important water monitoring parameters are discussed below:

- Ammonia. The ammonia level can change remarkably in all seasons and requires consistent monitoring. Ammonia reaction chlorine disinfection leads to formation of chloramines which produces different issues [51].

- Free chlorine: Free chlorine is mixed to the groundwater for ammonia transformation to chloramines, which breaks further to chlorine, hence making free chlorine as leftover disinfectant. The free chlorine monitoring is done to achieve the desired levels. It is also used to eliminate amalgamation of manganese and iron through filtration [85].
- pH. pH is used for chlorine disinfection process optimization. It indicates the acidity and alkalinity of water [25].
- Total organic carbon. The TOC is a measure of the carbon present in organic compounds of the water. It guides selection of proper treatment method through byproduct precursor removal [79].
- UV254. UV254 gets its name from its wavelength of 254 nm. It is used to measure organic matter (OM) in water. The OM reacts to chlorine to form disinfection byproducts (DBPs). Different events impact the OM in the water such as storm and increase in nutrients from human activities [128].
- Turbidity. Turbidity is the indicator of water transparency loss caused by the suspended particulates. Large turbidity levels negatively impact the disinfection process by preventing ultraviolet disinfection. Turbidity variations also indicate weather events such as rain and floods [96].

4.5 Sensing in Sustainable Water IoT

Real-time sensing is a vital component of the sustainable water IoT. The monitoring applications enabled through this sensing mechanism are being adopted by industry. It also enables improved efficiency water treatment and recycling operation. A detailed overview of water sensing technologies is given in the next section.

4.5.1 pH Sensing

A common measurement of water is pH, which is equivalent to the negative of the logarithm of the hydrogen ion concentration in water. It is used to measure acid and alkaline properties of water on a scale of 0–14, where 7 is considered as neutral. pH values higher than 7 denote alkalinity, whereas pH values less than 7 indicate acidity. An increase or decrease of 1 in acidity or alkalinity represents ten times change. Different types of the pH sensors are explained below:

4.5.1.1 Combination (Electrochemical) pH Sensor

The combination(electrochemical) sensor is a widely used method to sense pH values [10]. It consists of a reference and measuring electrodes. Whereas the actual detection of the pH variations is done based on the measurement electrode, the

reference electrode provides a steady signal for comparison purpose. An impedance-based metering instrument is used for pH value visualization which converts milli-volt signal to pH values.

4.5.1.2 Three-Electrode pH Sensor

The three-electrode pH sensor, also referred to as differential pH, uses three electrodes for pH measurements [55]. Whereas the differential detection of the pH variations is done based on the measurement of two electrodes, the reference metal ground electrode provides a steady signal for comparison purpose. The three-electrode pH sensor is less error-prone in terms of reference signal.

4.5.1.3 Laboratory pH Sensor

The laboratory pH sensor is a type of electrochemical pH installed in 1.2 cm glass/plastic unit. This type of sensor is used in laboratories for learning and discovery purposes. This is also used in environmental monitoring and pool sampling and can be easily tailored to match desired application requirements [82].

4.5.1.4 Single-Chip pH Sensors

The single-chip pH sensors are used for pipeline and underground tank monitoring. It is designed to provide continuous monitoring of the pH values. Its robust design can sustain harsh environment with capability to work for longer duration without interruption [41].

4.5.2 Conductivity Sensing

Electrical conductivity, reciprocal of resistivity, is the measure of the capability of a solution's or medium's electric conductance [80]. Without the presence of ions, water is not a high conducting medium. Therefore, conductivity measure indicates the amount of ion present in water. The electrical conductivity measurements can be presented in different units (e.g., ion concentration, TDS, and salinity). It is expressed in micro-Siemens per centimeter, $\mu\text{S}/\text{cm}$, micro-Siemen. For higher conductivity, values are also expressed in milli-Siemens. There are several different conductivity measurement units in use today.

4.5.2.1 Conductivity Measurement Units

Conductivity measurements are often converted into TDS units, salinity units, or concentrations. These units of measurements are explained in the following:

- **Total dissolved solids.** TDS is an indirect measure of the number of ions, which is measured through electrical conductivity and is indicated as parts per million (ppm) or mg/l [94]. In the environment, where highly dissolved ionic solids are present, TDS measurements produce accurate results. The TDS is also being used in the water treatment industry.
- **Salinity.** It is also an indirect measure which is usually expressed as ppt. Both TDS and salinity measurements are sensitive to temperature, ion types, and concentration. Accordingly, one unit can be converted to another unit [84].
- **Concentration.** Based on the knowledge of the composition of the ions, the concentration can be ascertained from the conductivity [8].

4.5.2.2 Conductivity Sensors

Electrical conductivity sensors are based on inductive, two-electrode-, four-electrode-based methods. These electrical conductivity measurements from these sensors can be changed to salinity, total dissolved solids, and concentration. Different types of conductivity sensors are discussed in the following:

Contact-Based Conductivity Sensors The contacting conductivity sensors are used for conductivity by making a physical contact, from two sides, to the understudy material [90]. These sensor sides are made by using different materials such as platinum, graphite, and steel. An alternate current (AC) waveform is applied and transmitted through once, which then propagates through the sample that is being sensed. Accordingly, the signal is received at the other side where its intensity is used to measure the conductivity in TDS or micro/milli-Siemens.

Inductive Conductivity Sensors The inductive conductivity sensors, also called the toroidal conductivity sensors, work on the principle of magnetic induction by using a two-coil (antenna) induction system in plastic assembly. The transmitter antenna induces a magnetic field that produces an electrical current on the understudy sample. The receiver antenna measures the magnetic field, where the corresponding current intensity indicates the ion concentration. Due to its ability to remove polarizing effects and fouling resistant, the inductive sensor produces high-quality measurements as compared to the contact-based conductivity sensor. The toroidal sensors are being used in sea water monitoring. A four-electrode conductivity sensor and an integrated temperature sensor unit are shown in Fig. 4.4.

Conductivity in Water Treatment Based on the application need, various levels of conductivity values are used to assess the purity of water (e.g., drinking water generally has the conductivity value of around 1 milli-Siemens per centimeter;

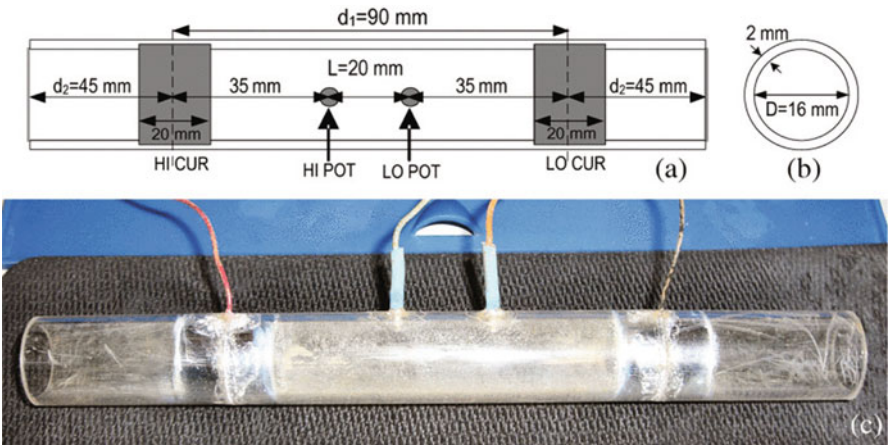


Fig. 4.4 A four-electrode conductivity sensor and an integrated temperature sensor unit. (a) Longitudinal sectional-view geometry. (b) Transversal sectional-view geometry. (c) Actual sensing unit [90]

Table 4.1 The conductivity levels of the different liquids

Liquid type	Conductivity level
Fresh water	0–1 mS/cm
Ultrapure water	0.00005 mS/cm
De-ionized water	0.00005–0.001 mS/cm
Reverse osmosis water	0.00005–0.2 mS/cm
Drinking water	0.20–0.80 mS/cm
Slightly salty water	1–45 mS/cm
Seawater	45–73 mS/cm
Highly salted water	72+ mS/cm

highly pure water has the conductivity values that are less than 1 micro-Siemens per second).

The conductivity levels of the different liquids are given in Table 4.1 [100].

4.5.3 Dissolved Oxygen Sensing

The oxygen dissolved per unit of water is called dissolved oxygen (DO) [83]. Water gets oxygen through different ways:

- The aeration also known as movement by turbulence
- Through diffusion in surrounding air
- Aquatic plants
- Plant waste by photosynthesis in water column
- Atmosphere

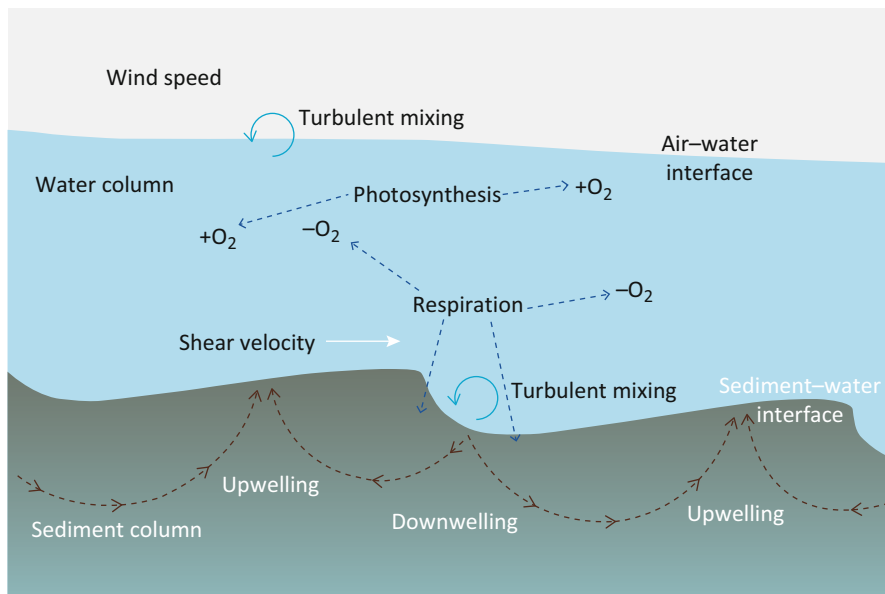


Fig. 4.5 A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations [9]

Still water sources (e.g., lakes) have low oxygen as compared to the running water source such as streams and rivers. A schematic side view showing major processes controlling stream and benthic dissolved oxygen concentrations is shown in Fig. 4.5. DO is a vital indicator of the quality of water and aquatic life as oxygen is a must for breathing. Different types of DO sensors are explained in the following.

4.5.3.1 Galvanic DO Sensor

The galvanic DO sensors use a cathode and an anode with an oxygen-permeable membrane to separate these two from the sample under study water [9, 37]. The purpose of the permeable membrane is to permit oxygen contained in the sample to be diffused in the instrument; accordingly, the cathode reduces it there. Due to this chemical reaction, an electronic signal is generated, which propagates from cathode to anode, and subsequently into the sensor, where the difference in pressure is measured, which changes according to the sample's oxygen's pressure. Because of the diffusion rate and partial pressure increase with oxygen concentration, there is a proportional increase in the current.

4.5.3.2 Optical Dissolved Oxygen Sensors

A dye is used in the optical dissolved oxygen sensor [66] to sense the wavelength of light. Then a paint layer of oxygen is placed on the dye in which molecules interact with luminescence. It acts as a filter for other compounds. The color of the dye changes to glowing red when it is exposed to light. The sensor measures luminescence from the emitted light by using the photodiode, which is compared to the reference value to ascertain oxygen dissolved in water.

4.5.4 Eutrophication and Nutrient Sensing

Eutrophication is unrestrained intake and enrichment of nutrients (e.g., nitrogen and phosphorus) that mostly come from anthropogenic sources (e.g., human activities) [53, 116]. This issue is being observed in reservoirs, rivers, estuaries, lakes, and other coastal regions. The presence of high concentration of nutrients leads to the production of toxins, hypoxia, fish kills, and harmful algal blooms (HABx) that are harmful to the aquatic life and humanity [11, 13, 36, 71]. These nutrients are carried along with agricultural runoff, domestic yard fertilizers and detergents, fossil fuel combustion caused by atmospheric deposition, stormwater, and wastewater. Due to infeasibility of mitigation, preventing that high intake in lakes, rivers, and oceans through nutrient sensing and in situ measurements is a viable option to avoid potential problems to the ecosystem. Accordingly, compliance limits for nutrient discharges can be established. Nutrient sensing also enables other policy-level decisions such as flow rate and treatment options at water bodies. It also provides insights into the relationship of geochemical, hydrological, and biological processes. With the increasing severity and intensity of HABs, there is a need for in situ nutrient sensors for nitrate, ammonium, nitrite, ammonia, total phosphorus, total nitrogen, and soluble reactive phosphorus with strong emphasis on the nitrate and nitrite sensors. Nutrient sensing technologies are discussed in the following:

4.5.4.1 Optical Nutrient Sensor

It works by using advanced spectral absorption (UV) [113] through a photometer and provides accurate and high resolution and chemical-free fast response time. However, it is expensive and only senses nitrate. Moreover, the energy consumption of the sensor is high. It can operate under harsh environments such as blue-ocean nitraclines and storm runoff in lakes and rivers and streams [72].

4.5.4.2 Wet Chemical Sensor

It operates on the principle of wet chemical calorimetric reaction with sensing through photometry [6]. It also provides accurate and high-resolution measurements

of phosphate, ammonium, and nitrate. It is suitable for point and nonpoint source nutrient measurements in different environments (e.g., lakes, reservoirs, rivers, streams, rivers, canals, channels, estuaries, and oceans). It supports real-time measurement of dissolved phosphate.

4.5.4.3 Ion-Selective Electrodes Sensor

It operates on direct potentiometry between a reference electrode and a detecting electrode [24]. It can sense ammonium and nitrate. However, it has low resolution as compared to the wet chemical sensor and optical sensor. The accuracy of this sensor is also sensitive to the ionic interference.

4.5.5 Water Flow Sensors

Water flow and discharge measurements are important to ascertain the amount of water flowing through a channel. These sensors are also used to predict flooding. In flow rate measurements, different inferential approaches such as change in water velocity and kinetic energy are employed. The different types of water flow sensors are explained in the following [50]:

- Rotameter. A rotameter is used for volumetric flow rate measurement of fluids in a closed tube. It works by allowing flow to the cross section where the travel of the flow changes and accordingly can be measured [59].
- Magnetic flowmeter. A magnetic flowmeter is a flow measurement instrument that works on the voltage induction principle. It measures the flow by using a magnetic field that causes difference in potential corresponding to the velocity of flow normal to flux lines [52].
- Turbine flowmeter. A turbine flowmeter is used to sense the volume of the flow by using the rotation of the blades caused by the movement of flow. By measuring the rotor velocity that is directly proportional to the fluid velocity, it provides accurate measurements [3].
- Venturi tube flowmeter. The Venturi tube flowmeter is used to measure flow by using a pipe's converging section to induce an increase in velocity, which leads to a proportional drop in pressure that is used to deduce the flow rate. The water supply industry uses the Venturi tube flowmeter for flow measurements [62].

4.5.6 Temperature Sensing

A temperature sensor, as the name indicates, is used to measure water temperature [114]. Different types of temperature sensors are explained in the following:

- **Thermocouple.** A thermocouple uses two different types of electrical conductors that are used to form junctions at two different temperatures [67]. A thermocouple generates a voltage that depends on the temperature (thermoelectric effect). Accordingly, the voltage interpretation provides temperature value.
- **Resistance Temperature Detector.** A RTD determines temperature by using the electrical resistance of the sample under study which changes with the change in temperature [5].
- **Thermistor.** The electrical resistance of the thermistor changes with temperature and accordingly is used to measure temperature [120].

4.5.7 *Satellite Sensing*

Water remote sensing is used for recording the water color spectrum (color of water body) and is based on optics and water's apparent optical property [19, 47]. It is used to sense the presence of different natural components of water. When the light field is applied to water, the angular distribution of the field impacts the water color depending on the type and amount of water substances. Therefore, the concentrations of optically active substances are determined with this distribution changes [30].

The reflectance of light from the water surface is measured using different types of optical measurement devices such as radiometers and spectrometers mounted on air- and space-born devices. The water quality is studied from different parameters such as chlorophyll-a and suspended particulate matter concentration, where high amount of detected concentrations of these parameters shows eutrophication-caused algal bloom (HAB).

The Ocean Color Radiometry Virtual Constellation (OCR-VC) is a system that produces data sets by using ocean color radiometry satellites to assess climate change impacts [38].

Various ocean color radiometry networks are listed in the following:

- International Network for Sensor Inter-comparison and Uncertainty Assessment for Ocean Color Radiometry (INSITU-OCR). The purpose of this network is to integrate and visualize different remote sensing tools for satellite sensor intercomparisons and uncertainty assessment for remote sensing products
- Ocean Color Essential Climate Variables (ECV) [97]
- Global Climate Observing System (GCOS) [20]
- International Ocean Color Coordinating Group (IOCCG) [136]

4.6 Sustainable Water IoT Technologies and Systems

In this section, sustainable water IoT technologies and systems are discussed.

4.6.1 Water Pollution Control

The discharge of toxic substances due to human activities (e.g., herbicides, domestic wastes, and insecticides) is one of the main factors contributing to water pollution [68, 91]. Various types of compounds and chemicals are being detected in water sources indicating the severity of this issue. Other water pollutants come from livestock farms, waste from food processing plants, and metal and chemical waste. Due to various types of water pollutants, a range of diverse techniques and methods are being used for water treatment. An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems is shown in Fig. 4.6. Surface water and groundwater are two types of drinking water that generally require treatments for the following types of contaminants [70, 132]:

- Biological contaminants (e.g., disease-causing bacterium, protozoa phylum, viruses, and parasitic worms [2])

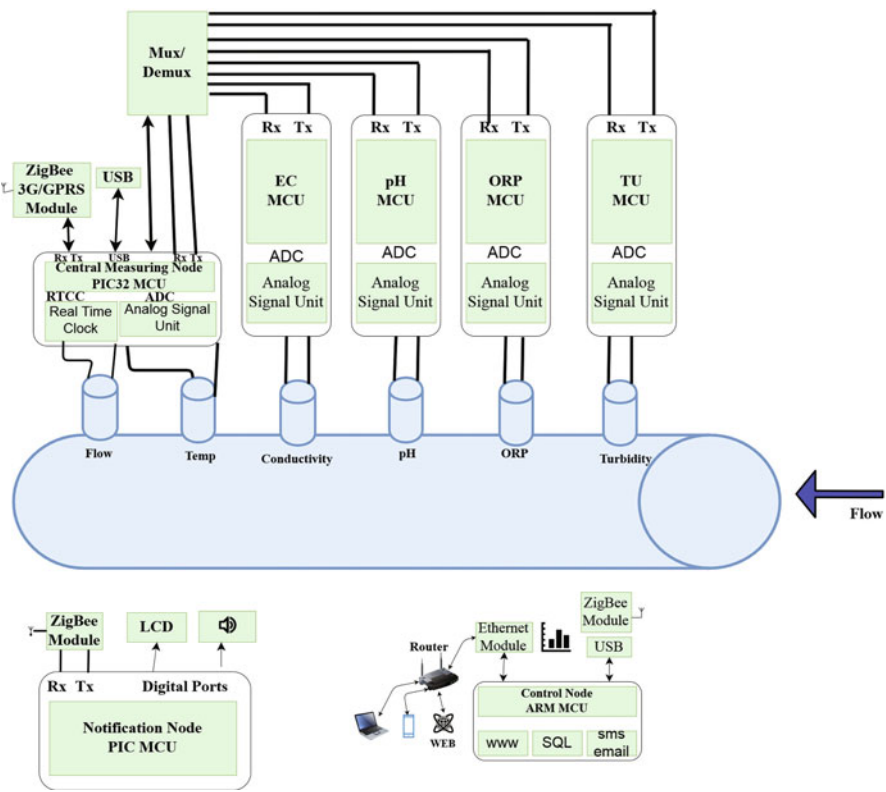


Fig. 4.6 An architecture of a low-cost sensor network for real-time monitoring and contamination detection in drinking water distribution systems [58]

- Inorganic chemicals (e.g., nitrogen species, metals, oxyanions, and radioactive nuclide) [134]
- Organic chemicals (e.g., natural organic matter (NOM) and faux organic chemicals from agro-industrial products) [7]

The major water treatment technologies are [15] as follows:

- Coagulation. Solids are separated through the sedimentation process. It is then followed by the filtration process because the slowly settling tiny particles are hard to remove through settling. Therefore, coagulation (grouping) is done through chemicals (e.g., alum) to form large particle groups.
- Membrane process. This treatment method is used to filter out undesired pollutants from water. A membrane also acts like a filter with a capability to block certain constituents. It is employed in ground and surface water to obtain water for drinking and to wastewater for industry needs.
- Adsorption and biosorption. Adsorption refers to surface accumulation of different components. It is a gas- or liquid-solid phenomenon. Biosorption includes ion exchange (arsenic removal), complexation (complex association), surface precipitation, chelation (bonding), and coordination.
- Dialysis. The dialysis water treatment process is used to remove microbial and chemical compounds in two steps: (1) pre-treatment, where compounds are eliminated from the source water to get an early stage clean water, and (2) deactivating the leftover chemical and microbial compounds.
- Foam flotation. Dissolved air flotation (DAF) is a wastewater treatment process that removes oils and solids. In this process, high-pressure air is dissolved in water. Then, at atmospheric pressure, it is released through flotation. The bubbles carry suspended matter adhered to them which is subsequently removed through skimming.
- Reverse osmosis. Reverse osmosis (RO) uses the membrane process to filter dissolved compounds and suspended particles from water. Activated carbon (AC) filtration is also used to filter pesticides, chlorine, and organic solvents that are not filtered by RO. Sediment filtration removed silt particles.
- Photocatalytic degradation. It is used for reduction and oxidation of metals and oxyanion contaminants (e.g., NO_3^- , ClO_4^-), and destruction of per-/polyfluoroalkyl substances (PFAS). The semiconducting material is also employed as the heterogeneous photocatalyst.
- Biological and bioanalytical methods. This process is based on the filtration of oxygenated water via different types of granular solids such as sand, coal, and granular activated carbon (GAC).

4.6.2 Ocean Acidification and CO₂ Mitigation

Ocean acidification (OA) is the process in which the acidity of ocean increases (decrease in the pH value below 7) [40]. The UN Conference on Sustainable

Development has declared OA as a major challenge to ecosystem sustainability economically and ecologically. The main cause of ocean acidification is increase in CO₂ concentration from higher emissions which leads to chemical changes in seawater. Local and coastal pollution is also attributed to ocean acidification. This process is harmful for the marine habitats in the ocean ecosystem. The following two methods are used for OA sensing [28]:

- **OA Observing Vessels.** In this approach, the sampling is done using research ships to sense variations in seawater carbon-related chemical properties. The pH is the main parameter which is measured using pH sensors. Moreover, by using this approach, ocean acidification mitigation methods can be deployed at large scales [21].
- **Buoys and Autonomous Systems.** For continuous and autonomous carbon measurements, the buoys are being used for high-frequency measurements to get insights into variability in ocean acidification over diurnal, monthly, and yearly scales. These can be used to measure pH, bio-geochemical, and CO₂ in coral reef waters, sea, and coastal areas [99].
- **Hydrographic Cruises.** This approach is used to obtain physical, chemical, and biological measurements of full vertical column base in harsh sea environments [23]

Although OA can be mitigated through by limiting the emissions of atmospheric CO₂ levels, other options include restoration of wetlands, planting new forests, and reforestation to increase absorption of atmospheric CO₂ levels and by adding alkaline minerals to seawaters. Through IoT-based decision support system, the following developments can also help in OA mitigation:

- Sensing of runoff and pollutants from fertilizers
- Digital fishery management approaches
- Monitoring and protection of sediment loading and development of application of marine spatial monitoring
- Monitoring of local emissions such as sulfur dioxide and nitrous oxide emissions from coal plants

4.7 The Sustainable Water Case Studies

The case studies are discussed in the following:

4.7.1 *Open Water Web*

The open water data is an initiative of the Advisory Committee on Water Information to integrate scattered water information into an open data web by leveraging

Open Water Web			
water data <i>Catalog</i>	water data <i>As a Service</i>	<i>Enriching</i> Water Data	water data and tools <i>Marketplace</i>
Find source data	Consensus standards	Include routing	Community exercise of tools & data
Create water & climate themes	Visualization and delivery	Coupling with models	Data usage tracking
Recruit/engage partners	Catalog and serve	Grounded to geofabric	Community-built extensions (eg map)

Fig. 4.7 Different components of open water web

prevailing infrastructure and systems for the purpose of development of novel water solutions and models and for data sharing purposes [4]. The different components of the open data web are shown in Fig. 4.7. The three different use cases of open water web are given below:

- The National Flood Interoperability Experiment (NFIE). The purpose of this experiment to develop next-generation flood hydrology tools.
- Water Supply Decision Support System. A tool used for past and future water interactions in lower Colorado River basin.
- Spill Response/Water Quality. To get better insights into the impact of spills on public health.

4.7.2
Waspnote Smart Water

The Waspnote Smart Water platform contains low-energy consumption sensors for real-time sensing under harsh environment for remote water quality monitoring [61]. This platform supports real-time measurements with connection to cloud online data processing. It is used for conductivity, dissolved oxygen, temperature, pH, and transparency loss. It supports the following type of nutrient and dissolved ion sensing:

- Fluoride (fluoride (F^-), nitrate (NO_3^-), calcium (Ca^{2+})
- Chloride (Cl^-), silver (Ag^+), and cupric (Cu^{2+})
- Potassium (K^+), iodide (I^-), and fluoroborate (BF_4^-)
- Ammonia (NH_4), perchlorate (ClO_4), and magnesium (Mg^{2+}),
- Nitrite (NO_2^-), lithium (Li^+), sodium (Na^+), and bromide (Br^-)

4.7.3 National Network of Reference Watersheds

The National Network of Reference Watersheds (NNRW) is a system of watersheds and monitoring networks with minimal disturbances [75]. These reference (pristine) watersheds are safeguarded from the impacts of human activities and related changes. These reference watersheds are used for empirical measurements of variations in water quality, physical, biological, and chemical properties of soil and vegetation. Accordingly, the data collected by these measurements is compared with the data collected from disturbed watersheds to assess impacts.

4.7.4 Hydrometeorology Testbed

The hydrometeorology testbed (HMT) is a testbed at the Weather Prediction Center (WPC) [32, 135]. It is used for enhanced forecasting of extreme precipitation, forcings, and hydrologic prediction, through experiments and advanced hydrometeorological and empirical observation. The schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station is shown in Fig. 4.8. At HMT, two types of experiments are conducted which are discussed in the following:

4.7.4.1 Winter Weather Experiment

In this experiment, the precipitation algorithms are applied to various models during different weather events to observe transition zones of precipitation types. Their use is analyzed as input to manually produced empirical forecasts. The winter weather event ensemble predictability is evaluated using a tool that uses ensemble clustering.

4.7.4.2 Flash Flood and Intense Rainfall Experiment

In this experiment, short-range flash flood forecasts are produced by using high-resolution data to synthesize atmospheric and hydrological guidance. This experimental hydrologic guidance includes parameters such as runoff, soil saturation, probabilities of quantitative precipitation forecast (QPF) exceeding recurrence intervals, and streamflow anomalies.

4.7.5 WaterWatch

The WaterWatch is a comprehensive tool that provides past and current streamflow data in real time. It supports data visualization in the form of graphs, tables, and

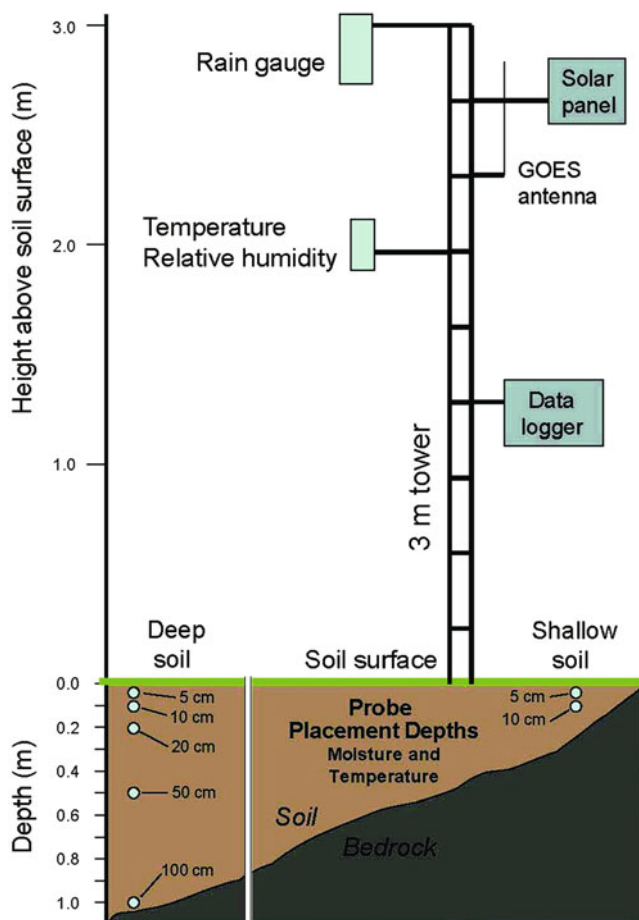


Fig. 4.8 Schematic diagram showing the orientation of the soil probes and surface meteorological observations used at a typical soil moisture observing station [135]

maps [119]. WaterWatch is used to produce multiple stream maps with the following features:

- Thirty years of location data of approximately USGS 3000 stream gages
- Color maps for streamflow conditions and historical streamflow
- GUI to get stream stage (water elevation) and flow graphs
- Identification of location of occurrence of extreme hydrologic events (e.g., floods and droughts)
- The real-time, average daily, and seven-day average streamflow stream gage-based maps with flood, drought, high flow, and below-normal conditions
- Support for hydrologic unit code (HUC) and the stream gage-based maps in hydrologic regions

Table 4.2 Tools in WaterWatch toolkit [117, 119]

WaterWatch tool	Description
Hydrologic unit runoff maps	Hydrologic unit runoff and runoff condition maps from 1901 to 2015
Rating curve	Streamflow rating curve
Runoff hydrograph	Runoff time-series plots
Streamflow conditions map	Streamflow conditions
Streamflow map animation	Real-time streamflow and flood-and-high flow maps
Raster hydrograph	Pixel-based plots for visualizing and identifying variations and changes in a streamflow data set
Seven-day low flow conditions	Seven-day low flow of an area for a specific period
Stream gage statistics	Statistics and a duration graph for a stream gage
Streamflow measurements	Streamflow measurements for a period and in an area
Flood-tracking chart	Flood stages with recorded peak stages of previous floods
Stream gage finder	Stream gages by region and river name
Flood and high flow	Table listing flood, high flow, and peak rank summary
Streamflow map viewer	Dynamic maps
Cumulative area-based runoff hydrograph	Graphical presentation of cumulative daily area-based runoff, plotted over the cumulative long-term statistics (median and interquartile range) of runoff
Duration hydrograph	Time-history of streamflow

A list of tools in the WaterWatch toolkit is given in Table 4.2 [117, 119].

4.7.6 Water Evaluation and Planning System (WEAP)

The WEAP is used for integrated planning assessments of different components of the water system and supports water planning, simulations, and water resource management tool [106]. Its robust integrated engines consider water quality, supply and demand, and other ecological parameters in single watershed, agriculture, urban, trans-boundary river basin, and environmental systems. The important features of the system include simulation capability to many different types of components such as precipitation, runoff, rainfall, reservoirs, and groundwater recharge. At the policy level, it supports demand analysis, rights and priorities, conservation, vulnerability assessment, hydro-power generation, and water quality. It can also provide the cost/benefit analysis of the simulated systems with various stakeholders' engagement. The component of the WEAP is

- **Water Balance.** A database for water demand and supply data
- **Simulation Based.** Supports simulations of various hydrologic and policy cases
- **Policy Scenarios.** Policies to develop and manage water systems
- **User-Friendly GUI.** A GUI to support multiple model output formats (e.g., tables, maps, and charts)
- **Model Integration.** Supports import and export from other models

4.7.7 CalWater

CalWater [27] deals with the empirical measurements of two vital factors: atmospheric rivers (ARs) and aerosols [12, 29, 81, 98, 108], in the eastern Pacific coastal region. The evaluation of these two parameters is important to understand variations in extreme precipitation events and water supply. The atmospheric rivers (ARs) [27, 49, 64, 65, 73, 77, 86–89, 102, 102, 104, 121, 124, 125] deliver significant water vapor related to major storms. Similarly, the aerosols (local and remote) impact the precipitation events in these coastal areas.

4.7.8 River and Reservoir Modeling Tool (RiverWare)

RiverWare is an advanced tool that is used for water resource modeling (e.g., river basin and reaches, reservoir, hydrologic processes, distribution canals, hydro-power production and uses, water quality, and diversions) [1]. It is also a decision-making tool with real-time operation support and policy-based simulations and post-processing. Another important feature of RiverWare is the problem solution and optimization engine under temporal and spatial constraints and scenarios. For this purpose, RiverSMART is used, which is a software framework, to create, execute, and archive the big RiverWare study plan-based hydrologic ensemble, needs, and strategic directions of water supply and use. The policy analysis, demand input, and study manager are other important tools of RiverWare.

4.7.9 Digital Coast

Digital coast provides data and tools for coastal services including coastal water quality, land cover, shoreline, and surface water. It helps coastal management community to address climate- and water-related issues [76].

4.7.10 European CoastColour

The purpose of CoastColour is to provide measurements and data that are relevant to coastal zone management at 300m spatial resolution along with processing algorithms for different coastal water types [26]. It is useful to obtain data about sea level, carbon cycle, and water mass distribution. It can also be utilized to develop and validate various coastal water algorithms (water leaving reflectance). The CoastColour data set is available online.

4.7.11 Water Harvesting Assessment Toolbox

The water harvesting assessment toolbox is used in understanding and development of the water harvesting processes to meet water-related challenges [118]. It is also a decision support tool to get better insights of water harvesting and supports various water harvesting techniques and system implementation.

4.7.12 National Groundwater Monitoring Network

The National Groundwater Monitoring Network (NGWMN) is a network of groundwater monitoring wells across the USA [74]. It is one of the critical networks to meet the needs of water research community about groundwater data, which is otherwise unavailable data. It supports various databases of past and current information about water quality, water level, physical characteristics of rocks (lithology), and well composition. It is used to assess the water level declines.

A list of sustainable water IoT databases and systems with their sensing parameters is given in Table 4.3.

4.7.13 Water Toolbox

The water toolbox is a data portal for integrated water resource management. It provides state-of-the-art tools, models, best management practices, legislative resources, policy guidelines, and comprehensive data sets to the international water community for education and research purpose.

Other water-related tools to support real-time decision-making in sustainable water IoT are discussed below [112]:

- SSMI Water Vapor Imagery. Latest integrated water vapor, cloud liquid water, and rain rate
- GOES West Satellite Imagery. Infrared, visible, and water vapor satellite images

Table 4.3 Sustainable water IoT databases and systems

Sensing	System	Description
Meteorological data	Global historical climatology network-daily (GHCN-D)	Meteorological data from satellites and radars
Streamflow	NOAA national water information system (NWIS)	Streamflow data for water and planning purpose
Water temperature and quality	NorWest	Historical data about water temperature and quality
Chemical, physical, and biological properties	National stream Internet	Geo-statistical data
Meteorological data	Quality controlled local climatological data (QCLCD)	Global Meteorological data of climate variables
Precipitation	Precipitation frequency data server (PFDS)	
Integrated water modeling	National water model	Hydrologic forecasting system of atmospheric conditions and their connection to river and streamflow
Soil moisture	Soil climate analysis network (SCAN)	Soil moisture monitoring
Snow	Snow survey and water supply forecasting	Real-time air temperature, precipitation, and snowpack information
Groundwater	National GW monitoring network	Groundwater for climate forecasting
Wetlands	National wetland inventory 2.0	Geo-spatial data and wetland maps and properties
Water use	NWISWeb	Water use data
Atmospheric	FLUXNET	Exchange of CO ₂ , water vapor, and energy
Water and human health	The waterborne disease and outbreak surveillance system	waterborne disease and outbreaks
Water and aquatic animal health	National wildlife health survey database	Aquatic animal health in the wild
Daily forecast and models	Network for environment and weather applications	Interactive forecast models

- AR Precipitation Observations. Gridded precipitation products at several timescales
- Atmospheric River Observatories. Analyses of water vapor flux, radar and disdrometer, and snow level
- Integrated Water Vapor. An experimental tool using NCEP's GFS and NAM systems

- Probabilistic Landfall Tool. The magnitude, probability, and timing of West Coast AR conditions
- Integrated Water Vapor Flux. An experimental tool using NCEP Global Forecast System.
- Precipitation Forecasts. The quantitative precipitation forecasts from NCEP/WPC & GFS

4.8 Sustainable Water Indices

The major indices are given below:

- The water footprint. The water footprint is an index of the volumes of freshwater appropriated/consumed/polluted by humanity. Its measurement is presented by using the matrix format at the spatiotemporal scale. The water footprint combined with other economic, social, and environmental data is a good indicator of water sustainability including SGD goal assessment.
- The US Climate Extremes Index is a US index of extreme conditions. The long-term values of this index indicate the tendency for extremes climate.
- Watershed Analysis Risk Management Framework (WARMF). The Watershed Analysis Risk Management Framework (WARMF) is a general tool to model and analyze the watershed and can be used with different watersheds. It is utilized for short- and long-term prediction process and management of watersheds and in the calculation of the total maximum diurnal load.

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Chapter 5

Internet of Things for Sustainable Forestry



5.1 Introduction

In the field of agriculture, there has been a lot of development in soil moisture capability and system design. However, soil moisture sensing in forests is lacking [52]. There are big gaps in data collection in forests and rangeland systems, particularly in 640 million public lands in the USA, which also include grazing lands and reserves. Thirty-three percent of the water comes from these lands which is supplied to the community in the Western USA. Loss of forests through droughts and fires will significantly impact the water supply [42]. This fact underscores the importance of sustainable forests for survival of human life [46].

In the twenty-first century, climate is changing dramatically [65, 72, 98]. The average temperature has increased by 1.8F from 1901 to 2018. This average increase in temperature with the same amount of precipitation has resulted in an increase in the evaporation rate [1]. This increase in temperature is highly correlated with the forest fires [57, 99]. In 2018 and 2019, the State of California in the USA witnessed a very significant fire season [79]. Out of this 1.8F averaged increase, 1.2F increased in the last three decades from 1989 to 2019. This rapid increase has caused many disturbances in the forest ecosystem, which is leading to extreme cases of shortage of water or abundance of water that the system is unable to handle [32, 61, 66, 98].

The IoT holds strong promise for digital forestry [105] applications. An efficient management system can be developed for effective resource management and decision-making in forest inventory, in situ and remote soil sensing, and forest fire prediction and control. Forest fires are another threat to sustainable forest management. In the USA, 8000 kilo hectares were burned in 2015 due to forest fires [79]. The IoT technology in forest environment can be used to sense, communicate, analyze, and make informed decisions for sustainable forest management. Currently, technology is being used in digital forest management. However, the applications of the technology in the forest management lack well-integrated systems for real-time

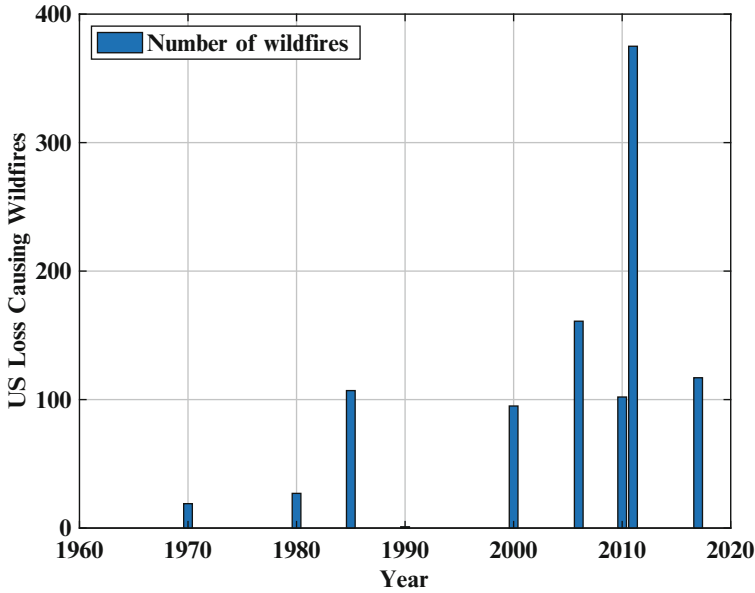


Fig. 5.1 The yearly data of the US wildfires

sensing and decision-making. IoT has the potential to fill this gap through its well-connected and integrated sensing and communication components.

Moreover, the presence of droughts in the entire forest landscapes [17] (short-term in agriculture and prolonged droughts [101] in the entire ecological system [28, 30]) presents a major challenge. These two drought systems are connected because of the flow of water from the forested mountains to the agricultural lands in the plains [89, 94]. In the ecological drought scenario, the drought progression over time leads to accumulation of droughts on the landscape in the time span of multiple years. Forests have the ability to survive only up to 2 years of drought that extends to 3 years for very healthy forests. After this, forests lose their ability to resist insects and diseases that contribute to rapid forest loss. Although it can be argued that this is because of the water-limited forest systems, this huge amount of biomass cannot be sustained. However, development of early warning IoT systems in forests and rangeland with the ability to sense soil moisture and detect and predict water patterns can play a vital role in sustainable forests. Such systems with adaptive capability can inform important decisions such as how to plant and when to reseed. These functions of IoT for sustainable forest management are discussed in the next section (Fig. 5.1).

Furthermore, when a forest is burned, it has to be replanted in a very short time span of 2–3 years in order to prevent proliferation of the invasive grass. Therefore, in the forest restoration, the knowledge of seeding conditions and weather pattern becomes of utmost important [43]. Due to expensive native seeds, the seeding carried out in poor conditions causes the wastage of valuable resources and times of imaging the forest restoration process. Seeding without considering the soil

moisture data and short-term weather projection has a success probability of less than 50%. The IoT system in forests can provide this data in real time, hence increasing the success rate of the restoration process.

Additionally, roads in the forest systems are also vulnerable to flooding, landslides, and mudslides after the fire event [16]. The potential risks of these events include burial roads in mudslides and destruction of bridges. An accurate prediction of these events through IoT sensing and communications makes the IoT monitoring a useful tool for sustainability and restoration. Particularly, the upper and lower watershed monitoring is not fully developed. There is a need for IoT solutions containing connected weather and soil moisture stations integrated to the cloud for real-time decision-making in forests. These can inform, hold, and absorb decisions in the case of big rain events in the upper and lower watersheds. Such IoT systems for digital forestry can bring significant improvements in the areas of climatology, hydrology, and vegetation.

5.1.1 Sustainable Digital Forestry

The UN's sustainable development goal number 15 is related to the forest management and entails terrestrial ecosystem's protection and restoration [6, 93]. The environmental benefits of the forests for the future sustainability span multiple SDGs (see Fig. 5.2) and support natural development of the ecosystem. Forests are the biggest absorbents of fossil fuel caused by carbon dioxide (CO₂) emissions [85]. To avoid the reduction of the CO₂, better forest management practices are required. Currently, the biggest challenges faced by the forest ecosystems include droughts, diseases, insect infestations, and high fire-caused tree mortality [101]. The bioenergy technique to meet energy needs by producing biofuels from organic sources such as biomass also underscores the need for restoration of forests. Other important digital forest management factors include land use and ownership, the global scope of forest markets, forestry markets, advancements in biopower technology, and forest policies and regulations. These challenges are discussed in detail in the following section.

5.1.2 Challenges in Sustainable Digital Forestry

The digital forestry is defined as follows:

Digital forestry is a framework that links all facets of forestry information at local, national, and global levels through an organized digital network [105].

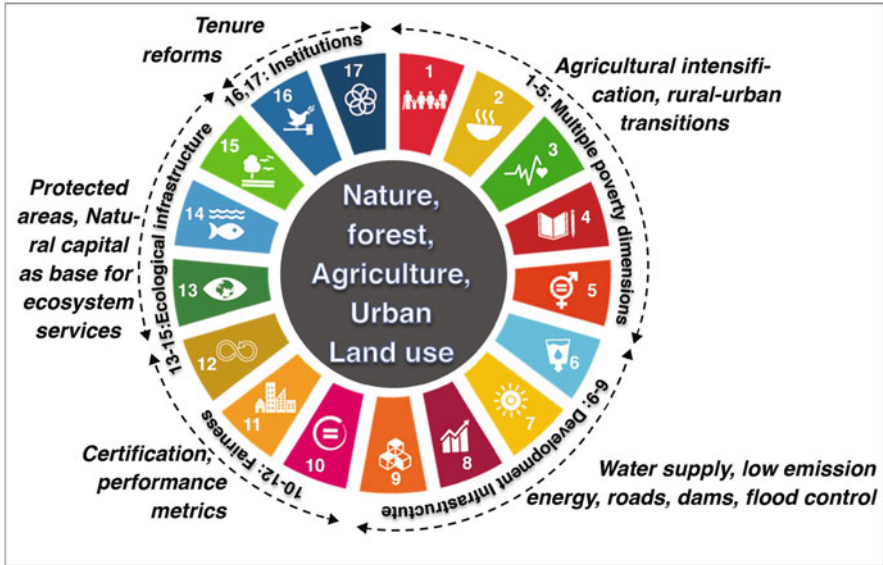


Fig. 5.2 The SDGs and forestry [93]

There are many challenges in the area of digital forestry including changing climate, human-caused disturbances to the forests [51], wildfires [56], and invasive species [12, 23, 107]. These are explained in the following:

- The increasing number of fires, insects, and fragmentation are major challenges in achieving sustainability, and these also leads to decrease in biodiversity. Diseases and insects are causing huge losses to the biomass. The water quality, quantity, and storage capacity are increasing. The wildland-urban interface (WUI) [98] is a zone in which forest and homes intermix. This intermixing is a major source of wildfires, disease spread, habitat loss, biotech invasion, subsidized wildlife, and fragmentation [21, 64, 78]. The wildland-urban interface also poses a threat to forests in terms of the forest predators due to the availability of abundant sustenance in WUI. To control and reduce the number of WUI-caused predators, there is a need for monitoring and elimination of their nesting and perching sites, invasive trees and unused poles, and other structures by placing a ban on establishment of water facilities, dumps, and garbage in WUI. These predators include species such as crows, ravens, coyotes, magpies, foxes, raccoons, skunks, and other species [9].
- The adaption of sensing and communication technologies in digital forest management practices is lacking. Adoption of these technologies has a huge potential to improve sustainable management of forests through development of decision support systems at large spatial scales in a timely manner [22].
- A related consequence of lacking of technology adoption is unavailability of accurate inventory forests [55]. Without the information of forest sources, it is

hard to design and implement sustainability initiatives. The non-native insects and other diseases and pests that feed on trees are causing significant tree mortality. The lack of technology implementation is hindering assessment of the impact of these species on the ecosystem.

To overcome these challenges in digital forest management, multipronged efforts are needed at different levels including forest managers, policy makers, scientists, and researchers. The technology can fill the gaps in forest data management and resource inventory by providing reliable data that can be used to create maps and other reports of resource assessment [84]. Accordingly, the real-time support systems can be developed for data analysis, sustainability, and actuation. Major data needs for sustainable forest management include:

- Forest health and diseases [91]
- Biomass and forest fuel loads for renewable energy [74]
- Forest carbon stock and sequestration [48, 82, 88]
- Forest species including invasive species [12, 23, 107]
- Fires and water data [62]
- Forest inventory [13]

Moreover, coupled with the data needs are modeling and analysis techniques developed based on the data and inventory. The development of such decision-making systems will also inform land-use decisions and their impacts and benefits to forests and grazing lands [47]. These analysis techniques can then accordingly be used for pattern prediction and quantification, measurements, valuation, monitoring, and assessment of emerging threats and challenges. The IoT for sustainable forest management can overcome these challenges through real-time sensing of the forest ecosystem. It is presented in the next section.

5.2 IoT in Digital Forest Management

The sustainable forestry IoT through its communication, sensing, and system technologies has the great potential to improve the resilience of forests. It can also reduce the impact of climate change on the forestry ecosystem [10]. Accordingly, it can provide bioenergy sources from biomass which will bring energy and economic prosperity to community while reducing stress on the fossil fuels. The nanotechnology applications will bring improvements in woods [45]. Moreover, detailed watershed insights can be gained (e.g., water resources, pollution, water shortage, water quality, and futuristic water and rain and patterns). Digital forestry IoT has the potential to meet the real-time needs of forest, grazing land, and range managers. These include:

- IoT early warning systems for drought stress to initiate and prioritize actions
- Forest soil moisture sensing used for informed restoration decisions

- The snowpack change detection to plan annual water management and to accordingly adopt effective management practices
- Grazing land productivity changes and projections to guide herd and range allotment
- Real-time sensing and detection in forest covers for informed changes in forest management policies and practices

5.2.1 Elements of the Forest IoT

IoT can be used to connect the upper watershed and user community in a systems approach. Soil moisture sensing and communication systems can be integrated with soil moisture collection system in forested areas. Moreover, forest drought monitoring interconnected with IoT and cloud can provide real-time forest observations for real-time decision-making by government agencies. Overall, IoT has the potential to fill the gap in forest soil moisture and impact information with advanced sensing and communication technology.

The IoT in digital forestry envisaged to have the following elements:

- Ability of real-time state-of-the-art data collection and wireless transmission of physical, chemical, environmental, and biological factor at the forest sites scattered across geographical, vegetational, and climatic forest zones
- Systems for motoring soil and climate patterns
- Storage of data in the cloud and real-time access to the decision-making through the visual interfaces

5.2.2 Forest Things

The things of the forest IoT are outlined below:

- Invasive Species. The current needs are related to minimization, reduction, and elimination of invasive species from being introduced, established, and spread [12, 23, 107].
- Inventory, Monitoring, and Analysis. The requirements are availability of resource data, analytic, and decision tools for efficient and reliable identification of the status of forest resources, insects, diseases, and fires, forecasts, and trends for sustainable management [7].
- Land Use and Recreation. Forests are major sources of community recreational activities, such as hiking, camping, fishing, canoeing, and skiing, and play an important role in sustainable community health. The land-use and management decisions impact these activities [97].
- Wildland Fire and Wildland-Urban Interface (WUI) [98]. For these, the emphasis is on minimizing the determinant impact of fires and enhancing the beneficial

effects of fire. Moreover, the WUI posed challenges to forest (e.g., fires and predators). Therefore, any forest decisions and their trade-off related to these need to be well thought of to minimize any negative effects.

- Water, Air, and Soil. Forests and grasslands play an important role in water and air purification, in prevention of soil erosion, and in provision of habitat to wildlife [77].
- Wildlife. The current focus in this area is on getting insights on complex interaction between species, ecosystem processes, emerging threats, land use, and management [44].
- Other things include agroforestry, forest products, landscape management, and operation [95].

5.2.3 The Montréal Process Criteria and Indicators (MP C&I)

In this section, the Montréal Process Working Group [40], its criteria and indicators for sustainable forest management are discussed.

5.2.3.1 Montréal Process

The Montréal Process Working Group consists of multiple representatives from different countries to address the issue of sustainable forest management. The working group was established in 1994. It has developed stipulatory criteria and indicators for forest sustainability and conservation of both boreal and temperate types of forests. Its members are different socioeconomic and ecological conditions. They are collaborating on forest monitoring, sustainability, and assessment issues. These members are from the regions that have significant presence of temperate and boreal forests. These countries are:

- The USA
- Argentina
- Australia
- Canada
- Chile
- China
- New Zealand
- Russian Federation
- Japan
- Korea
- Mexico
- Uruguay

5.2.3.2 Criteria and Indicators (MP C&I)

The Montréal Process Criteria and Indicators (Montréal C&I) [41] are used to collect sustainability and conservation data of temperate and boreal forests for the purpose of assessment, monitoring, and reporting. These criteria and indicators (7 criteria and 54 indicators) together present a comprehensive sustainability framework reflecting the vital components of forestry such as conditions, biological diversity, ecosystem health, soil, and water resources of forests. As this criterion treats forests as ecosystem, it enables robust range of socioeconomic and environmental services and benefits. Accordingly, the MP C&I facilitate regulation and policy development to achieve sustainability in forests. The seven criteria are shown in Fig. 5.3.

