Low-Power Wide-Area Networks: Opportunities, Challenges, and Directions

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ABSTRACT

Low-Power Wide-Area Network (LPWAN) is an emerging network technology for Internet of Things (IoT) which offers long-range and wide-area communication at low-power. It thus overcomes the range limits and scalability challenges associated with traditional short range wireless sensor networks. Due to their escalating demand, LPWANs are gaining momentum, with multiple competing technologies currently being developed. Despite their promise, existing LPWAN technologies raise a number of challenges in terms of spectrum limitation, coexistence, mobility, scalability, coverage, security, and application-specific requirements which make their adoption challenging. In this paper, we identify the key opportunities of LPWAN, highlight the challenges, and show potential directions of the future research on LPWAN.

CCS CONCEPTS

• **Networks** → **Sensor networks**; *Cyber-physical networks*;

KEYWORDS

Low-Power Wide Area Networks, Internet of Things, Sensor networks.

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1 INTRODUCTION

To support Internet of Things (IoT), recent developments in communication technologies have given rise to Low-power Wide-area Network (LPWAN). Complementary to cellular (e.g. 2G, 3G, LTE [46]) and existing wireless technologies (e.g. WiFi [18], Bluetooth [16], IEEE 802.15.4 [1], WiMax [64]), the LPWAN technologies promise to support long-range, low-power consumption, low cost for both the devices and infrastructure, and connect a massive number of devices [25]. Due to their increasing demand, several competing technologies are being developed including LoRa [20], SigFox [23], IQRF [2], RPMA (Ingenu) [3], DASH7 [4], Weightless-N (nWave) [5], Weightless-P [5], SNOW (Sensor Network Over White Spaces) [53, 54], LTE Cat M1 [6], EC-GSM-IoT [7], NB-IoT [62], and 5G [21]. Cellular based LPWANs (LTE Cat M1, EC-GSM-IoT, NB-IoT, 5G) operate in licensed band. The unlicensed sub-GHz ISM band is the operation band for most non-cellular LPWANs except SNOW that operates in the TV white spaces.

The LPWAN technologies are still in their infancy with some still being developed (e.g, 5G, NB-IoT, LTE Cat M1, Weightless-P), some having only uplink capability (e.g, SigFox, Weightless-N), while, for some, there is still no publicly available documentation (e.g., SigFox). Despite their promise, existing LPWAN technologies raise a number of challenges in terms of spectrum limitation, coexistence, mobility, scalability, coverage, security, and application-specific requirements such as data rates and real-time communication which make their adoption challenging. As LPWAN is considered to be one of the key technologies of today to drive the IoT of tomorrow, it is critical to address these challenges. In this paper, we identify the key opportunities of LPWAN, highlight the challenges, and show potential directions of the future research on LPWAN.

In the rest of the paper, Section 2 presents the characteristics of LPWANs. Section 3 overviews the state-of-the-art LPWAN technologies. Section 4 describes the opportunities of LPWAN. Section 5 presents the research challenges and future directions in LPWANs. Section 6 concludes the paper.

2 CHARACTERISTICS OF LPWANS

2.1 Long-Range Connectivity

In contrast to traditional short-range wireless sensor networks, the design goal of LPWANs is to offer wide-area coverage at low-power, and low cost. Most LPWANs [5, 7, 20, 23, 53] achieve long communication range and thus form a star topology where the devices directly communicate with the base station (BS). Excluding Ingenu RPMA (2.4GHz) [3], most non-cellular LPWANs operate on low frequencies (sub-GHz band) that provide long communication range (from few kilometers in urban areas to tens of kilometers in rural areas). Lower frequencies have better propagation characteristic through obstacles. These properties made sub-GHz band attractive for LPWANs technologies.

2.2 Low-Power

IoT devices are expected to operate for a very long time (several years) without the need to replace the battery. LPWANs achieve low-power operation using several approaches. **First**, they usually form a star topology, which eliminates the energy consumed through packet routing in multihop networks. **Second**, they keep the node design simple by offloading the complexities to the BS/gateway. **Third**, they use narrowband channels, decreasing the noise-level and extending the transmission range [53, 62].

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2.3 Low Deployment and Operational Cost

A major factor contributed to the rise of LPWANs is its low cost. Non-cellular LPWANs require no (or limited) infrastructure and operate on unlicensed spectrum, providing an excellent alternative to the cellular network. In addition, the advances in the hardware design and the simplicity of LPWAN end-devices makes LPWANs economically viable [28].

