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Low-Power Wireless for the Internet of Things: Standards and Applications

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ABSTRACT The proliferation of embedded systems, wireless technologies, and Internet protocols have enabled the *Internet of Things* (IoT) to bridge the gap between the virtual and physical world through enabling the monitoring and actuation of the physical world controlled by data processing systems. Wireless technologies, despite their offered convenience, flexibility, low cost, and mobility pose unique challenges such as fading, interference, energy, and security, which must be carefully addressed when using resource-constrained IoT devices. To this end, the efforts of the research community have led to the standardization of several wireless technologies for various types of application domains depending on factors such as reliability, latency, scalability, and energy efficiency. In this paper, we first overview these standard wireless technologies, and we specifically study the MAC and physical layer technologies proposed to address the requirements and challenges of wireless communications. Furthermore, we explain the use of these standards in various application domains, such as smart homes, smart healthcare, industrial automation, and smart cities, and discuss their suitability in satisfying the requirements of these applications. In addition to proposing guidelines to weigh the pros and cons of each standard for an application at hand, we also examine what new strategies can be exploited to overcome existing challenges and support emerging IoT applications.

INDEX TERMS Internet of Things, IEEE 802.15.4, Bluetooth, Physical layer, Medium Access Control, coexistence, mesh networking, cyber-physical systems, WSN, M2M

I. INTRODUCTION

The Internet of Things (IoT) [1] refers to the inter-networking of everyday objects that are equipped with sensing, computation, and communication capabilities. These networks can collaboratively interact and perform a variety of tasks autonomously. IoT promises to play a remarkable role in diverse application domains, such as smart homes [2], medical care [3], [4], industrial automation [5], [6], intelligent transportation [7], [8], resource management [9], smart cities [10], [11], and energy management [12], [13], as shown in Figure 1. For example, in a smart home application, based on user prescribed settings, different monitoring and control tasks are carried out by smart sensors and actuators, such as the heating control system, air-condition monitoring, and fire alarms. Closely related to the IoT are *Machine-to-Machine* (M2M) communication [14], *Wireless Sensor Networks* (WSNs) [15], *Wireless Personal Area Networks* (WPANs) [16] *Wireless Sensors and Actuators Networks* (WSANs) [17], [18], and *Cyber-Physical Systems* (CPSs) [19], [20], which are application-dependent terms.

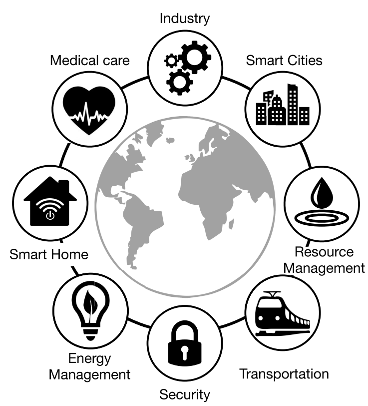


FIGURE 1. Applications of IoT in different domains.

The entire vision of the IoT surrounds the concept of communication among smart objects, enabling them to see, hear, think, act, and talk to one another to make smart decisions. It fundamentally embeds intelligence into the objects by utilizing ubiquitous computing, networking technologies, inter-networking protocols, and applications [21]. Both wired and wireless networks are utilized to support information exchange at the backbone and local access networks. The local access networks, in particular, are wireless, support multi-hop communication, and enable mobility [22]. As these networks are usually low-power and unreliable, they are referred to as *Low-Power and Lossy Networks* (LLNs) [23]. These networks lay the necessary foundation of IoT and contribute to making it highly accessible. The aspect of ubiquitous accessibility of services and objects to mobile users is imperative because most of the IoT services are targeted to mobile users. Another strong aspect is the autonomous operation, where IoT helps to decentralize the decision-making process to accomplish autonomous operations with minimal human intervention. This autonomous feature is of paramount importance for a multitude of industrial applications that enable smart processes and systems. This has amplified the vision of the fourth Industrial revolution, also known as the Industry-4.0 or smart factory [24].

Although IoT promises to revolutionize several application domains and enormously transform the way we live and communicate, it imposes challenging requirements from the networking point of view. The first essential requirement is *reliable* wireless network connectivity, which is particularly important for applications such as industrial process automation and control, healthcare, emergency situations, disaster recovery, home safety [25]. Second, *timeliness* or low latency are requirements that guarantee the bounded and deterministic delay of data transfer between different objects so that actions are performed on time. For example, industrial process control systems require real-time communication between machines and controllers. Third, the *low-power operation* requirement helps the nodes save power and avoid unnecessary communication attempts, thereby preventing early death and extending network lifetime. All of these requirements led to the development of several standards and technologies. These standards propose different features and protocols to satisfy the *Quality of Service* (QoS) requirements of different IoT applications. However, the practical use of these standards in different IoT applications has resulted in several limitations. These limitations accelerated the need for further analysis in order to seek viable solutions to meet existing and future demands of IoT applications. In this paper, we review the existing low-power wireless standards and technologies. We primarily focus on the *Physical* (PHY) and *Medium Access Control* (MAC) layers because they directly impact several performance metrics, such as reliability, latency, scalability, and energy consumption. In this paper:

– We present an overview of some of the active standardization bodies that are working on the development of sophisticated standards and protocols for IoT.

TABLE 1. Abbreviations.