5.3 Sensing in Digital Forestry IoT

In this section, different methods of sensing which are applicable to the forest environment are discussed.

5.3.1 Remote Sensing

Applications of the remote sensing approaches in digital forestry offer many benefits as compared to the in-situation sensing. With a sensing unit of 10 m–40 km, the remote sensing can be used for a cover area of up to 1000 km [4]. Therefore, a large geographical forest zone can be managed with this technique. Moreover, accurate maps can be produced for efficient decision-making. Currently, NASA is running missions for soil moisture measurements. The aim of these missions is to obtain high-resolution maps of soil moisture with multiple revisits of the target sites. In digital forestry, this can be used to investigate processes of terrestrial carbon, energy, and water cycles. It can sense energy and water flux in the forests. Moreover, enhanced drought predictions can be made using these missions. It can also be used to quantify the forest landscape carbon flux (Table 5.1).

Remote sensing in digital forestry is insufficient due to vegetation thickness. The sensing depth is limited to few centimeters. It further decreases with increase in measurement frequency. Moreover, the vegetation loss also increases with increase in the measurement operation frequency.

Radar- and LiDAR-based active sensing approaches [60] can also provide useful information. Radar operates at 1.26 GHz frequency with VV, HH, and HV polarization and has a resolution of 3 km. The radiometer functions in 1.41 GHz with polarization of H and V and has a resolution of 40 km. Although radar in comparison to radiometer has high spatial resolution (1–3 km), it is more sensitive to surface roughness and vegetation. It has limited accuracy in thick forests. However,



Fig. 5.3 The Montréal process criteria and indicators

Table 5.1 Satellite systems for remote sensing of soil

System	Frequency	Resolution
The Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E)	C, X-band passive	25 km
The Advanced Microwave Scanning Radiometer 2 (AMSR2)	C, X-band passive	25 km
WindSat-US Naval Research Laboratory	C, X-band passive	25 km
The Advanced Scatterometer (ASCAT)	C-band active	12.5 km
Soil Moisture and Ocean Salinity (SMOS)	L-band passive	25 km
Soil Moisture Active Passive (SMAP)	L-band passive	3–36 km
Cyclone Global Navigation Satellite System (CYGNSS)	L-band reflectivity	1–3 km
SATélite Argentino de Observación COm Microondas (SAOCOM)	L-band active	1 km
NASA-ISRO Synthetic Aperture Radar (NISAR)	Ka-band	200 m

radiometer has high accuracy because it is less impacted by the surface roughness and vegetation, but coarser spatial resolution of 40 km makes it less useful for small geographically separated forests. An alternative of combined radar and radiometer solution gives enhanced results of improved resolution and higher accuracy to meet IoT sensing requirements in digital forestry.

Overall, remote sensing can be used to obtain important data from the forest soils and vegetation. This includes spatial coverage of the vegetation, classification of forests, and soil moisture [60].

5.3.2 Per-Tree-Based Forest Analysis

High spatial resolution combined with aerial photography approaches can be used to analyze forests on per tree basis. For this approach to work, less than 0.5 m pixel size is required. Machine learning-based image processing techniques are useful for remote sensing-based tree detection and delineation approaches. Popular tree delineation methods include local maxima [96], boundary following [53], template matching [68], region based segmentation [102], and model-based methods. Extension of these approaches is also used for species genesis.

5.3.3 Phenology Sensing

In phenology monitoring, the impact of environment instigated events (e.g., the temperature and length of the day) on the plant and animal life spans is studied [38, 75]. The study consists of the flowers blooming in the autumn season to color change patterns and subsequently falling of leaves in the fall season for

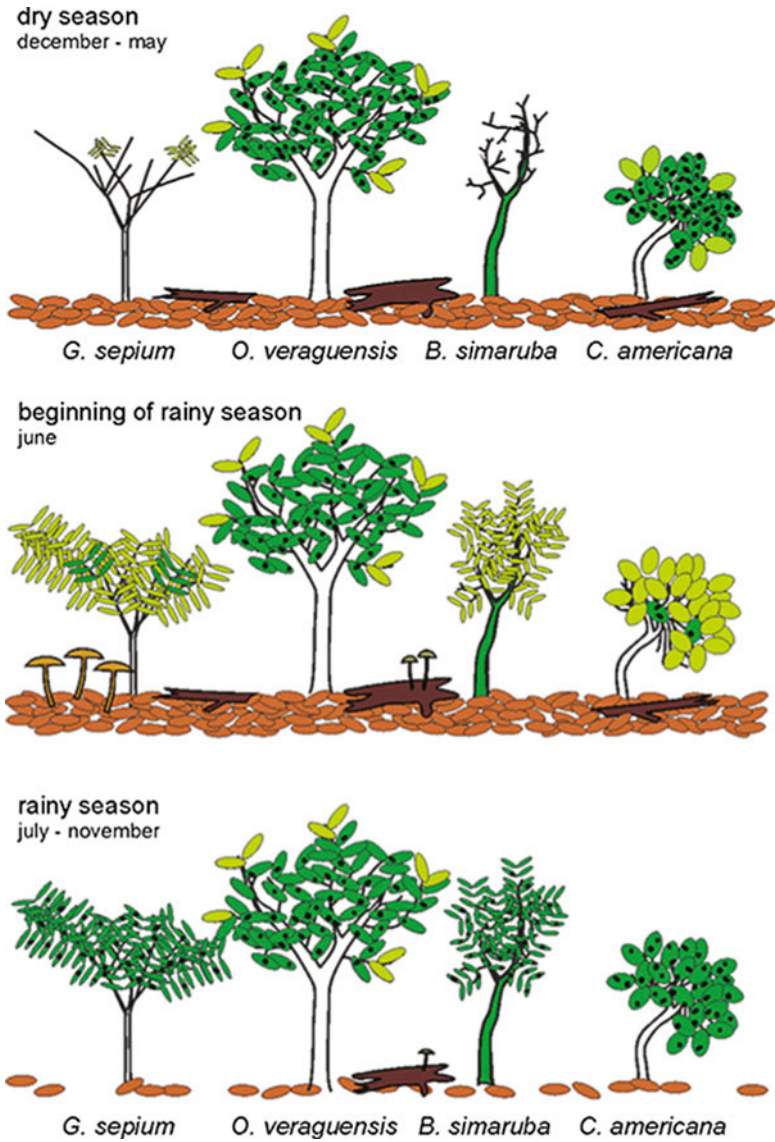


Fig. 5.4 A schematic representation of vegetative characteristics of *Gliricidia sepium* and *Bursera simaruba* (both deciduous), *Ocotea veraguensis* (evergreen), and *Curatella americana* (brevi-deciduous) at different times of the year [75]

the plants (Fig. 5.4). For the animals, this includes analysis of bird migration patterns and insects' hatching activities. Previously, the phenology monitoring activities such as forest canopy monitoring were conducted manually on leaves by recording their temperature and color change manually during different seasons

[106]. For automated monitoring purposes, IoT systems offer a strong monitoring potential. An IoT-based automated leaf monitoring system has been developed which is based on cameras and offers image capturing and automated analysis in the real time. The sensors used in the system can capture multiple colors by using different channels with abscission, coloration, and automated senescence tracking. These systems hold a promise for automated phenology monitoring in the forest environments.

5.3.4 Forest Species Sensing

An analysis of the species habitats in the forest environments is important to assess the impact of forest loss due to fires, droughts, and climate change. Ecological monitoring in the forest environments is a laborious job for human researchers. Often time such efforts require sitting in the field for hours to record birds species in forests. This increases when multiple species are under study requiring multiple experts to record multitude of sounds. The forest IoT system holds promise in this area of automated species monitoring. A monitoring system has been developed to monitor birds with the capability of listening to multiple birds at a time [15]. This system offers a detailed real-time activity of the birds such as bird arrival and departures from their nest, information about location, and nesting pattern changes. The system is based on the multi-label and instances and can also be used to identify drops from the rainfall events and human tree cutting and tree falling from the natural events. Currently, it has been tested to work with different species such as frog, grasshopper, crickets, and marine mammals. Major changes include interference from the natural and human noises in the forest environments. Moreover, the bat wings are also being used for monitoring bat populations.

5.3.5 Species Migration Monitoring

Knowledge of the bird's migration patterns can provide useful information to save endangered species and can help in conservation efforts. One such IoT system has been developed to monitor *Grus americana* (the whooping crane), a native American bird species in danger of extinction with a current count of fewer than 550 birds [2]. This system provides detailed environment and behavior of these birds to inform migration patterns by using sensing and communication devices attached to the birds. Through these IoT devices, real-time information is obtained about every move of the birds (Table 5.2).

Table 5.2 Number of in situ soil moisture sensing stations in the USA

Soil moisture measurement systems	Stations	In forests	Percentage
Snow Telemetry (SNOTEL)	445	289	64.9%
US Climate Reference Network (USCRN)	147	18	12.2%
Soil Climate Analysis Network (SCAN)	219	26	11.9%
The Automated Weather Data Network (AWDN)	59	1	1.7%
The U.S. Regional Climate Reference Network (USRCRN)	16	4	25.0%
Delaware Environmental Observing System	42	8	19.0%
Environment and Climate Observing Network (ECONet)	42	6	14.3%
Kentucky Mesonet	23	4	17.4%
NOAA's hydrometeorology testbed (HMT)	178	35	19.7%
New York Mesonet	126	13	10.3%
Oklahoma Mesonet	141	2	1.4%
Soil Moisture Sensing Controller and Optimal Estimator	155	39	25.2%
Georgia Mesonet	86	5	5.8%
Other networks	223	0	0.0%
Summary	1902	450	23.7%

5.3.6 Tree Health Sensing

Tree health sensing is done by detecting changes in vital metabolites and cellular functions for early identification of stress [29]. Moreover, it can also be assessed by analyzing the relationship of nitrogen in plants and soils. The high levels of ammonium nitrate and ammonium sulfate (that contains sulfur and nitrogen) are applied. Accordingly, the relationship between nitrogen assimilation and photosynthesis is analyzed. Moreover, stress exposures also lead to production of anthocyanin production.

The metabolic stress can also be used as an indicator in different trees [29]. By using this approach, low- and high-risk areas can be identified which can be used to decide treatment options. The tree metabolism and genomics are two approaches for stress sensing. They are related to the genes of the organism under study. This is also useful to establish long-term indicators for climate-related events. Similarly, in polyamine metabolism, physiochemical stress-related genes are separated and characterized at a single plant level, which is then expanded to multiple trees. Accordingly, the impact of disruptive variations in single metabolites and their interconnections can be identified, which can be used to engineer resilient biosynthetic genes to grow healthy plants.

The forest health also depends on photosynthesis, microbial diversity, and soil quality [22]. These factors are impacted by nitrogen, calcium, and aluminum. Therefore, sensing of these parameters is also important to assess tree health and lack of these can be used to inform customized improvement techniques. These health sensing approaches are useful in scenarios where visual analysis does not

either work or yield unreliable results. Accordingly, appropriate treatment actions can be taken before it becomes too late. Moreover, satellite spectral trajectories can be used to map forest health-related variations caused by fire, insects, land use, disease, wind, and harvesting. Furthermore, the tree mortality can also be done using aerial data collection and surveys to assess the area and intensity. This data is utilized to eliminate hazardous tree and fuel reduction before the fire season.

5.3.7 Sensing of Increased Soil and Air Temperature and Elevated Carbon Dioxide

Soil and air temperatures are good indicators of climate-induced variations and wetlands. For this purpose, a testbed has been designed to house different types of soils under field conditions. These soils are exposed to various controlled temperatures and different levels of carbon dioxide to assess the changes in the organisms [20]. The experiment outcomes are discussed in the following:

- This provides useful information about the physiology of plants under high carbon dioxide levels [8, 71].
- Insights about the relationship between the underground warming due to temperature increase and corresponding increase in greenhouse gases can be provided [11, 37, 63, 92].
- Accordingly, suitable soil and air functions for different environmental organisms can be established.
- Moreover, through this empirical analysis, climate-related threat and stress and threats to biogeochemical and hydrological services of the ecosystem can be answered.
- Furthermore, better models can be established for enhanced forecasting, mitigation, and adoption response to environmental changes.

5.3.8 Illegal Logging Sensing

Illegal logging is a major cause of degradation in forest ecosystems and leads to biodiversity losses and deforestation [35]. Sensing of illegal logging can be done using microphone sensors that can sense logging-related sounds such as saws, axes, and transportation. Accordingly, by using wireless communication links, this information can be communicated in real time to forest control centers for proper enforcement actions.

5.3.9 Fire Sensing

Fire sensing is discussed in detail in this section. First, the impact of the fire on soil is presented [39].

5.3.9.1 Impact of Fire on Soil

Forest fires have many negative impacts on the forest ecosystem.

- Due to prolonged presence of the long chunks of timber, the underneath soil is exposed to acute heat which impacts soil physical, biological, and chemical properties.
- Soil microbes are also eliminated depending on the burn extent because of the severe heat. The decreased amount of nutrients is detrimental to the vegetation growth and leads to staggering recovery.
- The structure of soil and texture is also impacted.

Due to the long-term impacts of intense soil heat, understanding the soil dynamics' bio-geochemical processes is important for proper forest management practices. In this regard, advanced DNA sequencing approaches are being considered for soil recovery after soil burning.

5.3.9.2 Fire and Environmental Pollution

When the height of the smoke coming from the fire exceeds the near-surface boundary layer, the pollution concentration starts. The fires in boreal forest have intense energy as compared to temperate forests. Therefore, these smokes tend to go well beyond the boundary layer. At those elevations, the negative impacts of those smokes include prolonged stay in atmosphere, wider horizontal and downward vertical transport, and health-related impacts such as asthma and eye burns. The HRRR-Smoke model is a fire smoke forecasting model for height and travel direction prediction of near-surface boundary layer smoke.

5.3.9.3 Impact of Fire on Fresh Water and Streamflow

Wildfires impact not only the soil but also the water supply. The preservation of the freshwater resources is important to achieve sustainability. These wildfire impacts and risks include:

- Watershed damages and hydrological disturbances
- Soil erosion after extreme rain events
- Sedimentation
- Ecosystem degradation

The models for hydrological disturbance framework are shown below [31]:

- Change point model (CPM)
- Double-mass analysis of precipitation and streamflow (DMC)
- Precipitation duration curves (PDC)
- Flow duration curves (FDC)
- Watershed climate elasticity model (CEM)
- Water Supply Stress Index (WaSSI) model

5.3.9.4 Fire Sensing and Danger Estimation Tools

Fire danger can be estimated based on different measurements that include the following:

- Using the light detection and ranging systems (LiDAR) for forest structure, carbon loss, smoke emissions, and dangerous fuel loads [104].
- Moreover, real-time measurements of moisture can be taken using a system of networked towers deployed for this purpose. These towers are also used to take other vital measurements of carbon dioxide and the eddy fluxes of energy.
- A sonic detection and ranging system (SODAR) to measure wind speed and direction at different heights can also provide useful information about the fire spreading danger and potential directions [18].
- Aircraft teams and satellites are also employed to get useful remote sensing data for fire management decisions, and teams on the ground make the best decisions possible. This airborne and satellite observation [50] is very useful to understand the intensity, perimeter, frequency, and spread of burning forest fires. With the advancement in technology and heat signature detection algorithms, the advanced radiometers with very high resolutions are able to detect tiniest fires from the space. The impact of the fire on the spatial structure of forest in the Yosemite National Park using airborne LiDAR and satellite data is shown in Fig. 5.5.
- The Moderate Resolution Imaging Spectroradiometer (MODIS), Visible Infrared Imaging Radiometer Suite (VIIRS), NOAA's GOES-16, GOES-17 geostationary satellites, Joint Polar Satellite System's NOAA/NASA Suomi-NPP, and NOAA-20 satellites are the satellites and tools used for remote sensing of fires. These works on the principle of detection, radiation, and reflection of the signal and can operate both in daylight and nighttimes by sensing the low-intensity visible light of fires. Moreover, using the special equipment with multiple cameras can be used to detect fire flame plume composition.

The IR-based heat sensors can overcome some of the limitations of the satellite-based fire detection with such low accuracy of perimeter and location, lack of capability to distinguish between fires and smokes, and inability to interpret fire intensity due to dense smoke layers that act as a curtain [58]. The National Infrared Operations Program (NIROPS) airborne sensing system utilizes infrared-based heat sensors. This system has the capability to sense 6 miles

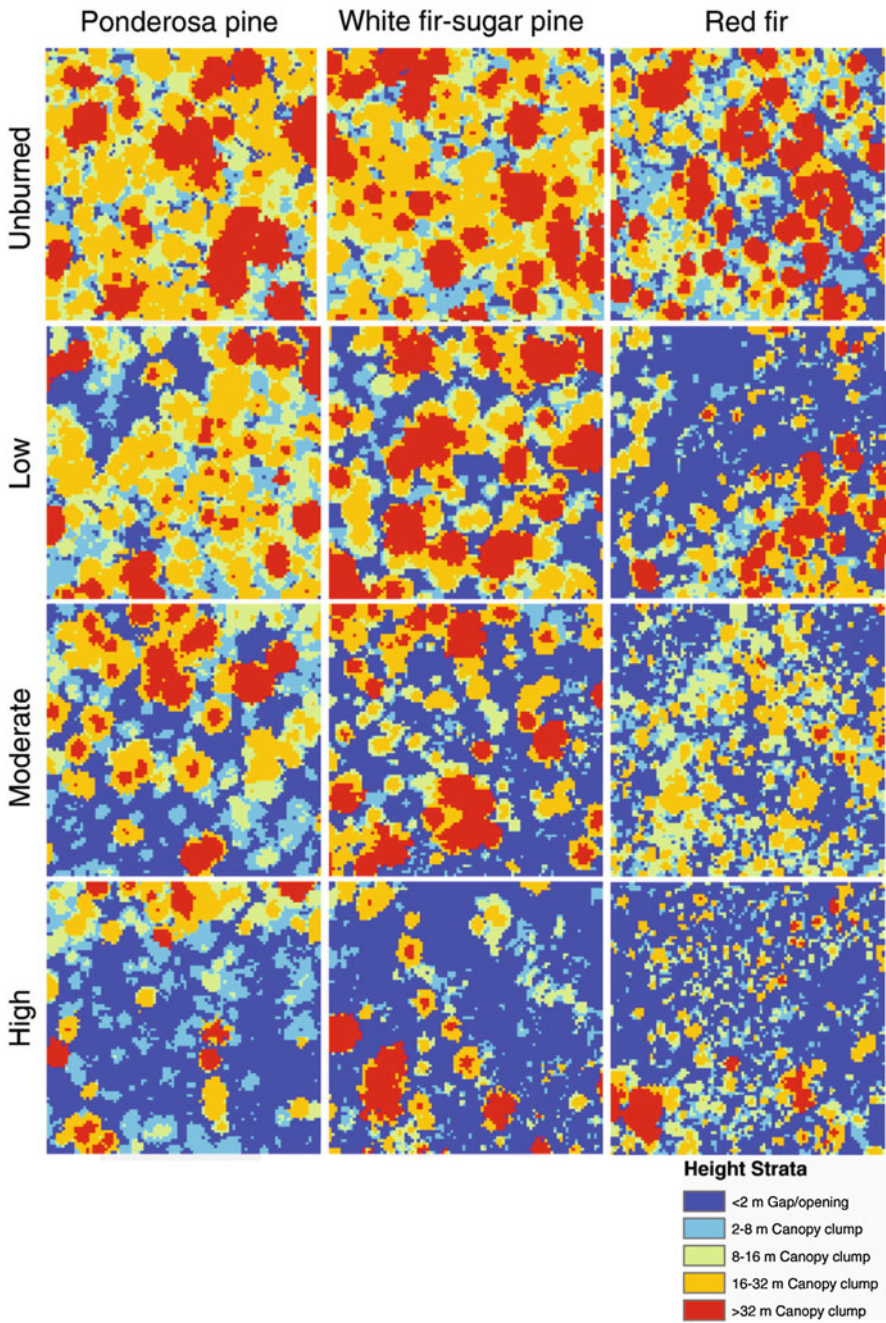


Fig. 5.5 The impact of fire on the spatial structure of forest in the Yosemite National Park using airborne LiDAR and satellite data [50]

under it with 6 in. resolution at 1.89 miles of flight altitude. It can map 468.75 square miles in an hour. By using the compressive sensing approaches, the data is transferred in real time to the base stations [5]. These sensors work much better at nighttime as compared to daytime due to the absence of sun glint interference. Currently, there is a need for wider area infrared sensing technologies to reduce flight times.

These measurements combined with past climate data, current indices (e.g., Hot-Dry-Windy (HDW) Index), and moisture data and models can produce highly reliable estimates of the fire danger. Accordingly, the maps can be developed for mitigation approaches to assist firefighters and fire managers. Accordingly important decisions such as evacuation orders and smoker jumper's dispatch can be made. This systems uses both climate and vegetation data for assessment of fire risks, transitioning to the canopy, where they are much more difficult and expensive to suppress. Moreover, the prescribed fires can also be used to reduce the danger of overhead fuel.

5.3.9.5 Remote Sensing of Amazon Rain Forest Fires

Forest fire sensing can be done using satellites, where the IR sensors are used to detect the infrared radiation emitted by wildfires. The remote sensing of the 2019 Amazon rain forest fires has shown that these fires started from forest lands that were cleared for the purpose of agriculture and planting. The satellite image of the Amazon fires is shown in Fig. 5.6, where the fires are shown in red color, the forest is shown in green color, and the deforestation is depicted in yellow. The land use and rapid deforestation of Amazon are major environmental issues. Because these are not caused by natural phenomena, human activities are the major cause of these fires.

The remote sensing of wildfires has many benefits:

- The real-time and enhanced fire monitoring can be done at large geographical areas. Accordingly, this information can be used by fire managers in real time.
- The fire weather data and relevant fire danger alert systems can be developed by using predictive modeling approaches.
- The aerial fire control fuel loading management policies can be developed for fire mitigation.
- The smoke thickness and movement can be predicted to prevent health-related consequences due to smoke inhalation.

5.3.10 Invasive Species and Fungi Sensing

The invasive non-native exotic species are a major challenge in forest managements. These species present major ecological challenges, and advanced sensing and

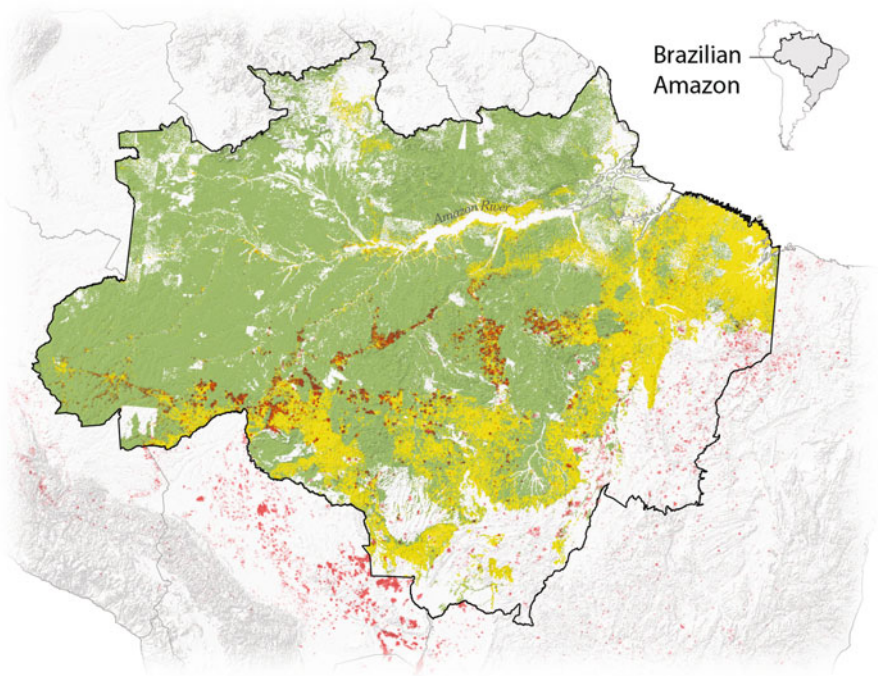


Fig. 5.6 The satellite image of the 2019 Amazon fires shown in red, the forest is shown in green, and the deforestation is depicted in yellow based on NASA data

monitoring approaches are needed to reduce, eliminate, and minimize the impact and spread of these invasive species. Their mobility media are generally the lumber, firewood, and forest vehicles. These mitigation and sensing approaches span across multiple areas [36] such as:

- Sensing of alien pests in forests
- The treatment of hardwood logs for removal of pathogens and insects
- Short for silviculture of Allegheny hardwoods
- Pest management with *Bacillus thuringiensis*
- Biological control and genetic management
- Technology to reduce impact

Moreover, various types of fungi related with the tree also present a conducive environment for invasive species, which outnumber native species. Moreover, these also lead to wood decomposition. Therefore, fungi sensing becomes important for invasive species management and also for sustainable forest management and restoration [46]. The white rot fungi is also related to carbon cycle of forests and causes detoxification, transport, and intense cell wall degradation (e.g., recalcitrant polymer and lignin). These also have the protection for biofuel conversion for bioenergy [27, 34, 87]. Various types of approaches can be used to identify such

as molecular and microscopic fungi. Genetic sequencing is also used to inhibit soil-related fungi. The GenBank is an example of sequencing database. The scanning electron microscopy (SEM) [3] approach is utilized for wood decay. The computer tomography (CT) and ground-penetrating radar (GPR) are also utilized for fungal decay and moisture detection providing information into the wood structure. The DNA analysis is also conducted for pathogen identification. Wood metabolite profiles can also be determined by using the time-of-travel approach (direct analysis in real-time (time-of-flight) mass spectrometry DART-TOFMS). These sensing approaches will provide deeper insight into the fungi-wood relationship in sustainable forest IoT.

5.3.11 Vegetation Height Sensing

The airborne LiDAR provides an accurate estimate of vegetation height. This approach operates by transmitting the laser beam in the vegetation to the ground. The reflected energy from the vegetation is detected to assess the vegetation height, density, and structure. This sensing approach is used to identify the area for bird habitat-related decision making. Moreover, the vegetation change tracker (VCT) [70] can also produce reliable forest estimates using satellite images.

The tracker uses an autonomous program for mapping using the Landsat data. The resulting maps can be used to distinguish forested and non-forested regions. Currently, in ground-based mapping systems, the false indicators of forest disturbances are a major challenge in forest management, particularly in wetland and agricultural landscapes. This tracker also helps to identify those false positives through improved mapping.

TimeSync is another system that uses over 30 years of satellite data to analyze variations in the vegetation status over the temporal scale by using the time-series modeling approach [100]. The high correlation with the drought periods and decrease in fresh canopy has been identified. It has been shown that the decay depends on the length and intensity of the short-term summer droughts and other factors such as:

- Geographic variation
- Structure and composition
- Soil and topography
- Insect and disease outbreaks

5.3.12 Machine-Induced Stress Sensing

Forest machinery and equipment affect the soil in forests and change the physical properties of the soil, such as compaction, pore size, bulk density, and resistance.

The mechanical stress is sensed using a pressure transducer that provides electrical signal for data logging [80]. The sensor can be used to assess soil conditions for replantation.

5.3.13 In Situ Soil Moisture Sensing Approaches

Because a large amount of sensor deployment is not feasible in large forests, sensor-free approaches can be employed in forests. The resonant frequency-based approaches and Di-Sense are two good candidates for this.

5.3.14 Radio Waves as Sensor: Propagation Based Sensing in Forests

In situ measurements and inversion approach can be used to measure the soil properties at higher depths with greater accuracy. In this paper, we have developed Di-Sense, an in situ, real-time soil moisture and permittivity estimation approach based on the wireless underground communications (WUC) in IOUT. For a transmitting antenna in the soil, the generated electromagnetic (EM) waves propagate through the soil and are not only affected by the depth, distance, frequency, and soil moisture [83] but also depend on the properties of the soil [24]. Path loss of these attenuated waves received at the UG receiver can be used to deduce the properties of soil and can also be used to estimate the soil moisture. Our approach to derive the soil moisture and relative permittivity is based on the path loss of the UG communication channel in IOUT. Path loss of transmitter-receiver (T-R) pair in WUC depends on the distance, depth, and soil moisture. In Di-Sense, a transmitter antenna buried at a certain depth in soil transmits a wideband signal in a frequency range of 100–500 MHz, which propagates through the UG channel. The received signal is measured at the receiver to determine the path loss. Di-Sense enables an IOUT system to communicate simultaneously besides real-time permittivity estimation and soil moisture sensing. A model has been developed to estimate the soil moisture and permittivity based on path loss using Di-Sense. The model has been validated through experiments in a software-defined radio (SDR) testbed and in an indoor testbed in different soils at different depths under different soil moisture levels. Relative permittivity results show a very good agreement with less than 8% estimation error from ground truth measurements, semi-empirical Peplinski dielectric mixing model [73], and Topp model [90] (Fig. 5.7).

When EM wave communication is carried through the soil in IOUT, the propagation loss, due to the water molecules held in the soil medium, is a function of the real effective permittivity (dielectric constant) of soil. Therefore, propagation path loss of the soil direct path (between the transmitter-receiver (T-R) pair) can be

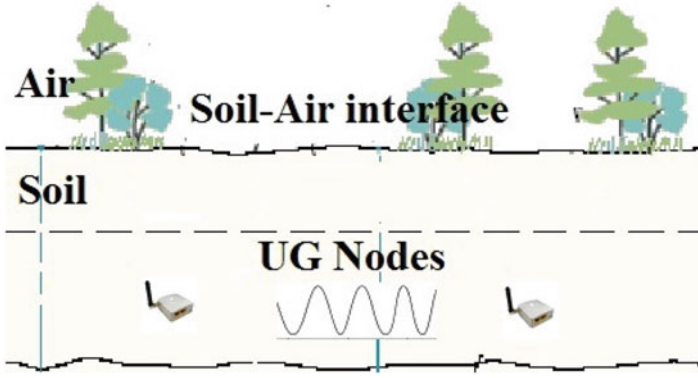


Fig. 5.7 Estimation of soil properties in forests using WUC

used to estimate the relative permittivity and soil moisture within 100–500 MHz range. To model soil permittivity, the lowest path loss (LPL) across the whole frequency range is found by transmitting a known signal. The propagation path loss is determined by measuring the received signal. The transmitter transmits one signal using the narrow bandwidth at a time, and frequency is increased sequentially in predefined step, Δf . Path loss is the ratio (expressed in decibel (dB)) of the transmitted power P_t to the power received P_r at the receiver. Path loss is determined as

$$PL = P_t - P_r = 10 \cdot \log_{10}(P_t/P_r) , \quad (5.1)$$

where PL is the system path loss and includes the effects of transmitting and receiving antenna gains G_t and G_r , respectively. Once the path loss is measured, the frequency of the lowest path loss is determined by

$$f_{\min} = F(\min(PL(f))) , \quad (5.2)$$

where $f_{\min}$ is the frequency of the minimum path loss. The $f_{\min}$ is not affected by the distance between transmitter and receiver antennas because of the antennas gains. Therefore, system path loss PL is inclusive of the antenna gains. Since PL measurements are done in narrowband, noise effects is minimal. Next the soil factor, ϕ , is calculated as

$$\phi_s = f_{\min}/f_0 , \quad (5.3)$$

where f_0 is the resonant frequency of the antenna in the free space. Once the soil factor, ϕ_s , has been determined, the wavelength at the f_0 frequency is found

$$\lambda_0 = c/f_0 , \quad (5.4)$$

where c is the speed of light. Accordingly, the relative permittivity of the soil is determined as

$$\epsilon_r = \frac{1}{(\phi_s \times \lambda_0)^2} . \quad (5.5)$$

Permittivity Estimation Through Velocity of Wave Propagation in Soil Due to the inhomogeneity of the soil medium, permittivity of the soil varies along the communication link from point to point. This leads to variations in wavelength and phase velocity, as the wave propagates in soil. Therefore, permittivity of the soil can be measured from the velocity of wave propagation in soil. Power delay profile (PDP) is measured to get the velocity of the wave propagation, which is determined from the known geometry layout of the testbed, by calculating the time that wave takes to reach at the receiver from the transmitter. Once the velocity of the wave in soil, C_s , is determined, the relative permittivity in soil is calculated from the difference of transmission and the arrival time of the direct component in the soil. The path of the direct component is completely through the soil. Accordingly, ϵ_r is determined as

$$\epsilon_r = \left[C_s \times \frac{(\tau_{dr} - \tau_{dt})}{l} \right] , \quad (5.6)$$

where l is the distance between transmitter and receiver antennas, $\tau_{dr} - \tau_{dt}$ is the travel time of the direct component in the soil, and C_s is the wave propagation velocity in soil. Due to different propagation velocities of the air and soil, direct wave is separated from the the lateral wave which travels through the air along the soil-air interface and has less attenuation as compared to the lateral wave [83]. In [85], an example power delay profile in the silt loam soil in the indoor testbed and attenuation in soil as a function of operation frequency are given.

5.3.15 From Permittivity to Soil Moisture

The relationship of the soil moisture and permittivity is independent of the soil texture, bulk density, and frequency [90]. Since soil permittivity depends on the soil moisture only, soil water content can be determined from soil permittivity [49, 90].¹ Since dry soil has a relative permittivity of 3, the relative permittivity of the water is 80. The soil permittivity is calculated using (5.5) and (5.6), and accordingly, soil moisture is determined as [49, 90] (Fig. 5.8):

$$\text{VWC (\%)} = \frac{\epsilon_r - 3}{0.77} + 14.97. \quad (5.7)$$

¹ Although there is some error in soil moisture-permittivity relationship, and its dependence is also weak for mineral soils, it has been shown to work well in fine and coarse textured soils [54].

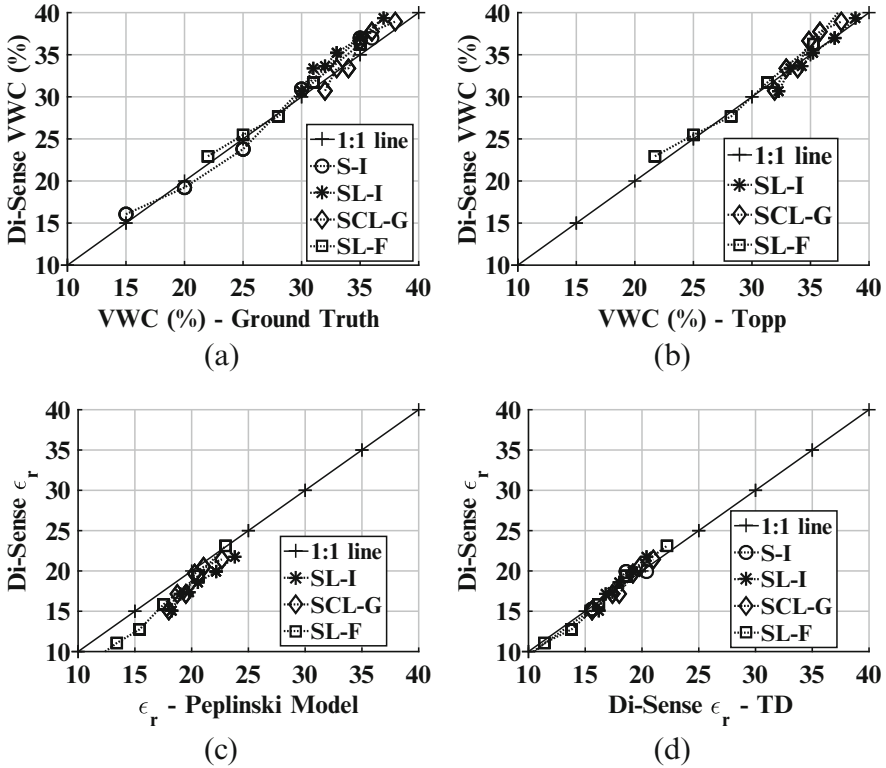


Fig. 5.8 (a) Di-Sense VWC compared with ground truth VWC measurements. (b) Di-Sense VWC compared with Topp model. (c) Di-Sense permittivity compared with Peplinski model. (d) Di-Sense permittivity by time-domain velocity of propagation comparison with the Di-Sense path loss propagation permittivity method

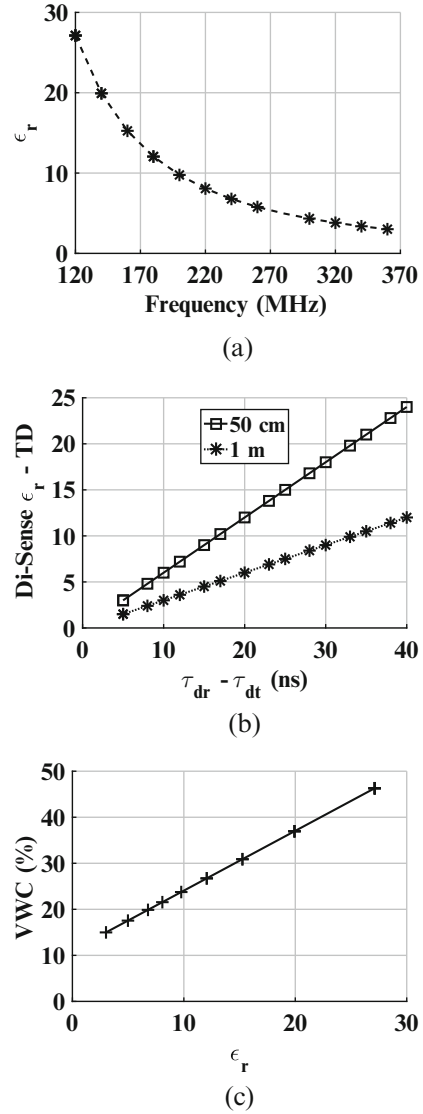
5.3.16 Transfer Functions

It is worth noting that the results presented here are intended for soil moisture and permittivity estimation, but these can also be used for IOUT communication system design. Moreover, effects of changes in soil permittivity with change in depth are likely to be reduced at higher depths due to the fact that the intensity of the reflected wave from the soil-air interface is reduced at the deeper depths. For estimation purposes, the following procedure would be used:

- Determine the lowest path loss frequency.
- Estimate the soil permittivity using (5.5) and (5.6).
- Estimate the soil moisture using (5.7).

Di-Sense transfer functions of the soil permittivity and soil moisture are shown in Fig. 5.9. The soil moisture and permittivity of the soil medium can be determined

Fig. 5.9 Di-Sense transfer functions: (a) soil permittivity, (b) soil permittivity time-domain, and (c) soil moisture



using these graphs from the measured values of the IOUT propagation path loss. The Di-Sense measurement technique is simple and easy to use, and no knowledge of type of radios, communication parameters, and antennas, being used in IOUT deployment, is required, as long as the propagation path loss can be measured accurately. Moreover, Di-Sense can also be used for different operation frequencies, f_0 , because (5.3) and (5.4) scale accordingly with respect to the operation frequency. Like other measurement-based techniques, there are some limitations for which the Di-Sense method is applicable. The major limitation is that propagation path loss of

the soil under test should be measured accurately. For the application of Di-Sense to the application scenarios, where higher accuracy is required, an empirical factor can be used to account for the specific soil properties and soil-water retention capability.

5.4 Modeling in Digital Forestry

The models in sustainable forest management also help to improve the forecasting, coupled with data obtained through sensing, satellite, and ground surveys. The spatial and temporal data combined with soil, organism, climate, and topography can be used to produce statistical models for futuristic ecosystem forecast at multiple scales. These different models are discussed in this section.

5.4.1 Habitat Modeling

The statistical habitat modeling provides useful insights about the impacts of future climate change on bird and tree habitats [69]. It has been developed based on the present habitat conditions and climate features. It has five different components:

- Climate Change Tree Atlas
- Climate Change Bird Atlas
- DISTRIB-BIRD: Modeling Potential Bird Habitats
- SHIFT: Modeling Potential Species Colonization
- DISTRIB: Modeling Potential Tree Habitats

5.4.2 Multi-Scale Machine-Learning Predictive Modeling

Deforestation is a major cause of biodiversity loss. A multi-scale machine-learning predictive modeling has been developed to model deforestation [25]. It provides reliable estimates about the risk of future deforestation. The deforestation model predictions can be used to inform the sustainability and conservation practices in forest management.

5.4.3 Smoke Prediction Models

The operational smoke prediction system (OSPS) is used to model fire-smoke-related hazards. Accordingly, public health alerts can be issued using the sustainability forest IoT systems in WUI zones to avoid the hazardous impacts [81]. Many

improvements are needed in smoke prediction modeling such as plume structure, fire dynamics, and weather. The advanced model can also incorporate sensing of fire, meteorology, and atmosphere to enhance the prediction capabilities.

5.4.4 Modeling Invasive Insects

Invasive insects pose a major problem to the forest health. A model has been developed to predict future invasions of various insects by considering their invasion routes and tracks [33]. It provides useful estimates about rates and the number of invasions. Currently, this model is being employed to predict the invasion from Europe to the USA. It can be used to forecast and prioritize potential invasions, and accordingly detection and identification mechanisms can be put in place in advance for efficient management and alerts. The Invasive Species Specialist Group (ISSG) network deals with invasive species [59]. Two other models are the following:

- Insect Flight Model. It is used to characterize cell-based flight attributes [86].
- Insect Ride Model. A stochastic model to predict the insect ride by using external media [76].

5.4.5 Forest Disturbance Modeling

Forest disturbances affect the ability of forest to render important ecosystem services such as carbon sequestration [48, 82, 88]. In carbon sequestration, carbon dioxide is captured and stored by forests [67]. A model has been developed by using a satellite data of forest spanning over 25 years to predict various types of forest disturbances. This model has two different components:

- The first step uses random forest (RM) models to predict various types of disturbances such as fires, winds, stress, harvest, and conversion [103]. The nonparametric shape-restricted spline fitting algorithm and other spectral change metrics are employed as predictors along with other topographic and biophysical parameters.
- In the second stage, rule-based spectral shape parameters are applied to first step output to identify temporal parameters of disturbances such as the year.

This model gives highly accurate predictions of disturbances using the spectral metrics and other parameters. The applications of this model are in the area of disturbance mapping in different geographic zones around the globe.

5.4.6 Fire Behavior Modeling

The wildland fire behavior can be modeled using the fuel analysis and other parameters such as inherent vegetative fuels, weather, vegetation, atmosphere, and ignition patterns (e.g., BEHAVE-Plus). These models are divided into physical and empirical models. Currently, many model exists in literature for modeling of different types of fuels. However, the models and fuel modeling science are lagging in terms of accuracy and fuel complexity issues. The different fuel models are listed in the following [14]:

- Grass Fuel (GR)-Type Models
- Grass-Shrub (GS) Fuel-Type Models
- Shrub Fuel (SH)-Type Models
- Timber-Understory (TU) Fuel-Type Models
- Timber Litter (TL) Fuel-Type Models
- Slash-Blowdown (SB) Fuel-Type Models

The fire spread models are used to estimate the spread of fire based on the type of fuel arrays. The test model (TSTMDL) is used for this purpose.

5.4.7 Wildlife Habitat Suitability Modeling

Wildlife habitat models are used to model the survival and reproduction of species in different environments. This model is used to assess the suitability of wildlife habitat over long periods of times with variations in forest, tree structures, biomass, timber, and wood debris and also considers harvesting regeneration processes. It can generate forecasts for large regions for periods of more than 100 years. It is useful to address wildlife conservation issues and challenges [19, 26].

5.4.8 LANDIS

The LANDIS is used to model forests (e.g., landscape, seed dispersal, succession, and disturbances). The grid cells are used to present various landscapes for per specie-based representation. It has the ability to simulate different complex ecological scenarios and successions such as age-only, biomass, forest carbon, BFOLDS, PnET, and Net Ecosystem CN for different types of disturbances such as fire, wind, biological disturbance of insects and disease, harvest, and drought.

5.5 Forest Database Integration with Forestry IoT

The important forest databases for integration into sustainable forest IoT are discussed in this section.

- **Urban Tree Canopy Assessment.** It is used to assess tree cover in urban environments and gives current and future canopy assessment. It can be used for planning purposes such as tree plantations. This decision can contribute to reduction of summer heat and air quality improvements.
- **iTree.** It is a sustainability tool that assesses the health of trees. It has global reach and provides robust information about the tree health. It can be used for both urban and rural settings for tree value education. It has three components: a database, a web-based mapping tool and model, and a mobile phone application.
- **i-Tree PRESTO (PProduct ESTimation Tool Online).** It is the enhanced version of iTree carbon storage estimation over large time periods.
- **The Forest Inventory and Analysis (FIA)** is a US forest database. It contains enormous information about locations, trends, and status of US forests. Various tools of FIA include DATIM, EVALIDator, Data Mart, fact sheets, and other reporting tools. It also provides detailed data about endangered plant and animal species. Overall, FIA integration with forest IoT is useful to achieve sustainable forest management goals.
- **Global Invasive Species Database (GISD).** A database for effective prevention, mitigation, and management of invasive species.
- **IUCN Red List of Threatened Species** provides valuable information about facing the dangers of extinction.
- **Spatial Hazard Events and Losses Database for the United States (SHELDUS)** is used to assess forest losses caused by different hazardous events.
- **NASA Disasters Mapping Portal.** It has SRI ArcGIS-based web interface to visualize disaster database in real time. Other tools for this purpose are Hazards US Multi-Hazard (HAZUS-MH) and Advanced Hydrologic Prediction Service (AHPS).
- **The GuidosToolbox** provides information about forest landscape and fragmentation at different scales.

5.6 International Organizations for Forest Sustainability

A list of organizations active in the area of forest sustainability is given below [41]:

- International Tropical Timber Organization (ITTO)
- Amazon Cooperation Treaty Organization (ACTO)
- Food and Agriculture Organization (FAO) Indicators Site
- FAO/ITTO Expert Consultation on Criteria and Indicators for Sustainable Forest Management
- International Union of Forest Research Organizations (IUFRO)
- Center for International Forestry Research (CIFOR)
- European Forest Institute (EFI)
- United Nations Environment Programme/World Conservation Monitoring Centre (UNEP-WCMC)
- Forest Europe (formerly the Ministerial Conference on the Protection of Forests in Europe)

- Lepaterique Process of Central America on Criteria and Indicators for Sustainable Forest Management
- The Dry-Zone Africa Process on Criteria and Indicators for Sustainable Forest Management
- Regional Initiative for the Development and Implementation of National Level Criteria and Indicators for the Sustainable Management of Dry Forests in Asia
- The Near East Process on Criteria and Indicators for Sustainable Forest Management
- African Timber Organization
- The Tarapoto Proposal of Criteria and Indicators for Sustainability of the Amazon Forest
- International Conference on the Contribution of Criteria and Indicators for Sustainable Forest Management: The Way Forward (2003)
- Collaborative Partnership on Forests
- Community Indicators Consortium

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Chapter 6

Internet of Things in Sustainable Energy Systems



6.1 Introduction

The United Nations seventh sustainable development goal (SDG) is targeted to eliminating energy sector poverty [103]. The continuous and sustained efforts are required both at the strategic and governmental levels to realize global access of energy [53, 120, 133]. Thus, the development of technologies and systems, coupled with policy making, governmental practices, and social transformation, is needed to enhance affordability and rapid global, regional, and local access of energy resources to the people [132, 134]. To ensure energy access at this scale, decentralized grid systems approach with resources distributed at the lower tiers will bring significant changes. The energy-related SDGs are shown in Fig. 6.1.

It can be observed that energy demand has a strong connection with almost all of the UN Sustainable Development Goals (SDGs). The energy access is highly correlated with the quality of life and plays a vital role in the following sectors:

- The health and education sectors rely on dependable energy infrastructure [23, 117, 137].
- Provision of clean water needs energy [8, 53, 102].
- Energy drives the agricultural irrigation systems [119].
- The transportation sector cannot function without energy.
- Household heating, cooling, cooking, and electric lighting require energy.
- The industrial sector also relies on energy.

6.1.1 Energy and Sustainability

The energy access [91] has the potential to reduce energy inequalities. The International Energy Agency (IEA) has defined the energy access as follows:

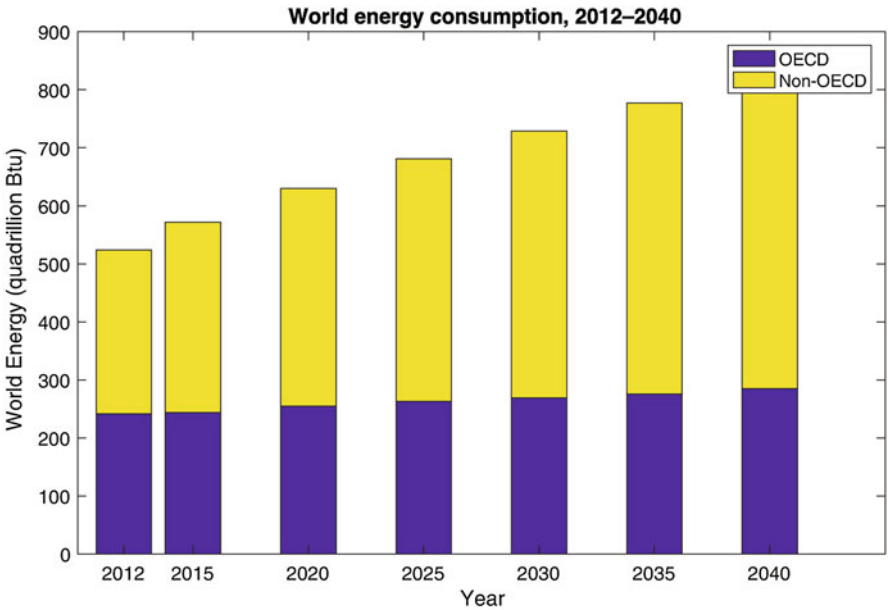


Fig. 6.2 The projected growth in energy demands of the world up to 2040 [87]

access is also useful to reduce gender inequality in developing countries where women spend their diurnal energy to collect firewood due to lack of adequate energy resources [91]. It also causes mental and physical health stress in girls and women [17, 73]. Therefore, in addition to being the fundamental requirement, the sustainable energy access has tremendous socioeconomic benefits to the community in terms of eradicating poverty and gender inequality. The UN’s sustainable energy for all [101] program is flag-bearer for this vital cause.

Likewise, the advanced nations are also in need of continuous provision of energy. The energy is required for the functionality of businesses, high priority infrastructure, public safety, healthcare, and other industries. Moreover, potable water and wastewater treatment systems are dependent on energy access, where failure in one area can trigger cascading effects in urban utility management. Therefore, achieving energy resiliency is becoming the top priority of city planners and managers [10, 23, 79, 92, 116, 117, 133, 136, 137].

6.1.2 Energy-Related Challenges

As the modern advanced energy technologies are developing, there are emerging challenges that the future energy systems should address by using these advances [49, 126]. The current and future energy-related challenges being faced by the

community are discussed below. These challenges impact the capacity of power generation and also result in energy distribution disruptions.

- Current energy system depends heavily on water. However, with the variations in availability of water (short-term and droughts), novel techniques for energy production are needed [144].
- High-voltage transmission lines lack security measures. They are overloaded and are being used afar their predetermined purpose. Moreover, transmission loss is also a major issue which leads to power outages and blackouts [130].
- Many energy facilities are located in coastal zones due to the high availability of water. However, rising sea levels and high tides, heavy downpours, and flooding from storm surge events are impacting coastal infrastructure and energy facilities and infrastructure [26, 61, 80, 104, 134]. The long-duration energy outage in urban and industrial areas results in productivity loss that is also associated with business and economic loss.
- Extreme heat waves and summer temperatures are also causing high-energy demands and corresponding increase in electricity usage. Due to peak loads, energy demands are projected to increase [135].
- The energy production and transportation infrastructure are also being impacted by extreme weather events [1]. Therefore, the frequency, duration, and intensity of these events cause energy disturbances that are occurring at different scales.
- One challenge associated with energy consumption is increase in greenhouse gas emissions [3, 138]. These emissions include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [127] emissions. These emissions are the second highest following the majority of emissions from the transportation sector.
- The energy consumption by information technology, mobile, and computing devices is increasing [105].
- With more and more electric vehicles (EV) being manufactured, the energy demand is increasing to fulfill EV needs [75].
- Other challenges related to energy infrastructure include a discrepancy between the demand and capabilities of energy systems and the complex energy needs of industry and community [49].