2.4 Reliability and Robustness

LPWANs are designed to provide reliable and robust communications. Most LPWANs adopt robust modulation techniques and spread-spectrum techniques to increase the signal resistance to interference and provide a level of security. In spread-spectrum, narrowband signal is spread in the frequency domain with the same power density resulting in a wider bandwidth signal [60].

2.5 Potential to Scale

Avoidance of multihop topology gives high potential to scale the LPWANs. In addition, LPWANs use narrowband to support a massive number of devices to efficiently utilize the limited spectrum. Besides some LPWANs (e.g., LoRa) use multiple antenna systems to enable the BS to support large number of nodes. Some adopts massively parallel communications in both directions using single antenna system (e.g., SNOW), thus providing opportunities to scale. Scalability of LPWAN is also affected by a number of factors such as the underlying MAC (media access control) protocol, duty-cycle, and reliability requirement.

3 OVERVIEW OF EXISTING LPWANS

Here we overview the current LPWAN technologies. Figure **??** classifies them. A summary of these technologies is shown in Table 1.

3.1 Infrastructure Based LPWAN Technologies

3.1.1 NB-IoT. NB-IoT (Narrowband IoT) [8, 62] is a 3rd Generation Partnership Project (3GPP) LPWAN technology offering flexibility of deployment by allowing the use of a small portion of the available spectrum. It supports up to 50k devices per cell, and requires minimum 180 kHz of bandwidth to establish communication. It can be deployed as a stand-alone carrier with available spectrum exceeding 180 kHz, in-band within an LTE physical resource block, or in the guard-band inside an LTE carrier. NB-IoT uses resource mapping to preserve the orthogonality of LTE signals by avoiding mapping signals to resources currently used by LTE signals [62].

3.1.2 EC-GSM-IoT. Extended Coverage-GSM-IoT [7] is 3GPP standard-based LPWAN technology. EC-GSM-IoT is based on enhanced GPRS (eGPRS), designed to support long-range, low-power, and high capacity communication. EC-GSM-IoT is backward compatible with existing GSM technologies. Hence, it can be added to the existing cellular network as a software upgrade, reducing the cost of infrastructure and deployment. EC-GSM-IoT extends the coverage of GPRS by 20 dB [25]. To support various application requirements, EC-GSM-IoT provides two modulation options, Gaussian Minimum Shift Keying (GMSK) and 8-ary Phase Shift Keying (8PSK). Using these two modulations, it achieves peak data rate of 10 kbps and 240 kbps receptively. Additionally, EC-GSM-IoT improves battery lifetime by using extended Discontinued Reception (eDRX) technique, which allows the device to choose the number of inactivity periods depending on the application requirements. EC-GSM-IoT can support up to 50k devices using a single BS.

3.1.3 LTE Cat M1. LTE Cat M1 is an LPWAN technology introduced as a part of 3GPP Release 13 offering long-range connectivity at low-power [6]. It is specifically designed to support IoT applications requiring low to medium data rate. In addition, it offers Voice over LTE (VoLTE) functionality, enabling new use cases for IoT. LTE Cat M1 make use of the existing cellular infrastructure to support mobility and seamless communication handover at similar speeds to LTE. Finally, LTE Cat M1 supports firmware updates over the air to ensure security over long distances [6].

3.1.4 5G. The 5th generation of mobile technology (5G) is expected to be commercially ready by the year 2020 [21]. 5G is expected to support a wide range of existing and future use cases in addition to the legacy mobile broadband. Specifically, for massive IoT applications, 5G will provide long-range, low-power, and low cost connectivity. In this case, several improvements over the 4G system are needed in terms of end-to-end delay, spectral efficiency, network capacity, cost-efficient deployment, and interference cancellation.

3.2 Infrastructure-less LPWAN Technologies

3.2.1 Long Range (LoRa). LoRa is a proprietary physical layer (PHY) design used in Long Range Wide Area Network (LoRaWAN) specification [20]. LoRaWAN is the specification defining the protocol and network architecture. LoRa network is organized in a special star topology, called star-of-stars, where the gateway nodes relay messages between end-devices and a central network server. LoRa defines three different classes for the end-devices to serve different application with different requirements. These classes offer a trade-off between downlink communication, latency, and energy efficiency (battery lifetime). **Class A:** End-devices of Class A support bi-directional communications where each uplink transmission is followed by two short downlink receive slots depending on the application need. The end-device randomly schedule the downlink slots based on ALOHA-like protocol [27]. **Class B:** Extend Class A random receive window by allowing extra receive window at scheduled times. The gateway node transmits a time-synchronization beacon to end-devices allowing the server to know when they are listening. **Class C:** In Class C, the receive window is continuously open unless the end-device is transmitting.