Symbol	Description
6LoWPAN	IPv6 over Low Power Wireless Personal Area Network
6TiSCH	IPv6 over Time Slotted Channel Hopping
ABI	Allied Business Intelligence
ACL	Asynchronous Connection-Less
AE	Advertising Extension
AFH	Adaptive Frequency Hopping
AmI	Ambient Intelligence
AMP	Alternative MAC/PHY
AP	Access Point
BE	Beacon Enabled
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BO	Beacon Order
BR/EDR	Bluetooth Classic
CAP	Contention Access Period
CBW	Channel Bandwidth
CCA	Clear Channel Assessment
CFP	Contention Free Period
CPS	Cyber-Physical System
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSS	Chirp Spread Spectrum
DSSS	Direct Sequence Spread Spectrum
DSME	Deterministic and Synchronous Multi-channel Extension
ED	Energy Detection
ERP	Emitted Radiated Power
ETSI	The European Telecommunications Standards Institute
FEC	Forward Error Correction
FER	Frame Error Rate
FFD	Full Function Device
FHSS	Frequency Hopping Spread Spectrum
FSK	Frequency Shift Keying
GFSK	Gaussian Frequency Shift Keying
GTS	Guaranteed Time Slot
HVAC	Heating, Ventilation, and Air Conditioning
IEEE	Institute of Electrical and Electronic Engineers
IEEE-SA	IEEE Standards Association
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPSO	Internet Protocol for Smart Object
ISA	International Society of Automation
ISM	Industrial, Scientific, and Medical
IWSN	Industrial Wireless Sensor Network
LLDN	Low Latency Deterministic Network
LLN	Low-Power and Lossy Network
LoRaWAN	Long Range Wide Area Network
LoWPAN	Low Power Wireless Personal Area Network
LPWAN	Low Power Low Power Wide Area Networks
LQI	Link Quality Indication
LR-WPAN	Low Rate Wireless Personal Area Network
M2M	Machine-to-Machine
MAC	Medium Access Control
MTU	Maximum Transfer Unit
OFDM	Orthogonal Frequency Division Multiplexing
OQPSK	Offset Quadrature Phase-Shift Keying
PAN	Personal Area Network
PER	Packet Error Rate
PHY	Physical
QoS	Quality of Service
RAW	Restricted Access Window
RFD	Reduced Function Device
ROLL	Routing Over Low power and Lossy networks
RSSI	Received Signal Strength Indication
SCO	Synchronous Connection-Oriented
SF	Spreading Factor
SIG	Bluetooth Special Interest Group
SNR	Signal to Noise Ratio
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TSCH	Time-Slotted Channel Hopping
TSMP	Time Synchronized Mesh Protocol
TWT	Target Wake Time
V2V	Vehicular to Vehicular
WBANs	Wireless Body Area Networks
WHO	World Health Organization
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WSAN	Wireless Sensors and Actuators Network
WSN	Wireless Sensor Network

- We discuss and analyze several low-power wireless standards and technologies. The *Institute of Electrical and Electronic Engineers* (IEEE) 802.15.4 standard and its derivations such as Thread, WirelessHART, *IPv6 over Low Power Wireless Personal Area Network* (6LoWPAN), and *IPv6 Over TSCH* (6TiSCH) are presented. We also study the Bluetooth standard and its variants, such as *Bluetooth Basic Rate and Enhanced Data Rate* (BR/EDR) and *Bluetooth Low Energy* (BLE).
- Various technologies and standards that share common frequency bands, such as *Industrial, Scientific, and Medical* (ISM), generate severe interference in a coexisting environment. We investigate how the inherent *Physical* (PHY) and *Medium Access Control* (MAC) layer design of these standards and technologies help to cope with interference issues.
- We explore the suitability of various standards across different IoT application domains, such as smart homes, smart cities, smart healthcare, and industrial automation. Possible limitations of each standard in different application domains are also highlighted.
- We emphasize the need to overcome the limitations of the existing standards to meet timeliness, reliability, scalability, and energy efficiency requirements of IoT applications.
- We explain how the stringent requirements of IoT applications and the constrained resources of objects introduce severe challenges in terms of protocol design.

The remainder of the paper proceeds as follows. In Section III, we discuss IEEE 802.15.4, in particular, its PHY and MAC features. Several standards based on IEEE 802.15.4 are also presented. Subsequently, we discuss how IEEE 802.15.4e overcomes the limitations of IEEE 802.15.4. Section IV describes Bluetooth and its radio and link layer working principles in detail. The discussion revolves around different versions of Bluetooth such as BR/EDR and BLE. Specifically, we demonstrate the communication principles in BLE such as beaconing and extended connectivity features. Additionally, we point out the limitations of each of the Bluetooth versions. Furthermore, we explain the BLE mesh specification. Section V presents the coexistence perspective of different standards and technologies that share the 2.4 GHz band. Other non-standard sources of interference are also described. In Section VI, we give an overview of the Z-wave standard. Section VII examines IEEE 802.11ah, which is another low-power wireless standard operating in sub-GHz. In Section VIII, the *Long Range* (LoRa) technology is presented. In Section IX, we discuss broad applications of IoT and their characteristics, requirements, and traffic categories. We explore the suitability of each standard relative to these application domains. In Section X we discuss the existing surveys relevant to IoT. Finally, a conclusion is drawn in Section XI.

II. STANDARDIZATION BODIES

A large number of devices from different technologies and vendors makes the IoT environment quite heterogeneous, which causes interoperability issues across different application domains. To meet this challenge, we witness several standardization bodies that accelerated the development of low-power wireless standards and technologies. These standards employ unique PHY, MAC, network, and application layer enhancements to meet low-power, low-latency, high reliability, scalability, and security requirements of IoT applications. In the following, we describe some of the well-known standardization bodies that are actively working toward developing IoT protocols.

IEEE Standards Association (IEEE-SA) [26] is the most well-known standardization organization. It mostly targets the lower layers in the OSI protocol stack, namely MAC and PHY. In this paper, we focus on IEEE 802.15.4, IEEE 802.15.1 (Bluetooth), and IEEE 802.11ah due to their low power operation. The IEEE 802.15.4 provides the fundamental blocks for many of the key technologies such as ZigBee, Thread, WirelessHART, and ISA100.11a. These standards are detailed in Section III. Up to 2017, IEEE-SA has published more than 1100 active standards, and it has more than 600 standards under development [27].

ZigBee alliance [28] is an open global standard based on IEEE 802.15.4 that is targeted to low-power wireless networks. The technical specifications of ZigBee are discussed in Section III. The most common applications of ZigBee are in home automation, industrial control, and healthcare. They will be described in Section IX.