6.2 The Sustainable Energy IoT

From the discourse of the energy and sustainability, it is evident that global energy access cannot be attained in the absence of technology adoption. Through application of technology, robust solutions for reliable low-cost energy access can be developed which can enhance the performance and operation of the current energy systems. Therefore, by using the next-generation sensing and communication technologies, the need for affordable energy can be met for the community (see Fig. 6.3). The IoT technology that can efficiently provide the affordable energy services is necessary to address this basic human need of energy.

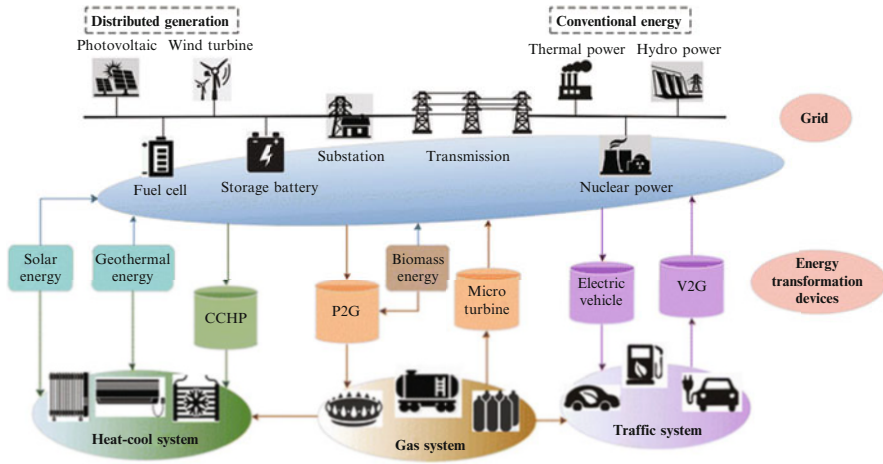


Fig. 6.3 An overview of the sustainable energy IoT

The IoT in sustainable energy systems is envisioned as the interconnection of the energy things in the entire paradigm grid system, service supply chains, and human capital using state-of-the-art technologies with the ability to meet future needs and clean energy access challenges of the current century. This paradigm with its potential to produce next-generation energy systems is useful to connect various energy technologies and innovative solutions at the global scale. The sustainable energy IoT has the tremendous potential to attain sustainability and resiliency of prevailing energy infrastructure. It also has the ability to reduce future energy risks through development of secure, novel, and efficient energy infrastructure and technology. The IoT in sustainable energy systems enables various methods and pathways to global energy access through commissioning of clean and renewable energy methods with large-scale availability and scalability for sustainable provision of low-cost energy sources.

6.2.1 Sustainability Energy Things

The sustainable energy IoT carries a huge value for efficient energy value chain. Yet, the main value of the sustainable energy IoT lies in the smart grids, which is a significant achievement of the twenty-first century. The sustainable IOT paradigm with IoT autonomous and efficient management of the grid has a tremendous potential to bring benefits in consumption and generation. The sustainable energy IoT through its real-time monitoring of the renewable energy generation resources coupled with environmental monitoring can enhance the efficiency in the area of solar and wind power generation. Accordingly, these can be integrated into the grid to maximize the supply. It will also reduce dependence and pressure on less

efficient, high-demand, pollution-causing fossil fuel-based energy sources by using the distributed and low loss smart microgrids. The sustainability things are outlined in the following:

- Smart meters, net-zero energy homes, green energy, and smart industry
- Generation, wind, solar, natural gas, water, renewables, and coal
- Transmission, phasor measurement unit, and transmission SCADA
- Distribution, smart and microgrid, and voltage control
- Billing, SAP, CRM, and work order management
- Customer, markets, retail energy provider, wholesale, and service provider
- Plant control, electric vehicles, and distributed intelligence
- Load, bulk, and outage management

6.3 Communication Technologies for Sustainable Energy IoT

Communication technologies are vital to provide connectivity in sustainable energy IoT. These form the integral part of the energy control systems, which are considered the backbone of the sensing and monitoring in energy systems. Most of the communication systems discussed in the first chapter of this book are being utilized in the energy sector. However, advanced communication technologies pertaining to the sustainable energy IoT are discussed in this chapter. An overview of these technologies is provided in Fig. 6.4. These technologies are the driving force of the innovation in the energy sector and bring efficiency to all aspects of the energy system.

6.3.1 *Wi-SUN*

The Wi-SUN wireless smart utility (ubiquitous) network is a field and local area mesh networking standard supported by Wi-SUN Alliance [55]. It follows IEEE 802.15.4g and has its own physical and data link layer protocols. Its biggest advantage is that it can operate with multiple vendors.

6.3.2 *Wide Area Monitoring Using SCADA*

The supervisory control and data acquisition (SCADA) was developed in twentieth century to collect power data from various geographical locations of the grid. It is the main medium of communications between substations and utility control stations. The SCADA has the capability to interface with large area monitoring

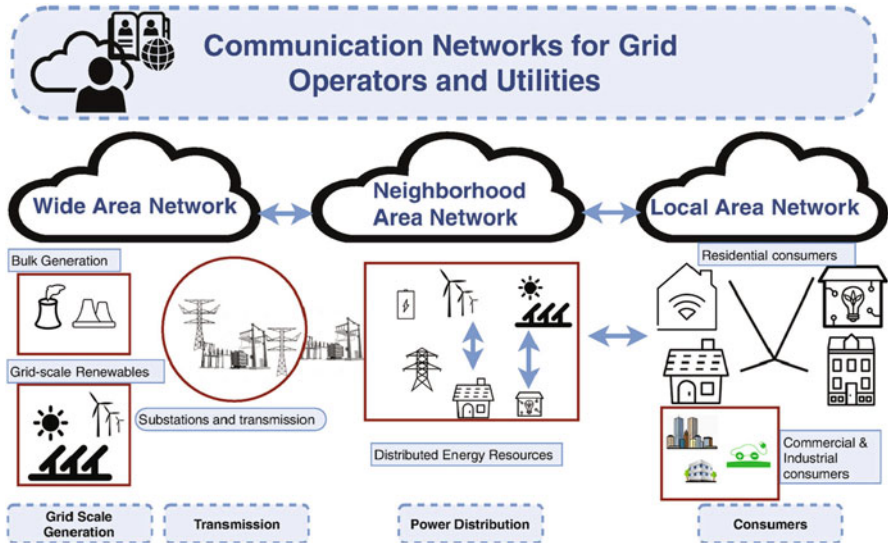


Fig. 6.4 Smart grid communications [37]

systems and Internet; accordingly, robustness and efficiency have increased with this feature [6].

6.3.3 Neighborhood Area Networking

A neighborhood area network (NAN) [81] is an extension wireless LAN to multiple blocks of a neighborhood for the purpose of connecting to the utility backbone network and also to the Internet. A NAN can connect multiple smart meters to the grid. These networks are utilized for billing, energy load planning, and demand response on neighborhood basis. In these networks, energy consumption is low and data rates are in the order of few kilobits per second. WiMAX standards can be used to extend the range of NAN and can provide data rates of up to 70 Mb/s. A design of the wireless NAN design for advanced metering infrastructure (AMI) in the smart grid with self-sustainable capability is presented in [141].

6.3.4 Power-Line Communications

In the power-line communication, power cables are utilized as a channel for data transmission. Since the electric energy companies already have a vast infrastructure to meet the needs of electric power supply, advancements in the power-line com-

munications will be beneficial for smart grid control and monitoring applications. These communications are divided into four types [110]:

- Ultra-narrow band (UNB) power-line communication (PLC): This communication is based on the use of ultralow-frequency (ULF) spectrum from 300 to 3000 Hz and also in 0.03 to 0.3 kHz.
- Narrowband power-line (NB) communication (PLC). This communication uses a frequency band of 120 kHz using amplitude modulation. It has low data rates.
- Quasi-band (QB) power-line communication (PLC). This communication operates in a frequency spectrum of 1–10 MHz and provides high data rates of more than 2 Mbps. This is a long-range communication approach for advanced metering infrastructure networks.
- Broadband (BB) power-line communication (PLC). This communication uses a frequency band of 1.7–250 MHz and supports high-level modulation schemes such as orthogonal frequency-division multiplexing (OFDM).

6.3.5 Other Communication Technologies for Grid

The advancement in power-line communication technology will also enable digital subscriber lines (DSL) over these power carriers. The DSL is able to achieve data rates of 1 to –100 Mb/s and is classified into the following types [97]:

- Asymmetric digital subscriber line (ADSL)
- Very-high-bit-rate digital subscriber line (VDSL)
- High-bit-rate digital subscriber lines (HDSL)

6.3.6 The Advanced Metering Infrastructure

The advanced metering infrastructure (AMI) consists of the following components [41]:

- Smart Meters. A two-way communication device that is used to measure the energy consumption of various appliances (e.g., electricity and gas heater). Smart meters are discussed in more details in the sensing section of this chapter.
- Home Area Networks (HAN). A communication and information network formed by various appliances running within the home to support various distributed applications.
- Neighborhood Area Network (NAN). Network of multiple HANs for collecting and sending data to data concentrator.
- Telecommunications Network. A data communication network used to carry the metering data to control centers.

- Gateway. A device that collects data from the HAN's member (also from the entire home as a whole) and transmits to the next level.

6.4 Sensing in Sustainable Energy IoT

In this section, the sensing in various energy systems is presented. First, the sensing in nuclear power reactors is discussed.

6.4.1 *Sensors on Nuclear Power Reactors*

The nuclear power generation is a pivotal element of the sustainable energy IoT systems. Due to the hazardous nature of the nuclear environment to humans, reliable and autonomous sensors can reduce contamination hazards to humans. The sensors used in nuclear power reactors are discussed in the following section.

6.4.1.1 Vibration Sensing

Vibration sensing in nuclear power reactors is carried to monitor and avert environmental radiation discharge [9]. The vibration sensing also ensures the health and safety of plant equipment and employees for unhindered power generation. Nuclear power plant failures lead to negative financial and environmental impacts. Piezo-electric ceramic sensors give electrostatic charge signal based on the application of acceleration [9]. These sensors do not contain electronic-based signal processing elements due to the high temperature nature on the environment. Accordingly, external signal processing is required for producing output. On the one hand, the use of smart sensors can mitigate this problem where signal processing, networking, and communication capabilities such as analog-to-digital conversions are done on board.

6.4.1.2 Temperature Sensing

Temperature sensing in nuclear power reactors is done both in control systems and in safety and performance analysis systems [62]. For this purpose, chromel–alumel (thermocouples) and resistance-based thermometers are used. Various types of temperature sensors are surface sensors and pool sensors. Currently, there is a need for advancements in high-temperature physical sensor technology for nuclear energy reactors such as in pebble bed reactors, where high drift is observed in thermocouples at high temperatures. Other temperature measurement approaches include [98] the following:

- Ultrasonic-guided wave thermometry. There are challenges in propagation of ultrasonic-guided wave [96].
- Johnson noise thermometry. It is susceptible to electromagnetic (EM) interference [18].
- Bragg thermometry. Susceptible to photo bleaching at high radiation [69].
- Optical sensors. The implementation of optical access ports to these sensors is challenging [24].

6.4.1.3 Pressure Sensors

The pressure sensors in nuclear plants are electromechanical instruments to determine pressure. These sensors can also measure the differential pressure, level, and flow [5]. These pressure sensors work by measuring the displacement of its mechanical parts which is changed to electronic form. There are also challenges in this conversion due to the high temperature. However, they suffer from leaks. The impulse line techniques suffer from salt contamination. The piezoelectric pressure sensors (Fig. 6.5) can also be utilized to sense dynamic pressure on short-term basis. Moreover, pressure sensors are also needed for higher reliability chloride salt and liquid fluoride environments. The polymer-derived ceramic materials are being investigated to fabricate pressure sensors; however, like temperature sensors, their interfacing to external circuits is challenging.

6.4.1.4 Liquid-Level Measurement Sensors

The fluid-level sensing is very important in reactors. The microwave techniques are used to sense levels of liquid salt. Other water-level sensing approaches include ultrasonics using waveguides and impedance matching, pulsed neutron, neutron detectors, gamma thermometers, displacer float, conductivity, gamma horoscope, optical, and microwave [43]. However, these approaches are used as a short-term solution. The development of non-insertion (contact-less) sodium-level sensors is important for real-time monitoring.

6.4.1.5 Flow Sensors

The flow sensing can be either single phase or multiphase which is based on acoustic and ultrasonic methods [123]. Ultrasonics and acoustics are further divided into three types:

- Time-of-flight. In the time-of-flight sensing, 1 MHz frequency wave is transmitted to the pipe at an acute angle, propagates through the pipe, and is received at the other side of the pipe. The wave velocity in the pipe is impacted by the flow of liquid. Accordingly, the travel time of the wave is used for flow measurements.

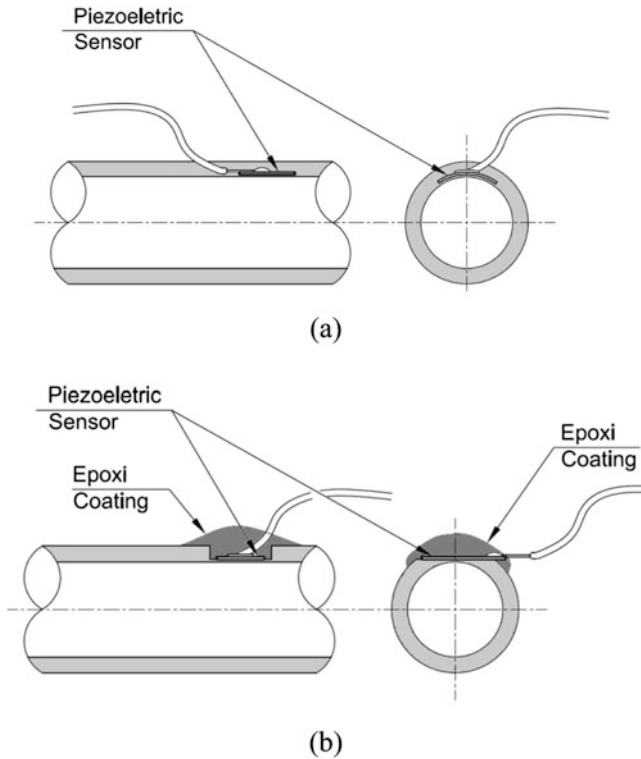


Fig. 6.5 Pipe with embedded piezoelectric sensors, (a) installed during fabrication of plastic pipes and (b) installed in fabricated pipes [71]

- The Doppler flowmeter. In this approach, the wave reflection is measured in contrast to the propagation (time-of-flight) measurements, where the shift in the reflected frequency in comparison to the transmission frequency is used to measure the flow [89].
- In contra-propagation transmission, acoustic transmissions are alternated between the transmitter and receiver (TR) pairs installed on both sides of the pipes. The frequency difference is converted to the flow rate.

Based on the physical contact, these sensors can be categorized into two types:

- Intrusive sensors. These work inside the flow stream (e.g., head-type, segmental wedge, drag-type, and impedance sensors).
- Nonintrusive without penetration into the flow stream (e.g., acoustic, electromagnetic, microwave, optic, and nuclear).

The ultrasonic sensors are unable to sense at high salt temperatures and can also cause salt freezing to the heat absorption characteristics of the waveguides.

Therefore, for nuclear power plants, the development of ultrasonic sensors with capability to operate at higher temperatures (750 °C) is needed.

6.4.1.6 Corrosion Sensing

For the corrosion sensing, it is important to identify corrosion causing processes. Currently, no techniques exist for in situ monitoring of corrosion and samples are analyzed off-line in the laboratory environment. In this regard, there is a need for sensor technology in tritium sensing. Moreover, the water content monitoring is done to avert imprudent oxidation of reactor materials [29].

6.4.1.7 Radiation Sensors

The sensing of neutron flux is vital for nuclear reactor safety and operation and also for radiation monitoring [21]. For this purpose, the neutron flux and gamma flux sensors are used which can work in three different modes [60].

- Pulse mode during start-up
- Direct current ion chamber mode at full power
- Variance mode for wide-range coverage

6.4.1.8 Water Coolant Chemistry

Water plays an important role in all power plants as the coolant. The production of energy uses water. Then impaired nontraditional water can be used as cooling with the advanced water recovery and reuse. The water chemistry sensing plays an important role in water quality and its cooling ability monitoring [93].

6.4.2 Sensors for Coal-Fired Power Plants

Coal-fired power plants are another important component of the sustainable energy IoT systems due to their ability to provide flexible energy. In these plants, monitoring is done to improve the efficiency of the combustion process and for sensor-based autonomous optimization. The coal-fired power plant sensing coupled with advanced stoichiometric control systems has the potential to improve the performance efficiency of these plants. These sensing approaches include coal, flame, carbon, and oxygen, and airflow sensing in various parts of the furnaces [124]. The sensors used in coal-fired power plants are discussed in the following section (Fig. 6.6).

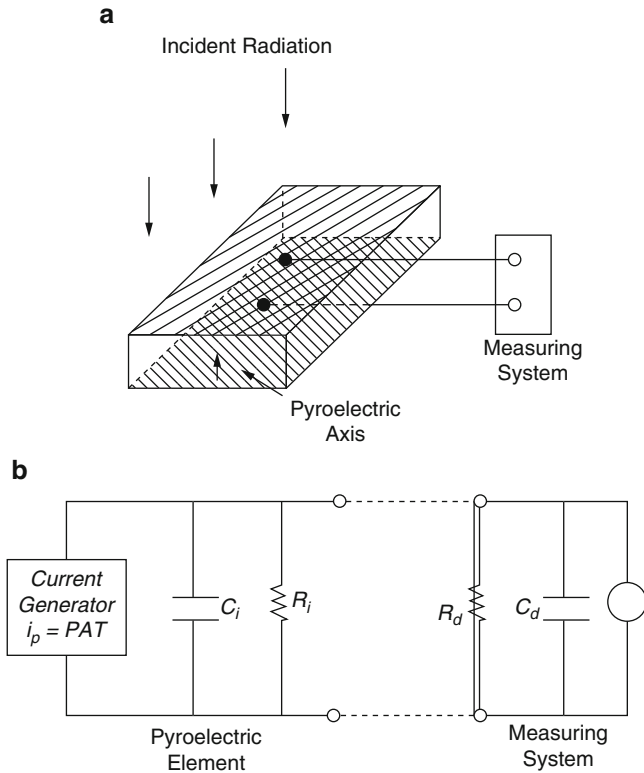


Fig. 6.6 (a) An experimental arrangement for infrared radiation detection and (b) the equivalent circuit [60]

6.4.2.1 Oxygen Sensing

The oxygen sensing is important for combustion monitoring in fossil fuel-fired power plants and is a good indicator of incomplete combustion [122]. The leftover oxygen is used to control the process by analyzing the use excess air in the combustion process. Accordingly, other firing rates and air intakes are regulated. The process is optimized based on the reduction of oxygen set-point while minimizing incomplete combustion [51]. Two types of oxygen sensors are used in this application [131].

- Electrochemical sensors based on zirconia utilized air preheater and economizer. In these sensors, the oxygen ion-conducting (for temperature 300 °C and higher) solid catalytic platinum electrodes are used which have the ability to separate and absorb oxygen into electrons and ions [100].
- Since the strong magnetic field attracts oxygen, the paramagnetic sensors can be used for oxygen measurements. It is based on the usage of two nitrogen-filled

glass in which oxygen is displaced resulting in suspension rotation that is sensed by photocells. This approach is less sensitive to other gases of the combustion process [59].

6.4.2.2 Carbon Monoxide Sensing

Carbon monoxide (CO) is another reliable indicator of the incomplete combustion process with optimum concentration levels of less than 200 ppm. This is also used to adjust the oxygen set-point [95]. The CO sensors are discussed in the following:

- **Electronic (Catalytic) Sensing.** In this process, a combustion-prone platinum catalyst is used in which on oxidization of CO and the resistance of the sensor are increased. To avoid catalyst poisoning, the ceramic substrate film thermistor is also used [57].
- **Infrared (IR) Sensing.** The sensors support both in situ measurements where IR sensor (a transmitter-receiver pair) can be installed along the flue ducts and also for extractive off-line sensing where gas samples have been removed from the ducts [33]. For the first in situ approach, the recent advancement in the area of tunable diode lasers for the transmitters has improved the accuracy of these sensors in high-temperature environments. In the second approach, one sensor is used which works by detecting the absorption frequency of CO.

6.4.2.3 Flame Sensing

The flame sensing in coal-fired power plants is crucial to the safety of the pulverized coal combustion. These sensors are installed on flame burners and work on optic principles by measuring the infrared, visible, and ultraviolet light frequency of the flames. This data about the flame stoichiometry and temperature is used to enhance the combustion process [145].

6.4.2.4 Coal and Airflow Sensing

The monitoring of the airflow in pulverizer mills and furnace is also used for combustion process optimization [16]. For this purpose, the flowmeters are used to assess the pressure reduction when passing through a narrow section of the pipe. The pitot tubes are also employed for pressure measurements.

The coal flow is also sensed by using the feeding rate of the coal (gravimetric) to the pulverizer mills that are dependent on the firing rate of the boiler and load demand on the plant. The electrostatic approach is also used for this purpose where two electrodes are utilized to sense the charge associated with the flowing coal between two points along the length of the coal flow. Accordingly, the time of travel based on the coal velocity is used to sense flow.

6.4.2.5 Sensing of Carbon Content in Ash

The carbon ash content is also a good indicator of the combustion process efficiency [34]. The content of less than 20% is generally maintained. The carbon content measurements are generally performed using microwave techniques. Due to high permittivity of the carbon, the EM waves are absorbed by the carbon depending on the dielectric constant. Accordingly, the resonant frequency changes are detected by using the resonance cavity sensors.

6.4.2.6 Gases and Temperature Sensing

The gas sensing [113] at a single location is generally not representative of the gas concentration. Hence, arrays of gas (linear and planar) sensors are employed for this purpose to get the overall picture. The tunable diode laser absorption spectroscopy is another development for sensing of the flue gas concentrations with very high accuracy. The furnace exit gas temperature sensing is also important for furnace control. The temperature sensing can be done by using some of the approaches discussed in the nuclear reactor section. The nitrogen oxide sensing is also carried out to sense nitrogen oxides in the plant.

6.4.3 Transmission System Sensors

The sensing of the grid transmission systems is vital due to many factors [86]. The smart grid sensing technologies are shown in Fig. 6.7. These sensing technologies either are fully developed or are still under development. Their applications are discussed in the following:

6.4.3.1 Substation Sensing Methods

The substation sensing methods are discussed below:

- **Substation Discharge Monitoring:** It is important to monitor potential discharge at substations to avoid catastrophic failures [140]. For this purpose, the antenna arrays are being used to sense, locate, and identify components that are causing discharge. Moreover, the 3D acoustic emission techniques are also being used for discharge sensing in transformers. The 3D acoustics is also used to sense bubbling sources and gas sources.
- **Video Imaging:** In this approach, the IR tomographic cameras are used to produce video thermal images of substation components.
- **Metal-Insulated Semiconducting (MIS) Gas in Oil Sensor:** In this approach, an inexpensive hydrogen sensor is used to measure the H_2 and C_2H_2 in

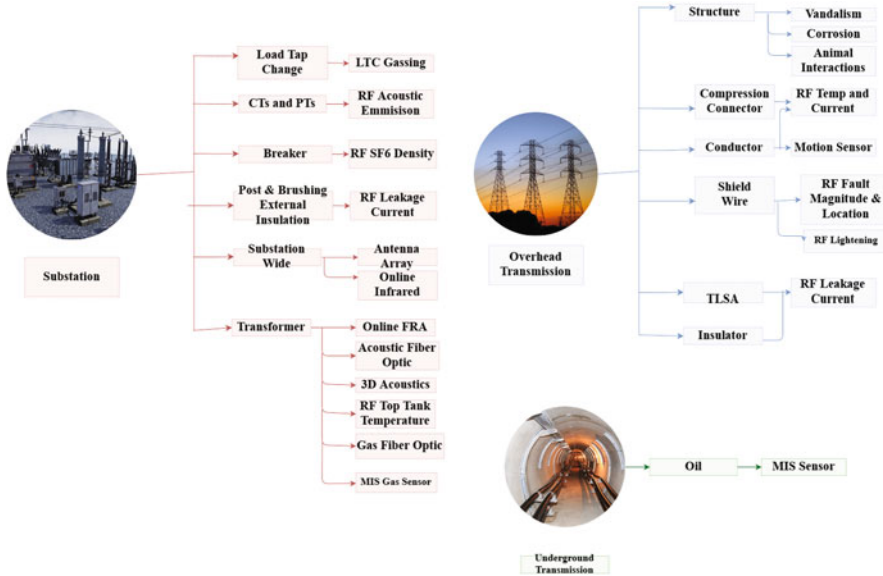


Fig. 6.7 The smart grid sensing technologies [86]

transformers' headspace and oil. The MIS gas sensor is manufactured on a chip [109]. This sensing approach is also used to sense hydrogen and potential acetylene in cable oil.

- **Fiber-Optic-Based sensing.** There are two types of fiber-optic-based sensing: acoustics and gas. In acoustics, the stress areas of the transformers are monitored for discharge using fiber-optic cable. In the second approach, the gas presence at the tip of the fiber optics is used to identify early failures and degradation in high-risk areas [32].
- **Frequency-Domain Analysis:** It works on the principle of frequency-domain analysis of the transformers. In the FDR approach, the variations in frequency response measurements are used to identify the configuration changes of the transformers. These measurements are done contentiously using natural transients [65].
- **Sensing Gas in System Load Tap Changer (LTC):** This sensing approach is capable of measuring the LTC gas ratios without the requirement of individual gas measurements [56].
- **Radio Frequency.** The RF-based sensing approaches are used to sense leakages of the current levels to inform insulation washing and flashover for various types of insulations [112]. These are also able to perform wireless/remote identification of high-risk components (e.g., acoustic-based internal discharge, current, jaw temperature of disconnect, and density of sulfur hexafluoride). The time and magnitudes of fault current flowing in the shield wires are utilized for this purpose.

6.4.3.2 Overhead Line Sensing

The overhead line sensing approaches are discussed in the following:

- In overhead transmission, the current and temperature sensing approaches are utilized to sense temperature of connectors, current magnitudes, and compression of conductor such as dead ends and splices. Accordingly, a histogram is created to assess loss and to identify high stress components. These sensors are capable of energy harvesting from the abundant magnetic field prevailing in the line environment [70].
- Similar to the substation environment, the overhead insulator leakage and associated currents are measured using RF approaches. The time and current magnitude of the current flowing are also measured in shield wire to identify the exact location of faults. The same measurements are also done for the lighting current distributions [30].
- The surge sensor is used to measure and log surges and total charge detected [39].
- The transmission structure sensing is done using sensing of the environment data and image processing for decision support systems. Accordingly, different incidents such as unknown outage and avian activities can be detected in real time [64].

6.4.4 Smart Meters

The smart meter is also a type of sensors in sustainable energy IoT. The smart meters are the fundamental components of the advanced metering infrastructure (AMI). These connect customers and service providers via different types of communications links [129]. The smart meters are also used for monitoring of duplex power flow. Accordingly, the dynamic billing, load monitoring, and remote functionality are enabled through the use of smart meters.

6.4.5 Wind and Solar Sensing

The reliable integration of solar [67, 72] and wind energy [10, 11, 15] resources in the sustainable energy IoT requires real-time sensing of these environmental parameters for the efficient energy generation process [114]. These environmental sensing is done for solar irradiance and wind speed. This type of weather-related variable sensing in sustainable energy systems has the tremendous potential to bring more multitude of energy sources to the power systems.

6.5 The Case Studies of Sustainable Energy IoT Technologies

In this section, the sustainability IoT case studies are discussed in great detail.

6.5.1 Electric Vehicle Energy Internet

The basic idea of electric vehicle (EV) energy Internet is to transmit energy from one place to another [35, 142]. The EV transmits, stores, and distributes energy from renewable energy sources (e.g., solar and wind) to the places where needed such as charging stations and houses. EVs are equipped with batteries and together can form a large network of distributed energy storage system, e.g., if all light vehicles in USA become EVs, then the entire power generated by them will be 24 times higher than the entire electric generation grid. In Fig. 6.8, a schematic of EV energy Internet is shown. It divides the EV into two layers [142]. The lower layer is the transportation network of the EV architecture. It consists of energy generation from renewable resources, energy transportation from EVs and energy substations, and consumers. The EV, after charging at renewable energy source, travels to a charging station and discharges at the charging station. Accordingly, other EVs pick up the energy from that substation and move to the next point.

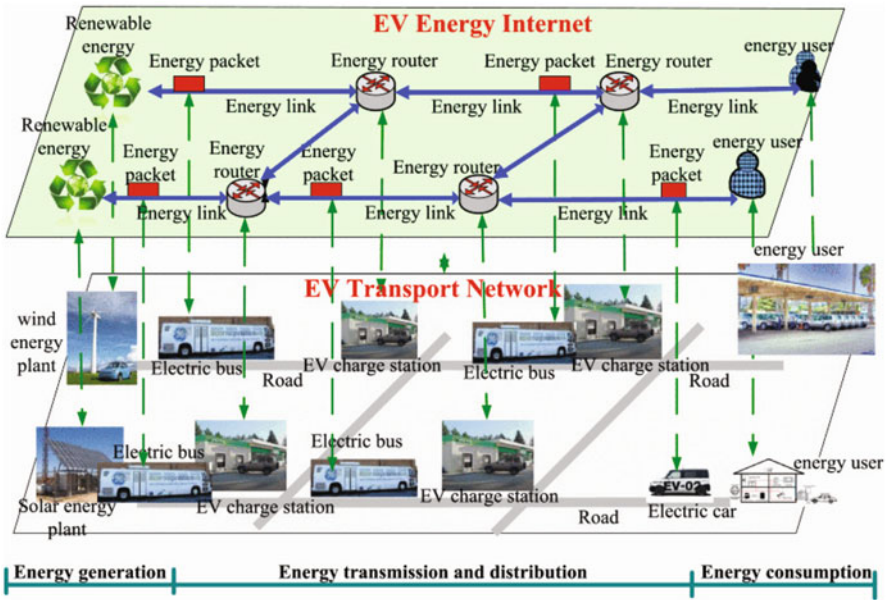


Fig. 6.8 A schematic of EV energy internet [142]

6.5.2 Combined Cooling Heating and Power System

The combined cooling heating and power system (CCHP) is a distributed generation system that can provide heating and cooling simultaneously. When compared with the traditional alternative, such as separate cooling and heating system, the fuel economy and system efficiency of CCHP are higher. It consists of power generation, heating, and cooling. The CCHP can balance the production and load requirement of electricity, heating, and cooling increasing the overall efficiency from 40 to 70–90%. Moreover, the emission reduction is an added advantage of the CCHP system [22].

6.5.3 Power-to-Gas (P2G) Energy Internet

Energy markets all over the world are now focusing on the shift from fossil fuel-based power generation to renewable energy-based generation. EU has proposed that a target of 20% renewable energy will be achieved, in their mix of energy systems by 2020. This is because of the low emission rate and environmental-friendly nature of renewable sources. However, as discussed in the previous sections, the production pattern of renewable sources such as wind and solar is very unpredictable and varied. In addition to unpredictable generation capacity, they may also cause fluctuations in the grid. Although, renewable energy has all these challenges, they are still considered as the future of the energy sources.

One solution to the above problem is to store a large amount of energy when the demand is lower the supply and using that stored energy when the demand is higher than the supply. This flexibility in the system can be achieved by power-to-gas (P2G or PtG) [47]. As shown in Fig. 6.9, the P2G is a process of converting water to hydrogen via electrolysis and then conversion to methane. The P2G is a very flexible option for long-term storage of energy produced by renewable energy

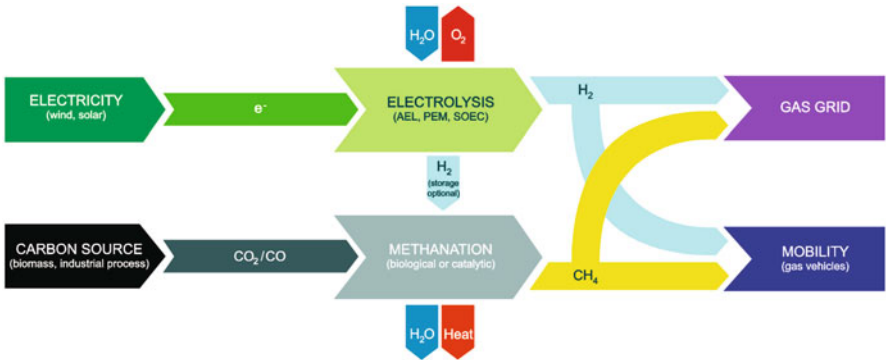


Fig. 6.9 The power-to-gas process chain [47]

source-based plant. It adds flexibility to the current energy-based system. The P2G offers three benefits in terms of flexibility: (1) time, (2) location, and (3) end-use. Apart from being a long-term energy storage technology, the P2G is also used to balance electric and gas networks [82].

6.5.3.1 Water Electrolysis

The key step of P2G technology is conversion of energy into hydrogen via water electrolysis. In water electrolysis, electric energy is converted into chemical energy [125]. The conversion process is carried out by an electrolyzer. Electrolyzers consist of (1) electrodes, (2) electrolyte, and (3) a diaphragm. Electrodes split the water into hydrogen and oxygen upon supply of electricity. Electrolyte is used to conduct ions and the diaphragm acts as an isolator to prevent evolving gas streams from flammable mixture. Electrolyzers can be classified into different types based on the type of electrolyte being used. In the following sections, various technical aspects and characteristics of electrolysis are discussed.

6.5.3.2 Alkaline Electrolysis

Alkaline electrolysis is considered as one of the mature electrolysis processes and it is present in the industry for a decade. They use aqueous alkaline solutions, e.g., KOH or NaOH, as an electrolyte. The highly perforated steel electrodes are separated by insulated diaphragm. It works atmospherically under high pressure. The atmospheric alkaline electrolysis has higher efficiency than the elevated pressurized one [63]. However, the advantage of pressurized alkaline electrolysis is that it produces compressed hydrogen with low amount of input energy. Some of the drawbacks associated with the alkaline electrolyzers are:

- Minimal load capacity of 20–40% PN.
- Long start time ranging from 10 min to an hour depending upon the purity of the gas.
- Long restart times. It takes typically 30–60 min before it can be started again.

6.5.3.3 Proton Exchange Membrane (PEM) Electrolysis

It was developed by General Electric (GE) in 1966 and was introduced to the market in 1978. It uses a polymer membrane as an electrolyte [42]. The nature noble metal is used as a catalyst due to its acidic property. Some of the advantages of PEM include faster cold start, high flexibility, and better coupling with the dynamic systems. However, usage of noble metal as a catalyst makes it a highly expensive option, and the life span of a PEM-based system is shorter than alkaline-based systems.

6.5.3.4 Methanation

Hydrogen and carbon dioxide are further processed via the Sabatier reaction to produce renewable power methane [125]. The process uses nickel- and ruthenium-based catalysts. It operates under the temperature of 250–400 °C and pressure of 1–80 bar. Due to exothermic nature of the process, highest conversion is attained at low temperatures leading to low kinetics. Almost 17% of the hydrogen energy is released as a heat limiting the maximum achievable efficiency to 83% provided that no extra heat energy is used.

6.5.3.5 Challenges

P2G is in the developmental stages. Research in P2G is going in two directions. The first direction is the improvement of modules such as electrolyzer and methanation [125]. The second is the improvement of P2G in systems. The main challenges to explore are:

- Establishment of proper framework for P2G as a system balancing technology
- Lack of precise data results in uncertainty in modeling of P2G technology which makes it impossible to get reliable results
- Lack of case studies to analyze the economic and social impact of P2G technology
- Design of smart management system for P2G

6.5.3.6 P2G Opportunities in Sustainable Energy IoT

The P2G opportunities in sustainable energy IoT are discussed below [2].

Sustainable Energy Systems Sustainable energy systems are the ones that remain operational even during the rapid changes in demand and supply. The response time of P2G technology is fast (typically takes from seconds to minutes). This adds up to the flexibility of energy systems. It also increases the flexibility of the energy systems by the significant share of the renewable energy sources.

Reducing Emissions in Energy Sectors The carbon capture and utilization (CCU) technologies are used all over the world to capture harmful gases before they are emitted to the atmosphere. The CCUs are developed to reduce the adverse environmental effects. Carbon dioxide is necessary for the production of hydrocarbons. It is a very good opportunity to use the CO₂ recovered from CCU units. Accordingly, there is a possibility of using captured CO₂ for the production of methane via P2G [12].

Congestion Management The high production from the large renewable power plants connected to an electric system can cause congestion in the power transmis-

sion lines. Therefore, to avoid the suppression of energy production, it is necessary to install P2G energy storage system in close vicinity to the power plants.

6.5.4 Sustainability and Net-Zero Energy Buildings

The sustainable development in the energy sector requires the new types of building designs with renewable integration for high-energy efficiency [38, 48, 74, 84, 85]. In this regard, the net-zero energy building (NZEB) is an emerging concept that is being conceived and implemented as a solution to minimize consumption of energy in buildings. There are different technologies of NZEB design [7]. The four different types of net-zero energy buildings are shown in Fig. 6.10. These buildings have different sources of renewable energy on premises in the vicinity to meet energy needs. The NZEBs are also connected to the electric grid as well for energy demand in case of low output of renewable sources. However, in favorable conditions for renewable energy (such as solar and wind), the NZEBs are not only able to meet their own needs but also dispatch the excess supply to the grid. Therefore, it balances the demand and supply in terms of the energy consumption.

The net-zero energy building also has the tremendous potential for environmental sustainability and economic benefits through their net-zero carbon emissions [108].

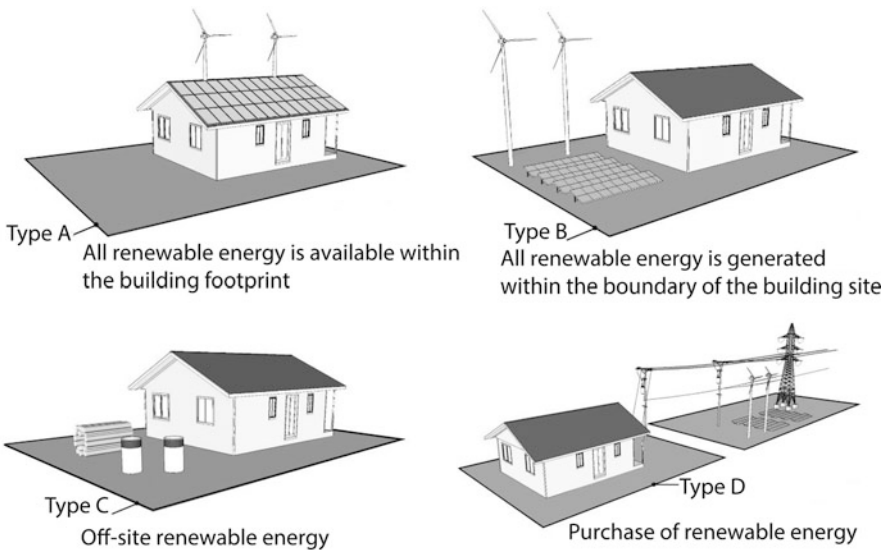


Fig. 6.10 The four different types of net-zero energy buildings [38]. Type A: All renewable energy is available within the building footprint. Type B: All renewable energy is generated within the boundary of the building site. Type C: Off-site renewable energy (e.g., wood pellets, biodiesel, or ethanol) is used to generate energy. Type D: Purchase the renewable energy that is generated off-site

However, mostly in buildings, gas and other petroleum energy resources are used in fossil fuel boilers and furnaces for heating needs. When replaced with renewable sources (such as air-, solar-, and water-based pump solutions), the carbon footprint is decreased. Moreover, through sustainable IoT's real-time monitoring, sensing, and visualization, the autonomous control can be implemented based on the dynamic needs and conditions of the environment.

6.5.5 Energy Supply Chain Management

The sustainability energy IoT has many benefits in the areas of energy supply chain management, infrastructure security, and logistics. For example, in fuel depot monitoring applications, various types of sensors provide useful information [13], such as the following:

- Sensing of temperatures, tank fluid levels, and flow rates is done for accurate and low-cost monitoring.
- The leakage can be detected in real-time using water, soil, and air sensing.
- The control, usage inventory, and ordering can be achieved through autonomous operation in online or remote fashion; accordingly, the exposure to food-related hazards is minimized.
- The motion sensor and camera things connected to the system enable enhanced infrastructure security.
- Early detection of failures can be done by sensing of corrosion and cracking in high-risk areas

6.6 Sustainability in Energy Generation

With the growth of the world population, fossil fuels are depleting rapidly. Accordingly, due to the increased usage and high stress on fossil fuel and other oil-based energy resources for transportation and power generation, there is an urgent need for mining energy from renewable sources [25, 54, 77, 78] and exploration of new resources. In this section, the sustainable energy generation from different sources is discussed.

6.6.1 Hydrogen

The hydrogen-based energy preproduction is also a good alternative to gas and electricity [111]. It can be produced by using electrolysis, reformation, and gasification. However, there is a need for carbon storage facilities for efficient sustainable

hydrogen production such as the hydrogen fuel cells. By using polymer electrolyte membrane fuel cell (PEMFC), hydrogen can also be used to produce electric power with no emissions. Electrohydrogenesis is another biohydrogen production method. It can be considered as an alternative to combustion fossil fuel engine in electric cars.

6.6.2 *Biobutanol*

The biofuel availability in the transportation sector is currently dominated by bioethanol and biodiesel [66]. However, biobutanol is being considered due to its superior properties as compared to bioethanol. It can be produced through the fermentation of butanol, acetone, and ethanol [139]. Fermentation and the latest research achievements in feedstock and process development are briefly pointed out. The new ethanol to butanol catalytic approaches are being considered as an alternative to fermentation.

6.6.3 *Bioethanol*

Bioethanol is an alternative to petrol and is obtained through biological techniques. The development of engines with the capability to solely operate on ethanol is bringing innovations in bioethanol production [20]. The steps in production technologies are [50]:

- Microbial fermentation of sugars to ethanol
- Pre-treatment of carbohydrate polymers
- Separation of ethanol by distillation
- Dehydration to fuel-level bioethanol

6.6.4 *Biodiesel*

Biodiesel is a sustainable and renewable alternative to petroleum. It is produced by transforming microalgal waste and cooking oils to biodiesel by using different methods including lipase preparations [76, 107]. Biodiesel produced by the enzymatic process has many environmental benefits compared to the ones produced by the chemical catalytic process. Other state-of-the-art production technologies include metabolic and genetic engineering and biological synthesization.

6.6.5 *Microbial Electricity*

Wastewater can be used to produce electricity by using bioelectrochemical equipment known as microbial fuel cells (MFC). The electro-active bacteria in the vicinity of electrode transfer electrons during their metabolic process, which are used to produce electricity. The success of this approach is very important for sustainable energy production [90, 115].

6.6.6 *Biomass*

Biomass [3, 27, 40, 94] (e.g., forest residues, bales and chopped straw, and pellets) has attracted a lot of research focus due to its applications in various energy areas such as power and heat and in production of biofuels and bioenergy [28, 52, 99, 106, 118, 128]. Different approaches are discussed in the following:

- The biomass gasification is a combustion-free thermochemical approach that converts biomass to fuels. Solid wastes and feedstocks can be converted into energy by using this approach. There is a need for innovative development in the area of gasification [68, 111].
- Anaerobic digestion (AD) is another emerging technology used to produce renewable energy from solid organic wastes and biomass. It also produces phosphorous, nitrogen, and micronutrient byproducts that can be used as fertilizer for soils in agriculture [88].
- Synthesis gas (syngas) can be produced from organic biomass by using the supercritical water gasification approach. This results in tar and char formations and currently has low gasification efficiency [14].
- Biomass is also used as co-fired along with coal in various forms. When pelletized, it achieved high-energy efficiency in coal combustion. Dendromass (a biomass of roots) is also another renewable energy source from short rotation woody crops [45].
- Woody biomass is also used to produce activated carbon through thermal means that can be utilized for waste treatment and gas purification [143].
- Perennial grasses are also used for energy production. They are species of giant miscanthus, switchgrass, and reed canary grass [58].
- Microalgal biomass and oil crops are other important sources [36].

Other major renewable energy sources are outlined in the following:

- Nuclear. It is a reliable source of energy generation. Currently, the second- and third-generation reactors are used. However, research is ongoing on fourth-generation reactors [31].
- Ocean. Ocean tides and waves are also good sources of renewable power generation [121].

- Hydropower. The run river, regular storage, and pumped storage are some of the examples of hydropower plants [83].
- Geothermal. Sustainable energy can also be produced from low-temperature heat reservoirs and sources [44].
- Wind. Many configurations of wind energy conversion systems (WECS) are in commercial use [10, 11, 15].
- Solar. The solar photovoltaic (PV) technology is highly scalable and is being used from milliwatt- to gigawatt-scale production [67, 72]. It is also being used in off-grid solar configurations [4].

6.7 Sustainability IoT Systems and Databases

Sustainability IoT systems and databases are presented in this section.

- Solar Roadmap. A community-level solar information database to increase adoption of solar energy.
- BioEnergy Atlas. It is an interactive mapping system for BioFuels BioPower.
- RETScreen. A Canadian clean energy software.
- Planning Framework for a Climate-Resilient Economy. A community-level framework for climate resiliency and economic vulnerability identification.
- Geothermal Prospector. A tool to map geothermal power resources.
- US Energy Information Administration (EIA) energy mapping system is a US energy infrastructure database.
- The Bioenergy Knowledge Discovery Framework (KDF) contains database for bioenergy analysis, research, and decision-making.
- HydroSource. It is an integrated data set for water, energy, and ecosystem sustainability. It has geospatial data sets for hydroelectricity production and water management.
- US Electric System Operating Data. A tool for visualization and analysis of hourly US and regional electricity demand.

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Chapter 7

Internet of Things for Sustainable Human Health



7.1 Introduction

The Sustainable Development Goals (SDGs) are a set of goals established by the United Nations (UN) following the Millennium Development Goals (MDGs), in 2015 by 193 UN member nations to address health, climate, and environmental issues being faced by the humanity [69]. These SDGs have laid a special focus on sustainable approach for future health and present a vital scope to foster the appropriate environment for an improved human health by the way of sustainable society. Thereof, four vital issues are identified [63]:

- Necessity of systems approach for sustainable health
- Importance of health society for community's prosperity
- Assessment of climate change impacts and additional perils to sustainable health and to provide expeditious health benefits
- Development of indicators, models, and metrics to observe and project different health impacts in terms of threats and risks

To achieve SDG objectives, a new systems paradigm is required across the various prongs of sustainable development (e.g., world, mankind, and well-being). For this purpose, integration of sensing, communications, monitoring, and decision support systems is required for sustainable health IoT paradigm, under the guidelines of the United Nations and World Health Organization.

7.1.1 Sustainable Health IoT

The sustainable health IoT enables development of a systems approach in the area of human health and ecosystem. It allows integration of broader health sub-areas in a bigger archetype for improving sustainability in health in the realm of social,

economic, and environmental sectors. This integration provides a powerful health IoT framework to sustainable health and community goals in the wake of changing climate [31, 41, 87, 89]. The other climate mitigation approaches using the IoT paradigms also carry many health benefits such as health community is achieved via sensing and corresponding improvements in air quality, green urban environment, and reduction in flooding [14, 123, 146, 150]. The IoT paradigm also enables many health benefits of adaption and mitigation while providing insights about climate-related health impacts [47, 86]. The climate change impact on human health is shown in Fig. 7.1 [153]. Because of this factor, either the current health problems become worse or new unparalleled health issues are generated.

The sustainable health IoT has the strong potential to bring tremendous improvements in human health and well-being through sensing and monitoring of health impacts across the whole spectrum of climate change. It is envisioned to provide health and environmental data that can be utilized to characterize the impacts of climate change on human health [47], which in turn enables identification, projection, and effective response to human health-related threats. The impact of climate change on human health is discussed in the following section.

7.1.2 Climate Change and Human Health

A significant threat is being faced by the humanity in health-related issues because of the climate change [15, 25]. The impact of weather and climate on human health is very significant and diverse. This exposure to climate-induced health issues is impacting the community and people in different ways. There are many ways (e.g., environmental emissions, ozone exposure, water and air quality, temperature, and weather) in which human health is being impacted by the climate change [46, 50, 101, 109, 126, 160]. Particularly, the increasing concentrations of the carbon dioxide and rising temperatures and their relation with variations in plants, flower production, and allergenic initiating time have led to increased production of the allergens [73]. The rise in emissions is also cause of rising temperatures and sea levels, variations in precipitation patterns, and increase in extreme weather pattern. Accordingly, water bodies are contaminated, diseases are transmitted through food sources, and air quality is degraded, which, consequently, bring cascading adverse effects upon human health and well-being. These problems are being exacerbated with rapid changes, hence increasing exposure of the human for longer duration of time [143]. Therefore, new challenges are being faced in the area of human health [45, 100]. The climate and holistic health outcomes are shown in Fig. 7.2.

It is important to note that the magnitude of impact of climate on human health varies on spatial and temporal scale [72, 90, 119]. The children, elderly, poor, and sick are the ones most affected [10, 16, 79, 135, 140, 141]. The research has shown the high correlation between the mold- and fungus-related indoor air quality

	Climate Driver	Exposure	Health Outcome	Impact
 Extreme Heat	More frequent, severe, prolonged heat events	Elevated temperatures	Heat-related death and illness	Rising temperatures will lead to an increase in heat-related deaths and illnesses.
 Outdoor Air Quality	Increasing temperatures and changing precipitation patterns	Worsened air quality (ozone, particulate matter, and higher pollen counts)	Premature death, acute and chronic cardiovascular and respiratory illnesses	Rising temperatures and wildfires and decreasing precipitation will lead to increases in ozone and particulate matter, elevating the risks of cardiovascular and respiratory illnesses and death.
 Flooding	Rising sea level and more frequent or intense extreme precipitation, hurricanes, and storm surge events	Contaminated water, debris, and disruptions to essential infrastructure	Drowning, injuries, mental health consequences, gastrointestinal and other illness	Increased coastal and inland flooding exposes populations to a range of negative health impacts before, during, and after events.
 Vector-Borne Infection (Lyme Disease)	Changes in temperature extremes and seasonal weather patterns	Earlier and geographically expanded tick activity	Lyme disease	Ticks will show earlier seasonal activity and a generally northward range expansion, increasing risk of human exposure to Lyme disease-causing bacteria.
 Water-Related Infection (<i>Vibrio vulnificus</i>)	Rising sea surface temperature, changes in precipitation and runoff affecting coastal salinity	Recreational water or shellfish contaminated with <i>Vibrio vulnificus</i>	<i>Vibrio Vulnificus</i> induced diarrhea & intestinal illness, wound and blood-stream infections, death	Increases in water temperatures will alter timing and location of <i>Vibrio vulnificus</i> growth, increasing exposure and risk of water-borne illness.
 Food-Related Infection (<i>Salmonella</i>)	Increases in temperature, humidity, and season length	Increased growth of pathogens, seasonal shifts in incidence of <i>Salmonella</i> exposure	<i>Salmonella</i> infection, gastrointestinal outbreaks	Rising temperatures increase <i>Salmonella</i> prevalence in food; longer seasons and warming winters increase risk of exposure and infection.
 Mental Health and Well-Being	Climate change impacts, especially extreme weather	Level of exposure to traumatic events, like disasters	Distress, grief, behavioral health disorders, social impacts, resilience	Changes in exposure to climate- or weather-related disasters cause or exacerbate stress and mental health consequences, with greater risk for certain populations.