3.2.2 SigFox. SigFox [23] is a proprietary LPWAN technology based on Ultra-Narrowband (UNB) modulation technique [65]. UNB offers efficient spectrum utilization resulting in increased network capacity and low-power consumption. SigFox adopts duty-cycled transmission of %1 in Europe. SigFox supports very low data rate compared to other LPWA technologies. SigFox allows only 140 12-bytes message per day, each transmission taking 3 seconds. To provide reliability, SigFox transmits the message multiple times, resulting in high energy consumption.

	NB-IoT	EC-GSM-IoT	LTE Cat M1	LoRa	SigFox	IQRF	RPMA	Telensa	DASH7	Weightless-N	Weightless-P	SNOW
Modulation	QPSK, OFDMA (UL), SC-FDMA (DL)	GMSK, 8PSK	QPSK	CSS	DBPSK, GFSK	GFSK	DSSS, CDMA	FSK	GFSK	DBPSK	GMSK, OQPSK	BPSK
Band	Licensed, Sub-GHz	Licensed, Sub-GHz	Licensed, Sub-GHz	Unlicensed, Sub-GHz	Unlicensed, Sub-GHz	Unlicensed, Sub-GHz	Unlicensed, 2.4 GHz	Unlicensed, Sub-GHz	Unlicensed, Sub-GHz	Unlicensed, Sub-GHz	Unlicensed, Licensed, Sub-GHz	Unlicensed, TV white spaces
Max Range (Km)	15	15	15	15	10	0 - 5	15	1 - 10	0 - 5	0 - 3	0 - 2	5
Peak data rate (kbps)	250 kbps (UL), 170 kbps (DL)	10	375	27	1	20	80	65	9.6, 55.666, 166.766	100	100	50kbps per node
Security	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A
Indoor	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No	No	Yes	Yes
Link budget (dB)	164	164	164	164	N/A	N/A	177	N/A	N/A	N/A	N/A	N/A
Mobility	No	Yes	Yes	Yes	No	Yes	Limited	No	N/A	No	No	N/A
Battery lifetime (Years)	10	10	10	10	5	N/A	15	10	N/A	N/A	N/A	N/A

Table 1: Summary of LPWAN Technologies.

3.2.3 IQRF. IQRF [2] is an LPWAN technology designed to support ultra-low-power operations, and low-rate, low traffic wireless connectivity. Unlike other LPWANs, it uses mesh network topology and can support up to 239 nodes using a single coordinator. It achieves hundreds of meters range per hop in the outdoors, and tens of meters in indoors. However, with a special arrangement, IQRF can achieve several kilometers per hop [2]. IQRF implements two transmission modes – *networking* and *non-networking*. The networking mode is implemented for communication with multiple nodes and non-networking mode is for single or multiple peer-to-peer communication.

3.2.4 RPMA (Ingenu). Ingenu [3] proposed an LPWAN technology based on Random Phase Multiple Access (RPMA) technology. It offers low-power, low cost, robust, and bi-directional communication. Operating on the globally available 2.4 GHz band, RPMA exploits the rules and regulation imposed on 2.4 GHz band, such as minimum duty-cycle, to provide long-range communications at low-power. It allows nodes to share the same transmission slot. The nodes acquire the time and frequency from the downlink frame. Then each node randomly transmits by adding random delay selected by the node itself [3]. Furthermore, it provides acknowledged transmission, adding reliability to the communication.

3.2.5 Telensa. Telensa is a proprietary LPWAN technology that pioneered the use of UNB operating is the unlicensed sub-GHz ISM band [26]. It provides low data rates and does not support indoor communications. Telensa focuses on smart city application, in particular, smart lighting and smart parking. In addition, it supports integration with third-party application by providing smart city API [26]. Although there is no publicly available information regarding the implementation of Telensa, there is an ongoing effort to standardize it through the European Technical Standards Institute.