The *Internet Engineering Task Force* (IETF) [29] is one of the non-profit organizations that developed IoT standards such as 6LoWPAN or *Routing Over Low power and Lossy networks* (ROLL). IETF encourages more people to communicate and collaborate on new ideas such as improving the IoT use cases in smart cities, healthcare, industrial Internet and other related applications by providing solutions to overcome issues such as scalability, timeliness, and IPv6 adaptation for low-power wireless networks. IETF provides a platform where developers and researchers can collaborate voluntarily to improve and build standards. The standard documents provided by the IETF, such as the Request for Comments (RFCs), can be accessed freely. For example, (RFC4944) [30] was developed in 2007 and updated by the drafts (RFC6282) [31], (RFC6775) [32], (RFC8025) [33], (RFC8066) [34] up until 2017 for developing 6LoWPAN standards. These documents cover a wide range of topics relating to issues of routing, security, and applications in IoT.

The European Telecommunications Standards Institute (ETSI) [35] is another non-profit body (like IETF) that works for standardization organizations in Europe. It produces globally-applicable standards for communication technologies for the Internet, such as fixed, mobile, and broadcast, and short-range technologies. *The Third Generation Partnership Project* ($3GPP^{TM}$) is an example of the

ETSI standards. Currently, ETSI has 800 member organizations from 67 countries.

OneM2M [36] is a worldwide organization formed in 2012 that aims to provide and develop technical specifications in order to meet architectural, security, and interoperability requirements for M2M communication. It targets applications such as smart cities, smart grids, smart homes, and healthcare. OneM2M cooperates with more than 200 companies.

International Society of Automation (ISA) [37] targets industrial IoT covering applications such as security, safety, batch control, and enterprise integration. A widely-adopted standard developed by this body is ISA100.11a [38]. ISA has more than 40,000 members and 140 committees, subcommittees, working groups, and task forces that are working to develop the ISA standards.

OpenWSN [39] is a project created by the University of California, Berkeley. It aims to provide an open source platform for developers and researchers to implement the IoT protocol stack. The stack implements different hardware and operating systems, such as OpenMote [40] and RIOT [41], respectively. One of the important goals of OpenWSN is the adaptation of the *Time-Slotted Channel Hopping* (TSCH) concept over IEEE 802.15.4e. TSCH provides the IPv6 support in the network layer based on the IETF 6TiSCH implementation [42]. We will discuss TSCH in Section III-H.

Internet Protocol for Smart Object (IPSO) alliance [43] is an active organization for enabling *Internet Protocol* (IP) connectivity for smart object communication in IoT. IPSO was founded in 2008 and targets IoT applications, such as smart cities, home automation, healthcare, and energy management.

Bluetooth Special Interest Group (SIG) [44] developed and licensed Bluetooth technology. It is a non-profit organization that was founded in September 1998. This body publishes the core specifications for the different version of Bluetooth. In Section IV, we will describe the different versions of Bluetooth developed by SIG. Currently, SIG is supported by more than 30,000 member companies [45]. Although SIG does not sell any Bluetooth products, it owns the Bluetooth word mark, figure mark and combination mark, which collectively make up the Bluetooth trademarks.

III. IEEE 802.15.4

IEEE 802.15.4 [46], which mainly defines PHY and MAC layer specifications, is considered the *defacto* standard for *Low Rate Wireless Personal Area Network* (LR-WPAN). The standard was developed for low data rate monitoring and control applications that require very low power consumption. Due to its appealing features such as low-power, low cost, and moderate data rate, it is the most widely used standard for home automation [47], industrial automation [48], [49], smart cities [50], and *Wireless Body Area Networks* (WBANs) [51]. Most of the existing standards, such as ZigBee [28], WirelessHART [52], and ISA100.11a [53], employ IEEE 802.15.4 as the PHY layer technology together with certain upper layer modifications. At the MAC layer, the standard offers a flexible protocol that tries to achieve a better trade-off among several performance metrics, such as energy efficiency, delay, coverage, and data rate.

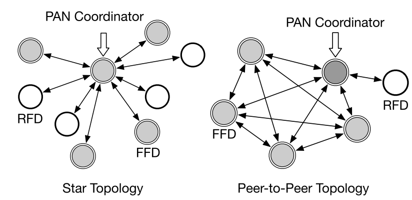


FIGURE 2. The star and peer-to-peer network topologies supported by the IEEE 802.15.4 standard.

TABLE 2. Frequency bands of the IEEE 802.15.4 standard.

	Europe	America	Worldwide
Frequency (MHz)	868-868.6	902-928	2400-2483.5
No. of Channels	1	10	16
Channel Bandwidth	600 kHz	2 MHz	5 MHz
Data rate	20 kbps	40 kbps	250 kbps
Modulation	BPSK	BPSK	OQPSK

The IEEE 802.15.4 network supports star, tree, and peer-to-peer network topologies as shown in Figure 2. The network is composed of two types of devices, namely *Full Function Device* (FFD) and *Reduced Function Device* (RFD). The FFDs can perform activities like network coordination, routing, and sensing, whereas the RFDs are constrained nodes that can only serve as end-devices to perform sensing tasks. As coordinators, FFDs can form, manage, and maintain a *Personal Area Network* (PAN), but a FFD can manage only a single PAN at a time. The FFDs can also serve as routers that relay traffic through intermediate routes from source to destination. They can also store routing tables.

The following discussion elaborates more on the PHY and MAC layer specifications of the standard.

A. PHY LAYER

The PHY layer uses the 2.4 GHz ISM [54] frequency band. Different frequency bands are allocated to different regions, as listed in Table 2.

The PHY offers services such as the transmission and reception of *PHY Protocol Data Units* (PPDUs) across the physical channel. It performs a number of suitable functionalities like the activation and deactivation of radio transceiver, *Energy Detection* (ED), *Link Quality Indication* (LQI), *Clear Channel Assessment* (CCA), channel frequency selection, and packet transmission and reception [46].

The purpose of the ED is to estimate the power of the received signal within the bandwidth of the channel so that the MAC layer can avoid interference.