Fig. 7.1 The climate change impact on human health [153]

issues and the high and extreme temperatures, and heat waves and precipitation [48, 53, 64, 64, 76]. The moist indoor environment causes elevated prevalence of asthma and upper respiratory tract symptoms [2, 2, 40, 53, 70, 102, 128, 142, 148]. The extreme heat contributes to air pollution, asthma, pediatric, deaths (e.g., hot cars), and increased frequency of emergency room (ER) visits, and hospitalization [7, 39, 91, 130, 159]. Similarly, the heavy precipitation also leads to severe flooding events, algal blooms, and waterborne diseases. The outdoor air quality is also

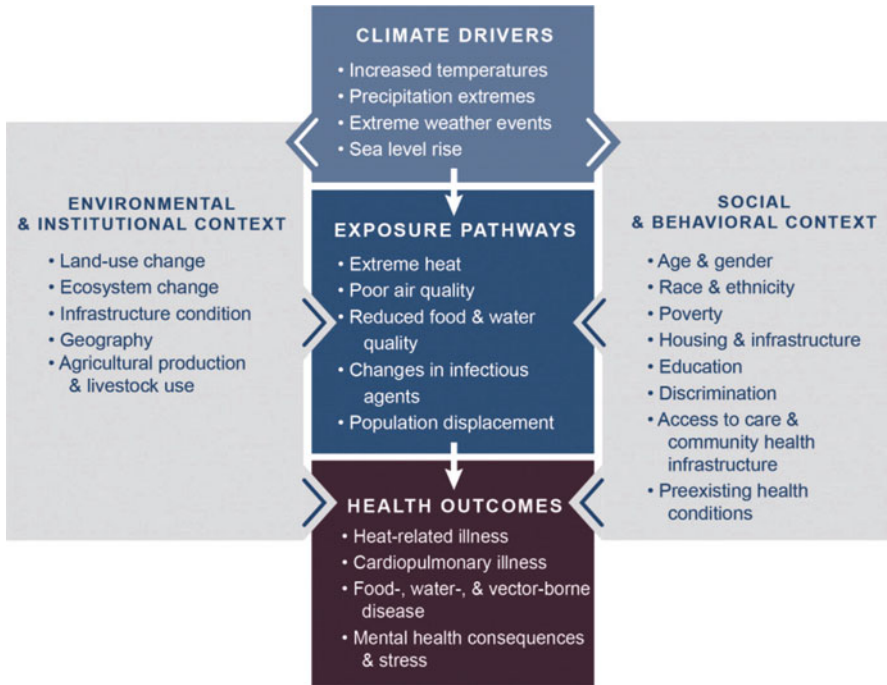


Fig. 7.2 The climate and holistic health outcome [153]

affected by the wildfires which leads to respiratory issues because of smoke inhaling. The human health is also being impacted by the worsening air quality and pollution of the ozone [118]. The climate change has also led to expansion of scope of some disease vectors and other epidemiological factors, such as Ixodes ticks (Lyme disease vectors). The climate change also impacts the mental health and causes stress particularly after disasters and displacement. The summary of these climate change impacts is outlined below:

- The increased exposure to ozone [8, 15, 19, 50, 95, 125, 126, 151]
- Extreme weather events [1, 7, 52, 105, 116, 124]
- Rising allergens [108]
- Increase in frequency and intensity of wildfires [81]
- Thermal extremes [13]
- Growing harmful algal blooms (HABs) [9, 62, 114]
- Mental health stress [37, 57, 65, 66, 98, 106, 111, 145]
- Expansion of vector-borne infectious diseases [21, 83, 85, 93, 110, 117, 129, 136]
- More water- and food-borne diseases [32, 67, 88, 115]
- Food quality and security [56, 132]

7.2 Benefits of Sustainable Health IoT

The sustainable health IoT has tremendous potential to bring improvements in human health and well-being by enabling real-time sensing and monitoring of the climate-induced impacts. These benefits are discussed below:

- Innovations in mobile healthcare
- Evolution of new sensing methods
- Novel communication techniques such as human body communications and molecular communications
- Remote diagnostic systems
- Human mobility models to predict disease outbreak
- Support for remote telehealth and self-monitoring and tracking on diurnal basis
- Efficiency and improvements in healthcare settings
- Quick diagnosis of medical conditions
- Improvements in patient condition management
- Development of novel treatment regimens

7.3 Sustainable Health IoT

The sustainable health IoT is characterized by its things which are the vital component of the paradigm for real-time sensing monitoring, medication compliance, wireless communications, and imaging-based decision support systems. In this section, the sustainable health IoT things are discussed:

- Patients, physician, and healthcare providers
- Smart ingestible, implantable, and injectable medical devices
- Medicines, health, and wellness products
- Physiological, wearable, and molecular sensors
- Actuators, treatment, and electronic health records
- Telehealth and precision medicine
- Insulin pumps, cochlear implants, and pacemakers
- Patient-generated and machine-generated healthcare data

7.4 Sustainable Health IoT Technology

In this section different technologies for sustainable health IoT are discussed.

7.4.1 Precision Medicine

The precision medicine is one of the emerging technologies in human healthcare [30, 96]. It deals with disease prevention and treatment approaches which are based on considering the human genetic, environmental, and other factors tailored to individual patients. The precision medicine practices are also called personalized medicine. The sustainable health IoT enables precision medicine by integrating DNA databases of clinical trials and application layer Health Level 7 (HL7) and other standards such as Fast Healthcare Interoperability Resource (FHIR) [120] to support treatments of different diseases.

7.4.2 Personalization of Diabetes Treatment

The sustainable health IoT also enables monitoring of the blood glucose levels in patients with diabetes [26]. By using sensing and wireless communication technologies, the advanced diabetes treatments can be utilized for extensive dissemination of blood sugar data to intelligent computing technologies and clinicians. There it can be evaluated for personalized treatment by generating prediction-based cautions for insulin dosage and hypoglycemia updates.

7.4.3 Automated Nutrition Control

The sustainable health IoT enables automated nutrition control where based on daily calories needs, the customized food plan can be developed for patients by using the food ingredients. This enables suitable food choices based on the recommendations of the physicians. Accordingly, physicians can view the impact the food consumption on patient health for real-time decision making [61].

7.4.4 Mobile Healthcare Connectivity

The sustainable health IoT supports integration of wireless communications-based interconnection of medical devices with the cloud for rapid online data management [144]. The Capsule Technologies Hub is a robust mobile gateway to provide connectivity using many different wireless interfaces [36, 167]. The mobile healthcare connectivity in sustainable health IoT enables development of healthcare applications based on the wireless technologies that enables patient management and coordination and leads to higher efficiency and decreased cost of medical care.

7.4.5 Cancer Treatment

Cancer treatment approaches can greatly benefit from sustainable health IoT monitoring and communication technologies, where patients can transmit updates through symptom tracking applications to their physicians [127]. The physician's response is helpful to reduce the frequency of regular clinic visits. Moreover, the side effects of the medicines can be identified and addressed quickly. Early warning can be issued when the levels cross a threshold.

7.4.6 Glucose Monitoring

The sustainable health IoT facilitates continuous glucose monitoring (CGM) in diabetic patients. IoT-enabled devices can continuously monitor the blood glucose levels by providing regular readings for subsequent transmission to cloud using wireless communications and Internet with easy access through mobile devices by patients and physicians [51]. Accordingly, the automated delivery of insulin enables efficient management.

7.4.7 Smart Inhalers

The smart and connected inhalers (Bluetooth spirometer [168]) in sustainable health IoT enable asthma and other chronic obstructive pulmonary disease (COPD) [133], which includes emphysema and chronic bronchitis) patients to take control of their symptoms and treatments by using Bluetooth. These can also send reminders to patient about their medicine intake, hence improving the disease management, attack avoidance, and symptom reporting to physicians.

Other important applications include connected contact lenses to monitor variations in eye dimensions causing the glaucoma [6]; the coagulation testing for blood clot formations to avoid stroke and bleeding [165]; and assisted living [122]. Overall, the sustainable health IoT enables, through its sensing, communications, and monitoring technology, efficient healthcare, drug and chronic disease management, and reduction in emergency room wait times.

7.5 Sensing in Sustainable Health IoT

In this section, two types of health-related sustainable health IoT sensing approaches are discussed: (1) the physiological sensing and (2) the environmental sensing for health [138].

7.5.1 *Physiological Sensing*

The physiological sensing is a vital monitoring approach in the sustainable health IoT to measure and analyze different physiological (biological) signals for medical and clinical healthcare applications [29, 164]. These data collected from these physiological sensor signals are discussed in the following:

- Heart rate (HR)
- Finger temperature (FT)
- Respiration rate (RR)
- Carbon dioxide (CO₂)
- Oxygen saturation (SpO₂)
- Patient position sensor (accelerometer)

The sensors to detect these physiological signals are given below [11]:

- Glucometer sensor
- Body temperature sensor
- Blood pressure sensor (sphygmomanometer)
- Pulse and oxygen in blood sensor (SPO₂)
- Airflow sensor (breathing)
- Galvanic skin response sensor (GSR—sweating)
- Electrocardiogram (ECG) sensor
- Electromyography (EMG) sensor

A detailed review of these physiological sensors is given in [11].

7.5.2 *Ingestible Sensors*

These sensors are ingested in capsules or pills and have the capability to dissolve in the stomach [84]. There, these are used to sense different physical parameters, which can be communicated to the external nodes through human body communications or by using wireless communications. The legal issues in ingestible sensors are discussed in [60].

7.5.3 *Wearable Sensors*

Wearable sensors are placed into wearable objects to sense different phenomena such as health conditions, environmental conditions, and physiological signals [11, 27, 54, 161, 166]. These can also be implanted in the body from where they can communicate using human body or molecular communications. Some important use cases of the wearable sensors are listed below:

- Wearable devices for environmental monitoring [94] such as air quality [20, 22, 28, 43, 80, 99, 137, 157, 158]
- Wearable AI system to detect a conversation's tone [155]
- Wearable devices for physiological sensing [75]
- Wearable system to help visually impaired users navigate [156]
- Monitoring metabolic energy expenditure, health, and fitness with a breath analyzer [112]
- Wearable sensor for athletes detects potential head injuries, gathers data on hard hits [18]
- Wristbands that keep wearers thermally comfortable [112]
- Wearable tracks increased skin conductance that signals stress, helps identify dangerous seizures [104, 149]
- Wristwatch to monitor depression and Parkinson's disease symptoms [113]

7.6 Environmental Sensing for Health and Wellness

In this section, the sensing of different environmental parameters and their impact on human health is discussed.

7.6.1 *Sanitation, Waterborne Diseases, and Human Health*

The viruses, bacteria, and protozoa are major causes of waterborne diseases also called water-related illnesses. The human-induced chemicals, toxins generated by cyanobacteria, and detrimental algae are other sources of some of these diseases [23, 131]. The patients are also exposed to these diseases when the contaminated water is inhaled or ingested. Other recreational activities in contaminated water and eating contaminated seafood are also causes of waterborne diseases. The water-related illness grows, spreads, and becomes viral and toxic based on different climate-related factors such as hurricanes, precipitation, runoff, and storm surges [32, 88]. Moreover, the exposure to these diseases also depends on individual's capacity of adaptiveness and sensitiveness.

The waterborne diseases are also major challenge in urban areas where the 6–40% of gastrointestinal illness are caused by extensive contamination of wells and surface water by various pathogens. The access to safe drinking water is also a major global issue with one billion population lacking access to safe potable water. Moreover, the increasing global temperatures are fostering production of toxic algal blooms. These organisms are serious risk to human health (see Fig. 7.3) [153].

The sustainable health IoT through its sensing of water quality, real-time monitoring and warning systems, and other treatment technologies enables effective prevention and mitigation of diseases caused by water contamination. It enables water flow and quality monitoring. The water quality sensing also informs the



Fig. 7.3 Water-related health issues [153]

selection of proper disinfection technique based on pathogen sensing and molecular sensing methods for specific pathogens and their ability to cause infection.

The sustainable health IoT holds great promise in water quality improvements and sanitation in less developed and advanced countries. Some examples are presented in the following:

- The smart meter and reverse osmosis (RO) technology in IoT systems and sensor networks is being used in India for provision of clean water and for water treatment to rural areas [134].
- The IoT technology is being used in China to monitor the water flow and usage by using sensors installed at different points in the water supply system [147].
- A biosensor network is utilized in Bangladesh for water quality monitoring using arsenic sensor [42].
- In Kenya, a smart connected water hand pump is being used to address the issues related to the nonfunctional water pumps for timely maintenance [92]. Special accelerometer-based devices were designed and installed with built-in 3G radios for water hand pump monitoring. With battery life of up to 18 months, this IoT

system has reduced downtime while ensuring consistent water supply service delivery.

- For sanitation and hygiene, the water flow and motion sensors are being used in Indonesia to identify human behavior (e.g., handwashing after toilet use) and to design enhanced hygiene training [152].

7.6.2 Ultraviolet Radiation and Human Health

The exposure to ultraviolet (UV) radiation can have multiple impacts such as corneal damage, skin cancer, sunburn, immune suppression, and cataracts [12]. The detrimental effects of ultraviolet radiation include damage to plastic, wood, and other infrastructure. Overall, UV radiation presents many challenges to health and environment.

The sustainable health IoT has the potential for robust monitoring of ozone and UV radiation levels at a large scale, which can be integrated to the cloud for new insights. Accordingly, models can be developed for informed decision making. A sensor called dosimeter determines the UV exposure by measuring absorbed amount of ionizing radiation. The ionizing radiation at its peak is capable of removing an electron from an item. A urocanic acid photoreceptor is used for the induction of UV immune suppression. The UV-induced (UVB induced) immune suppression is variation in cell immunity which produces suppressor cells. Various types of ultraviolet radiations and related concepts are discussed below [71]:

- UVA. The UVA has the longest wavelengths of 0.31–0.4 micrometer and impacts skin aging. The ability of atmospheric gases to absorb UVA radiation is low. Therefore, UAVs are able to reach surface of the Earth.
- UVB. It causes skin burning and suppression of immune system with its shorter wavelength of 0.28 micrometer to 0.31 micrometer. However, most of it is absorbed by stratospheric ozone.
- UVC. The UVC is mostly absorbed by the ozone and oxygen present in the atmosphere. It has shorter wavelength of 0.1 micrometer to 0.2 micrometer. UVC radiation is almost entirely absorbed by atmospheric oxygen and ozone.

7.6.3 Extreme Weather and Human Health

The thunderstorms' associated increased humidity levels are known to cause cardiovascular and respiratory diseases [34]. The natural disasters also contribute to the mental health issues (e.g., post-traumatic tension disorders). Moreover, the prolonged duration of the hurricanes, tropical storms, and extreme weather events also causes short-term stress-related issues with its disruptions to subsistence activities and to different modes of transportation, affecting overall health and well-being.

7.7 Wireless, Human Body, and Molecular Communications in Sustainable Health IoT

The applications of wireless communication technologies to human health are being used for sensing, data collection, modeling, and analysis of health information of patients using the Internet and various computing technologies [55, 59, 121, 162, 163]. Wireless communications play an important role to provide connectivity to sensors and system in sustainable health IoT in different topologies and configurations. The Bluetooth (IEEE 802.15.1) and Bluetooth Low Energy (BLE) are commonly used for this purpose due to its low cost and energy requirements along with other standards such 4G, WLAN, LTE, UMTS, Wi-Fi, and WiMAX. A list of different wireless technologies for sustainable health IoT applications is given below:

- IEEE 802.11x (Wi-Fi) is the widely used wireless local area network protocol for health applications. It operates in 2.4-GHz or 5-GHz frequency bands. The latest versions of the Wi-Fi can support data rates from 54 Mb/s to 0.5 Gb/s with communication range of more than 100 m [74].
- IEEE 802.15.1 (Bluetooth) operates in 2.4-GHz frequency band with communication range of up to 10 m. and supports data rates of 722 Kb/s for the classic version (BC) and 3 Mb/s for Bluetooth Enhanced Data Rate (EDR) [17].
- Bluetooth Low Energy (BLE) is a low-power variant of Bluetooth. It can cover communication distances of up to 68 m with maximum data rates of 1 Mb/s. It uses physical and data access layer of Wi-Fi.
- ZigBee (IEEE 802.15.4) is a less complex, low-cost and data rate, wireless personal area network (WPAN) standard for prolonged operation of devices and equipment. It supports 868-MHz frequency, 915-MHz spectrum band, and 2.4-GHz radio wireless channel with maximum data rates of more 250 kb/s, respectively, for communication range of up to 75 m [169].
- Long-range wide area network (LoRaWAN) has the potential for long-range communications in sustainable health IoT applications (e.g., the LoRa). It also supports 868-MHz frequency and 915-MHz spectrum operation with data rates of more than 50 kb/s [38].
- Chirp spread spectrum (CSS)-based nanoLOC operates in 2.4-GHz frequency band. It covers communication distances of up to 570 m depending on the environment with data rates of up 2 Mb/s [139].

More details about wireless body area network can be found in [68].

7.7.1 Human Body Communications

The human body communication (HBC) is another important connectivity mechanism in the sustainable health IoT. The body is a highly conducting material

(body tissues are lossy dielectric) because of the presence of the water and blood. Human body communications also are very energy efficient and require very low power for operation for implanted medical devices with long battery life, hence reducing the inter-surgery time significantly. Moreover, the human body communications are very secure and present resistance by preventing physical access of devices by hackers. These can be utilized to form the interbody and body-to-body communication networks, wearable sensors and devices, implanted medical devices, and in-body authentication instruments in the sustainable health IoT [55, 58, 78, 107, 164].

The wearable sensors can establish connection using HBC for critical data communications to external devices. The body area network (BAN) in the IEEE 802.15 working group has developed a physical layer (PHY) for human body communications. In HBC, there are three main components: (1) the human body channel, (2) radio system, and (3) modulation and transmission schemes.

Another alternative to wireless body area network (WBAN) is electro-quasistatic human body communication (EQS-HBC) [35], which operates by broadband low-frequency human body communications to achieve secure data transmission. A comparison of WBAN and electro-quasistatic is presented in Fig. 7.4.

7.7.2 Molecular Communications in Sustainable Health IoT

The molecular communications (MC) form the basis of the information transmission within the basic unit of human life such as biological cells and complex organisms

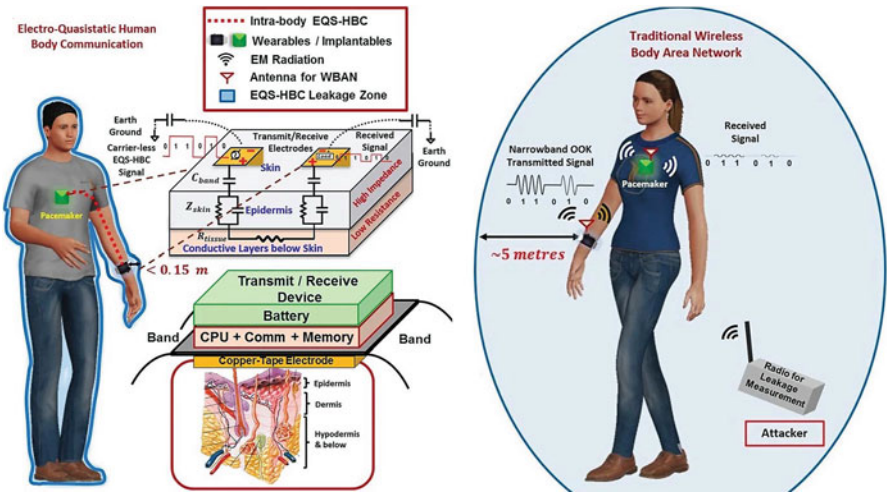


Fig. 7.4 A comparison of WBAN and electro-quasistatic human body communications [35]. EQS-HBC vs. WBAN: An overview of the Data Privacy Space, (a) persons wearing transmitter device (pacemaker) and an on-body hub communicating using EQS-HBC and (b) WBAN

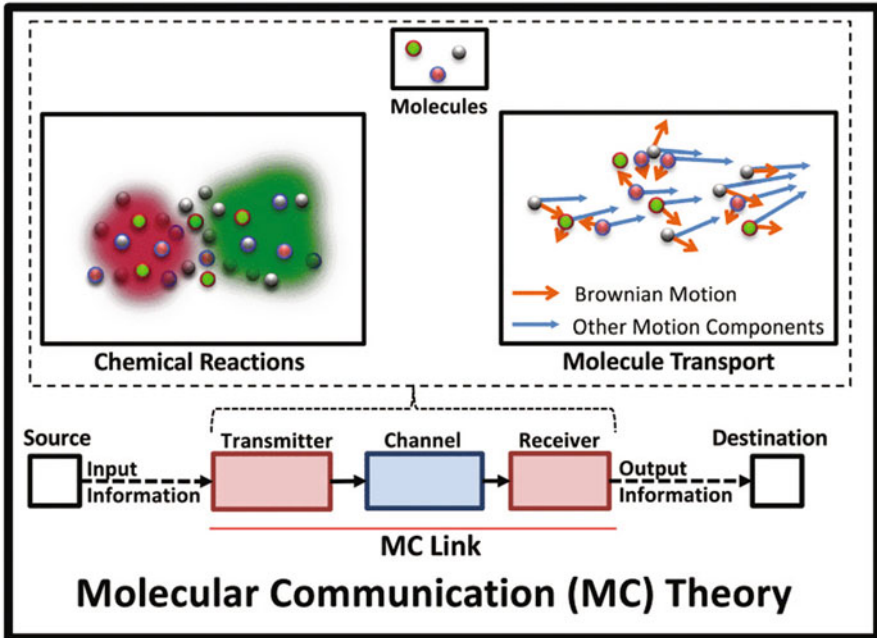


Fig. 7.5 The fundamental building blocks of molecular communications [4]. From moving forward with molecular communication: from theory to human health applications

[4, 97]. In molecular paradigm, the data bits are modulated on molecules, and communication propagation happens through the transport of these molecule and chemical reactions. The fundamental building blocks of the molecular communications are shown in Fig. 7.5 and are discussed below [4]:

- Molecules are the smallest distinguishable unit of a chemical compound and represent atoms bind together in the chemical composition of a particular substance [3].
- The chemical reactions are the manipulations and transformations resulting from the detachment and formation of molecules.
- The molecule transport is the process of their propagation in space and happens through flow, transport, and Brownian forces such as movement in the blood runnel or intra-cell motion [3].

The components of MC system include a transmitter, molecular channel, and receiver. The communication channel propagation depends upon various molecular transport models such as chemotaxis, gap junction, diffusion, and molecular motor. The current research focus in MC is to maximize data communication rates, and development of coding and information modulation approaches, and the design of suitable modulation and coding techniques, and novel networking topologies

for optimization of molecular data communication by molecules using multiple segments simultaneously [103].

The MC enables the sensing and monitoring applications through its propagation living organisms and the biochemistry underscoring the human body and cells (e.g., the cancers caused by the malformation polarity, and growth of molecules). The MC systems are envisioned to advance human health informatics and enhanced medicine with applications in natural and synthetic systems.

The monocular communications information flow theory in natural systems can model:

- At body scale, where a system is considered as an interconnection of tissues and organs.
- The cell coordination at cellular scale.
- The information modulation into compounds for subsequent propagation through chemical reactions and molecular transport.

For synthetic applications, the MC applications for system engineering purpose are:

- At interface level: Use of synthetic biology tools to develop genetic programs
- At device level: Development of bioengineering systems, programmed to perform specific actions.
- At network level: An interconnection of bioengineering systems human health monitoring and connectivity to cloud

These applications of natural and synthetic systems of molecular communications in sustainable health IoT are shown in Fig. 7.6.

7.8 Sustainable Health IoT Systems

In this section, various systems, tools, databases, and indices to achieve sustainability using Internet of Things are discussed.

7.8.1 Health Indices

The vital health indices related to the environment are discussed:

- UV Index. This index is used to predict the solar UV radiation. The UV index is a number, measured on a scale of 0–11, which reflects the diurnal threat of sunburn (overexposure to sunlight). The value of 0 represents the minimal exposure, and an index value higher than 10 indicates extreme risk to human health [154].
- Environmental Health Hazard Index. The US environmental health hazard exposure index provides information about harmful toxin exposure neighborhood

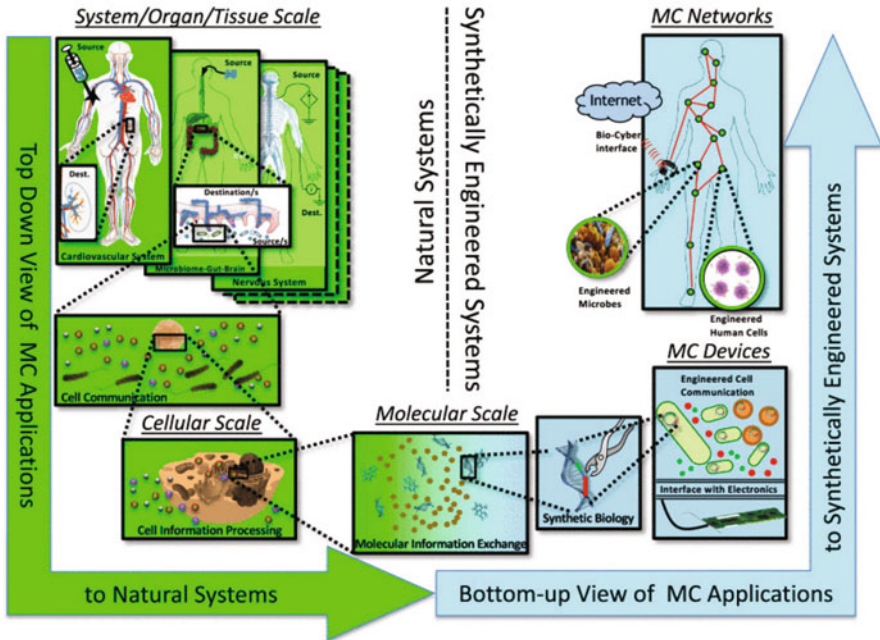


Fig. 7.6 Applications of natural and synthetic systems of molecular communications in sustainable health IoT [4]. From moving forward with molecular communication: from theory to human health applications

levels [49]. These health hazard exposures are determined using linear combinations of estimates of air quality respiratory, carcinogenic, and neurological hazard with indexing census tracts.

- AirNow: The air quality index (AQI) is an index to monitor the air quality and pollution. Accordingly, it informs about the related impact concerning human health [5]. It is ascertained by considering four air pollutants: particle pollution, carbon monoxide, surface ozone level, and sulfur dioxide gas.

7.8.2 Environmental Public Health Tracking Network

This US tracking network contains data and information on health effects, environmental hazards and substances, and human health [24]. This is an important data source for measuring hazardous substances in environment. The main features of the environmental public health tracking network are outlined in the following:

- It provides insights about spread of these substances over spatial and temporal scale and their impact on human tissues (e.g., carbon monoxide and air pollution in the environment).

- It also hosts data about health conditions and diseases, such as asthma and birth defects.
- It also contains exposure data. It contains vital information about the exposure relationship with the health effects, which relates specific health problems to age, race, sex, and behavior and lifestyle choices.

7.8.3 Mobile Healthcare Innovations

The mobile technology is an emerging innovation in healthcare solutions. Mobile applications are being developed to address mental health, cancer, active sports therapy, and rehabilitation with capability to support large-format displays, Bluetooth pen, AI, and cameras. This mobile technology when integrated with sustainable health IoT holds massive potential to make a profound impact by providing valuable healthcare services, such as telehealth [77], virtual care, and remote patient monitoring.

7.8.4 Mobility Models and Health

The human mobility models are used to analyze the population movement which can be used to mitigate disease outbreaks (e.g., development of malaria eradication strategies) [44]. During the 2014 Ebola outbreak in Sierra Leone, Guinea, Nigeria, Liberia, and Senegal, the call detail records (CDRs) from mobile cellular wireless network were used to monitor population movements through development of epidemiological models. These mobility models were used to forecast the spread of Ebola and potential outbreak of disease through analysis of movement paths of the affected population. The privacy concerns and security-related issues are some of the major challenges in implementation of this approach in sustainable health IoT [82].

7.8.5 Virtual Beach

This virtual beach is a decision support system to predict disease-causing pathogens at beached. The policy makers can utilize the statistical model for health-related beach decisions. It is also to issue alerts about the concentrations of fecal indicator bacteria (FIB) concentrations observed at beaches [33].

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Chapter 8

Internet of Things for Sustainable Mining



8.1 Introduction

The mining is the process of acquiring minerals from mines. In addition to the resource development, it has many economic, social, and environmental aspects. Recently, considerable progress has been made towards attaining sustainable mining practices and improving environmental quality [10, 13, 39, 41, 48]. Moreover, significant technical developments have also improved the mining practices. However, there are substantial efforts required to make mining sustainable [2, 32, 60].

8.1.1 Sustainable Mining

Apparently, it seems that there is no compatibility between the mining operations and sustainability, and both seem contradictory due to the limited nature of mining resources. Since the sustainability is related to capability of maintaining a certain level of resources for current and future needs, the sustainable development in mining is difficult to achieve if the rate of the mineral's extrication process continues to increase the replenishment rate of the geological processes [59]. The advances in mining practices (e.g., sensing, monitoring, and communication technology development) are needed in the areas of explorations, mining, and metal processing to improve productivity, safety, and health [29]. In 2002, the International Council on Mining and Metals (ICMM) Council espoused the Toronto Declaration for the Global Sustainable Development Initiative (MMSD) that underscores the value of technology tools and systems for the sustainable development (SD) initiative [51]. It also highlighted the importance of the best practices and verification protocols, best-practice protocols, and reporting for SD. The importance of the integrated mines and material management throughout the minerals value chain was also emphasized.

The mining practices conducted keeping in view the environmental and socio-economic factors and the Sustainable Development Goals (SGDs) are considered sustainable [10]. The exploration and development of novel technologies also makes mining sustainable. The three vital factors of the sustainable mining are:

- Analysis of current and future demands in mining
- Development of integrated approaches for decision making and adoption of practices based on SGDs and community involvement
- Advancements in metal recycling and reclamation methods

8.1.2 IoT for Sustainable Mining

Mine monitoring techniques seek to establish a proper environment to avoid accidents, destruction of equipment, loss of ore reserves, and closure of the mine with greatest effectiveness. Accidents happen because of roof fall and side fall that often take toll of human lives [56]. Proper mine monitoring minimizes these losses, maximizes response to other management practices, and optimizes mining. Mining management without real-time monitoring can also significantly reduce the potential for profitability. Proper mine monitoring using IoT will help to reduce the potential for runoff, run-on, deep percolation, and nitrogen and other chemical leaching to the ground and surface water resources and reduce soil erosion and mine contaminant movement into surface and groundwater [14].

Among existing techniques, Internet of Things in Mine Monitoring (IMM) is a growing technology in mining operations [9, 11, 19, 20, 53, 57, 62]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of mine minerals. Current mine sensing technologies are not best suited to provide IMM systems with almost real-time minerals data to facilitate fast decision making. Thus, accurate monitoring cannot be applied at the right place of a mine at the right time. Failure to consider the monitoring in active working face, goaf, and sealed-off areas in mining decisions results in mining accidents. Accordingly, human lives are wasted and the potential for chemical leaching from the mine is increased.

Timely information of temporal and spatial mining patterns can significantly aid mining producers in better managing their mine operations to achieve higher production efficiency. Real-time knowledge of spatial contaminant distribution can also further advance our understanding of variable soil water and mineral distribution as well as mine dynamics. Accordingly, more effective IMM strategies can be developed to enhance productivity and reduce leaching. This improvement, conservatively, can result in significant dollar savings. Challenges in communication between within-field sensors and decision-making systems, however, prohibit these research results to be successfully transformed into widespread mining practices. In general, sensors can be buried at different depths and wired to a data logger above

the surface, which can be used for manual data collection or wireless data transfer. Manual data collection is labor-intensive and requires significant amount of travel time. More importantly, by the time when the data are incorporated into decision making, it is late to achieve proper mining actions. Thus, mining companies, especially those with large-scale mining operations, are looking for more effective, within-field, faster, and more robust data harvesting technologies.

On the other hand, existing wireless communication solutions are disruptive to mine operations. A tower and temporarily installed sensors need to be deployed before exploration and must be retrieved during constructions due to the interference of the sensors and towers with the mine operations, adding to the maintenance, labor, and time costs. Moreover, high costs prohibit sensors to be deployed in multiple locations in a mine. Accordingly, mine variability cannot be captured by existing techniques. As a result, the spatial and temporal variability of the field and mine conditions cannot be accounted for within mine monitoring decisions. This project will address real-time and variable information acquisition challenges to enable autonomous mine monitoring solutions guided by in situ sensor information. It enables autonomous decision making for mining operation, minimize or eliminate the human error associated such decisions, and enhance operation efficiency. The sustainable mining IoT is envisaged as to provide key infrastructure and technology advancements for the next-generation IMM practices, in which mining systems are tightly coupled with proper underground mine mineral monitoring. These systems have the potential to provide significant advancements for mine monitoring in unmanaged or poorly managed systems, where mining decisions are not based on quantitative sensor indicators. To this end, novel wireless underground communication techniques in IoT can be employed:

- **Real-Time Mining Sensory Data:** Communication challenges prohibit real-time information gathering from highly variable mines (both spatial and temporal variabilities) with multiple sensors. The recent wireless underground communication techniques provide tools to gather real-time mineral information. However, real-time information has not yet been collected from practical mine fields. The sustainable mining IoT can be utilized for real-time data collection.
- **Autonomous Mine Monitoring:** The theoretical/scientific understanding of real-time and/or autonomous mine monitoring has not been well established for mining efficiency improvement. This is partly due to lack of technological advances that enable such data collection and autonomy on a mine scale. Even when the data collection from the mines that have spatial and temporal variability is accomplished, a scientifically and research-based practical tool for integration of all these data and information into central location for decision making for IMM does not exist. There is need to develop such a tool to integrate real-time mine disaster monitoring and early-warning system coupled with environment data to allow effective and fast decisions for proper IMM practices.
- **Field-Based Mining Prescription:** Mine monitoring practices heavily rely on the field properties, mineral type, mine type, climate, and, more importantly,

their interactions. Consequently, it is not possible to develop one-size-fits-all solutions. Instead, deep understanding of advanced mine monitoring tools for different fields is required so that mine monitoring prescriptions tailored to these properties can be developed and applied in various field conditions. These insights necessitate the development of a proof-of-concept sustainable mining IoT architecture for autonomous mine monitoring that enables extensive experimentation of next-generation mine monitoring practices in different types of fields.

- **Sustainable Mine System Operation:** The real-time mine disaster monitoring and early-warning systems have the potential to transform mining practices to help realize more efficient and sustainable mining solutions. Within this broader context, it is also important to devise sustainable system solutions for underground sensing systems. To this end, it is desirable to improve system efficiency in terms of communication reliability and energy consumption. With the long-term vision toward developing fully automated mine monitoring solutions, the mining IoT paradigm supports development of autonomous system that enables autonomy in mine monitoring with a capability to evaluate technology in practical conditions to devise autonomous mine monitoring solutions that advance mining practices. The sustainable mining IoT can be realized through advanced sensing, communication solutions, and information systems. An overview of sustainability mining IoT components is presented in Fig. 8.1.

8.2 Sustainable Mining Things

The mining methods are classified into four types depending on the type of the ore deposits(depth and inclination), depth, strength, and thickness of the rocks and roof/floor type. These are shown below:

- Surface mining for shallow deposits
- Underground mining to access deeper deposits
- In situ mining and augering to dissolve minerals in place
- Placer mining for shifting and placement of mineral

The sustainable mining IoT things are presented in the following:

- Metals, mineral deposits, ores, and rocks
- Mining-influenced groundwater and surface water
- Mine land, subsidence, land use, and reclamation
- Tailings and acid rock drainage
- Solid wastes, effluents, waste rock, and soil
- Hazardous materials

Fig. 8.1 Overview of sustainability mining IoT



8.3 Research Challenges in Sustainable Mining IoT

In this section, various research challenges to enable technological drivers in sustainable mining IoT are discussed.

The development of novel sensors and sensing techniques is vital for sustainable mining IoT [24]. This includes analytical sensors to detect chemical and mineralogical properties of ores and rocks with portable, mobile, fixed static settings [8, 21, 23]. For geophysical sensing, the aircraft and drone technology holds promise for seismic sensing [52] of surface features at shallow depths and hyperspectral sensing for detailed 3D analysis and to produce the geo-hydrological, chemical, and environmental models needed for ore deposits [18, 34]. The alternatives to seismic sensing are electromagnetic (EM) sensing and ground penetrating radar (GPR)

[1, 12, 16, 58]. The ore-grade analyzing systems can be utilized for mineral quality and quantity assessment in both surface and downhole configurations [49]. The sustainable mining IoT has the potential to integrate different type of sensors such as location sensors, gas, obstacle-detection, and water quality sensors. Models and simulations are also needed to get better insights into mineralogy, geological and hydrological processes in mines, and rock and soil properties [26, 31]. Moreover, the sensing data integrated would be beneficial for sustainable mining IoT decision support systems. These innovations in sustainable mining IoT will lead to reduction in lead times and improve the efficiency of recovery process.

The availability of variety of sensing and detection method is useful to get better perspective and resolution in different applications of sustainable mining IoT [24]. Real-time data processing and visualization techniques can be used to display the mine data for different type of mining applications. Moreover, channel models are needed for the mine-based communication channels for in-mine and mine-to-surface communications [38, 45]. Robotics can be utilized to automate mining operations such as nonexplosive rock fragmentation, drilling, transport, and mapping. The need of the total resource recover in mines without impacting the environment cannot be overemphasized [43, 46, 65]. The advancements are needed in fine and ultrafine minerals and particle recovery such as techniques to separate solids and liquids [54]. In this regard, developments of novel in situ methods to access deposits where ore permeability is low include casing, fracturing, rubblization techniques for in situ leaching and borehole mining, and drilling [27]. The reduced cost of biomining approach where bioagents are used to extract mineral will reduce waste and environmental impacts. In this regard, integration of innovations in biomedical, chemical, and physical sciences integration with mining practices will aid to attain sustainable development goals. The fracture process in mining consists of blasting, rock fracturing, drilling, excavation, and comminution. Currently, hydraulic fracture process is applied to petroleum and geothermal mining. It has many negative effects on air and water pollution. It has higher probability of oil spills with harmful impact on vegetation and soil. The sustainable mining IoT is envisioned to bring technology in cutting and fragmentation, where computer-aided cutting and blasting can inform the optimal fragment size with accurate procession. It can also reduce the dust by reducing the processing time and thrust and improved timing and tailoring of explosives. Moreover, for sustainable mining, the development of efficient water treatment is necessary for mining-influenced water (MIW) [50]. The mining process will benefit from developments in dewatering [33], dissolution of minerals [40], flotation [64], grinding and classification and other developments in chemical reagents [47], electrochemistry [61], thermodynamic and kinetic data [28], and microbiological agents [55].

The proper monitoring of mining pollutants is important to ensure that nearby water bodies are not impacted from it [63]. For environmental monitoring applications, sondes are used to sense conductivity, TDS, pH, salinity, and other parameters [3]. The development of strata control procedures is important for effective slope monitoring where excavation and rock properties (rock mass and intactness) are observed for stability and safety [22]. The improvements in technology for

difficult-to-mine deposits (e.g., thin coal seams) in longwall and continuous coal mining approaches are needed [15]. The existing directional drilling technology of petroleum and geothermal drilling can be applied. Moreover, in geochemical and geophysical exploration systems, there is need for portable and downhole analytical equipment to characterize cross borehole and to get improved insights into soil particle mobility. Use of drones in aerial geophysics will improve shallow seismic methods and better representation of hyperspectral data [35, 42].

For mining operations, the industry can benefit from research in advanced imaging methods with capability to propagate through surface vegetation and cover. The increased resolution and coverage is needed for magnetic, radiometric, gravitational, and spectral methods. For mineral processing, potential research avenues are to make advances in flotation systems, blasting alongside crushing, finding alternatives to electromechanical energy and phosphogypsum production, and modeling, and autonomous control. Similarly, innovations in hydrometallurgical and biotechnological techniques will advance metal extraction.

8.4 Sustainable Mining IoT Technologies and Monitoring Systems

The exploration (mineral identification), drilling, comminution (breaking to separate ore and waste), resource gathering, production, processing (crushing and grinding), closure, and land reclamation are important steps in the life cycle of the mine [17, 25, 36]. Therefore, the development of new technologies in these areas to reduce the environmental impact and waste will be beneficial for sustainable development. Due to hazardous and complicated conditions of mines, continuous monitoring of mines and early-warning systems is vital to ensure safety, to avoid health-related issues in miners. These disastrous events in mines include fire, explosion, water surge, and roof fall [4]. An architecture of sustainable mining IoT is shown in Fig. 8.2.



Fig. 8.2 The architecture of sustainable mining IoT

The sustainable mining IoT technologies and monitoring system collect data using different types of sensors and transmit this information to the database and cloud by using wireless communications. In this section, the technologies and monitoring systems for sustainable mining IoT are discussed.

8.4.1 Mine Monitoring for Health and Safety

The sustainable mining IoT is useful to monitor the safety conditions in mines, where technology is used to detect obstacles and obstructions to avoid hazards such as fall, berm, and equipment. The robust and reliable technology can also be used to assess health conditions in mining atmosphere to sense and identify the miner's mix-mode exposure to the oxidation, dust, diesels, and cutting pollutants. By using wireless communications, this information is then used for real-time alert system. Moreover, the lack of proper mine ventilation is another important health concern in mines. The presence of sufficient amount of oxygen is necessary to support breathing. Sustainability IoT-based mine ventilation systems are used to monitor air quality and cooling and control the air movement through direction and blocking.

8.4.2 Environmental Monitoring

The environmental monitoring in sustainable mining IoT is vital to protect the environment. For acid rock drainage, the acid-generating materials are identified to lessen and remove accumulation in pit floors and walls and to prevent encapsulation of wastes and passivation. Accordingly, the acidic wastewater and pit water can be treated by removal of metals and nitrate, and novel techniques of dewatering and consolidating slimes can be developed. Through sensing and improved predictive modeling, cyanide can be destroyed in situ. The new technology is needed to aid evapotranspiration and impede infiltration and fine particle emission.

8.4.3 Earth Crust Monitoring

The integrated mine monitoring system can be used to monitor the Earth's crust, where different types of subsurface sensors are used detect seismic activity and other underground conditions. The ground motion, displacement, and other disturbances can also be measured. The seismometers and vibration sensors are examples of some of the sensors used in earth crust monitoring. Because of the mining stress and deformations, the equilibrium of mine strata is disturbed. It depends on the mining technique used, rock mass and other proprieties, and depth of the strata. Accordingly, it results in falling rocks in mines. Therefore, the sustainable

mining IoT can be used to assess strains, load, stress, and deformation by using extensometers, electromagnetic and mechanical methods including linear variable differential transformer (LVDT), strain sensors, microelectromechanical systems (MEMS), resistance sensors, stress sensors, and vibration sensors.

In the open-pit mining, a large amount of overburden is removed. With continuous accumulation of waste, the dump level can increase and becomes susceptible to failure. Similarly, in open-pit mines, the sheer slants can fail and cause damage to mine equipment and machinery. Therefore, a slant strength monitoring system in sustainable IoT can be used to monitor the firmness of the dam and sheer slants using geo-sensors which can monitor different parameters (e.g., roof load and convergence, pillar pressure, and seismic activity resulting from blasting and fracturing).

8.4.4 Transportation Management

The sustainable monitoring system can be used to monitor the different aspects of the transportation in the mining such as mineral measurements and vehicle loading, route management, and illegal vehicle activity to detect unauthorized access. This information can be viewed in real time using wireless communications. The examples of sensors used in these systems are inductive loop, IR, and ultrasonic sensors, and acoustic arrays.

Moreover, mining machinery is often used under high load conditions. The machinery monitoring in mines is done using the sensors installed on the machinery for the purpose of health, load, location, and fuel assessment. The sustainable mining IoT enables prediction and early warnings of machinery faults using sensors such as thermocouples, accelerometers, acoustic sensors, and tachometers. The sustainable mining IoT has the great potential to benefit in real-time decision making, production management, and projections on resources. Through this paradigm the mining machinery (e.g., dumpers and shovels) can be minimized which leads to profit maximization.

8.4.5 Gas Detection

The gas emissions in mines are caused by either burning or from the crust of the earth due to seismic event, displacement, and rock fracturing. Miners come into contact with these various types of inflammable and toxic gases in mines such as nitrogen, carbon monoxide, sulfur dioxide, methane, carbon dioxide, and hydrogen sulfide. The sustainable IoT gas monitoring systems are used to mitigate and monitor gases using different types of sensors and chromatograph. Accordingly, real-time warning and alarm systems are developed. To monitor methane, the catalytic ball sensors are used to accurately sense different levels of methane.

However, the different factors such as exposure to high concentration of gases, silicones, and hydrogen sulfide negatively affect the performance of the sensor. The local methane detector (LMD) operates by using IR sensing. Accordingly, improved techniques for collection of methane drainage and dilution.

A summary of site monitoring and characterization techniques for gas is given below:

- Biosensors
- Colorimetric test kits
- Detector tubes
- Fiber-optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits. Three categories of field analytical methods use biological systems to measure target analytes: Immunoassays, immunosensors, and enzyme-based assays that do not require the binding of an antibody to a target analyte as antigen
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Liquid Chromatography (LC)
- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)

8.4.6 Goaf Fill Monitoring

The goaf is cave formed due to mineral extraction in the underground mines such as in coal and classified into working (active) and sealed (closed). The subsidence is caused by the goaf formations. Therefore, the stowing is used to pack the different material (soil, sand, and rocks) in order to fill goaf. The monitoring of the strata in goaf is important to assess the stability and strength of the structure and to reduce subsidence. The gas accumulation in goaf carries the risk of explosion. Therefore, goafs are also monitored using gas sensors.

8.4.7 Mine Fire Monitoring

One major concern in mines is fire hazard. The mine fire causality is attributed to friction, explosions, and combustion. The coal mines are more prone to mine fires as compared to the mineral mines because of being innate oxidized. In coal mines,

fire proliferation process is very rapid. Therefore, accurate and robust fire warning systems are needed. The sustainability mining IoT enables fire detection, control and warning systems through sensing of temperature, and gas. The IR sensors are used for the purpose of temperature at various locations in the mines. The ratios of concentration of oxygen and carbon monoxide at various places in mine need continuous sensing. Accordingly, alarm is generated based on the threshold values. The 3D temperature maps are also helpful in mine monitoring.

8.4.8 Conveyor Belt Monitoring

A conveyor belt is used in many mines for long-haul mineral and coal transport. The conveyor belt monitoring includes broken ball and idle bearings, broken cage, and failure detection on the belt. A fiber-optic cable alongside the belt which detects these failures by using pulse transmission and Rayleigh backscatter. Accordingly, the sustainable mining IoT enables smart conveyor belt control, sensing, and communication systems.

8.4.9 Water Monitoring

The groundwater is significantly impacted by the mining activities. The groundwater incursions happen because of the cracks and geological faults in structures and high water pressure and the temperature. The water properties monitoring is important due to many factors to prevent the water-related hazards and to prevent deterioration of water quality. The groundwater has high resistivity (reciprocal of conductivity). Hence, resistivity-based geophysical sensing methods are employed to water sensing in sustainable mining IoT.

8.4.10 Miner Tracking

By using miner tracking, the fall hazards can be detected, and trapped miners can also be located in case of accidents. The localization methods are used to locate miners in mines. The wireless and wire localization approaches are utilized by using general communication equipment such as routers. Accordingly, the 3D maps can be produced showing mine worker location.

8.5 Paradigm-Shift Technologies for Sustainable Mining IoT

Many novel paradigm-shift technologies are emerging in mining:

- **Autonomous mining.** In this fully robotic-based mining process, the robotics systems are used for underground mining. In fully automated and manless mines, the robots can operate drills in mines (remote-connected drilling) and ore carriers (self-driving ore trucks). The autonomous mining systems can be used in harsh, remote, and inaccessible areas (e.g., space and sea floor). Moreover, the robots can work alongside humans as assistants and carry out the mine monitoring and producing mine images.
- **Waste utilization.** It includes use of mine waste in construction industry and building material (such as tiles, bricks, cement, and pozzolana).
- **Biomining.** In biomining, the biological agents (e.g., bacteria, virus, and other microbes) are employed in the metals, minerals, and coal extraction process from the ores and rocks. This has become possible because of the recent advancements in the genetic manipulations of microorganisms. These techniques are more energy efficient and produce less pollution.
- **Advanced rock fragmentation analyses.** Development of new methods to find distribution of fragment size and uniformity index.
- **Soil reclamation.** It includes rapid development of different types of soils in mine wastes through different methods including vegetation.

8.6 3D Underground Mine Modeling

The underground mine safety threats include falling rocks, suffocation, and explosions. The 3D underground mine models help to improve the safety of miners and provide easy navigation. These are also utilized to characterize and assess resources, in geochemical mine engineering, groundwater modeling, geothermal resources, stochastic coupled dynamical systems, and reservoirs. The reliable 3D scans and models can be produced by using different methods such as by using photogrammetry solutions and laser scanner. Modeling and visualization approaches also use virtual reality for training, and in design of engineering systems, and to model fluid flow:

- **Photogrammetry systems** use high-resolution photographs of the mine sites to generate 3D models by using advanced commercial cameras.
- **Laser scanners** use time of travel of the laser waves (IR pulses) to produce high-quality images by using point cloud model at different position and orientation. Laser scanners produce accurate maps and are capable of operating at long-range distances.

8.7 Use of Time-Domain Reflectometry in Mining

The time-domain refractometer is an emerging technology to ascertain ground movements in surface mines, tailings, and underground mine-related subsidence. It is also used for subsidence and slant monitoring. It operates by sending EM pulses in transmission line (coaxial cables) and then detecting the reflections resulting from faults. The time of travel of the pulses is used to calculate distance based on the speed of the wave propagation. By using the TDR approach, ground movements can be detected through magnitude and rate of able deformation.

A time-domain reflectometry system with transmission cable is shown in Fig. 8.3. It consists of a pulse generator, an oscilloscope, and a sampler. The reflected wave (also shown in Fig. 8.3) is used to determine the properties of the understudy material.

8.7.1 Treatment Technologies for Mining-Influenced Water

The mining-influenced water (MIW) is defined as any water whose chemical composition has been affected by mining or mineral processing and includes

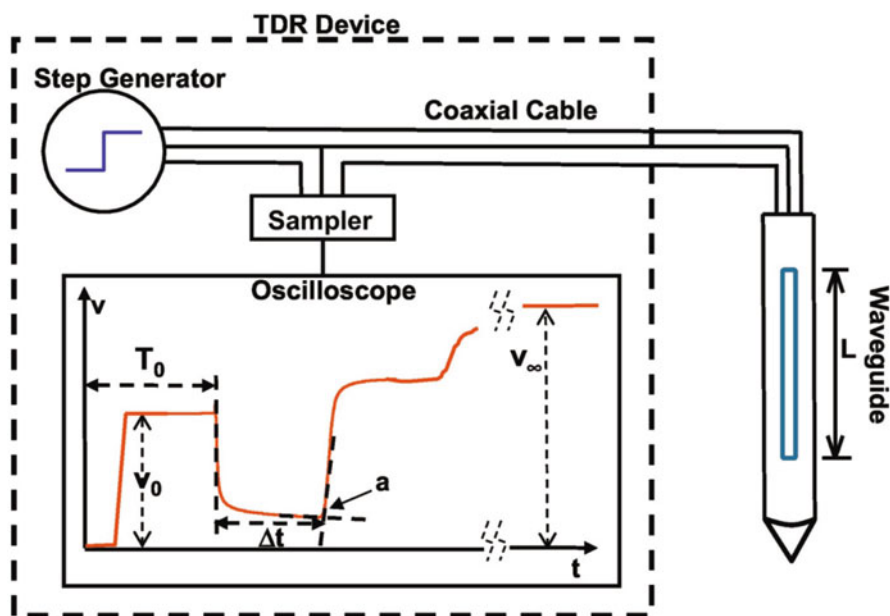


Fig. 8.3 Typical TDR system and waveform of a TDR penetrometer showing travel time determined using the dual-tangent-line method and a constant time offset [7]

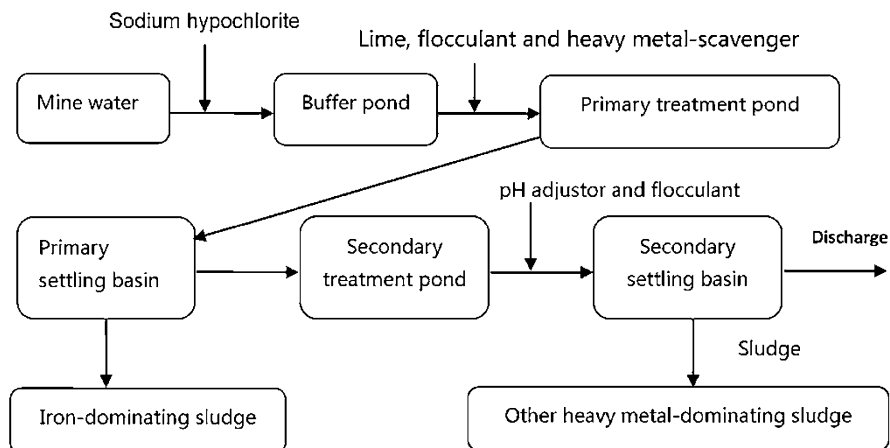


Fig. 8.4 The mine water treatment process [44]

acid rock drainage (ARD), neutral and alkaline waters, mineral processing waters, and residual waters. MIW can contain metals, metalloids, and other constituents in concentrations above regulatory standards. The steps involved in mine water treatment process are shown in Fig. 8.4. Some major MIW treatment technologies are shown in Table 8.1.