3.2.6 DASH7 Alliance. DASH 7 Alliance proposed an open standard for LPWAN, DASH7 Alliance protocol (D7AP) [4], developed for wireless sensor and actuator networks communication [63]. D7AP use the acronym BLAST to describe its features – Bursty (describes the data traffic pattern supported by D7AP), Light (has maximum packet size of 256 bytes), Asynchronous (indicates that the communication does not require synchronization), Stealth (meaning that D7AP device only replies to approved devices), Transitional (meaning D7AP devices are designed for mobility).

3.2.7 Weightless-N. Weightless Special Interest Group (Weightless-SIG) [5] proposed Weightless, an open standard offering LPWAN connectivity. Weightless-N (nWave) is similar to SigFox. Only supporting unidirectional communication for end-devices to the BS [44]. It achieves communication range of up to 3 km with maximum data rate of 100 kbps. The MAC protocol of Weightless-N is based on slotted ALOHA.

3.2.8 Weightless-P. Weightless-P is the latest standard introduced by Weightless-SIG. Unlike Weightless-N, it offers bi-directional communication with support for acknowledgments. It achieves data rate around 100kbps. Compared to Weightless-N, Weightless-P has shorter communication range (2 km) and shorter battery lifetime.

3.2.9 SNOW. SNOW is a new emerging asynchronous LPWAN technology with potentials to overcome the scalability limitation of existing LPWAN technologies. SNOW has a star network topology [53, 54]. Each sensor node is equipped with a single half-duplex narrow-band white space radio. The nodes are directly connected to the BS and vice versa. The BS uses a wide channel split into orthogonal subcarriers, each of equal spectrum width (bandwidth). The BS determines white spaces for nodes by accessing a cloud-hosted database through the Internet. The PHY layer of SNOW uses Distributed implementation of OFDM (Orthogonal Frequency Division Multiplexing) for multi-user access, called D-OFDM. If the BS spectrum is split into n subcarriers, then it can receive from n nodes simultaneously. Similarly, it can transmit n different data at a time. The BS can exploit fragmented spectrum as well. SNOW represents a novel PHY-layer design, eliminating the scalability limitations in existing LPWAN technologies. The scalability of SNOW increases with the availability of the TV spectrum.

4 OPPORTUNITIES IN LPWANS

LPWAN provides opportunities to enable a large class of IoT applications. We discuss several use cases in different domains (Figure 1).

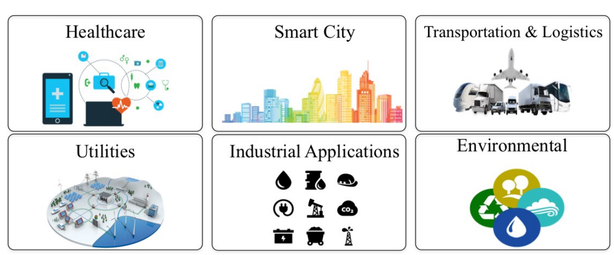

Figure 1: LPWAN enabled IoT applications

4.1 Smart City

The goal of *smart city* is to efficiently utilize the public resources, improve the quality of living, and reduce the cost of management and administrations of the public resources [68]. Multiple cities around the world have already started transitioning to smart cities [30, 51]. One example of smart city applications is **waste management.** In most cities around the world, waste management is extremely difficult and costly due to the operational service costs (e.g. trucks, fuel, and operators) and the limited storage areas [49]. Smart cities use smart waste containers, which detects the level of trash inside and send the information to a control center which then optimizes the collector truck route, eventually reducing the operational cost. Using LPWANs to provide affordable communication is beneficial to both taxpayers and city officials. Another application is **smart lighting**. Smart lighting significantly reduces the cost of street lighting by changing the light intensity according to the environment [68]. It also reduces the cost of maintenance by providing real-time fault monitoring [26]. Telensa is developed specifically for smart lighting and smart parking applications.

4.2 Transportation and Logistics

Today, millions of sensors and RFID tags are already deployed in vehicles, trucks, and airplanes that enable owners to track the movements of objects from the source to the destination across the supply chain in real-time [35]. One specific application is **connected vehicles**. Most of the newer vehicles include sensors, networking capability, and processor. IoT can utilize these to improve the driving experience in several ways such as enhance road sharing, accidents reporting, and parking detection. Long-range communication, low-power, low cost, and support for mobility are required to support transportation and logistics applications.