CCA is a reliable method to determine any activity on the channel before making a transmission. CCA works based on multiple sampling of channel energy. For example, it may sample the channel five times and report a free channel if there is at least one sample less than the noise floor. There are total 27 different channels available across all of the bands as defined by the IEEE 802.15.4 standard. For example, the 2.4 GHz band includes 16 channels numbered from 11 to 25, where each channel has a bandwidth of 2 MHz and center frequencies are separated by 5 MHz. They offer an achievable data rate of as much as 250 kbps [55]. IEEE 802.15.4 uses *Direct Sequence Spread Spectrum* (DSSS) which mainly supports coexistence by spreading the signal over a larger bandwidth.

Upon receiving a request from the MAC sub-layer, the radio transceiver may operate in one of the three states: transmit, receive, or sleep. The energy consumption states of a transceiver can be classified into the following states: transmission, reception, and sleep. During idle listening, the device is listening to incoming packets, which may result in overhearing packets that are not destined for it [56]. It is observed that in most of the commercial IEEE 802.15.4 compliant transceivers the energy consumed during idle listening is almost the same as receiving or transmitting a packet [57] and is a significant cause of energy waste. For example, the TI CC2420 transceiver at 0 dBm output power consumes 17.4 mA in transmission and 18.8 mA in idle listening states [58].

Since nodes have constrained resources, the IEEE 802.15.4 implements duty cycling in the MAC protocol to save power. Duty cycling allows a node to sleep by turning off its transceivers to conserve energy periodically.

B. MAC LAYER

The standard proposes a flexible MAC that can mainly switch between two channel access modes known as *beacon enabled* mode and *non-beacon enabled* mode.

1) BEACON ENABLED (BE) MODE

In this mode, communication is based on a superframe structure. The superframe starts with a beacon period followed by an active period and an inactive period, as shown in Figure 3. The active period consists of the *Contention Access Period* (CAP) and *Contention Free Period* (CFP), while the inactive period allows duty cycling. The active period is further subdivided into 16 equally spaced parts called *time slots*. The superframe information is broadcasted through beacons at the start of the network. A beacon is a specific frame generated periodically by the PAN coordinator to update synchronization and other network related information among the nodes. A superframe is bounded by two beacons. After the beacon, the CAP immediately starts where nodes compete, using slotted *Carrier Sense Multiple Access/Collision Avoidance* (CSMA/CA) to transmit new packets to the coordinator or request pending packets. To minimize the probability of collisions over the channel, slotted CSMA/CA uses the *Binary Exponential* (BE) Backoff algorithm. After the CAP is the CFP, which contains *Time Division Multiple Access* (TDMA) like *Guaranteed Time Slots* (GTSs) for transmission. GTSs are allocated by the coordinator to the nodes that

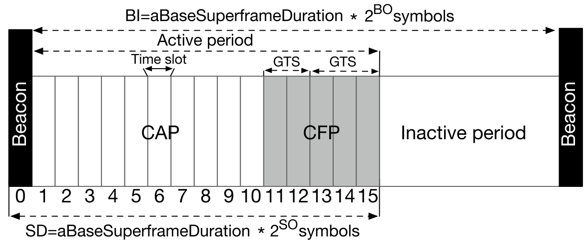


FIGURE 3. **The superframe structure of the BE MAC mode of IEEE 802.15.4 standard.**

require special bandwidth reservations [59]. Nodes request the GTSs from the PAN coordinator during the CAP. GTS can be used either for transmission or reception, and a maximum of seven GTSs are allowed per superframe. During the GTS, the node has exclusive access to the channel at its disposal.

The total duration of the superframe, including active and inactive periods, can be configured through two important parameters known as *Superframe Order* (SO) and *Beacon Order* (BO). The network coordinator defines the superframe structure by a *Beacon Interval* (BI), which is the time between two sequential beacons, and a *Superframe Duration* (SD), which is the active duration of the superframe, as shown in Figure 3. The values of BO and BI are related as follows [46];

$$\text{for } 0 \leq BO \leq 14$$
$$BI = \alpha \times 2^{BO} \text{ symbols}$$

α is known as *aBaseSuperframeDuration*, which is the number of symbols forming a superframe when the SO is equal to zero. The SO defines the duration of the active period including the beacon frame. The values of SO and SD are related as follows:

$$\text{for } 0 \leq SO \leq BO \leq 14$$
$$\text{SD} = \alpha \times 2^{SO} \text{ symbols}$$

Therefore, in the case of 2.4 GHz, the value of SD $= 15.36 \times 2^{SO}$ ms with a BI $= 15.36 \times 2^{BO}$ ms. Thus, the value of BI can be adjusted between 15 ms to 245 s [59], depending on the value of BO and SO.

2) NON-BEACON ENABLED (NBE) MODE

No GTS allocation is employed in this mode. Nodes mainly utilize unslotted CSMA/CA for channel access and perform only a single CCA operation without synchronization to backoff boundaries [60].

C. LIMITATIONS OF IEEE 802.15.4 MAC

Although IEEE 802.15.4 MAC has several appealing features for general IoT applications, yet it has several limitations for applications that require high reliability, low latency, and energy efficiency, as pointed out in [61] and [62]. To address this issue, several investigations on the performance analysis of IEEE 802.15.4 MAC were conducted [63]–[66].

Studies in [67] show that the selection of the binary exponent is random and does not take into account the number of available nodes, the communication activity level, or the priority of data packets, resulting in a higher likelihood of collisions. The random nature of the binary exponent causes nodes to sleep for prolonged periods than required. This leaves the medium unnecessarily idle for an extended period, impacting the throughput.

A simulation-based evaluation of slotted *Carrier Sense Multiple Access* (CSMA) for beacon-enabled mode for dense networks was conducted in [66]. The authors showed that the backoff algorithm is not flexible for large-scale networks, since the lower limit of the backoff delay is always 0 which is fixed. Thus, it prevents particular ranges for the backoff delays. Therefore, it is not sufficient to avoid collisions for large-scale networks. The impact on the selection of the BO and SO was analyzed based on the average delay. A node that cannot complete its data transmission in the current CAP is forced to defer its transmission to the following superframe. Therefore, the node has to re-contend to access the medium and face collisions. Such a situation makes the delay for the data transmission not only non-deterministic and unbounded, but it also deteriorates the throughput.