8.8 Applications of Nanotechnology in Mining

Nanotechnology is a developing field through which unique systems, devices, and materials are created in dimensions of nanometers (1–100 nm). Recently many advancements have been made in the field of biotechnology in mining. Novel nanoscale materials (e.g., dendrimers, nanotubes, ferritin, metalloporphyrinogens, and silica) are being developed for contaminant adsorption and destruction contaminants through in situ or ex situ techniques in groundwater remediation. The nanomaterials are classified into three different types: (1) nano zero-valent iron (nZVI), (2) bimetallic nanoscale particles (BNPs), and (3) emulsified zero-valent iron (EZVI). There is need to improve the performance and efficiency of these nanoscale materials. The activated carbon (AC) is also being used for in situ remediation of soil and groundwater by using emplacement of AC-based amendments. Moreover, various types of sensors are also being developed using this technology. Furthermore, researchers are working to get insights into the fate and transport of various nanoscale materials in environment, to assess their persistence and toxic impact on different biological systems.

Table 8.1 The MIW treatment technologies

Technology	Description	Elements treated	Limitations
Electrocoagulation	The electrolysis MIW with cathodes and anodes	Arsenic, copper, lead, zinc, total suspended solids, heavy metals, phosphates	High energy consumption
Bioreactors	The contaminants transformation using microorganisms	Selenium, cadmium, copper, nickel, lead, zinc, arsenic, chromium	Large footprint
Aquafix	pH levels raise	Aluminum, copper, iron, manganese, zinc	Iron hydroxides clogging and granular lime accumulation
Nanofiltration membrane technology	Semipermeable membrane-based filtration	Metals, sulfate	Low tolerance levels of membrane
Photoreduction	Ultraviolet light the electron-hole pair generation using ultraviolet light (wavelength of 380 nanometers)	Selenium	Sophisticated equipment
Successive alkalinity producing system	The combined organic substrate and ALD system	Acidity, aluminum, copper, iron, manganese, zinc	Complicated design
Reverse osmosis	Pressure-driven separation	Metals, sulfate	Requirements of high operating pressure
Permeable reactive barriers	In situ permeable treatment zone	Trace metals, including: chromium, nickel, lead, uranium, technetium, iron, manganese, selenium, copper, cobalt, cadmium, zinc radionuclides, anion contaminants, including: sulfate, nitrate, phosphate, arsenic various methanes, ethanes, ethenes, propanes, and aromatics	Long treatment periods
Ion exchange	The exchange of contaminant ions with good ions	Metals, hardness	Pre-filtration needed
Fluidized bed reactor (FBR)	The contaminated water is passed through a granular solid media at high enough velocities to suspend or fluidize the media	Selenium, perchlorate, nitrate	High energy requirements
Iron Co-precipitation	A two-step physical adsorption	Selenium, arsenic	High costs
Electrodialysis reversal (EDR)	Electrochemical separation process in which ions are transferred through ion exchange membranes	Arsenic, radium, nitrate, dissolved solids	Sophisticated operation

8.9 Mining Site Uncluttering and Restoration

The sustainability mining IoT has a great potential in cleanup and restoration of mining sites by providing characterization tools for this purpose. The characterization of physical and chemical properties of the mine wastes is a complex process. However, by using sensing tools for contamination sensing, the health and environmental impact can be mitigated along with selection of proper techniques for restoration and prospective future use of forsaken mine lands.

The mines which are located close to the water sources can release the main pollutant of surface water also called abandoned mine drainage (AMD) to lower mines under treatment, hence causing recontamination, wastage of efforts and resources, and restoration delay. Therefore, the proper selection of mine treatment approach is important. The sustainability IoT can benefit from this process of mine cleanup and restoration through its connected, decision support-based holistic approach. Accordingly, the watershed contamination caused by these deserted mine lands can be avoided by proper cleanup.

The approaches for mine cleanup and restoration are discussed in the following section. The important mining waste treatment technologies are also discussed:

- **Electrokinetics**—The electrokinetic remediation (ER) is operated by desorption and elimination of polar organics and metals by applying electrical current electrodes in ground. It is an in situ remediation technology that works in soils, marine dredging, sludge, and mud having low value of permeability. It can treat a wide range of concentrations from few ppm to high ppm. The applications of the electrokinetic method of remediation are shown in Fig. 8.5.
- **Excavation and Disposal**. The excavation and disposal process involves removing contaminations by using heavy machinery in tailings, soil, and sediment. This process is generally tailored to the specific site based on the site condition. After the excavation, the targeted treatment techniques are applied to the remaining material. Either the excavated material is buried on site in a suitable depository or it is transported off-site for reuse in recycling.
- **The process of revegetation** involves the replanting and reclaiming the soil of the mines in cleanup and restoration process.
- **Soil Amendments**. This process involves making amendment to soil by adding nutrients to support replanting. It revitalizes and enables sustainable plant life development. Different factors are considered such as impact on subsurface, likelihood of leaching to surface waters, and the potential impact on animal and plant life.
- **Covering**. In covering approach the solid mining wastes are covered to reduce environmental impacts of the waste. It also prevents erosion, harmful dust emissions to the environment, and water contaminant leaking to the surface water.
- **Subaqueous Disposal**. In this process the contaminated material is removed from the surface and placed in subsurface environment to prevent exposure. It also reduces waste oxidation, acid generation, and release of metals.

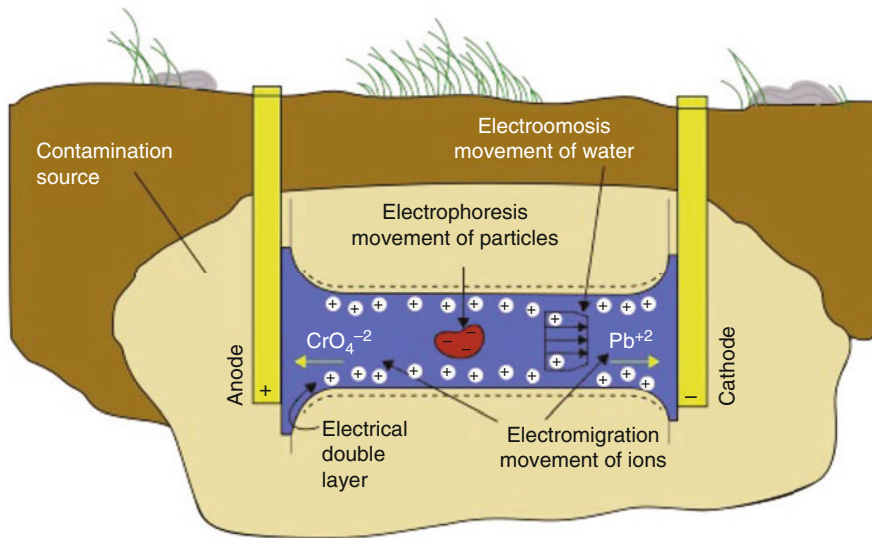


Fig. 8.5 Application of the electrokinetic method of remediation [5]

- **Biosolids.** In this approach the nutrient-rich biosolids and other organic matter materials are utilized for stabilization, reclamation, and revegetation of mine wastes.
- **Chemical Stabilization.** This ex situ and in situ treatment approach uses phosphate (phosphoric acid) to reduce the transport of heavy metals. It is considered as the permanent fix to the mine waste.
- **Biological Treatment.** The biological treatment uses a biological layer to filter metals from the mining-influenced water (MIW).
- **Passivation Technologies.** In this process the acid-generating materials are passivated by removing contact of sulfide with water and oxygen. This can be achieved by eliminating one of the water, sulfide minerals oxygen, and bacteria.
- **It uses plant restoration in tailings, mining solid wastes (MSW), and mining-impacted waters (MIW) and acts as a hydraulic control for drainage.**
- **Reuse and Reprocessing.** After the application of the treatment technologies, the contaminants are removed. @ Afterward, the reuse and reprocessing technologies turn the leftover mine waste into environment safe useful products.

8.10 Sensing in Sustainable Mining IoT

The sustainable mining IoT can be used to sense surface and groundwater in mines and geotechnical behavior of tailings as they transition from mineral slurries to soils. Remote sensing including unmanned aerial systems (UAS) and satellite imagery can

be used to analyze, assess, monitor, and identify mining activities, water properties, soil contamination, and active geological faults. The sensing technologies for sustainable mining IoT are discussed in this section.

8.10.1 Ore Bodies Sensing

In this section, different approaches for ore bodies sensing are discussed.

8.10.1.1 Underground Gravity Sensing and Rock Mapping

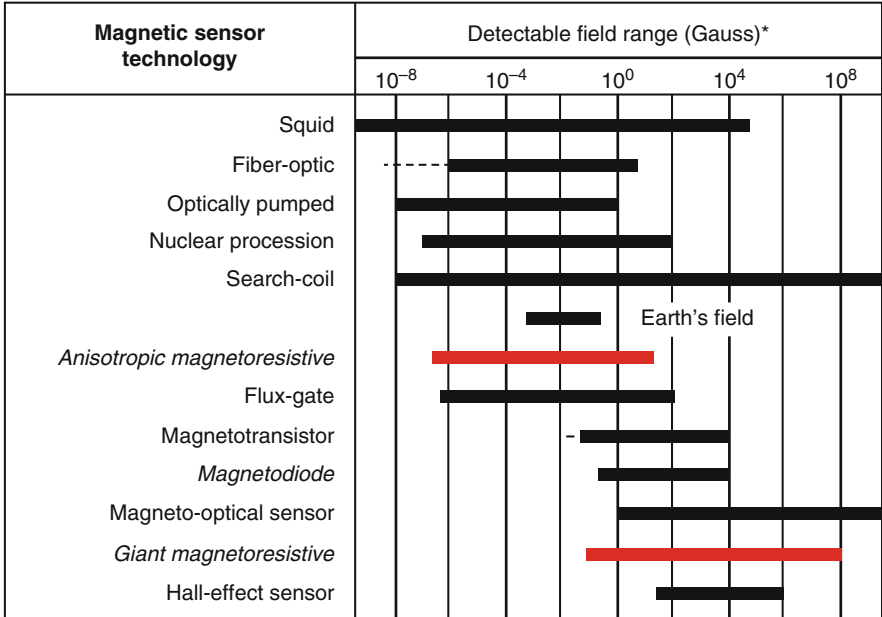
Gravity measurement is a process to locate locating deposits of ore bodies and dense metallic minerals in Earth's crust. Accordingly, the mapping of different ore bodies, types of rocks, and their geological structures is carried out. It can be used to produce density layers at different depths. The gravity and density distribution is impacted by changes in rock strain and stress, relocation due to slides, and water infiltration. A special instrument called the gravimeter is used for gravity sensing. There are two types of the gravity meters: (1) absolute and (2) relative gravity meter.

8.10.1.2 Magnetic Sensing

The steel materials, mineral ore deposits, and sedimentary rocks impact the magnetic field of the earth. A magnetic sensing is done to sense and map these changes in the magnetic field of the earth. Many different features of the ores can be mapped (e.g., location, size, and shape). Magnetometers, a very high precision instrument, are used to conduct the magnetic sensing by measuring the magnetic field. The magnetometers use an electric coil as antenna by employing proton-rich fluids. When the current is applied, it generates a magnetic field, which causes the polarization of protons. Accordingly, the magnetic flux density is measured. There are two types of magnetometers used for sensing: (1) vector magnetometers and (2) scalar magnetometers (quantum magnetometers). Magnetic sensing can be done using magnetometers mounted on aircraft. However, the aerial magnetic sensing is challenging due to the height and terrain issues. To overcome this challenge, the backpack mounted Overhauser quantum gradiometer can be used. The sensitivity range of various types of magnetometers is shown in Fig. 8.6.

8.10.1.3 Ground-Penetrating Radar Subsurface Sensing

In mining operations the ground-penetrating radar (GPR) is the widely used sensing/imaging method used to identify underground objects and structures (fractures,



*Note: 1 Gauss (Gs) – 10⁻⁴ Tesla (T) – 10⁵ Gamma (Y)

Fig. 8.6 The sensitivity range of various types of magnetometers [6]

joints, and faults) by using radar pulses. GPR operates by transmitting the EM waves to the earth by using one antenna as transmitter and other antenna as a receiver to receive the reflected signal. The bedrock depth in the subsurface environment is obtained using GPR which is then subsequently used for analysis purpose (e.g., planning, texture, and density estimation). Other applications include explorations of minerals, mass stability, grading of deposits, and marking of ore zones:

- Tunneling and Underground Mines. The GPR provides solutions to many of the geological issues (rock mass stability examination, exploitation of mineralogy zones for potash and salt) by providing deep insights into the subsurface environment.
- Placer and Mineral Exploration. The GPS is commonly used in exploration of the iron-rich minerals, diamond and gold fluvial deposits (gold and diamonds) and beach deposits (e.g., titanium) and iron-rich heavy minerals. It is also used to detect and track fault zones and mineral veins and in nickel exploration.
- Structural Integrity Sensing. The GPR can sense the integrity of the structures to detect cracks and other issues for development and planning purpose.

8.10.1.4 Seismic Sensing

In seismic sensing approach, the shock waves are transmitted through the Earth. The propagation speed of these waves is impacted by the density and other properties of the rocks. These variations in the speed of the wave are used to identify different underground materials. Generally, the transverse, exchange, and longitudinal waves are employed. Different seismic sensing approaches include side-scan sonar, wireless, flip-flop source, and slip sweep.

8.10.1.5 Tomographic Sensing

The tomography is used to measure and visualize the three-dimensional (3D) Earth's reflectivity and velocity distribution, by using multiple transmitters and receivers. Different types of the tomographic sensing are discussed below:

- In transmission tomography, the propagation measurements are done in different type of wireless channels (e.g., surface to borehole, surface to surface, and borehole to borehole). The borehole tomography is used for exploration and identification of underground geological structures and soil profile. A setup for the field experiment is shown in Fig. 8.7.
- The reflection tomography is based on the reflection seismology.
- In diffraction tomography, the Fermat principle is used for analysis instead of Snell's law.

8.10.2 Mine Water Sensing

The groundwater sensing in mining operations is vital to assess the quality and to detect variations in chemical properties of the water both in underground and at point of emission. It is required to ensure compliance with regulatory standards. The water mine sensing can also be used to control the flow and emissions of mine-influenced water (MIW) in and around mining sites.

8.10.3 Remote Sensing

8.10.3.1 Hyperspectral Sensing

Hyperspectral sensing is a remote sensing approach, also known as imaging spectroscopy, and is used to detect and identify minerals. It operates by sensing absorption characteristics which are affected by the presence of chemical bonds in a gas, solid, and liquid. A spectrometer is used to distinguish and measure different

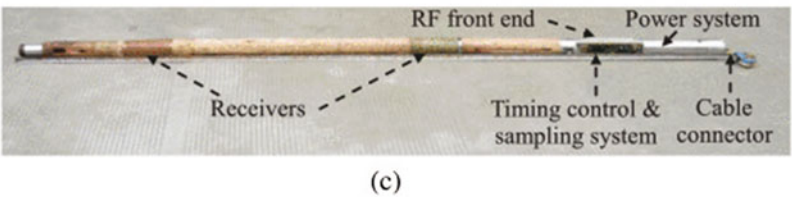
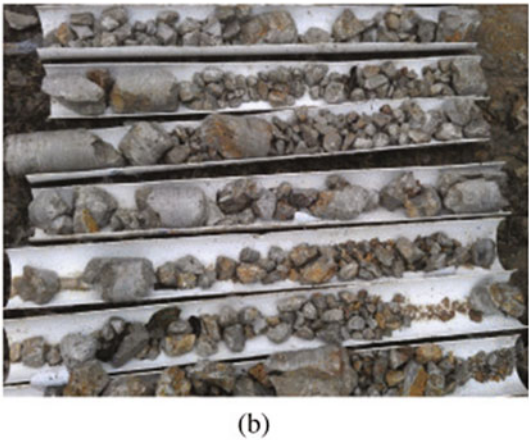
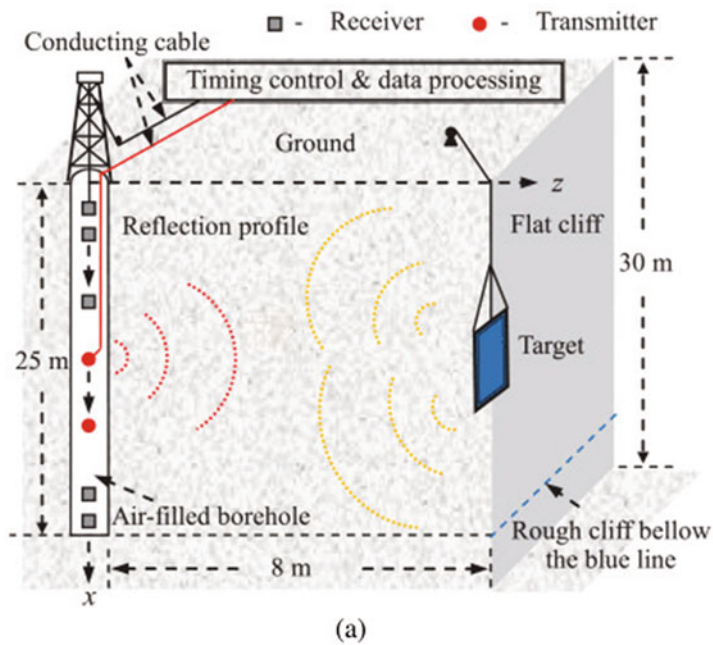


Fig. 8.7 Setup of the field experiment. (a) Schematic of the experimental field setup. (b) Sample of the surrounding media. (c) Subsurface system of the borehole radar [30]

spectral components. Accordingly, a map or cube representation of the ground surface mineralogy is developed. The accurate hyperspectral sensing depends on the type, resolution, quality, signal-to-noise ratio (SNR) and its wavelength of spectrometer, and the absorption properties of the minerals under study.

8.10.3.2 Thematic Sensing and Mapping

The Landsat Thematic Mapper is a high-resolution multispectral mineral scanner with support for spectrum separation. With an opto-mechanical sensor, it provides 30-m resolution with a capability to operate in seven different bands.

8.10.4 Multispectral Scanner

The multispectral scanner (MSS) transmits the S-band radio-frequency spectrum used for control of the satellite, and so is not affected by the Thematic Mapper's communication difficulties.

8.10.5 Mine Water Contamination Sensors

The pathogens that are found in mine-influenced water and toxic substances present a major sustainability challenge. The detection of these disease-causing substances can be done using chemical and biological sensors. These sensors can be deployed in underwater and underground environments. These sensors operate by using organic transistors and fictionalized gate electrode, where molecularly imprinted polymer (MIP) enables detection of biochemical compounds. It can be integrated with sustainability IoT paradigm using wireless communications.

8.10.6 Sensor Technologies for Gas Leaks in Mines

Gas sensors are used to sense gas pressure in mines and play a major role to detect gas leaks in mines. These sensors are characterized based on different parameters which are explained in the following:

- **Dynamic Range.** Quantity range from low to high concentrations
- **Sensitivity.** A measure to detect small variations
- **Limit of Detection (LOD).** Sensing ability to detect lowest quantity (concentration)
- **Resolution.** A measure to detect smallest variation

- Selectivity. Capacity to different gases
- Response time. Time required from absent to particular quantity
- Linearity. Graphical representation in calibrated values in straight line
- Stability. Time duration to operate for longer time periods

In sustainable mining IoT, gas sensors enable real-time actuation in mines. Many types of sensor technologies for gas leak sensing are discussed in the following.

8.10.6.1 Pellistor Sensor

The combustible gases need a certain temperature for ignition, but in catalytic combustion due to certain chemicals, the combustion can happen well below the certain temperature. A pellistor is a sensor used to sense combustible gases. It has two types: catalytic and thermal conductivity (TC):

- The catalytic sensor is based on glass-covered wire coil catalyst-coated wire. When the coil is heated, its temperature increases with heat generated from gas burning. Accordingly, the variation in resistance is measured.
- Thermal conductivity sensors are used for sensing based on the thermal conductivity variations of various gases in mines such as hydrogen, helium, and methane, 0–100% volume.

8.10.6.2 Infrared Gas Sensor

The infrared gas sensing method uses infrared light for combustible hydrocarbon gas. The component of the sensor includes optical IR transmitter, receiver, and a wavelength filter. The molecules absorb and emit energy IR waves depending on their properties. The absorbing molecules vibrate more as compared to reflected molecules.

8.10.6.3 Electrochemical Sensors

The electrochemical sensors consist of fuel cells and contain a cathode, an anode, and an electrolyte. These are used to detect toxic gases and oxygen. A current is generated due to chemical reaction when the target gas is detected in fuel cell. The produced current represents the volume of the gas and is used for sensing.

8.10.6.4 Semiconductor Sensor

These semiconductor sensors are used for sensing of combustible hydrocarbon (CHC) gases. These are manufactured using silicon substrate. The gas being sensed

leads to variations in conductivity of the substrate when heated. These sensors have low current leakage and capacitance.

8.10.6.5 Laser Sensor

Different types of the laser sensors are explained in the following:

- Tunable Diode Laser Absorption Spectroscopy. It has two components, (1) tunable diode lasers and (2) laser absorption spectrometer. TDLAS is used to measure gas concentration in methane and water vapor. These receivers sense the wavelength unabsorbed by concentration.
- Differential Sensor (LiDAR). It is based on backscattering wave strength from the concentration and operates in IR, UV, visible wavelengths.

8.10.6.6 Other Gas Sensors

- Fiber-Optic Gas Sensor. The fiber-optic sensors work on the principle of measuring the wavelength by the absorption of the target analyte.
- Mass Sensor. The Flame Ionization Detector (FID) is used to sense hydrocarbon gas concentration and operates on mass sensing instead of concentration sensing.
- Photoionization Detector. It works by sensing the organic volatile components in UV spectrum by using mobile ion spectrometer technique.
- An array of microelectromechanical sensors (MEMS) on silicon substrate is used to sense different gases.
- Hydrogen Sensor. This works by detection of the resonant frequency due to molecular adsorption.

8.10.7 Autonomous Sensing of Groundwater Quality in Mines

A mining site contains multitude wells which requires the autonomous sensing systems. Therefore, sensing of the quality of the groundwater is of critical importance during mining operations. This sensor system in sustainable mining IoT improves the efficiency of mining operations by data collection and real-time decision-making systems. The cloud technology is also useful in mine sensing and automation. Overall, the sustainability mining IoT has the strong potential for beneficial improvements in all areas of mining including machinery monitoring, mine sensing, exploration and mining technology advancement, environmental monitoring, and cleanup and restoration.

8.11 Global Sustainability Efforts

The following organizations are supporting the sustainable mining efforts [37]:

- The American Society of Mining and Reclamation
- The Australasian Institute of Mining and Metallurgy
- The Canadian Institute of Mining, Metallurgy and Petroleum
- The European Federation of Geologists
- The Iberoamerican Association of Mining Education
- The Institute of Geologists of Ireland
- The Peruvian Institute of Mining Engineers
- The Society for Mining, Metallurgy, Resource and Environmental Technology
- The Society of Mining Professors
- The Southern African Institute of Mining and Metallurgy
- The Spanish Association of Mining Engineers

8.12 Wireless Communications in Sustainable Mining IoT

The importance of the wireless communications in sustainable mining IoT cannot be overemphasized. It provides connectivity among different sensing and monitoring components of the IoT paradigm and enables real-time decision making by integration of different components of the system. The over-the-air (OTA) wireless communications discussed in Chap. 1 have limited application in some type of mining activities such as underground due to the higher path loss of radio wave propagation in wireless underground communication channel. The higher attenuation as compared to OTA is caused by the complex permittivity of the geological strata, and other multipath components forming from the uneven structure of the mines which block the line of sight (LoS) path. Therefore, empirical channel modeling and impulse response analysis are needed for detailed insights into the physics of radio wave propagation in mines.

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Chapter 9

Internet of Things in Water Management and Treatment



9.1 Introduction

The survival of humanity depends on the availability of the water resources. The water stress is a major issue due to decreasing freshwater reserves in different regions of the world [2, 20, 23, 53, 89]. The issues of water shortage have exacerbated due to the climate change-related variations in frequency and quantity of precipitation [5, 41, 98, 99]. Moreover, the growth in population and emerging human mobility patterns have also contributed to the worsening the issue of shortage. Therefore, the sustainable water resource management and treatment is vital to maintain and conserve the water supply to meet current growth needs and future generations [24]. The water amount and quality interactions impact the water security [33]. The water security is defined as [14, 38, 42]:

The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against waterborne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

In this chapter, the IoT applications using sensors for waste and stormwater monitoring across networked landscapes in water treatment and sustainable management are presented. The impacts of the human activities on amount and quality of the water are discussed in the next section.

9.1.1 Impacts of the Human Activities on Amount and Quality of Water

The human activities affect the water quantity and quality in different ways [111]. These activities span in various disciplines such as agriculture and forests. The human-induced impacts are discussed below:

- The irrigation water and drinking water withdrawals reduce the stream base flow and surface water table [26]. Accordingly, water temperature and oxygen concentrations are impacted, which lead to rise in summer water temperature and nutrient concentrations whereby decreasing oxygen concentration.
- Similarly, in agriculture, the tile drainage results in disruptions to natural hydrology by increasing flow and flooding [101]. Accordingly, the wetland water and discharge levels are impacted that lead to increase in nutrients, pesticides, and sediments and reduce soil infiltration and nutrient cycling.
- The impervious surfaces in urban and industrial areas are another factor that impacts the quality and quantity of water. These surfaces are generally covered with impenetrable asphalt or concrete materials. These also cause disruptions of natural hydrology and causation of increasing peak flow and flooding [62]. Accordingly, the turbidity and nutrients are impacted which result in an increase in sediments and contaminants which reduce nutrient cycling.
- In forests, the harvesting is done due to many different reasons that increase peak flow and disrupt natural hydrology [63]. The water turbidity, algae, and temperature are impacted. The forest harvesting practice leads to an increase in sediments, nutrients, and pesticides.

Therefore, to ensure water security, there is a need for efficient management practices for water sustainability (Fig. 9.1). These water management practices are discussed in the following:

- **Source Management.** As discussed above, the watershed deterioration, due to agriculture and other land-use practices, accelerates the nutrients' and sediments' runoff process, which subsequently requires extensive treatment at the receiving end for cleanup operation [19, 102]. In source management, the water supplies are protected at the source; however, the source tracking is a complex and challenging task. Water systems consist of different horological elements in wide geographical areas.
- **The purpose-fit management.** In this approach the treatment is done based on the end-user needs [25].
- **Other management practices** include conservation, treatment, and reuse, which are discussed in detail later in the chapter.

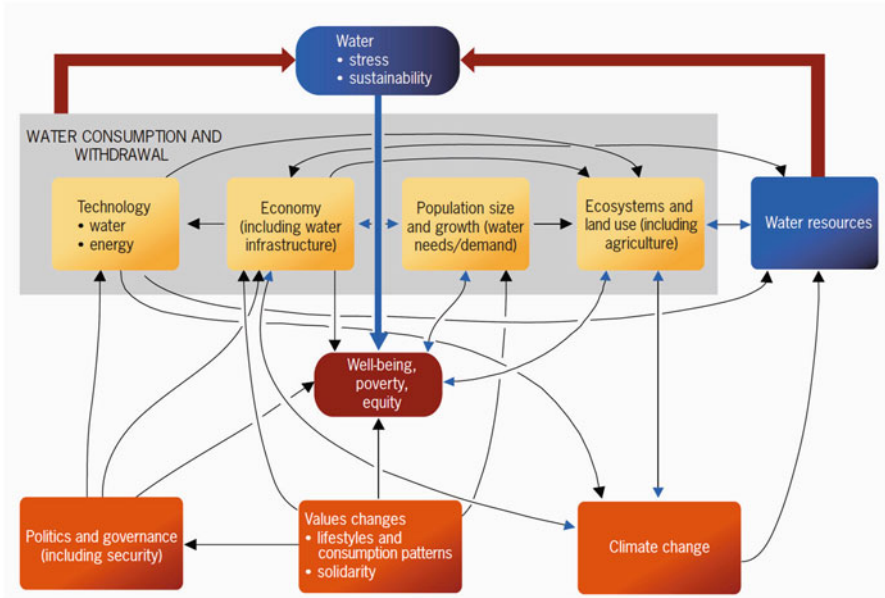


Fig. 9.1 The key factors in water security [34]

9.2 Water Management and Treatment Using IoT

The water management and treatment using IoT has the potential to overcome these key challenges for sustainable water management [51, 67, 68]. Through its sensing and communication technologies, it can provide useful insights into the sustainable water management approaches by using real-time data and decision support systems for better management and policy decisions. Novel technologies can be developed and connected to the system for water cycle and resource forecasting and understanding the connection between water quantity and land use. The adoption of modern sensing technologies can meet need of water use, quality, quantity sensing, and treatment. Accordingly, the inventory and indicators of the baseline conditions can be developed. It also enables efficient management of water stresses, pollutants, water data, land use, nutrients, and overflows using wireless communications and remote sensing.

The water management IoT's large scale monitoring of the chemical, physical, and biological properties in different types for water mediums (e.g., groundwater and mine-impacted water) has tremendous potential to inform better treatment options [103]. It is useful for large-scale water contaminant data collection and provides useful insights into the impacts of the contaminant. Accordingly, analytical models can be developed to set limits on contaminant. Moreover, based on the real-time sensing capabilities of the water management using IoT, the health alerts can be issued by the authorities. New techniques for toxin identification and quantification

can be integrated into system for performance analysis. Accordingly, the treatment of large areas with high contaminant concentration becomes possible.

Furthermore, the movement of contaminant from watersheds to other water bodies such as rivers, estuaries, and other coastal zones. Moreover, real-time monitoring systems can be developed for in-water HAB [13, 36, 56] observations (such as environmental conditions conducive to HAB) that will aid in rapid species identification and timely mitigation actions. Accordingly, the large-scale empirical studies enabled by the Internet of Things paradigm can inform about the efficiency of different treatment techniques and vulnerable factors. This knowledge is useful to develop new tracking role of different sources (such as wild, human, and animal sources) for microbial contamination. Based on this approach, the combined water organisms can be studied.

It has the potential to establish urban underground infrastructure monitoring stormwater and wastewater overflow monitoring capabilities through integration of subsurface sensing and wireless underground communications [80]. This enables community managers to take timely management actions to control rising water levels which not only cause damage to infrastructure but also lead to community inconvenience. The water management using IoT is also an innovation driver for different sensing technology integration into real-time decision-making, such as in situ sensors, satellite based sensing, and LiDAR, and other in-water sensing methods. Through development of novel sensing techniques, it has also benefits to monitor the post-treatment quality of the water to ensure its safety for human consumption [11, 58, 66, 110].

9.2.1 Water Management and Treatment Using IoT

The things in water management and treatment are presented in this section.

- Stormwater, wastewater, gray water, flooding, and overflow
- Percolation, precipitation, runoff, and flow regimes
- Sediments, nutrients, and pesticides
- Water temperature, dissolved oxygen, and turbidity
- Treatment and recycling

9.3 Groundwater Sensing and Treatment

The groundwater is saturated into the pores underground. The groundwater remediation process includes converting the water pollutants into safe content for drinking or altogether eliminating them. Different techniques are used for groundwater treatment such as biological, chemical, and physical treatment methods. These are listed below [57, 60]:

- Excavation/removal
- Pump and treat
- Capping
- Soil vapor extraction (SVE)
- Multiphase extraction systems (MPE)
- In situ bioremediation
- Air sparging
- Monitored natural attenuation (MNA)
- Vertical engineered barriers (VEB)
- In situ chemical reduction (ISCR)
- In situ thermal treatment

9.3.1 Applications of Nanotechnology in Groundwater Treatment

The nanotechnology is also being applied for remediation of groundwater [29, 97]. In Fig. 9.2, three different approaches of groundwater remediation based on iron particle applications are shown. In this approach, the contaminants in groundwater and dense nonaqueous phase liquid (DNAPL) interact (physical contact or on being dissolved) with the iron particles for treatment. In Fig. 9.2a, a standard porous reactant barrier fabricated with high-quality grainy Fe of the millimeter size is shown. In Fig. 9.2b, an area for reactive treatment is established by serial inoculation of nano-sized iron to develop converging areas of particles for adsorption in the grists of underground water. In Fig. 9.2c, the DNAPL contamination treatment approach by inserting movable nano-sized particles is shown. In both Fig. 9.2b and c, the nano-sized particles are shown in black, whereas the impacted zones are shown in pink color plumes. Moreover, in Fig. 9.2b there is no particle mobility, and in Fig. 9.2c, the particles are mobile.

9.3.2 The Nanomaterials for Contaminant Remediation

Several types of nanomaterials have been used for the remediation of contaminants such as chloroethene, trichloroethylene (TCE), tetrachloroethylene, and 1,2-dichloroethane (DCA). Various types of nanomaterials with their remediation capabilities are shown in Fig. 9.3. The nZVI are utilized in water treatment due to their elevated surface reactivity [52]. The iron particles (BNPs) are employed in groundwater by using the oxidation-reduction reaction process in order to attain contaminant degradation. The EZVI are used to treat human carcinogen chlorinated hydrocarbons.

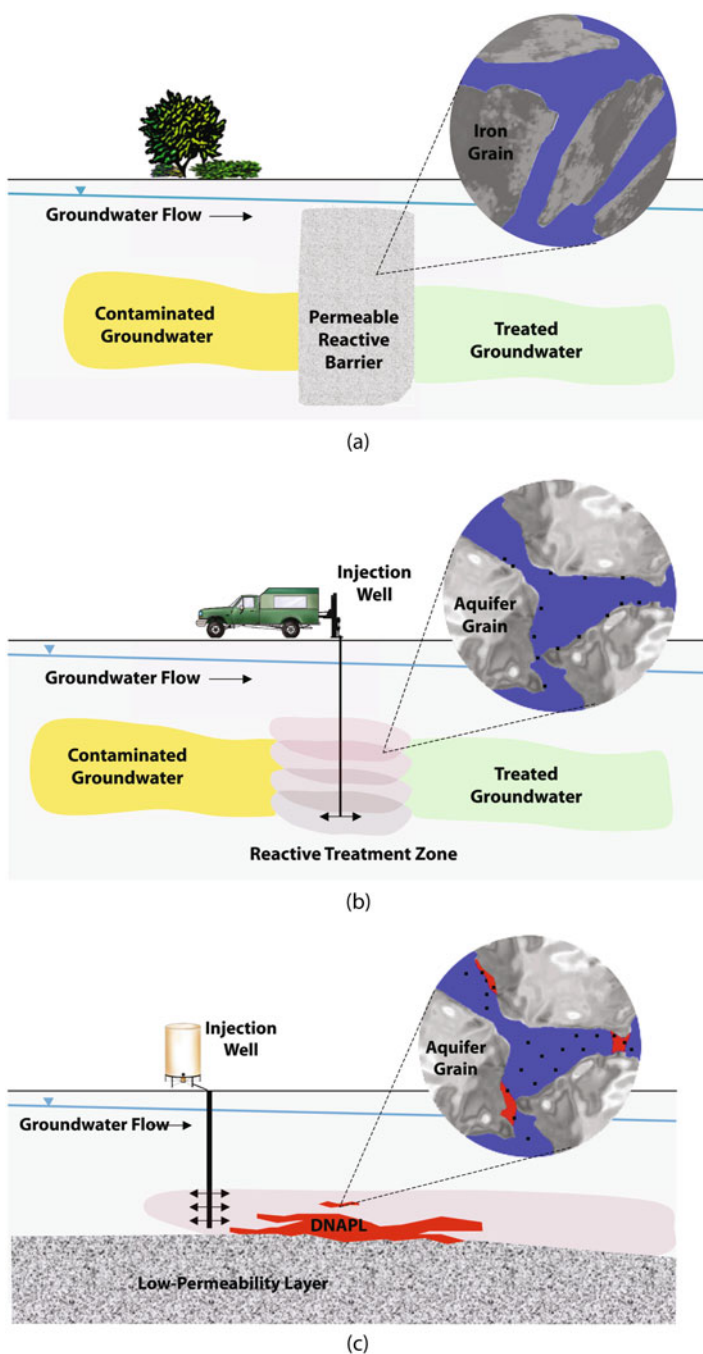


Fig. 9.2 Three approaches to application of Fe particles for groundwater remediation: (a) an area for reactive treatment is established by serial inoculation of nano-sized iron to develop converging areas of particles for adsorption in the grists of underground water, (b) a “reactive treatment zone” formed by sequential injection of nanosized Fe to form overlapping zones of particles adsorbed to the grains of native aquifer material, and (c) DNAPL contamination treatment approach by inserting movable nano-sized particles [97]

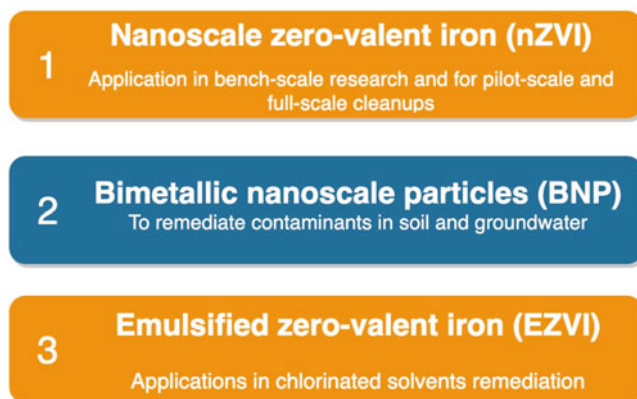


Fig. 9.3 Types of nanomaterials with their contaminant remediation capabilities

9.3.3 Hazardous Water Sensing and Treatment

The technologies for hazardous waste cleanup are discussed in the following. These contaminants can be found in different mediums such as surface water, soil gas, soil, sediment, light nonaqueous phase liquid (LNAPL), groundwater, fractured bedrock, and dense nonaqueous phase liquid (DNAPL) [31]:

- **Phytotechnology.** In this water and soil treatment technology, different types of plants are used to debase, remove, restrain, and disable contaminants [31].
- **In situ chemical oxidation.** In this approach, various oxidants are inserted in the underground environment to transform the contaminant into immobile components such CO_2 and Cl^- . This technology is very effective in treatment of nonaqueous phase liquids (NAPLs) [31, 100].
- **In situ flushing.** In this soil and groundwater treatment technique, the flushing solutions (e.g., cyclodextrin, cosolvents, surfactants, oxidants, and chelants) are injected into the contamination areas to make contaminants either mobile or soluble. Accordingly, the mixed solution is treated either in situ or through extraction. The contaminants receptive to this type of treatment include polychlorinated biphenyls (PCB), NAPLs, volatile organic compounds (VOCs) and semi-VOCs, cyanides, pesticides, dioxins, metals, corrosives, and radioactive components [65].
- **Heating Technologies.** These are based on contaminant treatment by heating of water and underground environment using different heating techniques (e.g., conductive, electrical resistive, RF, steam, and hot air injection). These are used in PCB, polychlorinated, oil contaminants, and chlorinated solvents [47, 112] (Fig. 9.4).

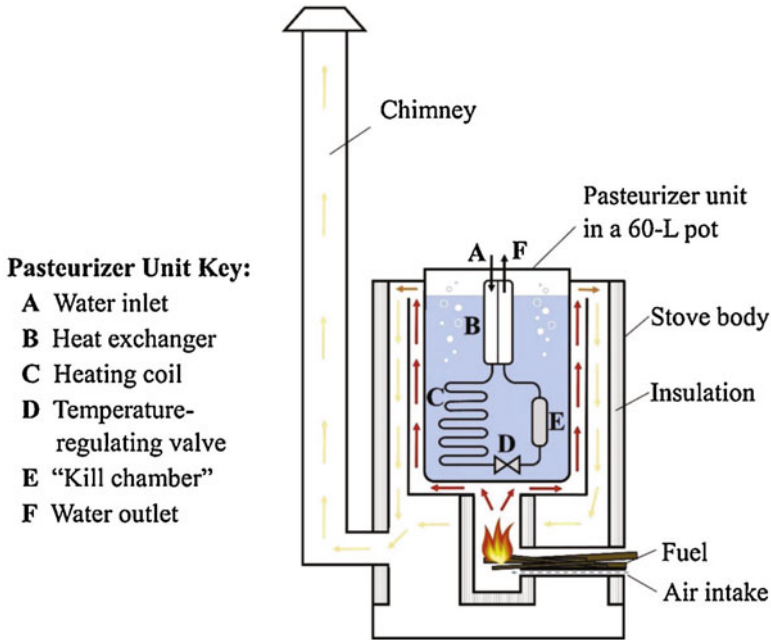


Fig. 9.4 A self-regulating biomass-powered system designed to heat water to the pasteurization temperature [22]

9.4 Underground Communications in Urban Underground Infrastructure Monitoring

In this section, the path loss analysis of wireless underground communications in urban underground IoT for wastewater monitoring has been presented. The potential of wireless underground technology and sensor solutions in different transformative urban underground IoT applications (e.g., real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids) is explored. The path loss model evaluations are done in different communication media under different layer thickness levels. The design of sewer and stormwater overflow monitoring systems can benefit from these findings.

9.4.1 Wastewater and Stormwater Monitoring Needs

Urban areas have public infrastructure worth billions of dollars located underground. City governments spend significant budget annually to support this underground infrastructure. The underground IoT solutions are rare due to challenges in connectivity and needs for extensive cabling to leverage over-the-air communication

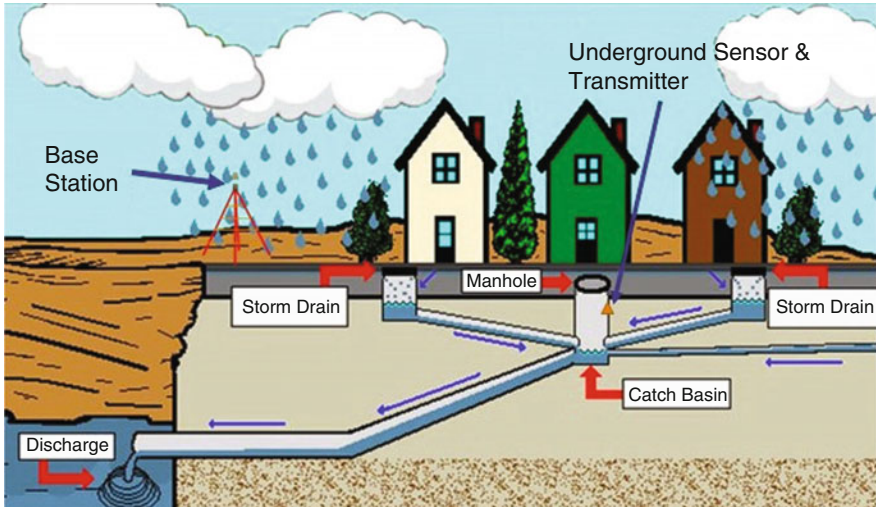


Fig. 9.5 The architecture of urban underground IoT for wastewater monitoring [80]

solutions, which increases costs. By combining wireless underground technology and sensor solutions [50, 106], many transformative urban underground IoT applications such as real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids can be developed.

The city wastewater bodies are responsible for collecting and treating wastewater at wastewater recovery facilities by processing many million gallons a day [49]. Cities have a strong need to monitor the quantity and quality of wastewater entering the collection system and reaching these recovery facilities [8, 10, 15, 28, 88]. Extra quantities of water entering the pipes can cause backups that result in sanitary sewer overflows [35, 59]. Eliminating I&I is important for controlling the flow of extraneous water into the pipeline [35, 95]. However, currently most cities do not have access to affordable underground sensor and connectivity technologies designed to detect problems in time to take preventive action. In this paper, we present the path loss analysis of wireless underground communications using urban underground IoT for wastewater monitoring [46, 90]. The architecture of urban underground IoT for wastewater monitoring is shown in Fig. 9.5. It shows different components of the system (e.g., base station, catch basin, UG transmitter and receiver, and drainage system). A storm drain is a major component of the drainage system and served as inlet and outlet for the runoff. Accordingly, it discharges the runoff to a water body (river, stream, channel, or creek).

The wastewater flow monitoring application can utilize wireless underground communication technology [104], which allows IoT radios to be buried underground [30]. Underground pipe monitoring sensors, connected to wireless underground software-defined radios, can wirelessly connect to the roadside urban infrastructure at the nearest traffic light pole. This wireless underground technology has been

shown to be successful in agricultural fields for several years with effective communication ranges of 100–200 m [106]. We present a theoretical path loss analysis for wireless underground communication through asphalt to design long-range wireless communication radios, which will allow underground radios to be deployed sufficiently deep to keep cabling to the underground pipes at a minimum while maintaining connectivity [9, 81, 86]. Providing this information to mobile devices will enable large-scale dissemination of timely alerts during emergencies. This application can also drive realistic wireless traffic for evaluating solutions for wireless underground networks.

9.4.2 Internet of Underground Things for Wastewater and Stormwater Monitoring

Internet of Underground Things (IOUT) has numerous applications in the field of digital agriculture [3, 18, 30, 39, 54, 70–79, 81–85, 87, 94, 96]. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [4, 93]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [39, 91, 92].

The IOUT delivers consistent access to data garnered from the farming areas via underground networking, aboveground networks, and the Internet. IOUT incorporates in situ underground sensing [1] of soil physical, chemical, and biological factors which includes water content sensing, salinity sensing, pH and nitrogen sensing, and temperature sensing. It also has the communication capabilities built-in as one of the integral components to provide the sensing data from the plants, roots, and soil. Moreover, it has the ability to include the environmental sensing capability to provide the real-time data pertaining to the diverse environmental phenomena such as wind data, rain information, and solar potential [107]. When integrated with agricultural machinery and farm equipment on the field (e.g., seeding equipment, irrigation controllers, harvesting machines, and combines), the IOUT leads to the full self-sufficiency on the smart farming fields, and has the strong potential of development of enhanced food production solutions and applications in the area of digital agriculture [106]. The IOUT is also being utilized to provide useful decision-making information to the growers in the field in real time.

In Sect. 9.4.4, the model evaluations are performed using different parameters.

9.4.3 Path Loss Model for Stratified Media to Air Communications

In this section we present the attenuation in the stratified medium and dispersion of subgrade of soil.

9.4.3.1 Attenuation in the Stratified Medium

The layered structure of the underground medium is shown in Fig. 9.2. The distinctive properties of wave transmission in the stratified medium need expressions of the path loss by taking into account the characteristics of different layers involved in the wireless communications [108].

Free Space Path Loss

From Friis equation [37], the received transmission power in over the air medium (OTA) at the transmitter-receiver (TR) communication path r from the transmitting antenna can be expressed by using the logarithmic scale as

$$P_r = P_t + G_r + G_t - L_{fs}, \quad (9.1)$$

where the transmission power of the transmitter is P_t , the antenna gains of the transmitting and receiving antennas are expressed as G_r and G_t , and L_{fs} is over-the-air path as exhibited in the free space (expressed in dB), and it is written as

$$L_{fs} = 33.2 + 20 \log(d) + 20 \log(f), \quad (9.2)$$

where the length of total transmission path (e.g., the distance between the transmission and the receiver antenna expressed in meters) is denoted by d and the frequency of the operation of the communication system is expressed as f with unit in MHz.

We consider transmission loss at two levels: (1) free space path loss and (2) loss through stratified layers.

Propagation Loss in the Layered Medium

For the propagation through layered medium, loss through medium should account for the effect of the properties of different layers involved in communication. Accordingly, the strength of the signal received at the receiver can be rewritten as [105]

$$P_r = -L_m + G_r + P_t + G_t, \quad (9.3)$$

where $L_m = L_{fs} + L_l$, and L_l denotes the extra signal attenuation exhibited by the transmission of EM waves through the stratified medium, which is ascertained by taking into account the existing dissimilarities of EM wave propagation occurring in the layered medium in comparison with that of the free space. The extra prorogation wave loss, L_l , in the stratified medium, hence, consists of accumulative loss occurring in the total number of layered medium through which wireless communications is carried out:

$$L_l = \sum_{n=0}^{N-1} L_n, \quad (9.4)$$

where L_n is the attenuation loss in the n th layer for each of the N layers.

The transmission loss exhibited in a particular layer denoted as L_n is mainly dependent on the dielectric permittivity, and the wavenumber of the medium in that particular layer, which can be expressed as $j\beta + \alpha = \gamma$ given as

$$\alpha = \omega \sqrt{\frac{\mu\epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}, \quad (9.5)$$

$$\beta = \omega \sqrt{\frac{\mu\epsilon'}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right]}, \quad (9.6)$$

where the ω , which is equivalent to the $2\pi f$, denotes the angular spectrum of the frequency, the magnetized permeableness is expressed as the μ , and the imaginary and real components of the permittivity of the material are denoted as ϵ'' and ϵ' , respectively, (9.9). Consequently, the propagation loss, L_n , for a particular layer in the stratified medium is found as [48]

$$L_n[dB] = 20 \cdot \gamma \cdot d \cdot \log_{10}(e), \quad (9.7)$$

where $e = 2.71828$ and d is thickness of the n th layer.

It can be seen that the propagation loss depends on the complex dielectric permittivity of the electromagnetic wave propagation in medium, layer thickness d , operating frequency, f , and other properties of the medium. Next, we consider the dispersion of the next layer involved in the sewer overflow monitoring system.

9.4.3.2 Dispersion in Different Subsurface Layers

The ability of the materials in different subsurface layers to hold out against the applied electric charge defines its permittivity. The permittivity also depends on the electromagnetic absorption potential of the material. With the oscillation electric field, the charge flows and results in two charge components of the current (e.g., charging and loss). The heat loss represents the dissipated energy into the thermal excitation. The polarization of the soil and asphalt material in the subsurface layers is coupled with the dielectric properties and can be divided into dipolar, atomic, and electric types. It also depends on the frequency because the dielectric displacement and polarization responses are different at different carriers. In the following, we discuss dispersion of materials involved in the subsurface layers. The material permittivity prediction expressions are presented.