4.3 Agriculture and Smart Farming

The agricultural sector is one of the earlier adopters of IoT. To enable this, a network connecting the farm devices is needed. Precision agriculture powered by IoT can help farmers better measure things like soil nutrients, fertilizer used, seeds planted, soil water, and temperature of stored produce through a dense sensor deployment, thereby almost doubling the productivity [58]. Companies like Microsoft (FarmBeats project [17, 58]), Climate Corp [9], AT&T [10], and Monsanto [11] are promoting agricultural IoT.

4.4 Healthcare Applications

The healthcare sector is a great market for IoT applications. Examples of IoT applications for healthcare include remote health monitoring, elderly care, chronic disease [41], etc. The key requirements for IoT in most health-related applications are noninvasive sensing and secure and reliable communication. Currently, short range wireless technologies, such as ZigBee [69], WiFi [18], 6LowPAN [56] and cellular technologies such as LTE are widely adopted in the healthcare sector. However, with the increase in the number of sensors, these technologies will not scale due to interference. The limitations in short-range wireless technologies and the high cost of cellular technologies drove the attention to LPWANs as an alternative communication solution for healthcare applications.

5 CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In this section, we discuss the challenges and limitations of existing LPWANs, and research directions to address the challenges.

5.1 Future Scalability and Coverage

Scalability in dense networks will be a big challenge for LPWANs [37]. Specifically, the performance of LoRa, widely considered as an LPWAN leader [12, 13, 19, 32, 34, 47], drops exponentially as the number of end-devices grows [29, 31, 33, 37, 40, 61]. A typical smart city deployment can support only 120 LoRa nodes per 3.8 hectares [33], which is not sufficient for future IoT applications. Without line of sight its communication range is quite low [34], specially in indoor (<100m compared to its specified 2-5km urban range [59]). SNOW has been shown to be superior to LoRa in scalability. But SNOW implementation is still on USRP devices and its hardware realization is not done yet. Scalability can also be considered in terms of coverage area. Most LPWANs are limited to star topology while the cellular based ones (EC-GSM-IoT, NB-IoT, LTE Cat M1, 5G) rely on wired infrastructure for integrating multiple networks to cover larger areas. Lack of proper infrastructure and connectivity hinders their rural applications such as agricultural IoT [17, 58], oil-field monitoring [14], smart and connected rural communities [15, 24, 45, 48] that need extended coverage.

Existing research focuses on scalability in cellular and short-range wireless networks. For LPWANs operating in unlicensed spectrum, approaches such as offloading (from licensed spectrum to unlicensed spectrum) typically adopted in cellular-based technologies are not affordable. Currently, the use of narrowband channels is common among several LPWAN technologies. While narrowband channels provide an efficient spectrum utilization and support for a larger number of devices, in the future, the increase in the number of devices and LPWAN technologies will result in a very dense spectrum limiting spectrum availability. To address the scalability problem in LPWANs, future research would need to consider opportunistic spectrum sensing, adaption of spectral efficient modulation schemes, adaptive data rate MAC protocols, and exploring channel diversity for LPWANs. In addition, several research directions suggest the use of adaptive power control as a factor to increase the scalability [36]. Another approach is to use Non-orthogonal Multiple Access schemes (NOMA). NOMA supports multiple connections with different desired power rates by exploiting the path loss difference between multiple users, thereby increasing the spectrum utilization. For applications and deployments over very wide areas, future research needs to address wireless integration of LPWANs for extended coverage.

5.2 Technology Coexistence

High popularity of LPWANs brings forth a new challenge, called *coexistence*. Many independent networks will be deployed in close proximity, and interference between them must be handled to keep them operational. Today, LPWANs are not equipped to handle this imminent challenge that will make the spectrum overly crowded [52]. Studies on LoRa, SigFox, and IQRF show that coexistence severely degrades their performance [40, 43]. When four LoRa networks coexist, throughput of each reduces almost to one fourth [61]. Coexistence handling for WiFi, existing WSN, Bluetooth [57, 66, 67] will not work well for LPWANs. Due to their large coverage domains, LPWAN devices can be subject to an unprecedented number of hidden terminals. Enabling different technologies to coexist on the same spectrum is very challenging mainly due to different entities owning different technologies. One research direction is to utilize the spectrum information to detect and identify the presence of other technologies. This can be achieved using an efficient spectrum sensing method or a dedicated hardware combined with machine learning techniques to identify interfering technologies [36].