Another study on the performance of slotted CSMA/CA for the BE mode was conducted in [63]. The authors showed that the default values of MAC parameters, such as MAC minimum binary exponent and number of backoffs, may result in lower throughput and high-power consumption. This analytical study was based on the Markov model for both saturated and unsaturated periodic traffic, and it was suggested to tune the MAC parameters to achieve better results.

Anastasi *et al.* [64] gave a comprehensive analysis on the MAC unreliability problem. The authors argued that if the power management is enabled, it will result in poor packet delivery ratio. The reason was found to be the contention access period and its default parameters, such as the minimum and maximum binary exponent value, the maximum number of backoffs, and maximum frame retries allowed.

The authors suggested that the MAC, in its current form, is not suitable for mission-critical applications and requires proper tuning of the MAC parameters for better performance.

Motivated by these shortcomings, several relevant standards and protocols emerged to overcome the limitations of IEEE 802.15.4 MAC [68], [69]. We overview these protocols and standards as follows. We will present different applications based on this standard and elaborates further on their suitability in each application domain in Section IX.

D. THREAD

Thread [70] is an open networking stack, which has received support from well-known organizations such as Google, Samsung, Nest, Freescale, and ARM [71]. It is built on top of the IEEE 802.15.4 PHY and MAC layer specifications, operating in 2.4 GHz band. It is cost-effective, reliable, secure, works at very low-power, and supports up to 250 devices in a single local mesh network. The technology is optimized for low latency (less than 100 ms) and smart home networking applications, such as access control, energy management, and light control.

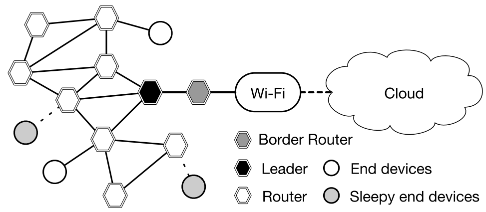


FIGURE 4. The mesh networking architecture of Thread.

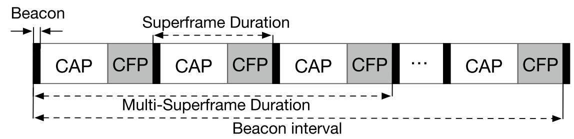
It does not suffer from a single point of failure due to its mesh networking capability, thus improving reliability.

It natively supports 6LoWPAN technology to benefit IPv6 capability in order to support interoperability. In this way, devices can be directly connected to the Internet and can be accessed from anywhere. Figure 4 shows the mesh network architecture of Thread. As shown, a typical Thread network consists of at least one or more border routers, a router, a leader, sleepy end-devices, and end-devices. The border router serves as a gateway that is responsible for connecting a Thread network to an adjacent non-Thread network that operates on other physical layers like IEEE 802.11 or Ethernet. Multiple border routers can be deployed to achieve redundancy. This keeps the mesh network functional in case of a failure of the single border router, thereby improving resiliency. A router offers routing services to the network devices. It also provides security and network joining services for the devices that wish to join the network. A router or border router can act as a leader which is required to make decisions for some specific functions like assigning router addresses and allowing new router requests.

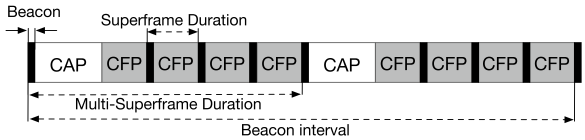
Sleepy end-devices can communicate through their parent router and serve as only host devices, but they cannot forward messages for other devices. End-devices can exchange messages with their parent devices. At the application layer, Thread does not impose any particular application layer protocol, however, the common light-weight protocols, such as *Constrained Application Protocol* (COAP), *Message Queue Telemetry Transport* (MQTT), and *Extensible Messaging and Presence Protocol* (XMPP), can be used.

The standard implements several security enhancements; it supports *Transport Layer Security* (TLS) [72] and its variant, Datagram TLS (DTLS) [73]. A network-wide key is used at the MAC that protects the IEEE 802.15.4 data frames against eavesdropping, tampering, and targeted disruption from outsiders.

Since Thread and ZigBee mostly share the same physical specifications and have several features in common, it is expected that they are likely to merge in order to create a uniform IoT standard [74]. Although Thread claims to have all of the features mentioned above, there are no practical implementations or deployments available based on Thread standard.



(a)



(b)

FIGURE 5. The multi-superframe structure of DSME MAC mode with extended and reduced CAP. The shaded bars show the CFP consisting of GTSs and the white bars show CAP. (a) DSME multi-superframe with extended CAP. (b) DSME multi-superframe with reduced CAP.

E. IEEE 802.15.4E

IEEE 802.15.4, in its 2011 version [46], supports enhanced physical specifications that enable a variety of applications (see section III-A). However, the standard cannot support mission-critical applications due to several limitations. Specifically, in order to meet reliability, low latency, and low-power consumption, which are the requirements of emerging applications like *Cyber Physical System* (CPS) based *Intelligent Transportation System* (ITS) [75], [76], smart health care [77], and industrial process automation and control, IEEE released an enhanced version known as the IEEE 802.15.4e [78].

It specifically introduces five enhanced MAC protocols in the form of *MAC behavior modes*. These protocols will be elaborated in the subsequent discussion.

1) DETERMINISTIC AND SYNCHRONOUS MULTI-CHANNEL EXTENSION (DSME)

DSME is an extension of the beacon-enabled MAC mode of the IEEE 802.15.4. DSME does not rely on a single channel. Instead, it uses multiple channels and has a multi-superframe structure, which has an extended number of GTSs. A multi-superframe consists of a collection of consecutive non-overlapping superframes as shown in Figure 5. The multi-superframe structure can flexibly support both periodic and a periodic traffic. DSME mainly targets multi-hop networks and uses *Enhanced Beacons* (EBs), which are shown as black bars inside the multi-superframe in Figure 5. EBs are used to announce the presence of the network and contain information related to the size of the time slots, slot frames, and time synchronization information to maintain synchronization among the network nodes. The superframe consists of only the active period, which is further subdivided into CAP and CFP. Nodes in the CAP use slotted CSMA/CA for channel access to transmit monitoring, urgent, or a periodic data. The CAP is fixed to 8-time slots during which the nodes should stay awake. The CFP occupies the remaining seven slots that are known as the *Guaranteed Time Slot*s (GTSs) (DSME-GTSs), which are used to transmit time-critical data. As mentioned before, nodes remain awake during the CAP; however, in order to save energy, DSME reduces the number of CAP periods, and only the first superframe of each multi-superframe uses the CAP. The rest of the superframes inside the multi-superframe structure do not make use of the CAP, but rather the whole period is treated as a CFP that consists of 15 GTSs, as shown in Figure 3 (Section III-B). DSME exploits channel diversity to select the best possible channel in order to ensure reliability and robustness against external interference and multi-path fading. Therefore, it is particularly suitable for factory automation, smart metering, and patient health monitoring.