9.4.3.3 Dispersion of Subgrade of the Soil Medium

By employing the findings of an extensive empirical campaign on soil permittivity [61], the permittivity spectra of the medium in the frequency range of 300–1300 MHz can be determined as shown in the following:

$$\epsilon_s = -j\epsilon_s'' + \epsilon_s', \quad (9.8)$$

$$\begin{aligned} \epsilon_s' &= 1.15 \left[1 + \frac{\rho_b}{\rho_s} \left(\epsilon_s^{\alpha'} \right) + m_v^{\beta'} \epsilon_{f_w}^{\alpha'} - m_v \right]^{1/\alpha'} \\ -0.69, \quad \epsilon_s'' &= \left[m_v^{\beta''} \epsilon_{f_w}^{\alpha''} \right]^{1/\alpha'}, \end{aligned} \quad (9.9)$$

where the relative complex dielectric permittivity of the soil medium is denoted by ϵ_s , the m_v is used to express the measure of the volumetric water content present in the medium, and the bulk density is ρ_b that is the indicator of the compaction of the soil material with unit of g/cm^3 and is used in relation to the solid soil particles ρ_s which is 2.65 g/cm^3 . The value of the α' is 0.65. The value of other soil dependent experimentally determined constants β'' and β' is given as

$$-0.52S + 1.28 - 0.16C = \beta', \quad (9.10)$$

$$-0.61S + 1.34 - 0.17C = \beta'', \quad (9.11)$$

where the amount of sand particles present in the soil is denoted by S and contents of the clay particles found in soil are expressed as C . The relative dielectric permittivities of the free water (both the imaginary and real components) are represented by ϵ'_{f_w} and ϵ''_{f_w} .

9.4.3.4 Dispersion of Asphalt

Since the medium of communications in sewer overflow monitoring application is multilayered structure, hence, it is important to determine the dielectric value of asphalt layer (top surface in Fig. 9.6). The formula is given as

$$\epsilon' = \frac{3}{4\pi} \frac{\epsilon_0 - 1}{\epsilon_0 + 2}. \quad (9.12)$$

It should be noted that when the frequency is increased, the value of dielectric constant of asphalt also increases. The impact of dependency of the dielectric constant on the frequency is caused by dipolar polarization (e.g., the disassociation molecule charges). The asphalt substance (bitumen) contains many aromatic and asphaltene molecules. Accordingly, it also depends on the applied electric field.

Fig. 9.6 The layered structure of the underground medium [80]



9.4.3.5 Dispersion of Base Gravel Aggregate

The base gravel aggregate layers are comprised of different materials such as of stones, sand, pebble, and air voids in less organized fashion. Because of this semi-random organization, the dispersion in these layers depends on the size of particles and wavelength. The effective permittivity of the gravel aggregate (consisting of a layer in which rock particles, sand particles, pebbles, and air voids with diverse dispersion properties are arranged together) is determined as

$$j \frac{\epsilon_0 - 1}{\epsilon_0 + 2\epsilon'}, \quad (9.13)$$

where j is the percentage of the solid material in the volume.

9.4.4 Model Evaluations

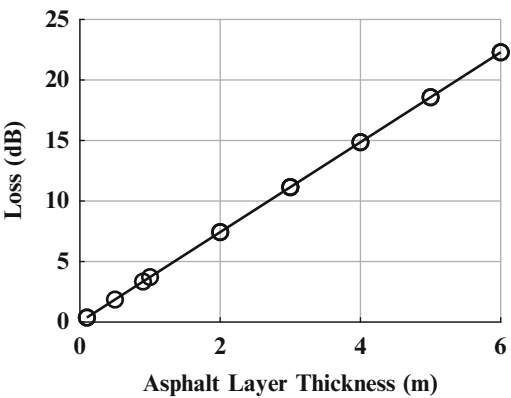
In this section, we present the path loss analysis. The model parameters considered for this evaluation are shown in Table 9.1. The soil and asphalt layer thickness are 20 and 10 cm, respectively, with soil moisture level of 5%. The operation frequency of 433 MHz is used with transmission power of 20 dBm. In Fig. 9.3, the propagation loss in the asphalt medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 1 m, the propagation loss is less than 5 dB. However, it increases with increase in layer thickness. It increases to 15 dB for the 4-m-thick asphalt layer.

The path loss with change in distance is shown in Fig. 9.4. It can be observed that for communication distances up to 4 km, the path loss is less than 100 dB. It increases to 107 dB for a distance of 10 km. The received signal strength indicator (RSSI) with distance is shown in Fig. 9.5. It can be observed that the RSSI decreases

Table 9.1 Model evaluation parameters [80]

Parameter	Value
P_t	20 dBm
Thickness of the soil layer	20 cm
Thickness of the asphalt layer	10 cm
Frequency	433 MHz
Noise floor	−90 dBm
Soil moisture	5% by Volume
Asphalt temperature	300 K/80.33 F/26 C

Fig. 9.7 The propagation loss in the asphalt medium with change in layer thickness [80]



with distance. This decrease is abrupt for distances less than 2 km. Afterward, it decreases gradually. At communication distance of 4 km, the −80 dBm RSSI indicates that underground nodes in urban underground infrastructure monitoring IoT can effectively communicate with urban roadside wireless communication infrastructure.

In Fig. 9.6, the propagation loss in the soil medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 2 m, the propagation loss is less than 37 dB. However, it increases with increase in thickness. It increases to 57 dB for the 4-m-thick soil layer. Moreover, it can also be observed that soil medium has higher loss as compared to the asphalt medium. This is caused by the higher permittivity of the soil as compared to the asphalt. The higher water-holding capacity of the soil in comparison with asphalt medium leads to the higher permittivity of soil.

The effect of temperature change on propagation loss in asphalt is shown in Fig. 9.7. It can be observed that with change in asphalt temperature from 300 K to 360 K, the path loss increases to 3.6 dB. Therefore, the wireless communication system in urban underground infrastructure monitoring IoT should be designed by considering the temperature change of the asphalt medium in different weather conditions (Figs. 9.8 and 9.9).

Fig. 9.8 The path loss with change in distance

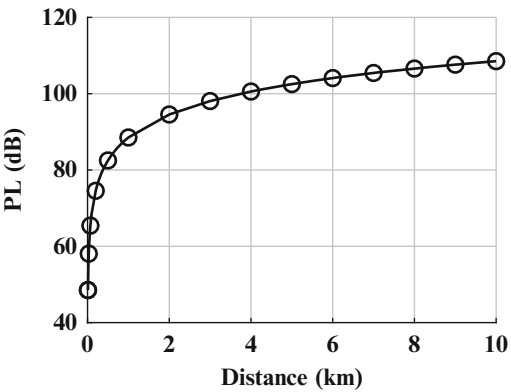
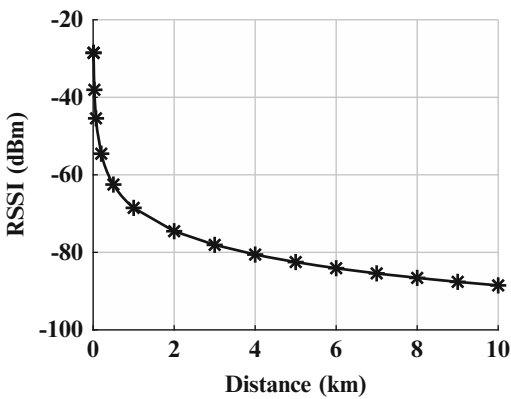


Fig. 9.9 The received signal strength indicator with distance [80]



9.5 Sensing and Sampling

In this section, different sensing related to water sampling needs are discussed. First the contaminant sensing is discussed (Figs. 9.10 and 9.11).

9.5.1 Contaminant Sensing

The contaminant sensing is not only important to detect the contaminants, but it is also useful to assess the extent and nature of contaminants. The different contaminants in need of sensing are shown in Fig. 9.12.

Fig. 9.10 The propagation loss in the soil medium with change in layer thickness [80]

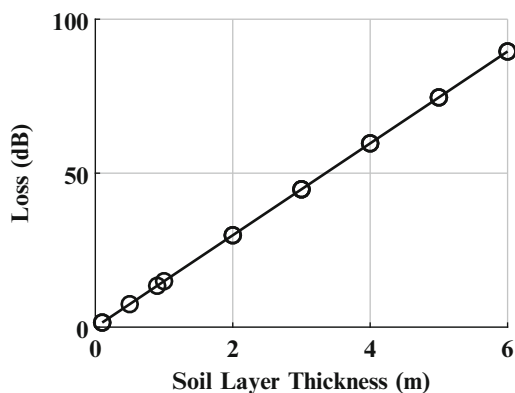
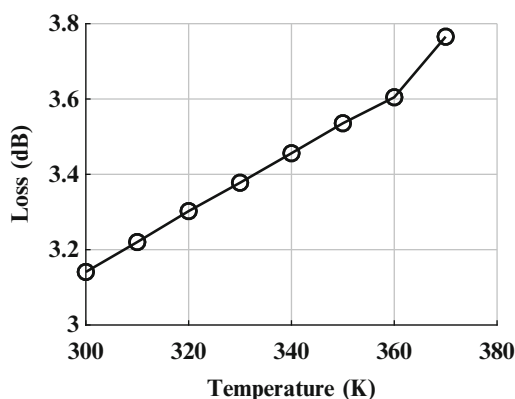


Fig. 9.11 The effect of temperature change on propagation loss in asphalt [80]



9.5.2 Sensing for Wastewater Treatment and Reuse

Another important source of water supply is wastewater reuse, where water from different sources (e.g., industry, agriculture, and domestic) is collected, treated, and recycled to mitigate its detrimental impacts using multiphase chemical, mechanical, and biological processes. The wastewater systems are also impacted by climate change [7, 27, 32]. Currently, the hazardous health environmental and health impacts of wastewater include its mixing with groundwater and surface water. Moreover, the health impacts resulting from consumption of this reclaimed water need more investigation. Moreover, the advanced methods for removal of bacteria, analytes, their genes, micro-pollutants, byproducts, and residual materials are needed. A summary of site monitoring and characterization techniques for water is given below [31]:

- Anodic stripping voltammetry (ASV)
- Biosensors

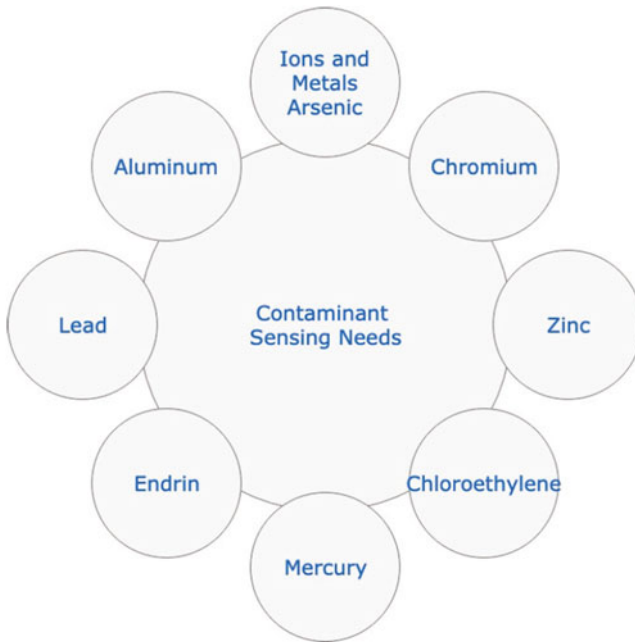


Fig. 9.12 The sensing needs for different contaminants

- Colorimetric test kits
- Direct reading probes
- Electro-optical sensors
- Fiber-optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits
- Inductively Coupled Plasma (ICP) Spectrophotometry
- Ion-Selective Electrodes (ISE)
- Liquid Chromatography (LC)
- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

9.5.3 *Agricultural Hazard Sensing*

The agriculture is becoming exceedingly vulnerable to the soil degradation, water scarcity, deteriorating mountain ecosystems, and more variable and intense weather patterns (e.g., floods, drought, frosts). However, there are major gaps in our understanding of changes in agriculture and how these changes will affect agriculture. Improved knowledge needs to be acquired to anticipate, plan, and adapt to these changes and to gain new grounds in agriculture. Furthermore, efforts are needed to develop better detection techniques for per- and poly-fluoroalkyl substances (PFAS), and PFAS-containing waste found in different soils. Among existing techniques, granular activated carbon (GAC) is a growing technology in PFAS treatment in water [17, 69]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of medium properties. The adsorptive and destructive technologies are considered for both soils and waters [12, 21]. Other remediation approaches are anion exchange, ozofractionation, chemical oxidation, electrochemical oxidation, sonolysis, soil stabilization, and thermal technologies [6, 45, 55, 64]. These treatment technologies are not best suited to provide PFAS management systems with almost real-time sensing data to facilitate fast decision making [40, 44].

To meet the need of practical approaches to manage the potential environmental impacts of PFAS, environmental researchers must develop and implement new technologies to enhance detection and control of PFAS with fewer inputs. Enhanced techniques that are more practical and efficient in control, treatment, destruction, and removal of PFAS in soils are needed. This complex and arduous task requires interdisciplinary endeavors that combine various environmental science disciplines to develop such tools and implement them in the field to achieve this purpose. A summary of site monitoring and characterization techniques for soil is given below [31]:

- Colorimetric test kits. Test kits are self-contained analytical kits that generally use a chemical reaction that produces color to identify contaminants, both qualitatively and quantitatively [43].
- Fiber-optic chemical sensors (FOCS). Fiber-optic chemical sensors (FOCS) operate by transporting light by wavelength or intensity to provide information about analytes in the environment surrounding the sensor. The environment surrounding a FOCS is usually air or water. FOCS can be categorized as intrinsic or extrinsic. Extrinsic FOCS simply use an optical fiber to transport [109].
- Gas Chromatography (GC). Chromatography is the science of separation which uses a diverse group of methods to separate closely related components of complex mixtures. During gas chromatographic separation, the sample is transported via an inert gas called the mobile phase [16].
- Gas Chromatography/Mass Spectrometry (GC/MS). Mass spectrometry (MS) is an established analytical technique that identifies organic compounds by measuring the mass (more correctly, mass to charge ratio) of the compound's molecule. Mass spectrometry is noteworthy among analytical techniques because

the signals produced by a spectrometer are the direct result of chemical reactions such as ionization and fragmentation, rather than energy state changes that are typical of most other spectroscopic techniques.

- Laser-induced Fluorescence (LIF). Laser-induced fluorescence (LIF) is a method for real-time, in situ field screening of residual and nonaqueous phase organic contaminants in undisturbed vadose, capillary fringe, and saturated subsurface soils and groundwater.
- Membrane Interface Probes. A MIP is a semiquantitative, field screening device that can detect volatile organic compounds (VOCs) in soil and sediment. It is used in conjunction with a direct push platform (DPP), such as a cone penetrometer testing (CPT) rig or a rig that uses a hydraulic or pneumatic hammer to drive the MIP to the depth of interest to collect samples of vaporized compounds.
- X-ray fluorescence (XRF). XRF instruments are field-portable or handheld devices for simultaneously measuring metals and other elements in various media.
- Direct reading probes
- Downhole pyrolysis explosive sensor
- Electromagnetic induction (EM)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Ground-Penetrating Radar (GPR)
- Immunoassay test kits
- Inductively Coupled Plasma (ICP) Spectrophotometry
- Ion-Selective Electrodes (ISE)
- Laser-induced Breakdown Spectroscopy (LIBS)
- Liquid Chromatography (LC)
- Magnetometry
- Mercury vapor analyzers
- Seismic reflection/refraction
- Soil/sediment micro-heterogeneity management to improve data precision
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

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Chapter 10

Internet of Things for Sustainability: Perspectives in Privacy, Cybersecurity, and Future Trends



10.1 Introduction

The cybersecurity in Internet of Things for sustainability is the process of protecting the systems, sensors, and wireless communications from digital attacks [24]. It is important to ensure that the sustainable IoT paradigm will operate in safe and secure environment to achieve sustainability goals using systems which are dependable, reliable, and trustworthy [10, 28, 32]. In many of the sustainability IoT paradigms discussed in this book, the cybersecurity risks to sensors and monitoring systems are different from the conventional networking systems in many aspects:

- The interaction of sustainability IoT with the physical world phenomena (weather, climate, water, and oceans) is generally not found in the modern information technology systems. Accordingly, the actuation (ability of these devices to make changes in real world) based on sensing and monitoring requires special consideration in terms of privacy and security. Moreover, the energy efficiency, safety, power, and performance requirements of these devices distinguish them from computers [90].
- The scale of IoT for sustainable community development expands beyond cities, to the global scale including oceans, climate, and water monitoring applications. Hence, diverse mediums of communications are involved (e.g., satellite, terrestrial air, cellular, and wide area networks) [91].
- Unlike server farms, various sustainability IoT are envisaged to function in harsh and challenged environment for prolonged periods of time without little or no physical access. Accordingly, unconventional security concerns emerge regarding remote access and data privacy [2, 101].
- Lack of upgrade and patching due to high cost is a major challenge as compared to conventional systems [58].

- The sensing data in some of the sustainability paradigms takes longer time to accumulate (such as in climate and agriculture), thereby presenting prolonged exposure-related security challenges [81, 82].
- The implementation of the security features on these sustainability IoT devices requires well-thought design keeping in view its integration in the holistic paradigm and novel insights (security by design) and innovations into the potential risks that can comprise information [32, 43].

In IoT for sustainable community development, it is vital to recognize that sustainability things do not function in a vacuum; rather these are parts of the entire ecosystem. Therefore, instead of the individual-based security, the holistic approach is of utmost importance. The holistic approach should take end-to-end strategy for cybersecurity across the entire sustainability landscape [32, 54]. Moreover, within each sustainability paradigm, each system has its own specific function and purpose with its ability to tolerate risks. Hence, no single cybersecurity protocol or set of rules can be applied to entire paradigm. These risk mitigation approaches vary based on system needs, functions, and use cases.

Accordingly, it is import to underscore the characterization of risk-based insights into functionality, deployment environment, set of behavior and applicabilities, and their integration into the paradigm [7]. In this regard, the outcome-based cybersecurity approach can be applied where the final outcome becomes more important as compared to less significant means to achieve those outcomes. The examples of weaknesses and unreasonable cybersecurity approaches toward sustainability IoT are discussed in the following [44, 53]:

- Data and information storage in plain text
- Negligence in adequate policy implementation
- Oversight of fixing current vulnerabilities
- Failure to utilize proper cybersecurity protocols
- Neglect of modern technology for protection such as firewalls
- Omission of network access regulations
- Lack of adequate incident response protocols

In sustainability IoT, both the device and data security are of vital importance. Different security issues in IoT are shown in Fig. 10.1.

Device security deals with protecting IoT devices from attacks, whereas the data security is related to protection of data integrity and confidentiality being generated from IoT sensors and other monitoring instrument. This also applies to the user privacy. The first step toward the securing IoT devices is risk identification and categorization, in which the impact of different IoT devices is considered. A three-pronged stratagem can be employed to identify risks, which include utilitarian, feasible, and verifiable. The first prong follows the utilitarian principle to identify the practical importance and appropriateness of risk. Then, feasibility principle analyzes the implementation complexity, cost, and verifiable details which deals with the implementation verifiability. In this process, both sustainability IoT functionality and cybersecurity needs are considered (device usage and management,

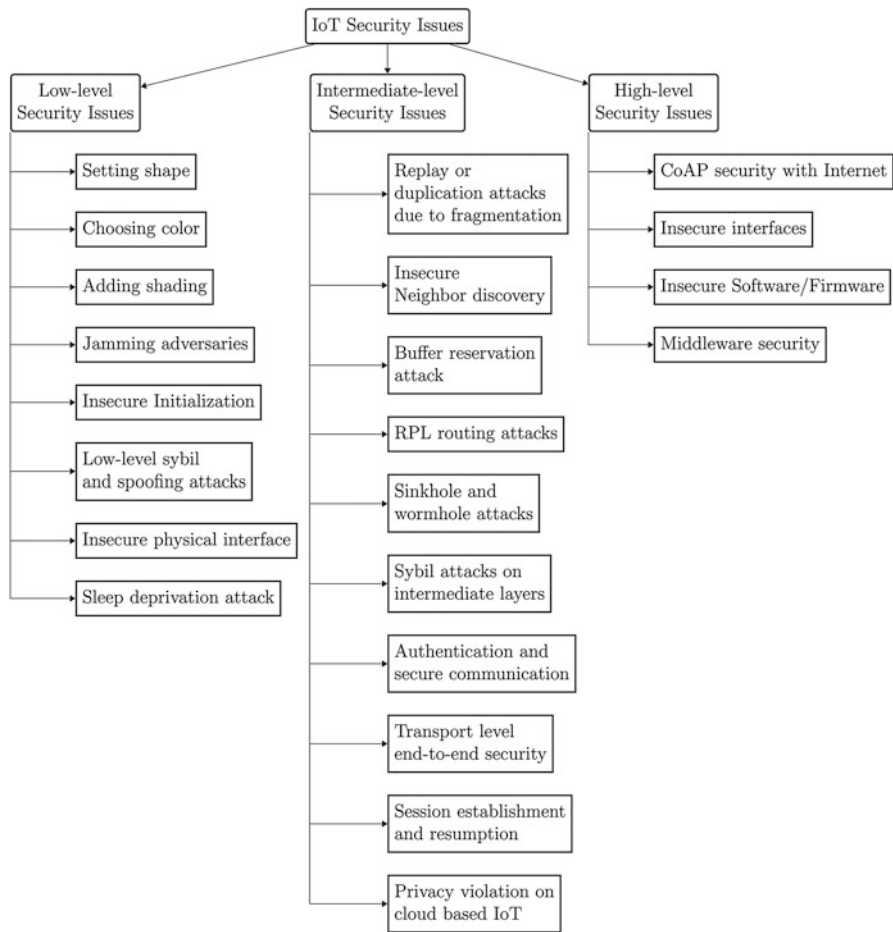


Fig. 10.1 Security issues in IoT [44]

configurations, networking capabilities, nature of data collection storage, access and actuation capacity). These risk identification and categorization includes [28]:

- A major factor for sustainability IoT risk categorization is consideration of things based on their information-related capabilities [28]. The sustainability IoT can be characterized into active and passive. The examples of the passive devices, which have no actuation capability, include water pH and nutrient sensors, in sustainable water IoT, soil moisture sensor in sustainable agriculture IoT. The active things collect data and also act as actuator to make changes in the physical world. The examples of active things include center pivot system controllers based on soil moisture sensing which are used in sensor-guided irrigation management systems and also in reservoir monitoring for flow control in dams.

- The physical accessibility of sustainability IoT is considered to establish the risk category. For example, underground soil sensors for monitoring physical, chemical, and biological properties of soil in decision agriculture are hard to locate, access, and excavate. Similarly, sensors in ocean floors, rivers, and other water bodies, in urban underground infrastructure, and mines are difficult to access. The remote access and authentication features should also be identified.
- The communication capabilities of these devices from short-range to very long-range communications using different mediums such as central office wire line, wireless, cellular networks, cable and broadcasting systems, and satellite communications should also be considered for risk categorization. Each of these communication mediums presents diverse challenges in terms of risk identification. Moreover, the types and duration of data collection transmission should be analyzed to characterize risks.
- The power source and energy efficiency are vital for sustainability IoT risk characterization. The things can be either battery powered or hard wired. Accordingly, energy-harvesting mechanism and power transfer mechanism to enhance battery life should also be considered [36].
- The IoT authentication capabilities, device software graduation, and patching approaches are also used to determine risks. It includes system and network authentication and device access identification. The personally identifiable information (PII) poses high risks [96].
- The sustainability IoT firmware and software module complexity and configuration are also fundamental components of the risk identification and categorization [17].

Accordingly, based on sustainability IoT risk categorization, the risk mitigation goals and areas are defined based on the significance of the risk categorization identified in the first step. These risk mitigation challenges and recommendations in different areas are discussed in the following [15, 68]:

- To prevent unauthorized access to system, adequate logical and physical access procedures should be instituted using the state-of-the-art authentication mechanisms. Moreover, all access and use of resources by anyone should be logged properly for proactive avoidance.
- For the purpose of efficient management of cybersecurity risks, a database should be maintained for IoT and their operational characteristics (firmware version, services, functionalities, and software version) as discussed above. This should also include all relevant information about the device status.
- Keeping track of software and hardware vulnerabilities is useful to reduce exposure of system to digital attacks. Accordingly, these vulnerabilities can be fixed by employing a systematic approach.
- The data generated from all phases of sustainability IoT life cycle should be protected at all stages during sensing, collection, transmission, analysis, and visualization from manipulation and compromise by using best cryptography and security practices.

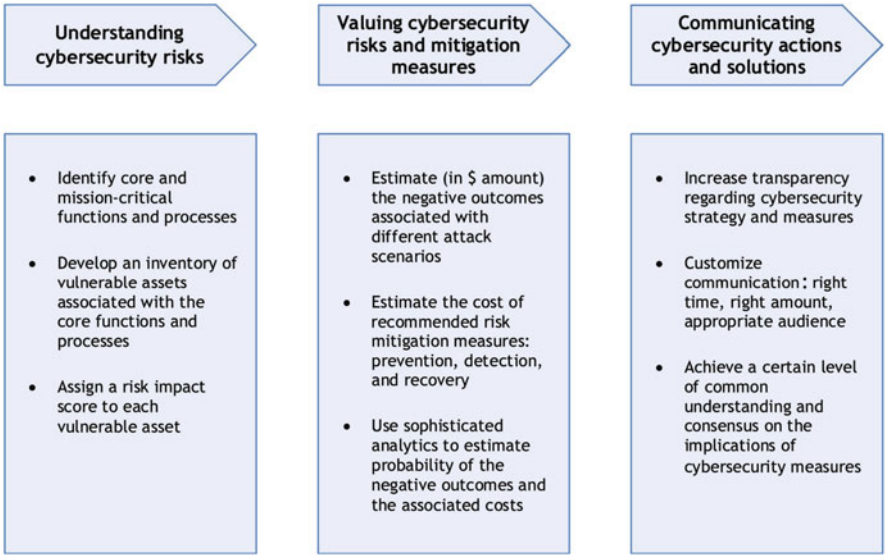


Fig. 10.2 A cybersecurity risk management road map

- A continuous monitoring of data and devices is important to identify any incidents of data and security breaches, vulnerabilities, and bugs.

The next step in securing sustainability IoT paradigm after identification of cybersecurity goals and areas is implementation of these goals (also called the cybersecurity feature implementation). This process is performed considering the technical specifications of sustainability things (e.g., hardware needed to support a particular feature keeping in view the current in future needs). The emphasis is on hardware-based feature implementation because of efficiency and use of some of the existing built-in features in the devices. A cybersecurity risk management road map is shown in Fig. 10.2. In this process, system performance is also monitored to identify any adverse impacts of the features. The adoption of a system-level approach has tremendous potential where all elements of the sustainability IoT are considered such wireless communications and interaction with other things. For example, precision agriculture cybersecurity features should be implemented considering all farm equipment and privacy issues [1].

There are many common security vulnerabilities that go unnoticed during development and shipment phase. The update-related issues that are generally observed include user/devices never getting an update (inability in terms of device capabilities), failure of the vendor to send updates (due to absence of autonomous sending patches and updates), and user’s failure to apply updates.

Moreover in the absence of adequate authentication and encryption mechanisms in place, the update and patch push approach is unlikely to be successful because of security issues and devices can be compromised. Moreover, data theft issue

can happen at unsecured device (no or plain text passwords), cloud (man in the middle attack), and network communication levels (no encryption). The detailed IoT security considerations at different levels are outlined in the following:

- At data and application layers in IoT Applications: It includes malware, theft of data, unauthorized access, man-in-the-middle attacks, unauthorized software, spoofing, fraud, denial of service, and inconsistent software versions.
- At networking level: It includes denial of service, spoofing, protocol tampering, hijacking, clear text communications, false base station, man-in-the-middle attacks, and lack of monitoring.
- At device level: It includes back doors and call home functions, reverse engineering, unauthorized software, side channel, device cloning, proxy acts, and resource limitation.

10.1.1 IoT Security Principles

The US Department of Homeland Security in its report Strategic Principles for Securing the Internet of Things (IoT) has defined the following principles to address IoT security challenges [24]:

- Incorporate Security at the Design Phase
- Advance Security Updates and Vulnerability Management
- Build on Proven Security Practices
- Prioritize Security Measures According to Potential Impact
- Promote Transparency across IoT
- Connect Carefully and Deliberately

10.1.2 Digital Forensics in Sustainability IoT

The digital forensics in sustainability IoT deals with the investigation of data on IoT and digital devices related to legal matters and computer crime. Currently, there is no standard set of guidance for data retrieval for the purpose of the litigation investigation in case of cyber compromise, theft, or other crimes. To meet this requirement, there is a need for collaboration to cyber, digital, computer, and network forensics experts, industry, and government authorities.

10.2 Openness Paradox and Data Dichotomy: Privacy and Sharing

In sustainability IoT, data collected at large spatial, temporal, and environmental scales carries a huge economic value. The openness and data flow are of vital

importance for decision support systems and for developing sound data-driven practices, and at the same time requires protection as well [30]. In this section, the challenges of data sharing and privacy in sustainable IoT are discussed in detail.

10.2.1 Privacy in Sustainability IoT

The identification of privacy regime and concerns is important in sustainability IoT due to the sensitive nature data in sustainability IoT. Due to its large-scale sensing and data monitoring capabilities, the enormousness amount of data is being generated in different paradigms such as climate, water, energy, and health. In this regard, the data privacy and protection is being considered pivotal for successful functionality of the system. However, different IoT generate different amount of data. One big motivation for protecting data is to avert users data being revealed and to block circulation of protected information. For the first case, well-designed sifting approaches can be used to curb revealing individual information. For proprietary information, formation of proper training is vital to protect dissemination of the data.

10.2.1.1 Data Sifting

Data sifting is an important privacy mechanism to ensure privacy and achieves balance between the scenarios of no data sharing at all and everything being shared. This approach also ensures that the important information and data about climate change, water, and health-related issues while protecting the privacy of individuals (e.g., age, name, address, location, and social security numbers). However, removing this information entirely makes gender-, age-, and location-based analysis impossible to conduct.

Another important privacy-achieving mechanism also called the differential privacy includes adding a well-calculated noise to the aggregated understudy data set such that results are twisted to make identification of the individuals difficult. In this approach, the exact data is replaced with range and data granularity is reduced statistics based data summarization. The quantity and quality of noise depends on the size of data set being analyzed. Accordingly, machine learning [14] can be used for data mining and to construct models from the data. An aggregation approach is shown in Fig. 10.3.

10.2.1.2 Proxy Data Analyzer

In this approach, intelligent proxy data analyzers are used to process data based on the data request. This approach enables selective data sharing across different domains based on metadata, data sensitivity, and previous requests. Using proxy

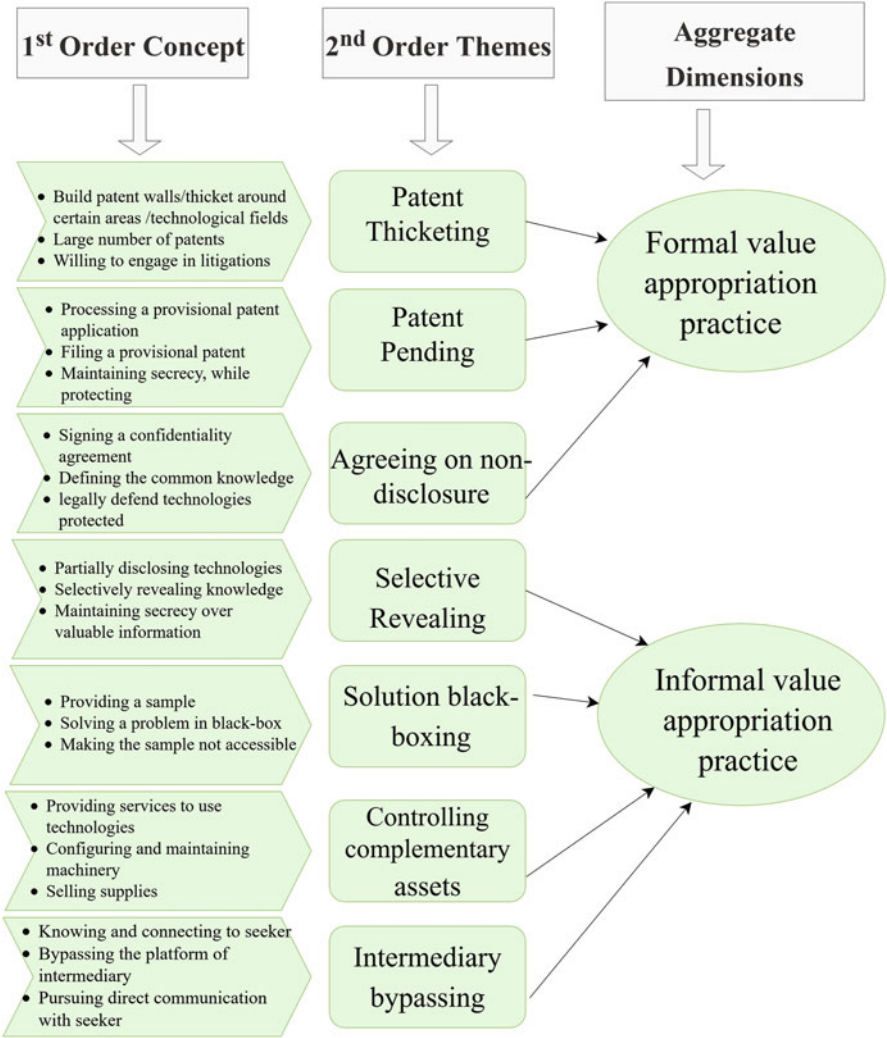


Fig. 10.3 An analytical aggregation approach [30]

data analyzer, multiple sustainability IoT data sets can be combined to regional to universal planning. The FLEX is an example of proxy data analyzer that provides differential results by using a set of precomputed data metric. These privacy-preserving approaches will enhance end user trust in system, hence removing barriers in technology adaption by encouraging innovation.

10.2.1.3 Multilayered Approach to Privacy

In a multilayered approach to protect privacy in sustainability IoT paradigm, each layer can guard against the specific set of data being revealed. For example, data element encryption added an additional layer of protection. Similarly, at the session and presentation layers, use of encryption mechanisms is useful to mitigate attacks conducted during data communications. In summary, the strong privacy protections will be helpful to advance the sustainability IoT paradigm.

10.2.2 Universal Data Flow, Sharing, and Standardization

The open flow of data and sharing coupled with best management practices brings tremendous value to sustainability IoT and is the lifeline of the entire ecosystem. The design of new data sharing platforms for sustainability has the potential to bring robust policy planning and decision making in different areas such as environment.

10.2.2.1 Significance of Data Sharing

The data localization inhibits global-scale mitigation, cross-border forecasting, and planning efforts, whereas more socioeconomic and environmental benefits can be realized by global sharing. For example, in energy sector, loads can be identified and proper system planning can be done. Similarly, in health sector, the underlying causes of spread of a particular disease in affected communities can be established, which will also be beneficial for world population at large to prevent disease outbreak. In transportation, better public services can be designed. Similarly, the availability of timely and certain data has a vital role to play in improving the urban underground infrastructure monitoring. It can also facilitate the development of monitoring systems for sewer and storm water overflows through real-time operation. The data localization also presents a barrier to international adoption of different sustainability IoT paradigms. In this regard an establishment of a global cloud for sustainable IoT will be a good step in the right direction. The data flow and sharing can be conducted at two levels:

- At strategic level (community and large geographical level): to give certain pertinent data about the community to policy makers for analysis and strategic decision making
- At tactical level: for local operation, planning and forecasting, and behavior identification to understand and address the societal, social, and environmental issues and challenges.

10.2.2.2 Data Standardization

The deployment of sustainability IoT devices in different infrastructures with multitude of sensors and instruments provides many tremendous avenues for valuable data collection. The data collection from different sustainability IoT can be classified into (1) exhaust, (2) sensing, (3) crowdsourcing, and (4) web-based. However, different schematics and data access procedures, variations in data storage formats, and difference in spatial and temporal granularity present big challenges in combining, comparison, analysis, and interpretations of these data sets.

The data standardization deals with data storage and management using reliable mechanisms in structured format to enable large-scale data analytics. The availability of structured data makes it extremely easy to make futuristic predictions. Accordingly, advanced data analytics can be used to predict, estimate, diagnose, and prognose events and outcomes from past and current data flows in real time. It also enables a consistent aggregation of data across different sources and places. Accordingly data-driven and analytical models can be developed in different areas related to sustainability (e.g., renewable energy profiles, weather forecasting, water monitoring planning, and analysis for sustainable community development).

10.3 Opportunities and Challenges in IoT for Sustainability

The IoT has strong potential to transform different sustainability areas using sensing and communication technology. It is capable of effectively responding to the current environmental, energy, water, and health challenges using the technology and hence can achieve the sustainability goals and bring improvements to quality of life. Its sensing and monitoring brings benefits to the society by fixing environmental issues, and also guides regulations and policy making. For example, sensors in water bodies are used to obtain useful information about the quality and flow of water, which helps in waste and treatment management. Similarly, soil sensors provide useful information about the physical, chemical, and biological proprieties of the soil which aids in improving crop yield and water resource conservation. Yet, bountifulness of these opportunists comes with many challenges at the technical level and policy level. These challenges are discussed in the following section.

10.3.1 Technical Challenges

The challenges in IoT for sustainability are:

- Sustainability data management. Novel approaches are needed for data collection, storage, sharing, and analysis due to size, scale, and distributed nature

- In privacy and cybersecurity, and equitable access regarding exposure, manipulation, and misuse of critical data
- Lack of encryption, resources for a certain level of protection, privacy guidelines, and protection against malicious cyberattacks
- Sustainability device homogeneity increases vulnerability of cascading and repetitive attacks
- Existing public infrastructure compatibility and integration issues. Lack of interoperability (at network, system, and data formatting levels) causes data silos, redundancy, and inefficiency

10.3.2 Policy Challenges

Smart global and national strategies for public regulations and policies, based on environmental, social, and economic factors, are critical for the success of sustainability IoT to deal with huge challenges in meeting sustainable development goals. The policies developed using collaboration and civic engagement will have strong impact on sustainability. The policy-level challenges and sustainable actions recommendations are discussed in the following section:

- Need of inclusive collaboration and civic engagement planning among different sectors keeping in view the current and future needs. For example, sensing in one area has the potential to meet the needs of other area too (e.g., carbon dioxide emissions in energy, climate, and transportation). In this regard engagement with public, academia, and private industry is also of vital importance to develop and deploy the state-of-the-art technologies.
- Community engagement should also be focused on people participation and citizen engagement. The sustainability things will be useless and wastage of resources and other infrastructure if citizens are unable to use the system. In this regard, providing access and expansion of services to rural broadband will certainly increase access to these systems. The constituency resources and demographics are of fundamental importance for the planning and deployment purpose.
- Policies for data access, ownership, and stewardship.
- Policies to mitigate behavior change resulting from the deployments of sustainably IoT systems.
- Development of trust and reliability frameworks.

10.4 Progress in IoT Security Standardization

The full potential of sustainability IoT will be realized only if it operates in an open and secure environment. Different security groups and industry are developing tech-

nology and security standards to promote interoperability, and to encourage open and secure cross-border data communications. The different technology and security groups for IoT and their standardization efforts are discussed in Table 10.1 [59].

10.5 Case Studies

In this section, different sustainability IoT cybersecurity case studies are discussed. First, the case study of cybersecurity and data privacy in digital agriculture is presented.

10.5.1 *Cybersecurity and Data Privacy in Digital Agriculture*

The digital agriculture has been envisaged as a novel archetype to transform present-day agricultural practices by real-time sensing, processing, and collection of data for the purpose of developing efficient seeding and irrigation techniques, fertilizer applications, and other farm operations [3, 9, 26, 35, 52, 71–79, 81, 83–88, 94, 97]. Many security threats are emerging in the nascent field of digital agriculture (also referred to as decision agriculture and precision). In digital agriculture, various types of sensing and communication technologies are used (e.g., in situ sensing, remote sensing, machine learning, and data analytics.) Hitherto, the agriculture field was dependent on mechanical device and technology use was minimal. Accordingly, by using these networked technologies for sensing and data collection, different types of field inputs such as water for irrigation, fertilizer, and pesticides can be applied precisely in agricultural farms that improve efficiency, bring enhancements in crop yield, and lower costs. However, with this rapid growth of agricultural technologies, there is corresponding increase in vulnerabilities. In this section, we discuss those vulnerabilities, prospective threats, and solutions.

It is important to note some of the common threats (e.g., malware, theft of data, unauthorized access, man-in-the-middle attacks, unauthorized software, spoofing, fraud, denial of service, and inconsistent software versions) found in conventional connected systems also pose risks in the field of digital agriculture [27, 70]. Therefore, these can be identified by using the conventional risk characterization approaches discussed in this chapter, and, accordingly the same established risk mitigation can be applied. However, due to distinctive operation of the farm machinery, equipment and underground sensors, and vast area of exposure from field to farms, various types of new threats are emerging which were not observed previously with a wide range of ramifications. These consequences range from interference to routine fieldwork to total disruption and unavailability of farm operations and compromised integrity and confidentiality of farm data. Moreover, the data leakage and theft negativity impact the agricultural resiliency and sustainability.

Table 10.1 The IoT technology and security standard developments activities [59]

Organization	Description
IoT Cybersecurity Alliance	A group of industry leading cybersecurity and IoT experts to help address the challenges that exist across the IoT ecosystem
Cloud Security Alliance	Best practices and research
Alliance for Internet of Things Innovation	It aims to strengthen the dialogue and interaction among Internet of Things (IoT) players in Europe, and to contribute to the creation of a dynamic European IoT ecosystem to speed up the take up of IoT
Broadband Forum	A nonprofit industry consortium dedicated to developing broadband network
European Telecommunications Standards Institute (ETSI)	Produce applicable standards for ICT-enabled systems, applications, and services deployed across all sectors of industry and society
GSMA IoT Security Guidelines	It includes 85 detailed recommendations for the secure design, development, and deployment of IoT services that cover networks as well as service and endpoint ecosystems. It addresses security challenges, attack models, and risk assessments while providing several worked examples
IEEE Internet of Things	Security and Encryption Standards. IoT security issues and vulnerability
Industrial Automation and Control System Security	It develops security standards and technical reports
Industrial Internet Consortium (IIC)	Security-related architectures, designs, and technologies
International Electrotechnical Commission (IEC)	International Standards and Conformity Assessment for all electrical, electronic, and related technologies
International Organization for Standardization (ISO) IoT Standards	Develops standards for security
Internet of Things Consortium	IoTC is a nonprofit member-based organization connecting a global ecosystem of leading companies building the Internet of Things
IoT Security Foundation	IoTSF is a collaborative, nonprofit, international response to the complex challenges posed by security in the expansive hyperconnected world
ITU-T SG20	An emerging standard
National Institute of Standards and Technology	CPS PWG cyber-physical system (CPS) framework, and NIST cybersecurity for IoT program
North American Electric Reliability Corp	Responsible for reliability and security of the bulk power system in North America
oneM2M	It is a global standard for machine to machine communications and the Internet of Things
Online Trust Alliance	OTA is convener of a multi-stakeholder initiative to address public policy and technology issues impacting IoT devices

(continued)

Table 10.1 (continued)

Organization	Description
Open Connectivity Foundation	The open connectivity foundation (OCF) is a group of over 300 technology companies, including Cisco, Intel, and Samsung, and is developing interoperability standards for the IoT and sponsoring an open-source project to make this possible
Open Mobile Alliance (OMA)	OMA device management security describes general security requirements, and provides description of transport layer security, application layer security
Open Web Application Security Project	The OWASP Internet of Things project is designed to help manufacturers, developers, and consumers better understand the security issues associated with the Internet of Things, and to enable users in any context to make better security decisions when building, deploying, or assessing IoT technologies
OpenFog Consortium	Enabling advanced IoT, 5G and AI with fog computing
SAFECode	The software assurance forum for excellence in code (SAFECode) is a nonprofit organization dedicated to increasing trust in information and communication technology products and services through the advancement of effective software assurance methods
Smart Grid Interoperability Panel (SGIP)	SGIP is an industry consortium representing a cross section of the energy ecosystem focusing on accelerating grid modernization and the energy Internet of Things through policy, education, and promotion of interoperability and standards to empower customers and enable a sustainable energy future
Thread Group	Thread was designed with one goal in mind: to create the very best way to connect and control products in the home
The Update Framework (TUF)	The update framework (TUF) helps developers to secure new or existing software update systems, which are often found to be vulnerable to many known attacks
US Food and Drug Administration (FDA)	Management of postmarket cybersecurity vulnerabilities for marketed and distributed medical devices
US Department of Homeland Security (DHS)	Strategic principles for securing the Internet of Things
3rd Generation Partnership Project (3GPP)	A global initiative that unites seven telecommunication standard development organizations (known as “organizational partners”), the 3GPP develops specifications covering cellular network technologies, including radio access standards
Internet Engineering Task Force	IoT Standards
CIS Center for Internet Security	CIS is a forward-thinking nonprofit that harnesses the power of a global IT community to safeguard public and private organizations against cyber threats

10.5.1.1 Information Privacy in the Field

In digital agriculture, the data privacy is a major issue in relation to technology implementation. Recently, plenty of critical data has been collected by farmers about their farms such as crop yield data which they are reluctant to share due to different factors (e.g., finance, market trends, and soil value) [104, 105]. Across a typical agricultural farm, many variations in soil texture, nutrients, and volumetric water content are observed [77]. The agricultural technology is used in these temporal and spatial variations to ascertain field conditions for variable applications of fertilizer and irrigation in order to maximize yields and profits which provides financial gains to farmers. To determine field conditions for best resource allocation, various technologies (e.g., GPS, GIS, and sensors) are being used where data can be collected and stored in cloud for processing.

Since, at large spatial scales, the soil texture and rain data is highly correlated, the cloud data collected from multiple farms can be utilized for decision support systems at regional levels. For example, soil moisture data along with temperature across different farms can be used to inform irrigation decisions [26]. Consequently, with this benefit, the data privacy becomes a concern particularly in geospatial usage of privacy information [19]. For the reason that location data is used by vendors, dealers, and digital agriculture service and equipment providers for developing analytics, improving service and for creation of new business models, the security threats and attacks make the farmers data exposed and vulnerable.

Such security breaches are detrimental as not only the farm's equipment and sensing data is revealed, the other proprietary information is laid bare such as irrigation cycles conducted in a typical growing season, software design and version, seeding approaches, and yields. Since the success of the farming depends on these, therefore, the farmers keep these information confidential. Currently, in the developing area, there is a dearth of mechanisms to protect data privacy [49]. One privacy protection mechanism that has applications in this area is obfuscation (see Fig. 10.4) where exact location information is replaced with confusing and ambiguous information. However, this will render geographic services unable to function because of lack of true data. Moreover, the obfuscation techniques are also vulnerable to the location deduction attacks. Thus, in digital agriculture, advanced mechanisms to protect privacy and location information without surrendering the location information are needed.

Farm data privacy-related threats in digital agriculture are discussed in the following [29, 105]:

- Deliberate stealing or unintended leakage of farmer information from decision-making systems and other agricultural information management systems to third parties. This targets mobile and tablet apps on the farm equipment and farmer phones. Currently, these applications lack update features and privacy protection mechanisms [92, 105].

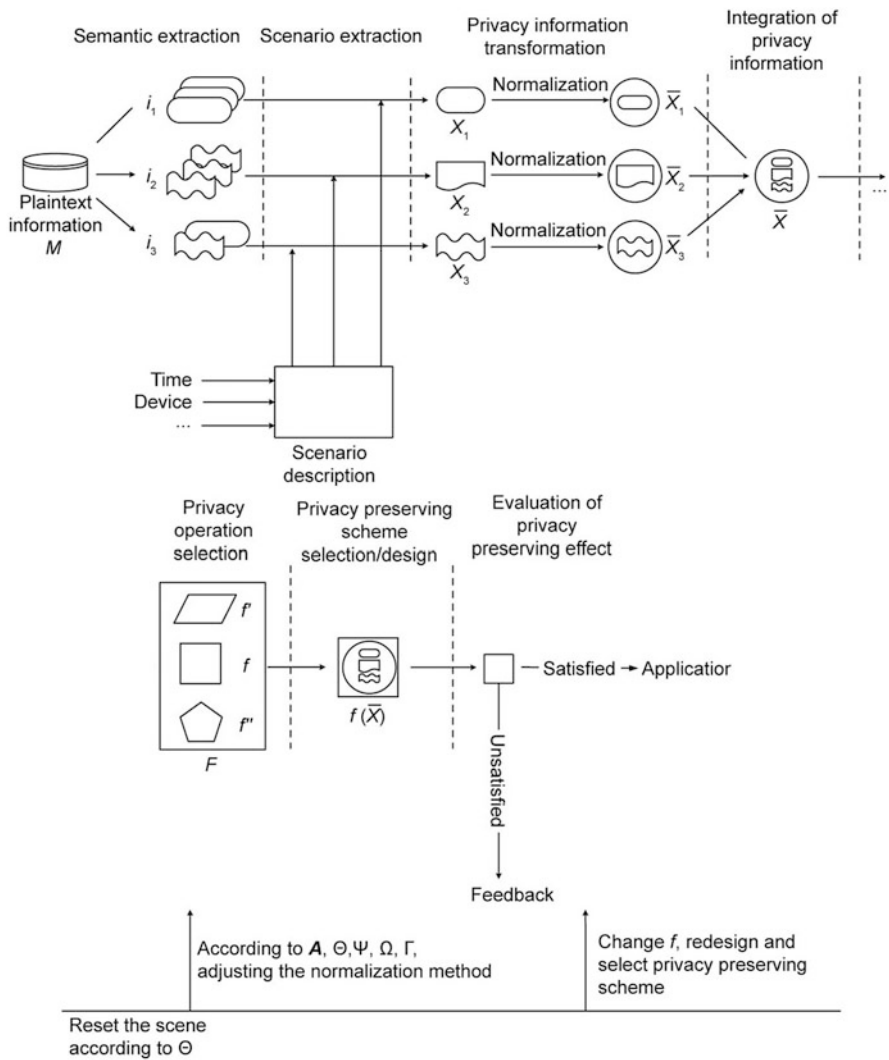


Fig. 10.4 A privacy computing framework [49]

- The purposeful publicizing of information to harm a company’s reputation and sow mistrust about technology in farmers’ minds leads to hindrances in adaption of decision agriculture [105].
- The exploitative trading of confidential data, where companies are approached to sell farmers data in return for some incentives [33].

10.5.1.2 Data Usability in the Field

In digital agriculture, sensors are being used for condition monitoring and real-time decision making at different temporal and spatial scales that cause data consistency issues. These challenges are discussed in the following [76]:

- Publishing of false data about crop disease or other related agriculture to create fears among farmers [70, 105].
- Injection of false data into the sensing networks to create false alarms or trigger harmful actuation such as overirrigation and underirrigation [81, 89].
- Inefficient control algorithms for farm machinery and other in-field equipment.

10.5.1.3 Farm Equipment and Data Availability in the Field

Because agricultural farm operations are heavily dependent on the farm equipment, therefore the data loss is the major challenge in the field. In this major disruptions to the availability are:

- There are some critical time windows in every crop where the of equipment usage is at its peak such as combination in the harvesting systems, center pivot, seeders during planting season, and drip irrigation systems in long dry weather or short-term droughts. Loss or malfunction of equipment during these intervals is detrimental to the crop health. It can also cause crop yield reduction leading to the financial loss to farmers. Attacks conducted to exploit vulnerabilities in the equipment can cause large-scale food shortage and harm the vendor's reputation [6].
- The overcrowding of wireless spectrum can cause disruptions to the wireless systems and GPS signals in the agricultural farms. The overcrowding of the spectrum can also lead to improper and unpredictable functionality of the system. The Federal Communication Chart (FCC) has permitted the use of the cognitive radio devices in the spectrum range of 470–698 MHz on farm machinery and agricultural equipment for digital agriculture applications [80].
- The limited availability of rural broadband leads to loss of data, slow data rate, maintenance downtime, and frequent service outages. The wireless communications can also be used to exploit the data being transferred in plain text [62].

10.5.1.4 Cybersecurity Recommendations for Precision Agriculture

Some important recommendations for protection of precision agriculture systems in the field are discussed in the following [16, 51, 103]:

- Security of applications and software being used in the field on farm equipment can be achieved using latest updates, patches, and security mechanisms [93]

- Blocking of communication loopholes by using strong encryption standards for data transfer, and blocking services and protocols not required for device functionality. The implementation of the latest security standards will also reduce risks [12]
- An updated record of device functionality, software, and current status. The continuous monitoring and logging of the device access to verify authorized users. Understanding of data ownership, protection, and recovery protocols is also useful to develop proper incident response strategy

10.5.2 Smart Grid

In modern smart grid systems, disruptions in one system can lead to cascading effects in the entire power system [40]. The cyberattacks in grid can cause substantial losses. There is strong need to increase the reliability of these systems by protecting them from cyberattack by incorporating the cybersecurity in the design process. This can be achieved through development of reference security architecture. An example of cybersecurity architecture for the power grid is shown in Fig. 10.5. The design of the next-generation power grid system including renewable energy systems can benefit from this which is based on the IP networking.