5.3 Inter-Technology Communication

With the rapid growth of LPWAN technologies, there will be many coexisting LPWANs in the same geographical area and their coordination may be needed. Specifically, LPWANs from different vendors may need to communicate which would be another big challenge. Recently, cross-technology-communication (CTC) [42] without the assistance of additional hardware has been studied for communication across WiFi, ZigBee, and Bluetooth devices. Such CTC is specific to technology. Future research is needed to enable CTC in LPWANs.

5.4 Real-Time Communication

Many IoT applications will require real-time communication (e.g. smart grid, manufacturing, healthcare, data center energy management [55]). Such applications require very low latency and very high reliability. Most LPWANs are designed to support applications with flexible requirements. In addition, the LPWANs operating in the sub-GHz band are required to duty cycle at 0.1 or 1% which make real-time communication extremely challenging. SNOW operates on dynamic spectrum which also raises challenge for real-time communication. Future research needs to focus on finding ways to enabling real-time communication in LPWAN.

5.5 Support for Control Applications

LPWAN will be a major communication infrastructure for a broad range of control applications in the future. Control applications rely on reliable bi-directional communications along with their real-time requirements. Most non-cellular LPWANs (e.g., LoRa, SigFox, Weightless-N) support uplink only communication at this time. LoRa can enable bidirectional communication, but it has to rely on time synchronized beacons and schedules, which is an overhead. DASH7 is specially designed for bidirectional communication but has only few hundred meters of communication range and has to rely on multihop. SNOW supports downlink communication but relies on dynamic spectrum availability which makes support for control extremely challenging. Investigating new techniques to enable reliable and efficient bi-directional communication represents a major direction of the future LPWAN research.

5.6 Support for Mobility

As the number of mobile devices grows, many devices in an LPWAN can be mobile. The usage of drones, tractors, vehicles, and human make mobility an immediate concern in agricultural IoT [11, 17, 39, 58]. Existing LPWAN technologies are not designed for handling mobility well except the cellular based ones that rely on wired infrastructure to handle mobility [38]. Such wired infrastructure does not exist in rural environments. Specifically, in remote areas (e.g. farms, oil fields etc.) often there is weak or no cellular signal/coverage. The high cost of subscribing to cellular service is also hindering the adoption of cellular technologies. In other LPWANs, handling mobility is quite challenging and not well-addressed yet. Their performance is susceptible even to minor human mobility [50]. Technology-specific features of each LPWAN also makes mobility issues such as base station discovery, handoff, and seamless communication quite different. The mobility feature of RPMA [22] is its transmitter's robustness to the Doppler effect, and does not mean the afore-mentioned mobility issues. Mobility imposes challenges for LPWAN in terms of energy consumption. The support for mobility has a direct impact on the battery lifetime of the node. Thus, the design of an energy-efficient, low cost mobility approach for LPWANs is needed.

5.7 Support for High Data Rate

The typical data rate supported by LPWAN technologies is ranging from 1 − 100 kbps. Narrowband offers long transmission range at the cost of low data rates. The advent of aerial imagery systems that involve drones and cameras for richer sensor data from the farms need high bandwidth in agricultural IoT [11, 17, 39, 58]. In the future, many IoT applications will evolve to include several use cases, such as video streaming, requiring very high data rate. LPWANs must investigate different approaches to support high data rate. Future research directions to enabling high data rates include enabling different modulation techniques, borrowing approaches used in technologies like WiFi, and designing new hardware to support multiple PHY layers offering different data rates.

5.8 Security

Transmitting a signal over the air is subject to jamming attacks, packets sniffing, eavesdropping, and variety of attacks. Most LPWAN technologies support a simple cryptography method where the device and the network share a secret key. On the other hand, cellular technologies have support for end-to-end authentication and privacy using Subscriber Identification Module (SIM). However, this comes with the high cost of cellular devices and more complex device design. The need for secure communication is essential for LPWANs. For example, enabling over the air software updates is important to ensure security for LPWAN devices. As LPWAN is a key technology driving the IoT, extensive future research is needed for the study of LPWAN security.

6 CONCLUSION

In this paper, we have discussed the opportunities and challenges in Low-Power Wide-Area Networks (LPWANs) as an enabling technology for IoT applications. We have presented the state-of-the-art LPWAN technologies and discussed their characteristics which allow them to achieve long-range connectivity, low-power communication, and low deployment cost for a large number of devices. Finally, we have outlined the opportunities and challenges in realizing the LPWANs for the future IoT applications. We have provided insights and directions for the future research in LPWAN.

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