DSME MAC mode is scalable due to its distributed nature. Specifically, slot allocation and beacon scheduling are not performed by a central entity, but rather they are performed by the network devices themselves in a distributed fashion. It is adaptive to time-varying traffic conditions and to changes in network topology, where each pair of nodes, based on their needs, allocates and deallocates GTS slots. Due to its adaptive capability, it can be a good candidate for mobile networks, where data rate requirements and topology vary over time. It improves energy efficiency through its *Group Acknowledgement* (GACK) option, where a single *Acknowledgement* (ACK) frame aggregates the acknowledgments of multiple data frames.

Although DSME MAC presents significant enhancements, some of its shortcomings have been identified as follows. For example, Rodenas-Herraiz *et al.* [79] pointed out the overhead of topology change in large-scale networks. In particular, the overhead may be high due to the rescheduling of beacon frames and/or selection of non-interfering frequency channels, assuming the multi-superframe structure is long enough and contains superframes of all coordinators. This increases the energy expenditure of the devices. On the other hand, in a dense network, DSME incurs considerable delays due to the TDMA multi-superframe structure, where the coordinator and the devices become active only in their respective superframes. Therefore, if the part of data transmission cannot be completed in the current superframe, it needs to be deferred to the following superframe. The coordinator and its associated devices would have to wait for the next multi-superframe to resume their transmission.

2) THE LOW LATENCY DETERMINISTIC NETWORK (LLDN)

LLDN targets applications that require low latency, such as manufacturing and robotics. It only works with the star topology and uses TDMA superframe time slots with small packets. The duration of the superframe is fixed and has distinctive slots, namely the beacon, management, uplink, and bidirectional time slots. The duration of a time slot is 10 ms, and the number of time slots determines the number of devices that can communicate. Since the size of the superframe is restricted to a certain number of time slots, it only allows a certain number of devices to participate in the network.

However, in order to make the network scalable up to more than 100 devices, the PAN coordinator can use multiple transceivers that each operate on a different frequency. Moreover, in order to further reduce latency, LLDN makes use of short MAC addresses to decrease frame processing and transmission time. Similar to DSME, it also exploits the GACK mechanism to minimize the bandwidth overhead. The use of star topology makes LLDN more suitable for factory automation, where a large number of nodes often communicate with a central entity. However, it has some limitations in terms of scalability, topology, and throughput.

The standard recommends using multiple transceivers in the PAN coordinator to create various networks operating on different channels. However, a study by Patti *et al.* [80] argues that this recommendation imposes a higher cost and greater complexity. They propose multi-channel LLDN, which improves scalability by allowing a higher number of nodes in the network while maintaining low cycle times without the need of multiple transceivers for the PAN coordinator. Berger *et al*. [81] indicate that using a star topology restricts coverage.

They propose the extension of the star topology, which is to collect data from two-hop sensors with the use of a relay node strategy. The relay nodes improve transmission reliability by retransmitting undelivered packets. The authors are of the view that the use of reserved slots and retransmission strategy in default LLDN reduces the number of sensor nodes per network, which impacts data throughput.

3) THE *Time-Slotted Channel Hopping* (TSCH)

TSCH MAC is considered one of the latest generations of MAC protocols in the category of reliable and low-power operation. It aims to satisfy the requirements of low-power mesh networks in industrial process automation. TSCH is considered the most viable MAC candidate for the IoT protocol stack because of its time and channel diversity features [82]. It incorporates mechanisms such as *time-slotted access* and *multiple channel communication* with *channel hopping*. Time-slotted channel access inherently avoids the nodes that are competing for the channel, eliminating collisions and improving throughput. It provides every network node guaranteed access to the wireless medium, offering deterministic latency, and builds on a communication schedule that coordinates the exchange of information among the nodes. In this way, each node exactly knows when to transmit, receive, or sleep. TSCH achieves low-power through synchronization, causing the receiver to be active precisely when the sender transmits.

The improved design of TSCH is influenced by *Time Synchronized Mesh Protocol* (TSMP) which is a proprietary MAC protocol designed by the Dust Networks [83]. TSMP became the widely accepted MAC protocol in the industrial domain, and in particular, is adopted by WirelessHART [84] for its MAC operation [52]. Standards like ISA100.11a [53] and WIA-PA [85] use the core concepts of TSMP in their MAC design, alongside some higher layer packet format modifications. Below, we present an overview of the TSCH slot frame and its functionality.

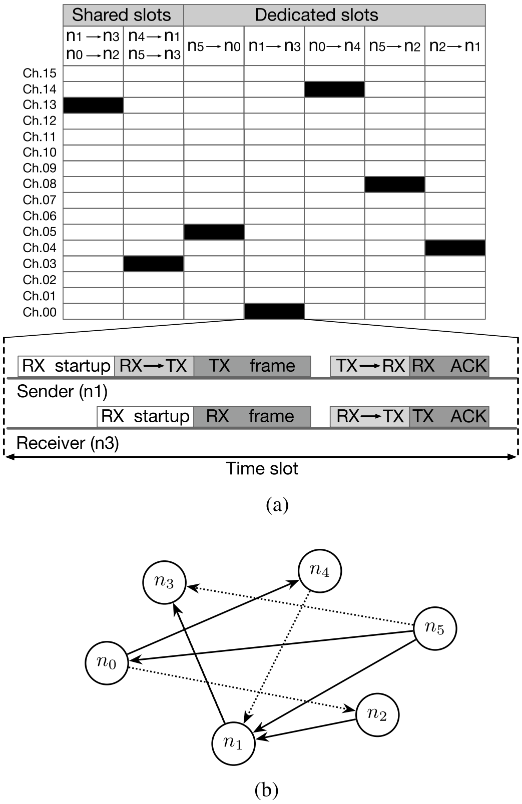


FIGURE 6. TSCH slotframe schedule based on the associated topology. (a) TSCH slotframe, it also shows sequence of transmission events within a timeslot for a transmitter-receiver node pair. (b) The associated topology where dotted arrows show transmission in shared slots and solid arrows represent transmission in dedicated slots.