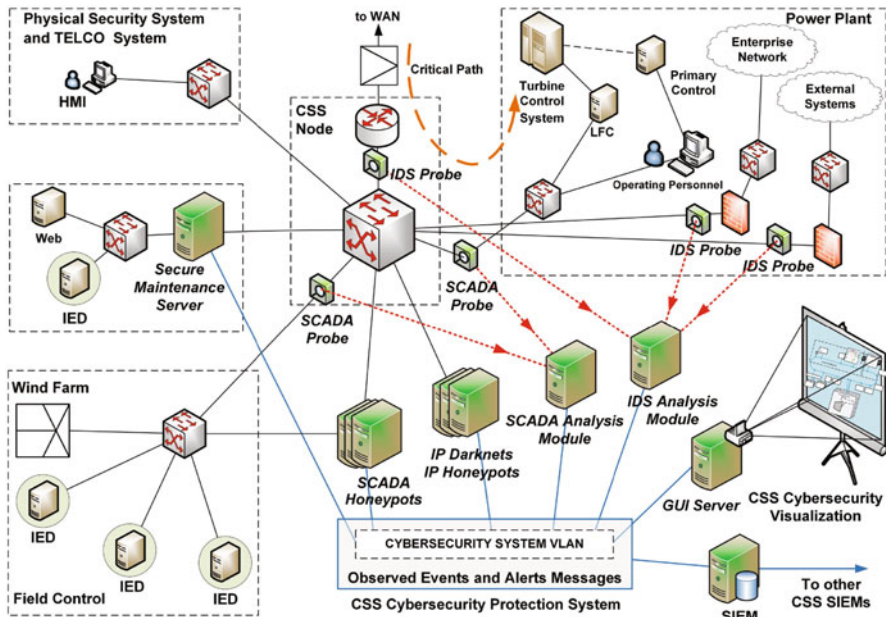


Fig. 10.5 A power grid control system and the designed cybersecurity protection system [40]

10.5.3 Health and Cybersecurity

The cybersecurity vulnerabilities and threats can affect the availability of critical lifesaving medical equipment and data. The cybersecurity threats can cause physical impact in patients and hinder the regular hospital operation leaving them unable to provide care [34, 37]. Therefore, attaining the highest level of cybersecurity in healthcare is important for patient safety. The identity theft, ransomware, and targeted patient hacking are some of the vulnerabilities. Other issues are addressed in the following section.

10.5.3.1 Critical Conditions of the Healthcare Cybersecurity

The challenges being faced by the healthcare industry in the area of cybersecurity are discussed below [37]:

- Healthcare industry is facing lack of expert security professionals.
- The legacy equipment is either old or unsupported and contains vulnerable operating systems. The funding dearth allows unsupported equipment to continue functioning.
- The network design is focused heavily on hyperconnectivity with less focus on security [31]
- The patient care outage incidents such as locking by ransomware are serious threats to healthcare industry [11]
- Unwillingness to address known vulnerabilities [42]

10.5.3.2 Healthcare Cybersecurity Objectives

The healthcare security objectives for different patient safety aspects are [1, 21, 34, 67]:

- Confidentiality. The protection of patient information from unauthorized disclosure and access [61].
- Integrity. The protection of patient safety from unauthorized modification of the adequate use of the medical device [102]. It includes the unauthorized access and modification of patient identifiable information including protected health data. The safety of patients' systems from malicious unauthentic actuation, protection of patient physiological data modifications to ensure correct functionality of the software (e.g., processing and algorithmic capabilities) particularly in the monitoring, and treatment components of the system are of critical importance.
- Availability. Ensuring the availability of patient information and medical equipment to authorized entities on a need basis [50]. It includes rapid updates, secure and authenticated patches, and updates to the equipment, and correct usage of the device for the right purpose, thus ensuring and maximizing optimum functionality.



Fig. 10.6 A list of healthcare cybersecurity risks

Therefore, continuing cybersecurity risk management is important to use secure state-of-the-art technology [108] to safeguard medical devices and their updates [41]. Some potential cases of risks in the connected medical systems are shown in Fig. 10.6.

10.5.4 Smart Meter

A smart meter is used for electricity usage monitoring. It is used to transmit data to service providers using various types of communication links where this information is used for customer billing, load balancing, energy consumption

analysis, and price optimization. The cybersecurity threats related to the smart grids and meters include [39, 45, 46, 63, 98, 98, 107]:

- Malicious attack to disconnect utilities service resulting in loss of power [95]
- Coordinated cascading network attacks on grids, using compromised meters [23]
- Theft and break-in planning when the homeowner is away based on the analysis of energy usage [55]
- Denial of service attacks where legitimate requests by the utility service provider are rejected [13]
- Data injection attack to produce invalid measurements of energy consumption [5]
- Smart metering privacy compromising attacks and man-in-the-middle attacks [69]
- The meter spoofing, authentication attacks, and disaggregation attacks are some of the other examples [109]

The smart metering cybersecurity threats are shown in Fig. 10.7.

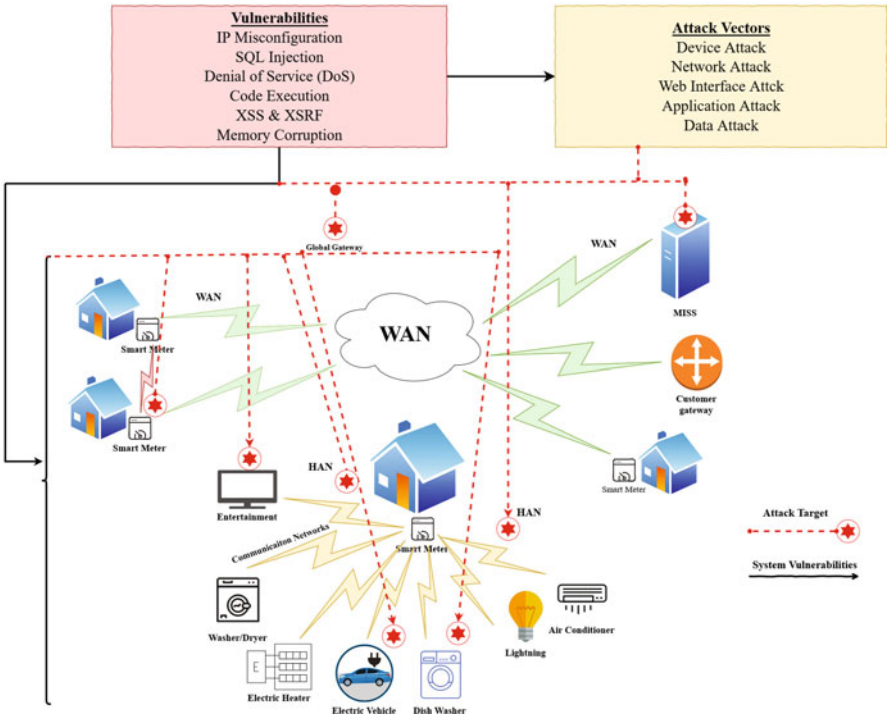


Fig. 10.7 The cybersecurity threats in smart meters [98]

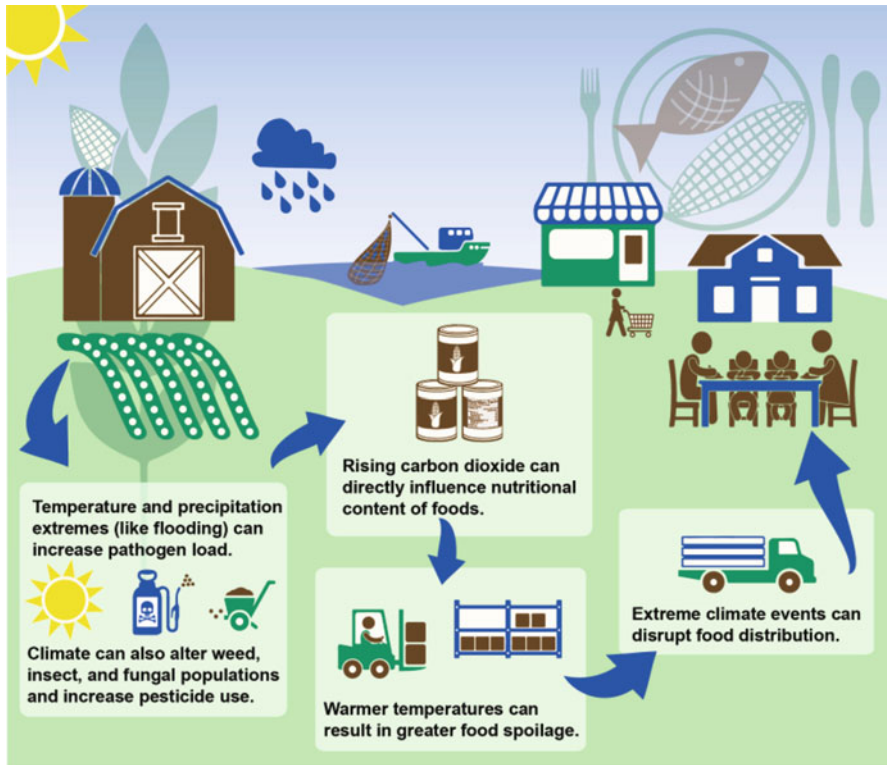


Fig. 10.8 The contamination cycle [99]

10.5.5 Water Systems

The freshwater is crucial for life on earth. The water systems face different types of threats such as natural, caused by human activity, disasters, droughts, earthquakes, and terrorism [20, 56, 66]:

- The contamination attacks and other terrorism-related activities, flooding, and storms are the direct threats to these systems [4]
- The water scarcity and lack of water resource availability are also major threats to the sustainability [8]
- Threats of contamination and pollution from point sources and nonpoint source and biodiversity loss [48] (see Fig. 10.8.)
- The climate-related threats on water [18, 22, 25, 47, 57, 60, 64, 100, 106]

The water system security threats can be mitigated by water system risk characterization and use of sustainable water IoT contamination monitoring and warning systems and through use of advanced machine learning systems for threat modeling [38, 65].

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Chapter 11

Medium Access in Internet of Things



11.1 Medium Access Control

Medium access control (MAC) is one of the important features of wireless networks. wireless underground sensor network (WUSN) architecture is distributed where each sensor attempts to communicate in a shared wireless channel [44, 45, 49, 50]. Therefore, to implement an optimized and efficient WUSN, it is very important to improve the sharing mechanism by improving MAC protocols for WUSNs [6, 7, 9, 12, 14, 43, 46–48, 51]. These MAC protocols are analyzed by performing the underground-to-underground (UG2UG) communication experiments and simulations. The analysis shows that the behavior of communication parameters, e.g., interference and carrier ranges, is completely different for underground than what it is in over the air (OTA). This significant difference results in increased contentions leading to large amount of packet collisions. A model is developed to capture the effect of soil on the performance of medium access in an attempt to propose a novel MAC solution for underground sensor networks and eliminate possible shortcomings. Here, the MAC protocols for (WUSNs) are described [45, 50]. This section discusses the performance of different traditional MAC protocols for underground environment, and study the feasibility of these MAC protocols for underground space and identify shortcomings due to complex communication medium [8, 10, 11, 13, 17, 26, 27, 53].

11.2 Performance Analysis

The topology consists of a total of five nodes [1, 46, 54, 55]. To capture different communication scenario, multiple experiments are performed with different number of nodes simultaneously transmitting the packets in each experiment. For each experiment, (1) all nodes have the same capabilities of sending and receiving

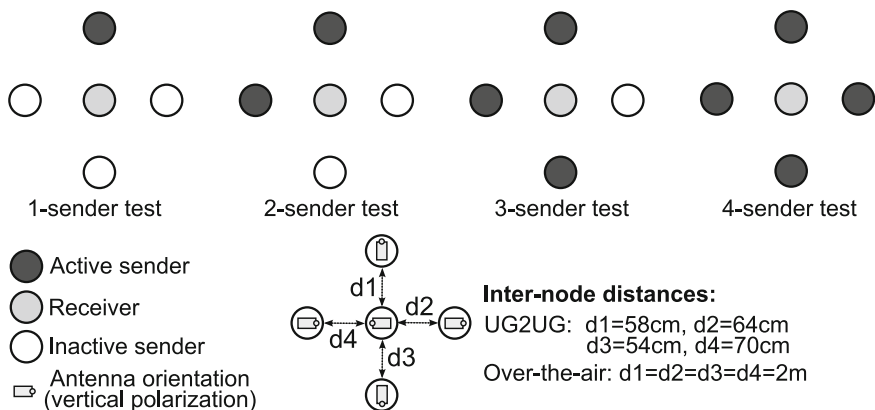


Fig. 11.1 Network topology and parameters for the experiments

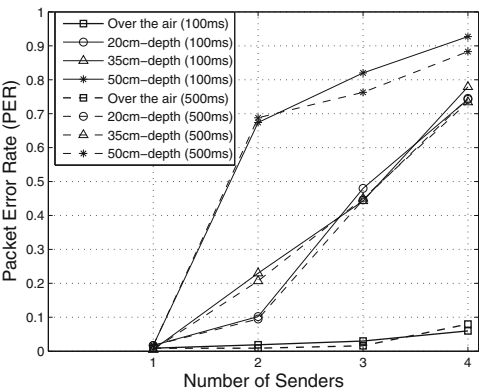
packets [47], (2) receive node receives packets from all sender involved in the experiment, and (3) it is not possible for a sender to receive packets from another sender. The number of packets was limited to 1000 for each experiment. For each successfully received packet, received signal strength (RSS) of the packet is also recorded. Moreover, RTS/CTS and ACK were disabled, but CCA was enabled for the experiment (Fig. 11.1).

11.2.1 Packet Error Rate

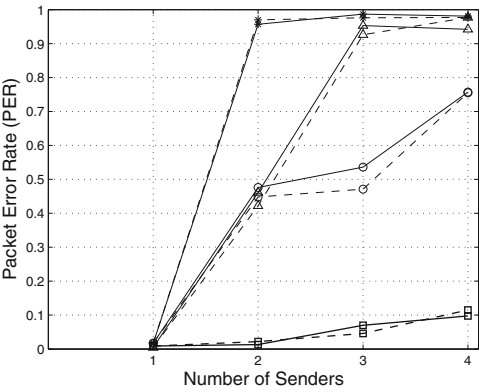
Packet Error Rate (PER) gives the idea about the number of incorrect packets arrived at the receiver. To that end, PER is analyzed for the varying: (1) number of senders, (2) message size, (3) transmission interval, and (4) burial depths. OTA results are also presented for the comparison purpose. Figure 11.2a–c shows the results from all scenarios:

- *Message Size*—It can be seen in Fig. 11.2a–c that the size of the packet has a significant effect on underground contention. For example, consider the results for two senders with transmission interval 100 ms. For message sizes of 10, 80, and 50 bytes, PER are 10.2%, 47.6% and 69.9%, respectively. It is important to note that message size is not affecting the OTA performance that much. The reason is the efficient operation of CCA in OTA.
- *Burial Depth*—Burial depth also affects the communication performance. For example, consider the results for 2 senders with transmission interval 100ms and message size of 10 bytes (Fig. 11.2a). For burial depths of 20 cm, 35 cm, and 50 bytes, PER are 10.2%, 23.0%, and 67.4%, respectively. If the burial depth is increased to higher level, the hidden terminal problem [51] due to transmission contention is also increased. For lower depths, reflected components

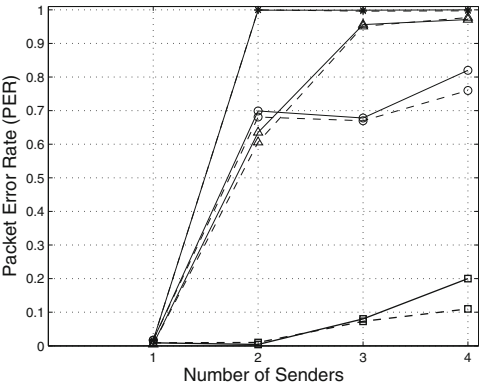
Fig. 11.2 Empirical contention results for different number of senders: (a)–(c) PER for 10-, 80-, and 150-byte message



(a) 10-byte packet



(b) 80-byte packet



(c) 150-byte packet

(from participating senders) is an important parameter to consider [43]. Such signals might not be strong enough to be decoded by any one sender, however can be detected by CAA process. Section 11.3 discusses this phenomenon in further detail.

- *Representative Cases* Fig. 11.3a shows the three representative cases for the experiments. It can be concluded that, even with the optimal combination of all the parameter values, total number of senders and burial depths are the dominant parameters which affect the communication significantly.

11.2.2 Received Signal Strength (RSS)

Figure 11.3b plots the normalized received signal strength (RSS) along with the total number of senders and varying depths. This scenario is also compared with the OTA. It is observed that RSS values do not change significantly with the change in the number of senders. Therefore, increase in PER with increasing senders cannot be regarded as channel error but collision in the channel. For depth values, the average RSS is decreasing as the depth is increasing. For example, 30 cm of increase in depth, i.e., from 20 to 50 cm, 17.3 dB of average attenuation is experienced. This behavior is similar to what was observed during the experiments in [10]. Moreover, PER is negligible for only one sender. Hence, comparing the observations, it can be concluded that the RSS and packet losses due to collision are not related.

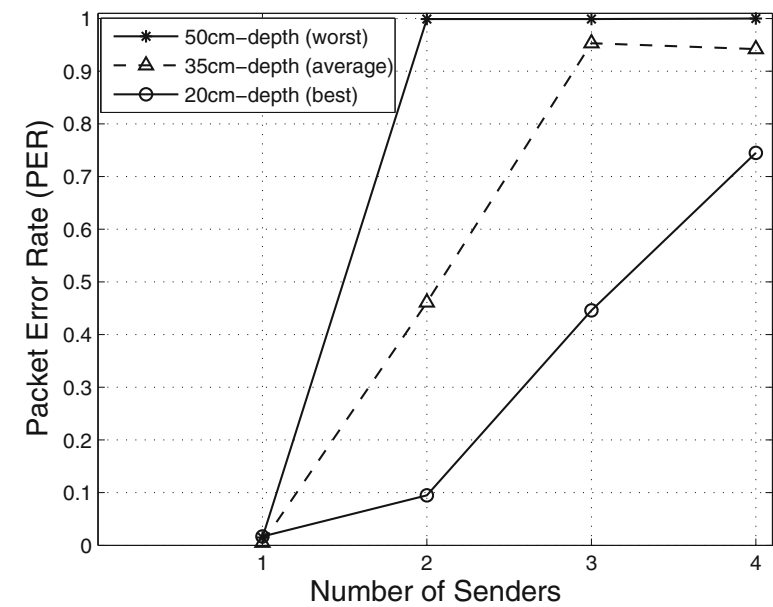
The discussion from empirical results can be concluded as follows: (1) contention degrades underground communication relatively more than OTA communications, and (2) using smaller burial depths mitigates the contention in underground. These results are used to develop a simulation model which is discussed with detail in Sect. 11.3.

11.3 Simulation Evaluations

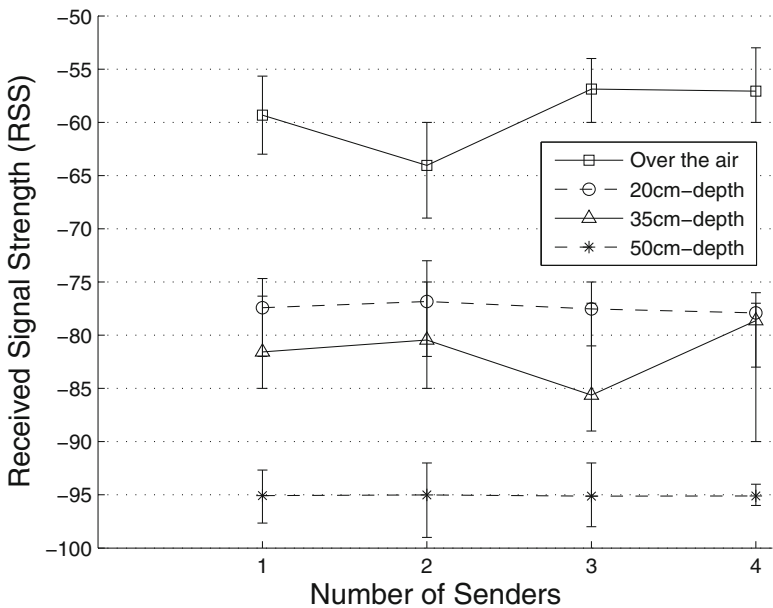
This section supports the results from Sect. 11.2 by a simulation model. There are a total of two inputs to this simulation model: (1) value of m which is used to create an $m \times m$ grid and (2) total one-hop neighbors of receiver also termed as senders in this literature. Senders range from 1 to 4. As an output, the model gives the PER values at receiver.

There are also some important shared parameters which are used by all the nodes. These parameters are given below:

- **Communication range** ($Comm_r$)—This is the node region where high-quality communication can take place. It is also known as *connected region* [23].
- **Interference range** (Int_r)—It is the contention region of the receiver. The region between the $Comm_r$ and Int_r is also known as *transitional region*.



(a) PER Summary: 3 cases



(b) RSS Summary

Fig. 11.3 (a) PER summary for three representative cases and (b) RSS for different burial depths

- **Carrier Sense range (CS_r)**—It is the region where node is susceptible to overhearing mechanism. A weak signal is difficult to decode; however, it can still be detected if it's in the CS_r region. $Int_r = CS_r$ in real radio communication environment.

Probability of occurrence of overhearing is given by using two empirical data sets. The data sets include empirically measured value for OTA and underground environment using 35 cm of depth. The values of $Comm_r$, Int_r , and CS_r are uniformly distributed for underground simulation. These values are varied 13% for each simulation iteration [14]. The random factor incorporates the sudden variation from empirical results from the scenario where message size of 80 bytes and transmission interval of 100 ms are used.

The model determines overhearing mechanism performance among the nodes and avoidable number of collisions on the basis of intersection between $Comm_r$, Int_r , and CS_r . The model performs a total of 1000 iterations to output the PER for senders. The burial depth is not used as an input parameter for the model. It is done intentionally due to the fact that smaller depth values are related to higher circular region values. Therefore, higher values of circular region will indirectly simulate for the lower depth values.

The values for the circular regions must be determined empirically for the basic cases. However, after using some empirical values, model should predict the PER for other values of the circular region. For OTA communication, empirical $Comm_r$, Int_r , and CS_r are 60 m, 88 m, and 105 m, respectively. It is important to note that these values are for the testbed discussed in Sect. 11.2 with sensor height of 1.5m and transmit power of +10 dBm. The experiments were also replicated for different burial depths of 20, 35, and 50 cm. Table 11.1 shows the model results in both absolute metric and *density-normalized* values.

A density-normalized value represents the distance between a node and its neighbor. This distance is given in terms of grid points. Consider an example for clear understanding: $Comm_r = 60$ m on a 10×10 grid will have a density-normalized value of 6 in the model. Using the same convention, input values of Int_r and CS_r to the model are 8.8 and 10.5, respectively. These values will differ for different deployment environment and topology. Table 11.1 also shows the OTA values for the circular region parameters. It can be seen that for a given node, a large number of neighbors exist in the CS_r region. Using higher region values along with high node density can result in reduced collisions occurring because of overhearing

Table 11.1 Communication ranges

Scenario	$Comm_r(m)$	model	$Int_r(m)$	model	$CS_r(m)$	model
Over the air	60	6.0	88	8.8	105	10.5
20 cm depth	0.61	1.0	0.82	1.34	0.92	1.49
35 cm depth	0.61	1.0	0.80	1.31	0.88	1.44
50 cm depth	0.61	1.0	0.78	1.27	0.83	1.36

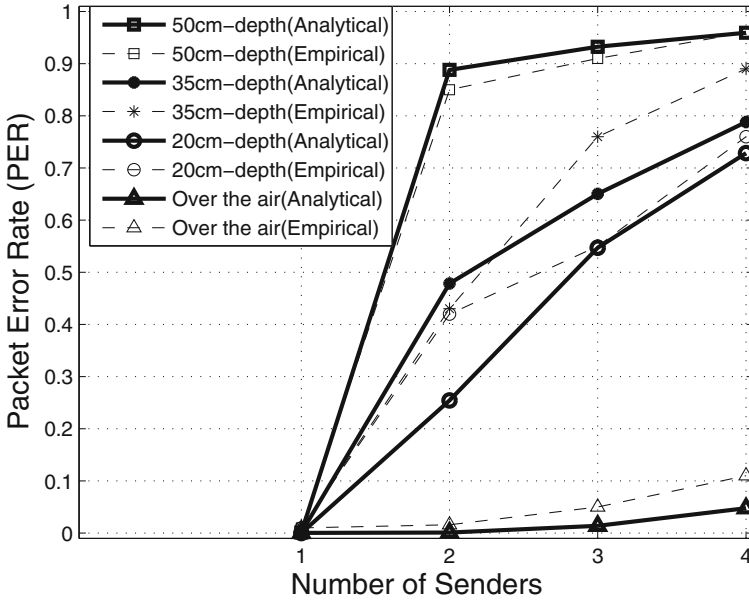
mechanism. To summarize, MAC protocols will perform well for OTA because of hidden terminal nodes with respect to $Comm_r$.

The region values ($Comm_r$, Int_r , and CS_r) are very low in case of underground communication; hence, they exhibit degraded performance. The performance degradation can also be observed in Table 11.1. One major reason for the performance degradation is the change in topology. The increased soil path attenuation brings down the $Comm_r$ value between 1 and 2 decreasing the one-hop neighbor of each node and accordingly reducing the Int_r and CS_r . However, it is seen in Table 11.1 that burial depth doesn't have the significant effect on the region values. However, as discussed in Sect. 11.2, even the small impact of burial depth can result in a large number of collisions. $Comm_r$ is not changing for the constant average inter-node distance of 0.61m (Table 11.1). It shows that, for all depths, transmission power level of the sender is maintained at such level so that it can at least fully satisfy its one-hop neighbor only. If the more transmit power level is available, then it can be used to access more neighbor by configuring the density-normalized value of CS_r to 2, and can efficiently exploit the overhearing mechanism.

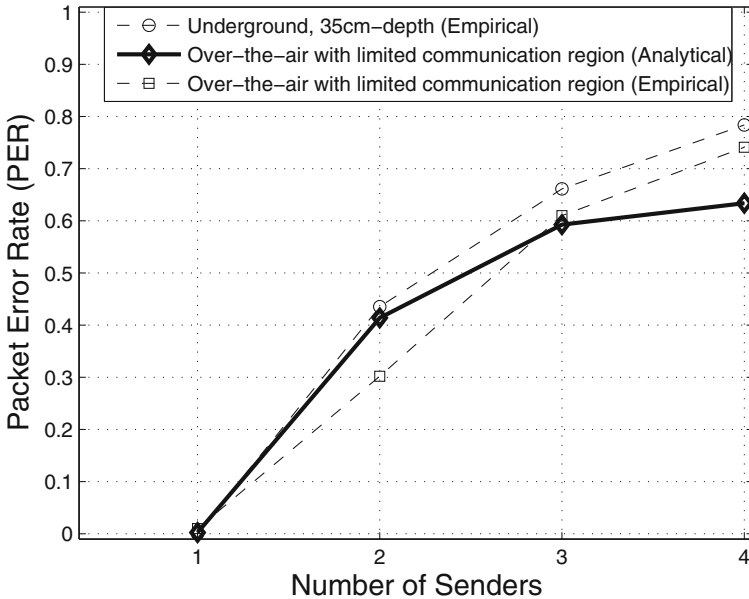
Figure 11.4 compares empirical and simulation PER values with the total number of senders which are contending for the channel. It can be seen in Fig. 11.4a that the results gathered from the model match the results in Fig. 11.3. These simulation results support the hypothesis that collisions increase with the increase in depths in WUSN environment. As the communication range of a node decreases, the overhearing mechanism becomes negligible. Smaller depths result in increase of the ranges which increase the overhearing and in turn decreasing the collision rate.

Another experiment is performed to validate the conclusion made in the above paragraph. For this experiment, OTA scenario with small communication range and small number of neighbors are considered. To simulate this scenario, range values for 35-cm depth underground scenario are used, i.e., $Comm_r = 1.0$, $Int_r = 1.31$. These parameter values can be interpreted as that each node can only be reached and detected by its communication neighbor only. Such experiments are difficult to conduct practically because even if the nodes have very low transmit power, it is still possible for the node to overhear the signals in OTA setting. Therefore, low transmit power is combined with the longer distance for the comparison between the empirical and simulated results. The topology in the Fig. 11.1 is used for the experiment. The sender-receiver separation is kept at 15 m, transmit power level at -18 dBm and height is 1.5 m for all five nodes. Figure 11.4b compares the average PER from OTA and previous UG results (at 35 cm depth) from empirical and simulated experiments. It can be observed that results from both empirical and simulated model experiments match each other confirming the effect of smaller region values on collision rate.

To summarize, conventional MAC protocols used for OTA are inefficient in WUSNs. The two major conclusions that can be drawn by comparing empirical and simulated results are that the communication, interference, and carrier sense ranges of UG nodes are significantly lower as compared to that of OTA scenario which also decreases the number of one-hop neighbors and compromises the overhearing mechanism. Moreover, lower burial depth can increase the carrier sense range of



(a)



(b)

Fig. 11.4 (a) Communication ranges for over-the-air and underground communication, comparison of empirical and simulated PER results: (b) results from Sect. 11.2 compared to simulation model and the effect of smaller $Comm_r$, Int_r , and CS_r values in the over-the-air scenario

WUSN node. The conventional MAC protocols are challenging to implement in WUSN; therefore, it is important to devise new efficient MAC protocol specifically for the underground environment [7, 15, 18–20, 22–24, 48].

11.4 Cross-Layer Modulation Using Soil Properties

The communication range is inversely proportional to the VWC of the soil, i.e., decreases with increase in VWC. The model explains the underground communication in great detail; however, it is not known how these characteristics will affect the high-level networking protocol. Moreover, an extensive empirical experimentation is required so that the underground wireless channel can be validated.

To assess the performance of underground communication in practical settings, we have conducted a series of demonstrations using both field experiments and a software simulation module that is developed in this research. The wireless sensor network lab already has a testbed of 50 wireless sensor nodes, and this testbed is used for field measurements. Using the capabilities and functionalities of the testbed, the effects of underground environment on wireless communication and networking can be evaluated to develop a generic framework. More specifically, the following research topics can be investigated:

Empirical Evaluations The propagation model derived in [9] is based on the electromagnetic propagation principles combined with the dielectric properties of soil [2, 4, 5, 16, 21, 25, 33]. This model can be empirically evaluated through field experiments. For the experiments, the transmitting signal strength, the receiving signal strength, as well as the packet loss rate can be recorded. Furthermore, the effects of depth, transmit power, and distance can be investigated in different test sites. Consequently, the results of the experiments can be exploited to develop a generalized channel model for underground communication.

Medium Access Performance In addition to one-to-one communication, the shared nature of the wireless medium necessitates investigation of multiple transmitting nodes. The motivation behind this is the basic difference between communication and interference. As an example, although a node *A* may not be able to successfully communicate with a node *B* at a distance 4 m, node *B*'s transmission may still affect the communication performance of node *A*. To investigate this property, under a controlled background traffic, the communication performance of multiple underground sensor nodes can be investigated [13, 53].

Effects of Seasonal Changes Weather is one of the main factors influencing the communication capabilities of underground sensor networks because of the direct influence of temperature and soil moisture on communication. Therefore, the effects of seasonal changes can be investigated throughout the 12-month period of the research. This will provide a clear mapping between the communication performance and temperature, humidity, and precipitation, which is valuable in the design and implementation of WUSN [31, 32, 34, 35, 37, 40, 42, 52].

Development of a Cross-Layer Communication Module Throughout the research, the empirical findings can be leveraged to develop a communication module that exploits the information from sensors to tailor the communication parameters. This cross-layer module dynamically uses real-time soil properties from onboard sensors to determine communication parameters such as modulation scheme, transmit power, as well as packet size and route establishment [3, 12, 27–30, 36, 38, 39, 41].

11.5 Future Trends

First, the results of the extensive experiments can be exploited to validate and improve the analytical model for underground channel. Consequently, a complete characterization of the underground channel can be provided. Furthermore, the results of the extensive experiments will result in identification of major challenges for networking in underground environment. Especially, the effects of soil conditions on medium access control and routing can be illustrated through the field experiments. Second, the proposed research will result in a comprehensive simulation module that models the underground channel for network simulations. This module can be made robust, with the objective of making it the simulator of choice for everyone in the underground networking community. Our simulator will offer a rich set of accurate models for underground communication, encourage the development of new models, and facilitate the integration of existing network software, simulators, and physical testbeds (i.e., a hybrid testbed and simulator). Finally, a cross-layer communication module that exploits the soil properties can be developed.

Besides the communication between sensors underground, the WUSN paradigm may also contain other devices aboveground, such as sinks, relay nodes, or control units. The data collected by the underground sensors should be transferred to the devices aboveground for delivery to a central location. Hence, the total communication process in WUSNs is a combination of communication underground part and above ground. Hence, the characteristic of underground-aboveground communication is an open research topic for the realization of WUSNs. Especially, the attenuation difference between the soil and air should be considered for this characterization. This area of communication in WUSN is an unexplored area and will provide important results for realization of efficient networks of underground sensors.

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Chapter 12

IoT in Hyperspectral Space: Terrestrial Integration Network



12.1 Introduction

Due to its large capacity, the free-space coherent optical communication system can essentially support communication between aerial-space, space-terrestrial, and space-space nodes. Using a new architecture based on laser-mm-wave convergence, the space-terrestrial integration network in a 6G uMUB scenario is called the 100-Gb/s hyperspectral space-terrestrial integration network. The following are key technologies: all-photonics satellite payloads; cheap cost; and an advantage in size, weight, and power. Dynamic networking with minimal latency and maximum dependability combined mm-wave and coherent laser communications included servo tracking systems as well as hybrid optical and millimeter-wave transceiver technology. Adjusting for wavefront distortion resulting from atmospheric turbulence with adaptive optics technology Technology for variety and laser-mm-wave aggregation.

The concept of converting cellular network cells to vertical space-ground coverage through dynamic beamforming technology is illustrated in research. The network architecture also includes the adoption of low-cost coherent optical links as relays between the space-based and ground-based networks, as well as mm-wave and laser hybrid arrays as communication links between the aerial, ground-based, and space-based networks. Spatial and spectral diversity between the two is required since the mm-wave has rain fading but no fog or cloud fading, while the laser has fog and cloud fading but no rain fading.

The six-generation hyperspectral aerial-space-terrestrial integrated network consists of the following: the space-based optical backbone system made up of satellite relay nodes (SRNs) and satellite access nodes (SANs); the space access network made up of SANs and user satellites; the aerial access network equipped with hotspots for airplanes; and the terrestrial access network made up of mobile access nodes and gateways (GWs). Depending on the situation and requirements, the access connection can dynamically adopt optical, mm-wave, and optical–mm-wave hybrid

links. An integrated network architecture for 6G is based on hyperspectral aerial, space, and terrestrial applications based on laser-mm-wave convergence.

12.2 Deployment Methodology

$$x_{ij\ell} = \begin{cases} 1, & \text{if a sensor is placed at location}(i, j, \ell) \\ 0, & \text{otherwise} \end{cases}$$

k : Required communication connectivity

r_c : Connectivity range

r_s : Sensing range

The objective in this problem is to find the optimal deployment of wireless sensors in a 3D volume underground such that coverage and k -connectivity are satisfied and the cost of sensors is minimized. It is assumed that all sensors have the same connectivity and coverage range. It is also assumed that the cost of deploying sensors at any depth underground is the same.

Sensors are deployed underground to collect environmental data and communicate the data to a base station located aboveground. The base station is assumed to be located in the middle of the field aboveground. The sensors that are deployed to cover the whole volume are called coverage sensors. Since these coverage sensors need to be able to connect to the base station, the objective is to develop an optimal deployment of the sensors such that only the coverage sensors will necessarily be k -connected to the base station.

The optimal deployment of wireless sensors underground is an NP-hard problem. Here we present a heuristic algorithm for the finding the optimal deployment. The algorithm first determines the grid size for placing the sensors in the 3D volume. It is assumed that sensors can only be placed on these grid points. The grid sizes are determined based on the connectivity and sensing ranges. It is assumed that connectivity range is always larger than or equal to the sensing range. If the ratio $r_c/r_s < \sqrt{3}$, then the grid size is set equal to the connectivity range divided by $\sqrt{3}$. However, if $r_c/r_s > \sqrt{3}$, then the grid size is set equal to the sensing range divided by $\sqrt{3}$.

We approach the problem of optimal deployment in two stages. In the first stage, we determine a network of sensors that covers the whole volume. We call these sensors the *coverage* sensors. In the second stage, we determine the best places to insert the relay sensors so that each coverage sensor will be k -connected to a base sensor located in the middle of the field aboveground.

A sensor placed on the grid (i_1, j_1, ℓ_1) covers the grid (i_2, j_2, ℓ_2) if the distance between the two grids $\sqrt{(i_1 - i_2)^2 + (j_1 - j_2)^2 + (\ell_1 - \ell_2)^2}$ is less than the sensing range r_s . In this problem, every grid must be covered by at least one sensor. The following optimization problem solves the coverage problem in a sensor field of n_x, n_y, n_z grids:

$$\text{Min} \sum_{i=1}^{n_x} \sum_{j=1}^{n_y} \sum_{\ell=1}^{n_z} x_{ij\ell}$$

s.t.

$$\text{cov}_{(i_1, j_1, \ell_1)(i_2, j_2, \ell_2)}(r_s - d_{(i_1, j_1, \ell_1)(i_2, j_2, \ell_2)}) \geq 0 \text{ for all pairs of grid points}$$

$$(1 - \text{cov}_{(i_1, j_1, \ell_1)(i_2, j_2, \ell_2)})(d_{(i_1, j_1, \ell_1)(i_2, j_2, \ell_2)} - r_s) \geq 0 \text{ for all pairs of grid points}$$

$$x_{i_1, j_1, \ell_1} + \sum_{i_2=1}^{n_x} \sum_{j_2=1}^{n_y} \sum_{\ell_2=1}^{n_z} [x_{i_2, j_2, \ell_2} \text{cov}_{(i_1, j_1, \ell_1)(i_2, j_2, \ell_2)}] \geq 1, 1 \leq i_1 \leq n_x,$$

$$1 \leq j_1 \leq n_y, 1 \leq \ell_1 \leq n_z$$

$$x_{ij\ell} = 0 \text{ or } 1, 1 \leq i \leq n_x, 1 \leq j \leq n_y, 1 \leq \ell \leq n_z$$

This problem is a nonlinear programming problem. It can be transformed into an integer linear programming problem, but even that for large problem sizes takes very long computational time.

In the second stage of the algorithm, we start inserting relay sensors into the network such that the connectivity will be increased as much as possible. We randomly pick ten random grids and among them choose the ones which will increase the connectivity the most. The algorithm continues inserting relay sensors until all sensors are k-connected to the base sensor. At the final stage of the procedure, the algorithm starts deleting relay sensors one by one and checks if the k-connectivity of the network is still satisfied. If the k-connectivity is still satisfied, it means the sensor can be permanently deleted.

12.3 Channel Model Based on Received Signal Strength (RSS)

In [1, 6, 7, 9, 12, 14, 43–51, 54, 55], the results of received signal strength (RSS) and the Packet Error Rate (PER) for both AG2UG and UG2AG communications are reported. It is observed that strong variance of the RSS values exists among different nodes. Even for the same node, there is an asymmetry between the case when the AG node is approaching the UG node and when it is departing the UG node. In this section, we adopt the channel models for AG2UG links and UG2AG links developed in [8, 10, 11, 13, 15, 17–20, 22–24, 26, 27, 53] to describe the characteristics of the AG2UG communication and the UG2AG communication.

Since only the horizontal distance between the AG node and the UG node is measured, the direct communication distance of the two needs to be calculated first. For both the AG2UG link and the UG2AG link, the channel is consisted of two parts, the underground portion (soil medium) and the aboveground portion (air medium). Assume the horizontal distance is d_h , the height of the AG antenna is h_a ,

the burial depth of the UG nodes is h_u , the length of the underground portion of the communication link:

$$d_{UG} = \frac{h_u}{h_a + h_u} \sqrt{(h_a + h_u)^2 + d_h^2}, \quad (12.1)$$

and the length of the aboveground portion of the communication link,

$$d_{AG} = \frac{h_a}{h_a + h_u} \sqrt{(h_a + h_u)^2 + d_h^2}. \quad (12.2)$$

Note that we ignore the distance difference caused by refraction at the soil-air interface since the communication ranges are short in our experiments.

The received signal strength at the receiver, P_r , is given as

$$P_r = P_t + g_t + g_r - (L_{UG}(d_{UG}) + L_{AG}(d_{AG}) + L^R), \quad (12.3)$$

where P_t is the power of the transmitter and g_t and g_r are the antenna gains at the sender and the receiver, respectively. $L_{UG}(d_{UG})$ is the loss at the underground portion, and $L_{AG}(d_{AG})$ is the loss at the aboveground portion, while L^R is the loss caused by refraction.

In [2, 4, 5, 16, 21, 25, 31–35, 42, 52], the underground loss is developed as

$$L_{UG}(d_{UG}) = 6.4 + 20 \log d_{UG} + 20 \log \beta + 8.69 \alpha d_{UG}, \quad (12.4)$$

where β is the phase-shifting constant and α is the attenuation constant, which is expressed as the following:

$$\alpha = \frac{2\pi c}{\lambda_0} \sqrt{\frac{\mu_r \mu_0 \epsilon' \epsilon_0}{2} \left[\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right]}. \quad (12.5)$$

Whereas, in [36–40], $L_{AG}(d_{AG})$ is given as

$$L_{AG}(d_{AG}) = -147.6 + 20 \log d_{AG} + 20 \log f, \quad (12.6)$$

in which f is the frequency of the signal.

The refraction loss L^R is different for the AG2UG link and the UG2AG link. As shown in [3, 28–30, 41], L^R for AG2UG link can be calculated as

$$L_{AG2UG}^R \simeq 10 \log \frac{(\cos \theta_I + \sqrt{\epsilon' - \sin^2 \theta_I})^2}{4 \cos \theta_I \sqrt{\epsilon' - \sin^2 \theta_I}}, \quad (12.7)$$

Table 12.1 Channel model parameters for UG2AG communication

Node	α	$20 \log \beta + L_{UG2AG}^R$	MSE
Approaching			
2	0.89	45.33	7.06
5	0.00	46.28	20.75
7	0.00	51.34	5.00
Departing			
2	0.22	40.75	1.60
5	1.02	47.97	18.60
7	0.00	55.01	3.06

Table 12.2 Channel model parameters for AG2UG communication

Node	α	$20 \log \beta + L_{AG2UG}^R$	MSE
Approaching			
2	1.10	36.47	4.58
5	0.00	43.08	19.74
7	0.00	50.85	10.87
Departing			
2	0.00	40.46	4.25
5	1.30	41.51	17.80
7	0.08	53.11	23.61

in which θ_I is the incident angle. Meanwhile, L^R for UG2AG link can be calculated as

$$L_{UG2AG}^R \simeq 10 \log \frac{(\sqrt{\epsilon'} + 1)^2}{4\sqrt{\epsilon'}}. \quad (12.8)$$

12.4 Received Signal Strength (RSS) Analysis

We apply the channel models to our experiment results. The estimated parameters and the MSE of the estimation are shown in Tables 12.1 and 12.2 for the UG2AG link and the AG2UG link, respectively.

12.5 Channel Model Conclusion

As shown before, the quality of the AG2UG link is better than the UG2AG link since $20 \log \beta + L_{UG2AG}^R$ is 1–9 dB lower than $20 \log \beta + L_{AG2UG}^R$. Also notice that α is usually quite small. For most cases, $\alpha = 0$. Because of the definition of α , this means that the imaginary part of the relative dielectric constant of soil, ϵ'' , is equal to 0. Since α , β , and L^R are all determined by the relative dielectric constant, which is

determined by the soil characteristics such as volumetric water content (VWC), bulk density, and soil composition, the variations of the values show that even in the same field, the characteristics of soil vary from location to location. The heterogeneity of soil causes a big challenge for the communication of the cyber-physical system, which needs to be adapted to a wide range of variations.

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Chapter 13

IoT in Cyber-Physical Systems



13.1 Introduction

With the goal of adding smartness across multiple domains, cyber-physical systems (CPS) integrate computational components into engineering systems enabling them to detect environmental phenomena, react to, and communicate these conditions [1, 6, 7, 14, 43–51, 54, 55]. CPS enrich human-to-human, human-to-machine, and machine-to-machine (M2M) in the physical and in cyberspace [8–13, 15, 17, 18, 23, 26, 27, 53]. Driven by the purpose of precision agriculture (PA), farm machinery can become CPS if they are aware of their surrounding and can react accordingly to their conditions. Wireless Underground Sensor Networks (WUSNs) complement PA as they provide high spatiotemporal resolution of environmental properties [2, 4, 5, 16, 19–22, 24, 25, 33, 52], transmit the information to an open-access media, and are inconspicuous to farm activities as the devices are buried underground [31, 32, 34–40, 42]. The control mechanism required for fully automation could be a cloud service. In other words, by adding an actuator to interact with the physical world and a cloud control application, a WUSN becomes a CPS solution [3, 28–30, 41].

Success and developments in agriculture impact the local community, the nation, and the world. When talking about a country economy, the agricultural sector is unavoidable because you either are a producer or a consumer. Aside from the economical benefits of PA, there is a social responsibility to make better use of the available resources and simply because people need to eat. The need to make progress in agriculture has pushed science in many different fields. Farming is impossible without water and soil, so underground detection and communication are discipline of great interest. WUSNs' inherent purpose is to detect and communicate a condition using the soil as a medium, one that still needs to be analyzed and which presents many challenges.

The world food production problem goes beyond the United Nations (UN) agenda of eradicating malnutrition and poverty by 2030. World population is expected to reach 9 billion people by 2050, which will require a 25%–70%

increase in food production. This increment also considers the grains to feed the livestock raised for consumption. Current agricultural practices have an impact on climate, which affects food production. Consequently, ending this dynamic cycle by applying environmental-friendlier techniques is an urgent practice that carries worldwide implications. Transforming grasslands and forests into arable fields increases the footprint for food production. However, this practice also alters the ecosystem and contributes to the greenhouse effect because of the deforestation and the gases released by the expanded fertilized fields. Extreme weather events have disastrous consequences for farmers. Drought and prolonged hot weather impact crops yield, while floods can spoil the work of a whole season.

One of the viable solutions is to make better use of the current available resources using technology, which plays a central role. Genetically modified crops and exact dosage application of chemicals and pesticides are important contributions. However, a shift of consumers toward organics and local grown produces means that these practices cannot be used extensively. Urban and small farms, especially in underdeveloped countries, probably lack the means to implement these improvements. Conversely, advances in water usage in agriculture have universal applications because water is the essential resource for life. Even in locations where water is scarce, agriculture is possible if the aquiferous capital is managed efficiently. Although three fourths of the Earth is covered with water, only 2.5% is freshwater. About 70% of the available freshwater is frozen in glaciers and the ice caps. The residual 0.75% of freshwater is in swamps, underground, lakes, rivers, living things, and the atmosphere. 70% of the remaining 0.75% of freshwater is “invested” in irrigation. Water is indeed a very limited and valuable resource. Under this light, every drop that can be saved and every drop that is spent wisely on food production is vital to the subsistence of mankind.

At the dawn of the Internet of Things (IoT), there are diverse commercial and proprietary sensors to determine the soil conditions and solutions to apply the appropriate amount of water. However, most of the efforts are focused on providing solutions in a specific area such as information acquisition, data storage, or communication. There is a requirement for complete frameworks capable of handling the sensing, the modeling, the decision support, and the actuation. The usage of cloud-based middleware platforms facilitates the exchange of information, provides global access data management, and procures a la carte processing services. In this research, an autonomous cloud-based application is developed to control a commercial irrigation system. Although it is designed to address the requirements and characteristics of the installed hardware, the model can be applied to other commercial or tailored systems and can provide guidelines for PA middleware development projects.

The main contribution of this work is the implementation of an irrigation control system that takes the soil moisture and temperature measurements from a WUSN and weather conditions from the Internet, and can interact with the available commercial CP irrigation solutions. To fulfill this main goal, these specific challenges are addressed:

- **Deployment of a wireless underground sensor network capable of measuring the soil moisture levels, temperature, and radio communication metrics.** The network should not interfere with other farm activities, require low maintenance, and should withstand year-around weather conditions.
- **Characterization of the underground/aboveground wireless channel to determine communication reliability.** Metrics like coverage distance and received signal strength indicator are used to quantify the communication channel characteristics.
- **Back-end software development for data management and visualization.** A cloud-based application is used to receive and store the data collected by the WUSN in real time when the GPRS/3G/4G link is available and in off-line mode when the information was captured locally. A second cloud-based application is used for real-time data visualization and monitoring of the soil sensors and nodes' communication activity. The visualization component shows in real time the power status of the AG node, any disconnected sensors, custom range of historical soil moisture readings and radio packet location, last reported pivot angle, and timestamp and signal strength of the most recent packet received from each underground node,
- **Usage of test software to interact with commercial irrigation solutions.** Although some existing literature include irrigation system controllers, production fields are more likely to be equipped with industrial solutions. Most modern commercial solutions provide a proprietary cloud-based control system with no API for custom program development. Test software replicates the user interaction with an application graphic user interface, allowing the programming of a control system.

As a discipline, CPS incorporate the modeling of physical processes with data abstraction. Therefore, in the presentation of a CPS, aside from providing a description of the proposed solution, it is also important to show the theoretical concepts behind each selected component and decisions taken. The evolution of engineering systems into CPS has pushed the development of a framework that can encompass the modeling and abstraction of this discipline. On the other hand, modeling the architecture of CPS into abstract black boxes has eased the integration of components developed by different disciplines, but, when put together, can lead to the discovery of emergent behaviors. Nevertheless, this systematic approach has helped multiple fields to make substantial advances in a short period of time like in wireless sensor networks (WSNs).

In the past decade, development in the field of WSNs has led to the discovery of novel communication protocols that have extended the range of the network, reduce the system energy consumption, or a combination of both. With the aim of extending the life of a WSN deployment, new methods for harvesting energy from light, vibration, heat, and electromagnetic sources are being developed. Conversely, WSNs have benefited on developments of microelectromechanical systems (MEMS) with smaller, precise, and more affordable sensors. This synergy of independent and interdisciplinary researches is possible when CPS abstraction

principles are being applied. For instance, a middleware can be used to distribute a series of commands or transfer data to devices of different manufacturers without caring about data type definition or if the information will be transported over a network or just locally.

A further development of WSNs are wireless underground sensor networks (WUSNs), where communications can take place between buried nodes and between underground (UG) and aboveground (AG) nodes. Soil composition plays a major impact in water retention, which affects wireless communication. Modeling the path loss in underground communication is another ongoing study area. WUSNs can benefit applications like precision agriculture, border surveillance, natural disaster detection (e.g., earthquakes and landslides), and mine safety. The common elements of a WUSN architecture are applied to PA. WUSNs are ideal for measuring soil water content and nutrient composition in soil. UG devices can be easily deployed in locations where measurements need to be taken and inconspicuous to the farming equipment and processes. AG nodes can also be installed in locations where they are unobtrusive but favorable to the overall system because the nodes communicate wirelessly. One particular example is mobile AG nodes attached to machines that move around the farm. Typically, a monitoring central is used for data storage and processing.