The earlier MAC protocol of IEEE 802.15.4 (see section III-B) used a single channel approach in combination with the backoff algorithm in order to avoid collisions in a shared medium. TSCH takes a multi-channel approach by utilizing channel hopping and maintaining a low duty cycle. Channel hopping intelligently mitigates external interference and multi-path fading [86], which makes TSCH highly reliable and robust. Today, TSCH commercial products offer 99.9% end-to-end reliability while consuming an average current that is below 50 μA at 3.6 V [87].

TSCH Slotframe: A slot frame combines several time slots that repeat periodically, as shown in Figure 6a.

Not only does this periodic repetition of slot frame provide each node the opportunity to communicate in the network, but it also helps to update synchronization and other network related information. TSCH does not define and impose a slot frame size; instead, the slot frame size is a design parameter that is decided by the application programmer. The size of the slot frame can be from 0 to 1000 time slots [88]. Enhanced beacons are sent by the nodes to advertise the network.

A time slot is long enough to send a maximum size packet and receive its corresponding ACK. A typical value of the

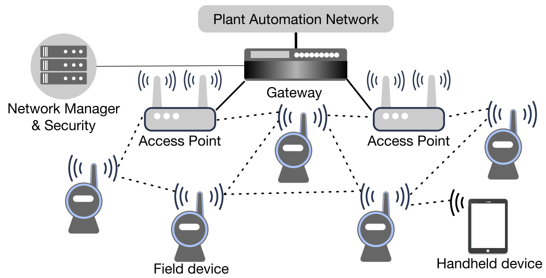


FIGURE 7. WirelessHART network architecture showing communication among different kinds of devices.

time slot duration is suggested to be 10 ms. If an ACK is not received in a defined time period, the retransmission will follow the subsequent time slot that is scheduled for the same (transmitter-receiver) pair of nodes. A possible communication schedule is depicted in Figure 6a. The slot frame is seven slots long, and there are sixteen channel offsets available. Each link is assigned a cell. Some of the cells could be dedicated to only one pair of nodes, while others could be shared cells, i.e., more than one pair of nodes can communicate in these slots. There could be a possibility of collision in a shared slot, but the standard implements a simple back-off scheme to deal with it. Each node only cares about the cell it is assigned to. For example, in Figure 6a, when node n_5 transmits a packet to node n_0, it uses time slot 3 from the dedicated time slots and channel offset (Ch.05).

F. WIRELESSHART

WirelessHART [84] is the first open wireless industrial standard, introduced by the HART (Highway Addressable Remote Transducer) [89] foundation. It is mainly designed for industrial process measurements and control applications while still being backward compatible with the HART legacy systems. It is a mesh network with self-organizing and self-healing capabilities in combination with a secure and reliable communication protocol. Although Bluetooth and ZigBee were prevalent before the release of WirelessHART, they could not fulfill the stringent requirements of industrial control applications [52]. Specifically, neither ZigBee nor Bluetooth offered guaranteed end-to-end delay and reliability.

1) NETWORK ARCHITECTURE

WirelessHART introduces different types of devices in the network as shown in Figure 7: network and security manager, gateways, access points, and field devices. The network manager is responsible for computing and maintaining the communication schedule and routing tables, as well as performing the overall network health monitoring. It can query a particular field device through the gateway as requested by the host application. The security manager and network manager work collaboratively to provide security against intrusion and attacks by generating a different session, joint, and network keys [90].

2) PHY AND MAC LAYERS

The PHY layer is based on IEEE 802.15.4 [55].

TSMP is the medium access and networking protocol which offers reliable, robust, and low-power communication. It features time synchronized, dedicated time-slotted access, link layer ACKs, graph-based routing, and multi-layer security on every packet. It targets reliability of greater than 99.99% at low-power, scalability of hundreds of mesh nodes, flexibility to support time-varying traffic, security, and the ability to withstand harsh industrial environments [91]. The communication is governed by a time-slotted schedule which lets the nodes know when to transmit, receive, or sleep. TSMP follows the same schedule scheme as of TSCH, where the schedule is computed and is represented through cells using different time slots and channel offsets as described in Section III-E3.

G. IPV6 OVER LOW-POWER WIRELESS PERSONAL AREA NETWORKS (6LOWPAN)

The underlying motivation to standardize 6LoWPAN [92], [93] was the need to integrate constrained devices to the Internet. IETF created the 6LoWPAN and *Routing Over Low-Power and Lossy Networks* (ROLL) [23] working groups with the goal toward standardized IP-based protocols for LLN. The ROLL focuses on developing routing solutions for LLNs over IPv6.

The fact that the IPv6 protocol imposes high overhead and complexity which makes it difficult to be deployed in constrained environments, such as the IEEE 802.15.4 network. Since the MAC payload of IEEE 802.15.4 cannot be larger than 127 bytes, the 40-byte header of IPv6 does not leave much space for actual payload. This prompted the need to form an adaptation layer between the network and data link layer in order to enable IPv6 packets to fit into the IEEE 802.15.4 specifications. *Low Power Wireless Personal Area Networks* (LoWPANs) impose several constraints, such as small packet sizes, different address lengths, small bandwidth, high density of nodes, battery operated devices, poor link quality, and duty cycling. This makes it challenging to develop an optimized adaptation sublayer to successfully map the service required by the network layer on the services provisioned by the link layer [93].