Precision agriculture (PA) is the practice of applying nutrients, water, seeds, and other agricultural resources accordingly to the requirements of the land, thus limiting waste while maintaining or increasing yield. Techniques include image analysis, creating soil maps, automation of farming equipment, variable-rate application, and measuring soil moisture and soil chemical content. Precision agriculture goes beyond increasing the land production in a sustainable way. Workers' conditions also improve as repetitive tasks can be completed in a scheduled manner or driven by real soil and weather conditions. There are also social impacts as there is more control over environmental effects. Precision agriculture approaches can have localized impact or could be used to manage large fields of several kilometers of resolution. For instance, on the low end, individual beds in a greenhouse are monitored, or, in a more ample scope, pollination of crops can be controlled by releasing insects and listening to the sound they emit.

13.2 CPS Soil Monitoring IoT

Determining soil moisture level is extremely important because it provides an overview on the state of climate and vegetation. Furthermore, soil water content affects wireless underground communication. Soil monitoring can be done at very different scales. Spectral image analysis taken from satellites or unmanned aerial vehicles (UAVs) provides overall information of several square kilometers of a geographical area. This approach is limited by unfavorable weather conditions like

the presence of heavy clouds that block the view or gust of wind that preclude a flight. These methods rely on the quality of still pictures and videos and the post-processing of captured images. Instrument calibration (especially compact cameras installed on small aircraft), atmospheric correction, normalization of off-nadir effects, and cloud screen can significantly affect the determination of soil properties from image analysis. Medium-range efforts include cosmic-ray neutron probes and the analysis of global positioning system (GPS) microwave signals in the L-band. In situ measurements can be invasive (e.g., gravimetric sampling) and time-consuming if data is retrieved manually. However, they are necessary to calibrate large-scale and medium-scale methods as they are literally the ground truth, which allows taking readings on deeper ranges and exact locations which are required by applications like precision agriculture. The usage of wireless technology to transmit local measurements reduces installation and maintenance costs and allows the information to be accessed in real time.

Most likely, the spatial scale of the soil moisture measurement and the one required by the application would not match. For instance, limited by the communication range, a UG node can be installed several meters away from the sensor it is monitoring. Upscaling the soil moisture information to cover the location where the UG node is installed will help to make better communication decisions. This research takes in situ soil moisture readings from a WUSN to program the rate of a CP irrigation system. Upscaling of the data provides an overall status of the entire field. Just as local readings are used to verify mid- to large-scale soil moisture sensing products, these remote solutions can be used to corroborate the upscaling of the WUSN data or for self-calibration. Next, a selection of large to local soil moisture sensing solutions is described. One of them uses the GPS signal, a major component of the control system, to determine the soil water content.

13.2.1 NASA CPS Systems

On January 31, 2015, NASA launched the Soil Moisture Active Passive (SMAP) research satellite which carries an L-band radiometer capable of detecting the passive microwave radiation emitted by the Earth and radars that send active microwave to the surface and detect their reflection. The main goals of this mission are measurement of soil moisture and the detection of water freeze/thaw states. The radiometer resolution is about 40 kilometers, while the radar resolution is close to 3 kilometers. Since backscatter from radars is affected by the surface irregularities, vegetation, and bodies of water, the signals from the radiometer and radars can be combined and processed to detect soil moisture with resolution of about 9 kilometers. On September 2, 2015, NASA reported that there was a failure in the radar amplifier that will impede it from working. However, using interpolation and deconvolution techniques, and taking advantage of the radiometer oversampling

feature, images of 20 kilometers in resolution have been possible. Another approach is using suitable images from other radars and applies the active-passive algorithm designed for the mission. Reading of 1-kilometer resolution is possible using this technique. The data collected during the mission are important in the development of weather, carbon cycle, and soil moisture models; however, the accuracy of SMAP is a significant issue.

13.2.2 Cosmic-Ray Neutron Probes

In neutron probes, beryllium and a radioactive material are mixed to liberate high-speed neutrons which loose high amount of energy when they collide with light hydrogen atoms. The low-speed neutrons form a cloud whose density increases with the soil water content. On the other hand, dryer soil has less water and fewer low-speed neutrons will be detected. This same approach is used by cosmic-ray neutron probes (CRNP) at a larger scale. The source of high-speed neutrons is the cosmic rays from space, and stationary or mobile neutron detectors can cover a range of several hundred meters. Effective depth is an inverse function of the soil moisture. However, calibration of the instruments needs to consider other sources of hydrogen like humus, decomposing soil organic component, and requires average local measurement of the soil moisture and neutron intensity. The following safety regulations and proper training are important to minimize radiation health hazard when working with neutron probes and CRNP.

We have compared soil water content (SWC) readings collected using a CRNP and in situ time-domain transmissivity (TDT) sensors obtaining mean absolute error of 0.0286m. However, because of the sparse distribution of the TDT sensors and since they were not permanently installed on the field, the average SWC comparison should be taken with a level of uncertainty. Vegetation type was omitted for the SWC determination using CRNP.

13.2.3 GPS Interferometric Reflectometry

Similar to SMAP, L-band microwaves are also used by the global positioning system (GPS). GPS Interferometric Reflectometry detects temporal changes in the signal-to-noise ratio (SNR) of the line-of-sight (LoS) signal and the multipath component, as it is reflected from the ground, to determine conditions like soil moisture, snow depth, and vegetation water content. Soil permittivity alters the reflected wave amplitude, phase, and frequency. These signal snapshots are called interferograms. Geodetic-quality GPS antennas installed on airborne devices and towers can detect soil moisture within two to five centimeters from the surface. A drawback of this technique is that it depends on the constellation of GPS satellites that traverse around the Earth, so only a few estimations can be achieved in a day. Therefore, the temporal scale is as best daily.

13.2.4 Wireless Sensor Networks

Sensor networks provide a high spatiotemporal resolution required for precise irrigation applications. With wireless communication, information is available remotely and in real time, so no manual manipulation of the data is required to determine the field condition. We have shown that a few amount of sensor are required to estimate the soil moisture on a location because of the rainfall cell radius magnitude and precipitation duration. The high spatio-temporal soil moisture correlation justifies low deployment density.

Several approaches are listed to determine the placement of nodes. In general, an inspection of properties like soil type, vegetation, and climate conditions helps to identify spots with different levels of soil moisture providing an average value for the field. In a mobile application is used to calculate the solar radiation and respective evaporation rate provided the geographical location. There calculations are similar to the data measured from an agriculture station. Proven that this methodology can be repeated in other locations, it helps to determine areas that will be exposed to similar radiation conditions. Then, clusters of sensors are placed in the selected areas, matching the recommendations.

Determining the number of samples that need to be taken is primordial in WUSN because sensing and transmission of the data consumes a significant amount of power. Shallow roots and high porosity create spaces that allow water to infiltrate or evaporate more quickly. Therefore, a higher sampling rate is required to capture this fluctuation.

13.3 CPS in Precision Irrigation IoT

If the soil and crop conditions are unknown, uniform irrigation can cause under- or overwatering. Variable-rate systems are an option to use water more effectively. Water-cost saving alone is a good incentive to consider switching, but there are other benefits such as avoiding fines for inadequate usage of water, limiting nutrient runoff, preventing erosion, and reducing maintenance cost of the irrigation system. Chemigation takes advantage of the existing irrigation systems to deliver chemicals uniformly and reducing human involvement and exposure. Although the benefits of smart irrigation are widely accepted, the cost associated with modifying current equipments can delay the adoption of precise irrigation until the equipment needs replacement. A meet-in-the-middle approach consists on installing less expensive valves instead of pressure control nozzles. In England, farmers adapted their hose-reel irrigation systems using on-off solenoid valves that are widely used in golf courses.

The industry and researchers have worked intensively in the application side of smart irrigation. Therefore, delivering cost-effective decision-making solutions should improve the adoption rate. One of the main obstacles might be the inter-

disciplinary approach required to match the machinery with actual agricultural requirements. If implemented by hardware, adapting a system to different soil and crop conditions can be expensive, but a software-based controller is a more flexible option to address the challenge.

The basic blocks of an irrigation control system are described next.

13.3.1 Sensing Node

To determine the “real” field conditions, sensors are installed on the field, or a remote technique like the ones described on Sect. 13.2 is used. The reality of the field could be blurred by insufficient or inaccurate/more affordable equipment. Most of the technology developed in this area is focused in monitoring the soil conditions, but approaches such as spectral imaging can be used to detect plant nutrient deficiencies. Sensed data could be forwarded immediately or locally stored for later retrieval. An optional gateway might be required if a direct link with the controller is unavailable.

13.3.2 Actuator Node

The actuator node consists of a microcontroller connected to an on-off valve that controls the water flow to an irrigation system, usually of the drip type. An actuator node does not necessarily need to be wireless as it is likely to be installed in proximity to the water source, which is a permanent location. The node can be easily affected by the farm activities, but it is also easy to protect. The power source for this actuator node is likely to be unlimited as energy is also provided to the irrigation system. A detailed design of an actuator node and the communication protocol used to interact with the rest of the system are provided. Solenoid valves control the water flow of the irrigation system. A latching circuit can use the signals from the microcontroller I/O pins to manipulate the power transistors that are connected to the valves. Also, the latching circuit provides a mean to save power by applying short pulses instead of continuous signals to control the system.

13.3.3 Controller

Similar to the actuator nodes, controllers are custom designed for a specific application following general guidelines. There are multiple characteristics that need to be considered during the design. The controller could be located in situ, remotely, or in the cloud. The controller could be a standalone device or also share other tasks. In situ controller can also save as a gateway node where information is

received and processed to make irrigation decisions. The hardware could be another microcontroller to save cost or a full computer system. It is suggested the usage of a real-time operating system to ensure that all the instructions will be carried out.

A reduction of 72% of water consumption was achieved using a wireless sensor network to monitor peach trees. The controller makes decision on the cloud and connects to a weather station to check if there was probability of precipitation. Tests show that the system will start watering the trees when the lower threshold was detected by any of the three sensors, but due to the depth of the installation, the upper threshold was overshoot which could have made the saving more significant. To go further by using a hydrological balance model to determine the exact amount of water to apply, the average correlation coefficient of the model estimation and the field measurements was 0.9331. In both cases, the actuator node was a valve that controls the water flow to a dripping irrigation system. Consulting growers to determine thresholds and irrigation actions is recommended. Their design also measures the soil temperature and whenever the soil moisture or the temperature trespasses the established limit, the controller will trigger the irrigation system for a fixed amount of time.

The lack of specific features in commercial controllers motivated to design a Wi-Fi reprogrammable and solar-powered precision irrigation control. The initial program also uses a threshold approach and also overshoot the upper limit.

The controls of commercial irrigation systems are usually proprietary, and modifying them could void the warranty or service terms. However, most of them will also include a cloud-based or graphical application to control them. Using software test applications, macro-like scripts can be written to aggregate other sources of data and extend the build-in features.

13.4 Microcontrollers Used in Agricultural Applications

One of the main usages of microcontrollers in agricultural applications is the sensing of soil and crop properties. With the incorporation of wireless transceivers, the requirement of human intervention is minimized greatly as the data collection can be done remotely. A variety of communication technologies (e.g., ZigBee, Bluetooth, and Wi-Fi) facilitates the customization of a system to meet the communication range while being power-efficient. However, the lack of formal protocols can be challenging when attempting to amalgamate solutions from different providers. Three agriculture projects that take advantage of microcontrollers are listed next:

Automated Irrigation System A design and implementation of an automated irrigation system for precision agriculture and water conservation has been shown. The solution consists of two units: (1) wireless sensor unit and (2) wireless information unit. Functionalities of these two units are explained below:

- **Wireless Sensor Unit (WSU):** A WSU unit consists of a microcontroller, modem, temperature and soil moisture sensors, and batteries and solar panels as power sources. WSU is responsible for collecting and transmitting data to the WIU.
- **Wireless Information Unit (WIU):** A WIU acts as a sink node. It collects data from WSUs and transmits data to a server using General Packet Radio Service (GPRS) technology.
- **Inter-Device Communications:** Communication between WSU and WIU is done using ZigBee, and GPRS is used from the WIU to the servers.
- **Sensing Capabilities:** VH400 is used for soil moisture detection. Temperature sensing is done using DS1822 digital thermometer.
- **Cost:** WSU and WIU costs are around \$100 and \$1800, respectively.

Soil Scout A soil scout system for real-time soil monitoring and decision making has been developed. First developed in 2006, soil scout has improved, and version two use wideband antenna. Components of the soil scout system are explained below:

- **Sensing:** Soil scout sensing unit consists of EC-5 soil moisture sensors and digital TMP122 temperature sensor.
- **Communication Links:** A WSN is formed using three types of links: Underground-to-Aboveground (UG-AG), Aboveground-to-Underground (AG-UG), and Underground-to-Underground (UG-UG). Only AG-UG and UG-AG channels are characterized.
- **Inter-device Communications:** Communication in the above links is done using 869.4-MHz ISM band. Maximum transmit power is 26 dBm. Gaussian Frequency-Shift Keying (GFSK) is used as modulation scheme on these links. 433 MHz is not considered due to antenna size limitations in the underground scenario.
- **Power Source:** Soil scout devices are battery powered using 2500 mAH 3 V lithium batteries, and energy efficiency is compared for different duty cycles.

Remote Sensing and Irrigation System Control A variable-rate irrigation system using wireless sensor networks is proposed. The main components of this system are explained below:

- **Sensing.** CS616 sensing technologies are used for soil moisture sensing with sensors buried at 30 cm and 60 cm deep in soil. CR10 data logger is used in data logging. Temperature sensing is done using TMP107 temperature sensor installed at 70-cm depth.
- **Inter-device Communications** is done using Bluetooth. Maximum transmit power is 15 dBm. By using the path antennas, maximum communication distance of 120 m is attained.
- **Power Source.** Battery and solar panels are used with total power source of 80 and 20 Wh. The system has the ability to operate 3.5 days without sunlight. One limitation is as the power supply gets under 5V, communication links are lost.

13.4.1 Miscellaneous CPS Testbeds

A testbed provides realistic scenario that can be used to carry out experiments with resource constraints and actual communication challenges caused by the medium and other devices. Results obtained from testbeds, especially of the outdoor type, are accompanied with metadata and anecdotal information that can provide a better understanding of the information collected. In this section, other testbeds used in WUSN researches are presented. Two of them consider agriculture as an application, but they are not set in a farm environment. The other two are used to study very specific applications: construction safety in enclosed environments and magnetic induction, respectively.

13.4.2 SoilNet

SoilNet encompasses 150 endpoint devices, each node with a pair of Decagon EC-5 soil water content sensor and a 5TE soil moisture, temperature, and electrical conductivity sensor installed at 5 -cm and 50 -cm depths, and a additional pair of 5TE at 20 cm. The nodes are transmitted over six million packets with environmental information for a 4-month period (August to November 2009) in a loamy-silt region in Wüstebach, Germany. Terrestrial relay nodes routed the packages, making this a sustainable hybrid underground wireless network.

13.4.3 Rome Underground Structural Integrity

During the construction of a 700 -m metro tunnel from November 2011 to February 2012, a WSN with vibrating strain gauges was deployed to ensure the safety of the project. Thirty-two nodes were installed in the walls of the project, and data was collected using a mobile station or by multi-hop communication to a gateway. In the middle of the tunnel, two nodes data delivery ratio (DDR) dropped to 90.8% and 92.5% in comparison with devices at the entrances with efficiencies of 99.9% and 99.1%.

13.4.4 Thoreau

Thoreau is a WUSN of 27 nodes deployed across the campus of the University of Chicago that track environmental and agricultural conditions in an urban setting. As platform, Thoreau uses the Sigfox IoT solution based on the MSP430F5529 microcontroller and CC1120 transceiver. Sensors consist of the Decagon MPS-

6 for water potential and a GS3 that measures volumetric water content (VWC), temperature, and electrical conductivity. Burial depth varies from 6 to 14 in, and the long-term nature of the project allows the analysis of seasonal events such as the ground getting frozen and the radio characteristics when there is snow.

13.4.5 Magnetic Induction Testbed

To study wireless underground communication using magnetic induction, a 255 cm×76 cm×76 cm tank is filled with sand that is kept wet using a mixture of water with electrolyte. Additional equipments used in experiments are 2D and 3D coils and relay coils. The testbed is being used to validate magnetic induction communication models.

13.5 Evaluations of CPS Control Component

Irrigation commercial solutions include cloud-based and mobile applications to control and monitor the device. The panel used to program the irrigation system is very simple and only includes a couple of buttons used to cycle through all the options, increase or decrease a value, and accept or cancel an action. The cloud-based application provides more intuitive options to manipulate the irrigation system. For instance, the scheduling of jobs like starting and stopping the CP at a specific time will require to make sure that the pivot control system real-time clock is synchronized and to select multiple menu options to program the job. A cloud-based application can automatically connect to a time synchronization system and includes a rich graphical user interface where all required options for a command can be displayed on a single screen.

13.5.1 Testbed Applications

Software automation testing is a cost-effective method to ensure that an application is able to complete a designed task appropriately and consistently. It also provides a dependable methodology to revise a procedure as upgrades are made to a system. Applications are tested to verify that they produce the expected output given an input, to quantify the amount of users that can run the application concurrently, and to determine its compatibility under different platforms. Replay software is used to record the actions executed by a user on a graphical user interface. The interaction is then replayed under some specific study conditions to verify if the application can withstand the setting. Replay programs are especially useful when working with web applications to ensure their compatibility with different Internet browsers and operating systems.

13.5.2 *Capture-Replay Testing*

The shift from desktop-based applications to Internet online tools triggered the development of replay application for software testing. They are designed to detect the interactions of a user when navigating an Internet website which can include key logging every input from a keyboard, cursor position, mouse click counts, and, more recently, saving all gestures and pressed locations using a touch screen.

13.5.3 *Programmable Testing*

Websites are rendered differently by various Internet browsers (or the same browser engine used on different operating systems). Graphical elements could be shifted by the screen resolution, and page content can change dynamically. Therefore, it is a good approach to program a script that lists elements and actions to complete when the result is more important than repeating end-user actions. Moreover, it is the only option when using a headless browser. Script can contain programmatic elements like loops and conditional statements. Selected HTML elements are identified using XPath queries and CSS selector patterns rather than the absolute position of the cursor on the screen. XPath identifies the object parents and uses indexes to identify similar elements at the same level (e.g., the index of the third element on an unordered list is three). CSS selectors use the information of HTML elements tags and their attributes to identify them. The most common example is using an element ID attribute to identify it since this value should be unique for all the elements of an HTML document. However, a repeated ID value can cause unexpected behavior. Replay applications can be used to detect noncompliance of standards.

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Chapter 14

IoT in Adaptive Control Systems



14.1 Introduction

In adaptive control systems, a network is used to capture soil information in the testbed. A mobile sink is installed on top of the third controller towers, which is located 147 m from the center of the pivot. The current configuration includes 2 antennas facing opposite directions allowing the reception of data from nodes that are over 150 m away. A solar panel provides sustainable energy in the field. Underground (UG) nodes are deployed in the field usually installed about 1 m from the path of the third tower. Each device is capable of measuring temperature and soil moisture from four external sensors buried at depths of 1, 2, 3, and 4 feet. The nodes are powered by lithium-ion batteries and protected by a watertight enclosure. The spatiotemporal real-time information from the UG nodes is fused at the mobile sink and sent to the cloud using 4G communications. The cloud communicates with the center pivot (CP) controller for automated irrigation control.

Off-the-shelf components were selected for the aboveground (AG) node for speed up development time. However, custom circuits were designed for the interaction between the different devices. The main component is a Beaglebone Black development platform which features include an AM335x 1 GHz ARM Cortex-A8 processor, 4GB 8-bit eMMC onboard flash storage, 3D graphic accelerator, USB host port, and six serial ports. The amount of serial ports is important as they are used to communicate with the GPS module and the microcontrollers, which are used to communicate with the underground nodes. Localization information is collected using Adafruit Ultimate GPS Breakout that can track 22 satellites on 66 channels [1, 44–46, 49, 50, 54, 55]. Additional features of the GPS module include a –165-dBm high sensitivity receiver, efficient power performance only drawing 20 mA at 5 V, built-in LOCUS data logger, internal patch antenna, and a Hirose U.FL radio-frequency connector for an external active antenna. The antenna selected for this application is a Hercules high performance, 30-dB gain, thread mount, IP67, and IP69K waterproof-rated model from Taoglas [6, 7, 9, 14, 43, 47, 48, 51].

For underground wireless communication application, low-frequency and low-power transceivers are required because the signal suffers less attenuation from solid objects. A device that fulfills these requirements is the Wizzimote [8, 11–13, 17, 27, 53]. Developed by Wizzilab, the Wizzimote integrates a Texas Instruments CC430F513 16-bit ultra-low-power microcontroller unit with a CC1101 low-power sub-1GHz RF transceiver, four analog to digital input/output pins, eight configurable GPIOs, and female SMA antenna connector. The CC430 MCU has 32 KB of flash memory, 12-bit analog to digital converter and consumes 3.2 mA when running at full capacity but can be lowered to 1.0 μ A with all power-saving features enabled. The Wizzimote is designed for 433-MHz applications. The CC1101 transceivers sensitivity at this frequency is reported at -116 dBm at 0.6 kBaud with a 1% packet error rate.

Communication between the server and the AG node is possible by wireless mobile telephony communication using a PANTECH UML290 LTE USB modem [10, 15, 18, 19, 22–24, 26]. The USB dongle uses the 1900-MHz cellular band and CDMA 2000 1X EV-DO Rev. A protocol. Service is provided by Verizon Wireless.

The AG node is powered by a 12 V, 35 A h, sealed lead acid (SLA) battery. The battery is recharged using a 40-watts, 20-V solar panel. Power management is controlled using a Mini-Box.com OpenUPS intelligent uninterrupted power supply (UPS) [2, 4, 5, 16, 20, 21, 25, 33]. Power status reporting can be achieved using USB or SMBUS. A step-down voltage converter decreases the feed to suitable 5 volts required to power the BeagleBone Black. This circuit also uses a metal-oxide-semiconductor field-effect transistor (MOSFET) as a power switch. The MOSFET gate is controlled by an Arduino Pro, which set the system to duty cycling when the CP is not rotating. This additional microcontroller was added because the USB modem will not work properly after a soft reset.

The Arduino Pro is a microcontroller board based on the ATmega328 with 14 digital input/output [31, 34, 35, 42, 52]. The power consumed by the Arduino Pro is minimal compared to the BeagleBone Black because it is not connected to any wireless device. To ensure autonomous functionality, the Arduino is powered independently by a SparkFun Sunny Buddy, an MPPT solar charger. A smaller 5-watt solar panel provides power during the day and recharges the lithium-ion polymer battery that keeps the Arduino running at night.

The AG node is enclosed in a Pelican 1060 IP67 watertight and dustproof micro case [32, 36, 37, 39, 40]. The case uses an automatic equalization valve to balance the internal pressure and prevent water condensation. Several waterproof cable gland connectors were installed on the case for the external components. The 12-volt SLA battery and the OpenUPS board are protected using a Graybar 12" $\times$ 12" $\times$ 6" PVC junction box [29, 30, 38]. For ease of access, the OpenUPS board was moved to a Pelican 1010 micro case which specs are similar to the 1060 model except for smaller dimensions.

The last major components of the AG nodes are two Sirio WY 400-10N Yagi-Uda 10 element direction antennas [28, 41]. These antennas are designed to work with frequencies in the 400–470-MHz range and provide a max gain of 14 dBi, max power of 150 watts at 30°C, and a front-to-back ratio greater than 18 dB. The

anodized aluminum material is lightweight, and each antenna only adds 4.5 pounds to the CP load.

An unresolved bug will disable the USB port on the BeagleBone Black after entering sleep mode, so to duty cycle the device when the pivot is not rotating, the Arduino Pro is used to cut off the power and restore it after 15 min. The Arduino function as a watchdog that needs to be pet by the BeagleBone Black.

The AG node was designed such that the impacts of the applied irrigation can be validated in real time. To this end, the AG node is implemented with two directional antennas facing opposite directions to facilitate data collection not only *before* the CP sprinklers reach the UG node location but also *after* the irrigation has been completed. The improved communication range behind the CP provides connectivity to observe changes in soil moisture. Accordingly, onboard models regarding the amount of irrigation to reach a certain soil moisture value can be updated in real time for the particular field, and tailor-made solutions can be developed.

14.2 Adaptive Control System

Existing prototype irrigation control systems use custom-design mechanisms to control the flow of water [3]. Most commercial irrigation systems used in production fields provide limited options to use custom control devices, and warranty restrictions might prohibit the manipulation of the control circuitry. Moreover, most current commercial systems include a cloud-based interface and/or a mobile application to display the field status and send operative commands.

To develop an adaptive control system that is brand-agnostic and can easily be adapted to existing systems, we used a headless browser, which can automate inputs to a cloud-based interface. The control system is designed to interact with the provided system and add additional features. Accordingly, nonexistent commands or information from other sources such as weather services can be implemented within the adaptive control system. For instance, the commercial control system used on the test field is unable to reduce the application rate to zero (turn off irrigation) when a wet run has been started. This action can only be achieved by stopping the wet run, starting a dry run, and starting another wet run. A combination of these commands can be programmed as a macro call. Such cloud-based control system provides flexibility and scalability to interact with custom-design or commercial available systems. The design of the interfaces is not complex, and information can be shared with well-known mechanism such as JSON strings.

The use of cloud-based controllers introduces a new set of challenges that need to be addressed to ensure a reliable system. The performance of the developed system depends on the reliability of the network used to access the Internet. Depending on the network workload, a Web page could take longer time to load. Moreover, a website redesign can render replay commands and may need a redesign of the control interfaces. Web pages can also introduce restrictions that need to be

considered during the design of the cloud-based control system. For example, there might be a timeout between commands that need to be considered and can add several minutes to the execution of an action. The adaptive control system has been developed following a modular approach such that these considerations can be handled effectively without requiring a major upgrade to the system.

The adaptive control system operation is as follows: Soil moisture, temperature, and the timestamp of the data are transmitted wirelessly from the UG nodes to the AG node installed on the irrigation control pivot. As the CP traverses the field, the AG node uses a 4G cellular connection to send the retrieved soil information and the CP location to the back-end system. The back end consists of a database for data storage and the visualization system. The controller is programmed in JAVA and hosted in a JAVA Enterprise container. The database and the web applications developed for the control system was initially hosted on computers that are fully accessible to the researchers. The software components are moved to a shared server. The fact that the controller can be hosted in different system implies that it is not limited to a specific hardware and can be run from the cloud as long as the required services are available. Specifically, MariaDB is the selected database, Dashing framework is used for visualization, and Glassfish is the JAVA enterprise container. A brief description of these products is provided next.

14.2.1 Database

Maria DB server project was forked from the original MySQL project followed by its acquisition by Oracle in 2009. Although both projects are under continuous development, the main concepts that govern a relational database system are unaltered. However, some of the command syntax is different. This is considerable as most of the database queries are carried out by the cloud-based application using predefined procedural statements. The entity-relationship diagram of the database schema used by the WUSN to store information is vital. Aside from storing the soil properties and radio communication characteristics, the system receives message and collects information of the commercial controller.

14.2.2 Visualization Framework

To be able to display multiple pieces of information concerning the agriculture and communication aspect of the project, instead of developing individual Internet applications, a dashboard is used to present the information. Dashing is a dashboard framework where custom- and open-sourced widgets can be loaded to represent different types of information. Widgets are developed using CoffeeScript, a short-handed version of JavaScript. To update the content, batman.js pushes and formats the data. Information to the widget is sent using JSON data-interchange format.

Accordingly, soil moisture, location of the CP, and wireless communication quality information are displayed in real time as data is received. A list of underground nodes provides individual sensor status that is very useful to detect shorted or disconnected sensors. A gauge displays the AG battery voltage. A map of the underground nodes shows the location of the irrigation CP and the trail of the recent radio packages received by each underground node.

14.2.3 Web Services

Glassfish is an open-source web service for the Java Enterprise Edition (Java EE) platform. The requirement of services that need to be ran periodically to determine the status and send scheduled commands to the CP is the main reason to require a server capable of running the full Java EE platform rather than just a web servlet container like Tomcat. Individual pieces of software that needed to be maintained separately now run on a single JAVA Enterprise Application.

14.3 System Evaluations

The prolong deployment provides the opportunity to analyze wireless underground-to-aboveground communication in the spatiotemporal dimensions. An analysis on the communication performance metrics gives way to separate the information in different data sets that are used to empirically evaluate a channel model that considers the path loss and multipath. Then, the soil moisture information captured by the WUSN is compared with reading taken using commercial data logger for calibration purpose. Due to the importance of the pivot location for irrigation purposes, a field test was carried out to measure the GPS accuracy, and a correction algorithm was developed. The last section of this chapter is dedicated to the CP automate irrigation control system. First, individual command evaluation results are presented, and then, a test of the complete system is provided.

The effectiveness of the irrigation control system relies on the timely analysis of accurate soil moisture measurement. This part of the research focuses on the wireless communication aspects of the system by analyzing metrics including the communication time window and distance ranges when transmission of the information is possible.

14.3.1 Communication Time Windows

The irrigation system automation requires that the information for the decision-making process be collected before the CP arrives to the application location. UG

Table 14.1 Communication time window metrics—summary of a CP dry run in first year

Node	First packet received	Last packet received	Duration	Packets received
106	21:01:31	22:00:12	0:58:41	168
102	21:02:03	23:02:04	2:00:01	619
107	22:08:14	23:36:56	1:28:42	259
101	22:53:23	01:06:04	2:12:41	96
108	00:25:38	01:37:37	1:11:59	183
104	01:02:51	02:58:11	1:55:20	333
105	02:26:54	03:59:33	1:32:39	275
103	03:09:30	04:56:50	1:47:20	285
106	03:52:17	05:38:56	1:46:39	281
		Average	1:39:20	278

nodes store the soil moisture reading in a First-In-First-Out (FIFO) queue. The AG node is programmed to request soil moisture readings following a round-robin fashion. Then, the delay between the readings is determined by the total count of UG nodes installed on the field. Measurement of the communication window provides an estimate of the time available to empty the UG node queue and ensure that the decision-making process is carried out with updated information. A complete dry run around the field takes about 8 h 22 min when the CP is set to the fastest speed/lowest application rate of 0.20". A dry run on first year as described is shown. Individual time communication windows are displayed for each UG node. Metrics from this run are summarized in Table 14.1. Since moisture readings are recorded every hour by the UG nodes and based on the average packets collected, it is feasible to retrieve at least 5 days of information or 120 packets. If the queue is empty, current soil moisture data is provided. If the field is being irrigated, effects could be captured immediately.

14.3.2 Analysis of Communication Range

The communication range is another way to discern when transmission is achievable in the WUSN. Gaps in the time communication windows could be attributed to dropped packages. Analysis on the range can be used to identify blind spots where communication could be obstructed. At the end of first year, six nodes were relocated to the east side of the field. Taking the east node as a reference, a node was placed 35 m meters facing east, and another UG was installed 35 m heading west. Again, taking the east node as a reference, two nodes were placed facing north 50 m and 150 m away. Similarly, heading south, two more enclosures were buried 50 m and 150 m away.

A yearlong registry of distances is provided where communication was received. For the nodes installed at the end of the year, since the CP remained stationary

during the winter, these sensors should only be communicating at a distance equal to the separation between them and the AG node. However, there is a significant variation detected by the nodes installed at 50 m north and south from the CP stationary location. The cause of these fluctuations is inaccurate AG location information reported by the GPS. This issue with the GPS leads to other experiments that are presented in Sect. 14.4.2. An update of the AG antennas in 2016 caused an increase in the communication range achieving distances above 200 m. The antennas were replaced with brand-new ones of the same model. Another discernible characteristic is that the range of the counterclockwise-facing antenna is larger than the clockwise one. This is also true for the first year deployment, but the difference is not as noticeable. There is the necessity to keep a quality control registry of the hardware to ensure the same conditions on the experiments and measurements taken.

During first year, communication performance was evaluated during a wet run, nine dry runs at maximum transmission power, and eight asymmetrical runs where the AG was transmitting at maximum power, but the UG nodes were set to -3 , 0 , 3 , and 7 dBm during two runs at each power level. Additionally, the system was also ran three times with both AG and UG set to 0 , 3 , and 7 dBm, respectively. During the wet run, 13,551 packets were received by the AG from 9 UG nodes. The maximum distance achieved was 149.34 m. When the UG node transmission power was reduced to -3 , 0 , 3 , and 7 dBm, the system can still communicate over distances of about 100 m. For instance, in a run where the AG and the UG were set to 0 dBm, communication was achieved at 102.16 m. This finding is important because by reducing the receiver power consumption, the UG node can significantly extend their life on the field. However, fewer packets were received when the UG node transmit power was set low. This could be caused by a narrower communication window and the possibility that more packets are corrupted or dropped. Additional research with these settings is scheduled for future work.

During Summer-Fall 2016, wireless communication performance was evaluated during 18 dry and 9 wet runs. Communication performance during a dry run is done, where the channel quality is shown in terms of received signal strength as a function of the distance of the CP to each underground node (negative values indicate CP is approaching the underground node). The results indicate that the aboveground system can communicate in both directions within a wedge of about 135 degrees with an arc of about 325 m. Compared to results in first year, this is an improvement of about 45 degrees and 125 m. It can be observed that a single antenna can communicate with ranges of up to 300 m. A comparison of the duplex communication from the clockwise-facing antenna and the counterclockwise-facing antenna shows the directivity of the antennas allows longer communication range in the direction of the antenna main beam.

The longer communication ranges provide ample opportunity to retrieve data, process information, and adjust the irrigation application rate before reaching the target area. This is illustrated by the results of four dry CP runs between 4 days; communication packets received from an underground node located on the southeast of the field (Google pin) are analyzed. The circles indicate the locations of the CP where these packets are received, and the rotation direction of the CP is also shown.

Soil moisture data on the southeast side of the field is first received when the CP was on the northeast of the field (a distance of 225 m that is traversed in 2 h at the fastest pivot application rate). This high communication distance and long communication duration allow the CP to collect any historical data that could have been stored at the underground node since a previous run. Accordingly, irrigation decisions can be made based not only on the real-time soil conditions but also on historical trends. It can also be observed that the CP stays connected until it reaches the south end of the field (a distance of 120 m that is traversed in 1.19 h). Accordingly, the impacts of the irrigation application can be observed through real-time soil moisture reports from the underground node while in the communication range. Compared to a dry run at the fastest pivot speed, irrigation slows down the CP, and hence, real-time reports could last more than 1.19 h after application.

14.3.3 Antenna Radiation Pattern Analysis

On a multielement antenna, the placement of the elements can reduce the wide pattern of each individual element and achieve high directivity values. The radiation pattern is calculated around the antenna following the coordinate system, where zero degree is located on the east and 90 is on the north. Meanwhile, angles calculated using coordinates use the compass bearing where zero degree is at the north and 90 degree is at the east. In this section, the arrival angle of the communication packets is converted to the coordinate system so it can be contrasted to the antenna radiation pattern. Although the radiation pattern represents a gain in the signal, and the information extracted of the package is the received signal strength (RSS), the expectation is that the RSS should be stronger in areas of the antenna with higher gain. The second purpose of determining the arrival angle is to sort the packets with similar gain for the empirical evaluation of the path loss and multipath.

The radiation pattern of the aboveground antenna is shown, where the expected communication gain is illustrated. The direction of packets sent from the aboveground nodes to the underground nodes is shown for the front-facing and the back-facing antennas, respectively. The direction is the result of the pivot movement (curve path followed by packets) and the radiation pattern (a higher gain improves the SINR and likelihood that packets will be received successfully). The packages located at 90 and -90 degrees are the ones received by the side lobes of the antenna. Packages on the main lobe at about 150 m are the ones received when the pivot was stationary during the winter of 2016.

14.3.4 Path Loss and Multipath Effect Empirical Evaluation

Attenuation causes electromagnetic signals to lost power as a function of the distance. This explains why wireless communication has a limited range. The

longest distances captured by the WUSN are uncommon and are a consequence of the randomness of the wireless channel. Reflection and scattering cause a wireless signal to spread out and change directions. Some of these electromagnetic waves will reach their destiny at slightly different times due to the multipath effect. Equation (14.1) considers attenuation and multipath effect in wireless communication. The findings on Sect. 14.4.2 allow the empirical evaluation of path loss and multipath effect at a given distance and angle of communication:

$$P_{rx}(d_{x,\theta}) = P_{tx}(d_{x,\theta}) - PL(d_{0,\theta}) - 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (14.1)$$

where:

- $d_{x,\theta}$: is the distance between the transmitter and the receiver with angle θ
- $d_{0,\theta}$: is the reference distance with angle θ
- P_{rx} : is the receiving power
- P_{tx} : is the transmission power
- $PL(d_{0,\theta})$: is the path loss at the reference distance
- n : is the path loss exponent
- X_σ : is a normal random variable with zero mean and standard deviation σ

The following steps are used to determine the path loss exponent and standard deviation of the normal random variable using empirical data:

1. Separate in bins all the packets based on all possible communication links (e.g., East UG to counterclockwise AG node).
2. Further divide all the items on a bin based on the communication angle. Since the AG antenna radiation pattern is symmetric, packet with 30 degree and -30 degree can be placed together.
3. Select a reference distance. Ideally, there should be at least a hundred entries with this reference distance.
4. Calculate the mean of the receiving power at the reference distance $d_{0,\theta}$. Averaging over a hundred readings will cause the normal random variable to go to zero. Then, Eq. 14.1 will be rewritten as 14.3

$$\bar{P}_{rx}(d_{0,\theta}) = P_{tx}(d_{x,\theta}) - PL(d_{0,\theta}) - 10n\log_{10}\left(\frac{d_{0,\theta}}{d_{0,\theta}}\right) + 0X_\sigma \quad (14.2)$$

$$P_{rx}(d_{x,\theta}) = \bar{P}_{rx}(d_{0,\theta}) + 10n\log\left(\frac{d_{x,\theta}}{d_{0,\theta}}\right) + X_\sigma \quad (14.3)$$

5. From the remaining entries, select those where the distance is greater than $d_{0,\theta}$. Calculate $P_{rx}(d_{x,\theta}) - \bar{P}_{d_{0,\theta}}$ and $\frac{d_{x,\theta}}{d_{0,\theta}}$.

- 6. Plot the values. The slope of the best fit line represents the path loss coefficient n . The root mean squared error is the standard deviation of the normal random variable. The process described for the AG2UG communication link between the East UG node and the counterclockwise-facing AG Node communicating using the main beam of the antenna is of significant nature.

14.4 Soil Moisture Sensor Calibration

In PA, irrigation application rates are determined by many factors, but water soil content can be considered the main one. Soil moisture sensors, like many other measurement tools, are calibrated in a controlled environment to determine if the instrument output is within the range of acceptable values. In the field, soil moisture readings need to be calibrated based on the soil composition. Comparing the soil moisture readings detected by the WUSN with the ones obtained using the data loggers is a benchmark on the system reliability.

14.4.1 Soil Moisture Readings

Time series is a representation of the soil moisture readings collected for 6 months from the west side of the field as reported by the underground node and the Watermark data logger. The collected data captures the historical trends of irrigation events and precipitation. Drops in the soil water potential are reflections of these events. A comparison of 60,995 readings collected from underground node sensors and the Watermark data loggers is conducted. Individual analysis of each sensor indicates that correlation is affected by the sensor depth. A subset of these sensor data is discussed next. At the 1-foot depth, nodes located in the west, northwest, east, southeast, and southwest have R-squared values (0.06, 0.03, 0.48, 0.15, and 0.38, respectively) which are lower than the R-squared value (0.57, 0.95, 0.58, 0.69, and 0.71) from sensors installed at 4-feet depth on the same location. Complete comparison is summarized in Table 14.2. These initial calibration plots help identify improvements to the real-time sensing component of the wireless underground node.

Table 14.2 R-squared of UG soil moisture readings and Watermark entries

Location	1ft	2ft	3ft	4ft	All depths
West	0.05974	0.89189	0.77051	0.56871	0.37096
Northwest	0.03433	0.71033	0.42548	0.95424	0.21241
Northeast	0.48490	0.85550	0.45867	0.58165	0.45954
Southeast	0.14544	0.82374	0.01742	0.68740	0.18273
Southwest	0.38053	0.44056	0.66468	0.70954	0.18658
All nodes	0.06703	0.45172	0.41644	0.12348	0.23706

14.4.2 Localization Information Accuracy

The mismatch on the location reported by the GPS is of great concern because this information is used to determine where irrigation should be applied. In the deployment of first year, the number of decimal places reported by the AG node was increased from four to six providing more accurate coordinates. Not logging the hundredth thousands and the millionth decimal places can alter a distance about 5 m. The readings also showed the CP locations outside the testbed field.

14.4.2.1 GPS Field Test

A field test was carried out to analyze the GPS accuracy. Wagnet system was purchased and established and used as a benchmark for the experiment. Three GPS data loggers were installed on the second, third, and fourth towers of the CP system. The CP angle reported in Wagnet website is used as a reference for this experiment. The coordinates of the loggers were used to calculate the angle of the CP as it moves around the field.

The coordinates gathered from the third and fourth pivot towers are used to calculate the angular location of the CP. The angles were compared with the Wagnet pivot angle. The reported angles from the three sources are valuable for a constant-speed pivot run in second year. The regression line parameters for a constant-speed movement are also of vital importance. It can be observed that the angle reported by the Wagnet is highly accurate, supported by an R-squared value of 0.9999 with the regression line.

The GPS angle errors with respect to the Wagnet pivot angle are critical. Readings from the third tower have an average error of -9.8467 degrees with a standard deviation of 3.3898 degrees. It can be observed that reported GPS reading from the third tower was 15.2606 degrees behind the actual CP location at the end of the pivot run. The GPS reading from the fourth tower has a maximum angular error of -10.5237 degrees, with an average error of -6.0323 degrees, and standard deviation of 1.5411 degrees. From second year, the CP was stationary on the southeast side of the field. The GPS angle errors from the third tower during this period are less variable. It can be observed that, compared to errors during CP run, GPS angle errors are smaller when CP is stationary. The average angle error is 1.1808 degrees with a standard deviation of 0.7881 degrees, and a maximum error of 3.77 degrees:

14.4.2.2 Pivot Angle-Aided GPS Correction Algorithm

The commercial control system keeps timestamped records of the CP angle, direction, and application rate on Wagnet online platform. Entries are automatically taken every 30 min or whenever a command is sent to the CP. Since these are discrete

Algorithm 1 Create Lookup Table

```

1: procedure DetectMovingPivot(entries)           ▷ Detect if pivot is moving to groups entries
2:   previousAngle = entries(1).angle
3:   consecutive = 0
4:   for i = 1 → Size(entries) do
5:     if entries(i).angle == previousAngle then
6:       consecutive ++
7:     else                                     ▷ Pivot is moving
8:       if consecutive! = 0 then
9:         storeStatic(angle)                 ▷ Save static entries
10:      end if
11:      storeMoving(angle)                   ▷ Save moving entry
12:      consecutive = 0
13:      previousAngle = entries(i).angle
14:    end if
15:  end for
16:  calculateAngularVelocity(movingEntries)
17:  lookup → concatenateEntries
18:  lookup.sortByDate
19:  return lookupTable
20: end procedure

```

Algorithm 2 Pivot Angle-Aided GPS Correction

```

1: procedure GetPivotLocation(lookup, timeStamp)
2:   if timestamp match static entry then
3:     return staticLocation
4:   else
5:     Calculate location using angular velocity
6:     return movingLocation
7:   end if
8: end procedure

```

entries, to retrace the location of the CP at any given time, the log must be analyzed, merging the entries with repetitive information, and calculating the angular velocity when the CP is moving (Algorithm 1). Then, the Pivot Angle-Aided GPS Correction algorithm can be run to retrieve the CP location in any specified timeframe.

On the initial experiments, the coordinates of the aboveground were recorded with very low precision (four decimal places). With the developed algorithm, these entries can now be included for analysis. The algorithm is also useful for analyzing entries that were logged with six decimal places to detect outliers as the difference. The discontinuity can affect the modeling of path loss.

14.5 Cloud-Based Adaptive Control System Evaluation

Not tampering with the installed control system was one of the requirements that was stated very early during the development of the CP automation control system. Furthermore, the web interface provided by the manufacturer was rich in options. The next step was the evaluation of programs that could be used to manipulate the web application of the Precision Link commercial solution.

14.5.1 Test Software Evaluation

In this section, the results of the evaluation of two applications considered for the implementation of the CP automation controller are presented. Both Selenium Web Driver managing Google Chrome web browser and HtmlUnit, a headless browser, were tested and are capable or run the command to control the Precision Link web application. Other software that were evaluated are HttpUnit for the lack of relevant documentation and Selenium Web Driver controlling HtmlUnit headless browser because exceptions are thrown when accessing pages with noncompliant JavaScript. The decision has great implications since Selenium Driving Chrome requires a graphical operative system. Graphical web browsers are better handling malformed Web pages as they can lessen the restriction and enable quirky mode. To evaluate how well both application can handle the same job under very similar conditions, a cyclic executive task was set up, and both solution will attempt to log into the Precision Link website successively a hundred times. To evaluate performance, the time between logins was registered. A summary of the statistic is displayed on Table 14.3.

Selenium was only able to log in successfully to the website 40% of the time before timing-out. HtmlUnit was always able to log in. When Selenium was able to validate the credentials, it outperformed HtmlUnit. However, the fail rate is too high to consider the solution viable for the project.

Next, HtmlUnit was tested against multiple tasks. The cyclic executive was modified, so after successfully entering to the website, HtmlUnit will visit the page of the CP and retrieve its location. Results of this second set of test are shown on

Table 14.3 Comparison of test software attempting to log into the Precision Link website. Selenium has a successful rate of 40%. HtmlUnit was able to complete the task 100% of the time

	Selenium driver ^a	HtmlUnit
Min	18.00	30.44
Mean	20.29	37.44
Max	41.10	97.66
SD	4.59	10.17

^a Used the values when the test did not timed-out

Table 14.4 HtmlUnit
execution time when
completing multiple tasks

	Login	Retrieve pivot location
Min	30.24	8.73
Mean	32.79	10.09
Max	56.78	12.25
SD	3.02	0.63

Table 14.5 Pivot control test
results

Command type	Total	Successful
Time-based	29	26
Angle-based	27	22

Table 14.4. HtmlUnit took less time during the login task, and it was also perfect completing the requested tasks.

14.5.2 Command Type Evaluation

Commands programmed into the control system can be triggered based on time or the CP location. Both of these approaches were evaluated through control system tests. The results of the control system test are summarized in Table 14.5. It can be observed that time-based commands result in a success rate of 89%. Two of the unsuccessful timed commands were caused by malfunction of the GPS installed on the commercial control system. Accordingly, the CP does not start if GPS signal is lost. The third failed timed command required a restart of the project control system.

Average delay between command time and execution is 2 min 22 s with a maximum delay of 3:53. Delays on the execution of the commands include the waiting time of the control loop, the time to replay the command, page loading time, and communication delay between the website and the control system installed on the CP. Based solely on the project control system, the correct execution of timed commands relies on an accurate system clock; the success rate is expected to be better than angle-based commands because they do not depend on external inputs. During the testing of angle-based commands, an unexpected behavior was detected: the reliability of the GPS system installed on the aboveground node is questionable.

Angle-based commands require knowledge of the CP location to trigger their execution; there are two sources for coordinate information: (1) GPS data attached to communication packets sent from the aboveground node to the back-end system and (2) pivot angle information from the installed commercial control system. As shown in Table 14.5, the angle-based commands result in a success rate of 89%. Average difference between programmed angle and actual CP location is 9 degrees with a maximum error of 20 degrees. Moreover, the pivot angle reported by the system changes around 3 degrees when the CP starts and stops moving. When in motion, the reported angle information is found to be reliable. However, retrieval of this data in real time is inconvenient. Information from the website is automatically

Table 14.6 Irrigation collected during the controller test

Expected	Gauge 1	Gauge 2
0.92"	0.19" ^a	0.20" ^a
0.86"	0.20" ^a	0.18" ^a
0.62"	0.30" ^a	0.33" ^a
0.32"	0.30"	0.27"
0.00"	n/a	n/a

^a System received the application rate, but invalid values cause the system to reject the command. System switched to default application rate of 0.20"

logged every 30 min. For more frequent information, a reading request can be sent at command. Accordingly, as the project control system is designed to be independent from other systems, information from this website can be used as a fallback resource when GPS data from the aboveground cannot be accessed.

It can be observed that relying solely on GPS information can lead to significant errors in precision irrigation applications. While higher-end GPS devices may decrease the errors to some extent, GPS errors should be considered in system design due to the wireless nature of the GPS system and cost considerations. On the other hand, while the CP angle reported by the Wagnet is reliable, it is not provided in a timely manner. The system automatically reports the CP angle every 30 min. To address this issue, during the experiments, a system reading was requested every 5 min through the use of the adaptive control system. The consecutive CP angle report registered an average time delay of 8.74 min, in addition to an outlier period of 1 h 39 min when no angle information was reported. The occasional large delay between pivot angle reports prohibits from relying to this source for real-time operations (Table 14.6).

14.5.3 Automation Controller Evaluations

During Spring 2017, the Pivot Automation Control System was run for the first time under controlled conditions. The right side of the field was divided into five wedges with specific application rates. UG nodes located on each of the regions were programed to report a specific value that will trigger the designed application rate. The controller was programmed to only consider the readings received during the last 10 min to prevent that previous readings could alter the application rate. Two rain gauges were installed per sector to measure the irrigation levels. Once started, the experiment will not be halted, so the measurements would be accurate.

The Wagnet website keeps a record of every command issued. As the test ran, all the commands issued by the controller were logged by the system. The IP address of the system issuing the command corroborated the source of the command. The

tables with the application rates were uploaded successfully to the Precision Link controller. The tables were short as only the information of the closest UG nodes to the AG node were used. However, the pivot did not update the requested application rate. The irrigation rate was set to the default application rate of 0.20 inches. When the pivot was close to the east UG node, a software bug was determined as the cause of the malfunction. The Precision Link web controller works properly with larger application rate tables. The controller was updated to create additional wedges on the opposite region where the pivot was located. The updated controller started to work as the pivot was leaving the east side of the field toward the southeast. The application rate registered in this sector was registered as 0.30" and 0.27". The expected application rate was 0.32". However, the Precision Link website also rounds all input application rate to the nearest 0.5".

14.6 Conclusions

An adaptive control system has been deployed and it has been reporting soil moisture conditions during the last past 3 years. Every season, improvements to the system have contributed to the reduction of the footprint of the system over the surface. The prototype fully underground enclosure has been tested for the past 6 months, and the electronic equipment is still operational. Empirical analysis of the data received during the past 2 years has established that the path loss coefficient for the field is approximately 2.66704 depending on the direction of the communication of the transmitting and the receiving antenna. Communication range was over 150 m during first year and over 200 m during second year. At the maximum speed when the application rate is 0.20" in average, the communication windows are about 1 h and 39 min.

A dashboard framework called Dashing has been adapted to provide real-time status of the WUSN and the CP irrigation system. Widgets specific to agriculture have been developed to provide a richer view of the system status. A cloud-based controller and an actuator module able to interact with commercial web control system have been developed to expand the WUSN into a cyber-physical system. In a preliminary test, the controller was able to issue the correct commands to set the expected application rate. Additional tests on the controller are necessary to ensure reliability.

Automation of the CP irrigation system to react to the soil conditions contributes to the preservation of freshwater. However, the effect of this decision over the yield is of greater concern. Crop production studies require a long-term commitment. The controller has been tested to set an irrigation rate based on the information received by underground nodes. However, there are other system improvements that can be considered to make it more efficient. With the goal of making the WUSN self-calibrating, remote soil sensing technologies can be considered to adjust sensors installed close to the surface. GPS interferometric reflectometry is an attractive method because GPS is an indispensable component of the control system. The

movement of the CP will allow the calibration of UG nodes located close to the irrigation system path.

Due to the inherent errors and delays in CP angle and GPS measurements, a multimodal design with other sources for system localization is needed. Alternatives include using image detection to determine the field location or the addition of a compass using a 9-degree-of-freedom sensor. There are potential opportunities for improvement with the UG node. Currently, it cannot take more sensors, and the software platform disables one of the most required characteristics for an embedded system which is reduction of power consumption.

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