In essence, 6LoWPAN defines an adaptation layer through header compression (HC) in order to transmit IPv6 packets over the IEEE 802.15.4 network. It supports packet fragmentation and reassembly in order to meet the Maximum Transfer Unit (MTU) requirements of IPv6, and it allows forwarding to the data link layer for multi-hop connections [94].

The 6LoWPAN adaptation layer defines two header compression techniques that compress large IPv6 headers (in the best case) to several bytes. The compression technique, 6LoWPAN-HC1, compresses IPv6 packets that contain IPv6 link-local addresses. The size of the packet is minimized by eliminating fields such as IP version, traffic class, flow label, and hop limit. The 6LoWPAN-HC2

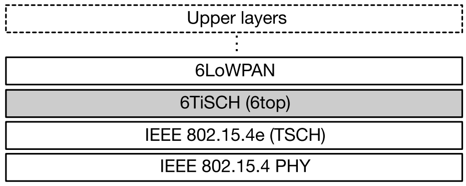


FIGURE 8. Envisioned 6TiSCH protocol stack [101].

technique is proposed for the compression of UDP, TCP, and ICMP.

The main objective in proposing the HC1 and HC2 techniques was to perform compression in a stateless manner that did not require any previous agreements between the two nodes.

H. 6TiSCH

IETF formed 6TiSCH [95] working group to support IPv6 over TSCH (see Section III-E). 6TiSCH contributes to the IoT by bonding the unique features of TSCH and IP networking mechanisms in order to produce an interoperable Industrial IoT (IIoT) protocol stack [96]. This will support TSCH MAC being placed under an IPv6 enabled protocol stack running 6LoWPAN, IPv6 RPL [97], [98], and CoAP [99], [100]. Figure 8 shows the reference protocol stack for 6TiSCH [101]. For the successful integration of TSCH with upper layer protocols, 6TiSCH introduces a functional entity that is responsible for scheduling TSCH time slots to be sent on the network. This entity resides at the higher layer and is known as 6TiSCH Operation Sublayer (6top).

6top is a logical link control that resides between the IP layer and the TSCH MAC layer. It controls the TSCH schedule, collects the connectivity graph, and monitors and optimizes the schedule of the cells. It supports both centralized and distributed scheduling approaches. The scheduled cells are labeled as either hard cells or soft cells. Hard cells cannot be dynamically reallocated by 6top. Rather, they are typically scheduled by a scheduling entity such as *Path Computation Entity* (PCE), that can move or delete cells in the TSCH schedule. In contrast, soft cells can be reallocated by the 6top dynamically. Typically, a distributed scheduling entity schedules these cells. 6top records the performance of the cells to the same neighbor. If a cell performs poorly compared to the other cells with the same neighbor, it moves the cell to a different *channelOffset* and *slotOffset*, where *channelOffset* and *slotOffset* perform better. In this way, the 6top sublayer can cope with the interference reliably.

IV. BLUETOOTH

In this Section, we discuss the history of Bluetooth technology and technical details such as radio, link layer, and network topology. Bluetooth is a low-power wireless technology used for short-range communication. It was designed to replace serial cables with the wireless links [102]. Nowadays, aside from connecting devices like mice, keyboards, cell phones, headsets, and multimedia devices, it is used to connect sensors, actuators, controllers, and critical wireless infrastructures. Availability is one of the main advantages of Bluetooth. The *Allied Business Intelligence* (ABI) research group predicted that by 2021 there would be 48 billion devices connected to the Internet, 30% of which would be Bluetooth enabled [103]. Bluetooth was introduced in 1999, and the first specification was released in 2001 [104]. In 2002, IEEE assigned the 802.15.1 standard for it [105].

The technology is divided into two major categories: First, *Bluetooth Basic Rate and Enhanced Data Rate* (BR/EDR) refers to the earlier versions of Bluetooth mainly designed for file transmission and audio streaming. It is reported that in 2015, 116.32 million BR/EDR headsets were shipped [106]. Second, BLE refers to the recent versions of Bluetooth targeting low-power consumption for IoT applications. Due to the consumer demand for low-power and high throughput, both BLE and BR/EDR are available in some devices like smartphones and laptops. They are known as dual-mode Bluetooth and switch the protocol stack from BR/EDR to BLE and vice versa when is needed [107]. Table 4 highlights the key features of each version.

A. BLUETOOTH BASIC RATE AND ENHANCED DATA RATE

The first version of BR/EDR was only designed for file sharing by using an *Asynchronous Connection-Less* (ACL) link. The link is a single point-to-multiple point link that can be used for broadcasting data and can support both asymmetrical and symmetrical connection. The audio streaming capability has been added to BR/EDR by using a *Synchronous Connection-Oriented* (SCO) link in v1.2. The new link provides up to three symmetrical point-to-point links that reserve time slots in order to guarantee timely transmission. To avoid delay in voice transmission, SCO packets do not deliver ACKs. In 2003, SIG enhanced the link and released eSCO to improve voice transmission reliability. The higher quality is achieved by employing a limited number of re-transmissions for lost or damaged packets. Additionally, this version employs *Adaptive Frequency Hopping* (AFH) to improve coexistence with other wireless protocols [108] (Section V discusses AFH in detail). Bluetooth versions up to v1.2 provide a maximum throughput of 721.2 kbps, known as Bluetooth Basic Rate (BR). Due to the high demand for large file and audio transmission, BR was unable to fulfill the throughput requirements. Therefore, in 2004, SIG introduced Bluetooth v2.0 to improve throughput and named it as Bluetooth Enhanced Data Rate (EDR). This version increased the throughput by 2.1 Mbps by using the *Differential Phase Shift Keying* (DPSK) modulation technique [109]. Although EDR tries to improve the data rate, it does not satisfy the entire user requirements. Thus, in April 2009, SIG launched Bluetooth v3.0, known as Bluetooth High Speed (HS) [110]. Bluetooth HS delivers up to a 24 Mbps data rate by using the 802.11 radio. Alternative MAC/PHY (AMP) controller [111] changes the radio from BR/EDR to 802.11 and vice versa. AMP enables the 802.11's radio when higher throughput is

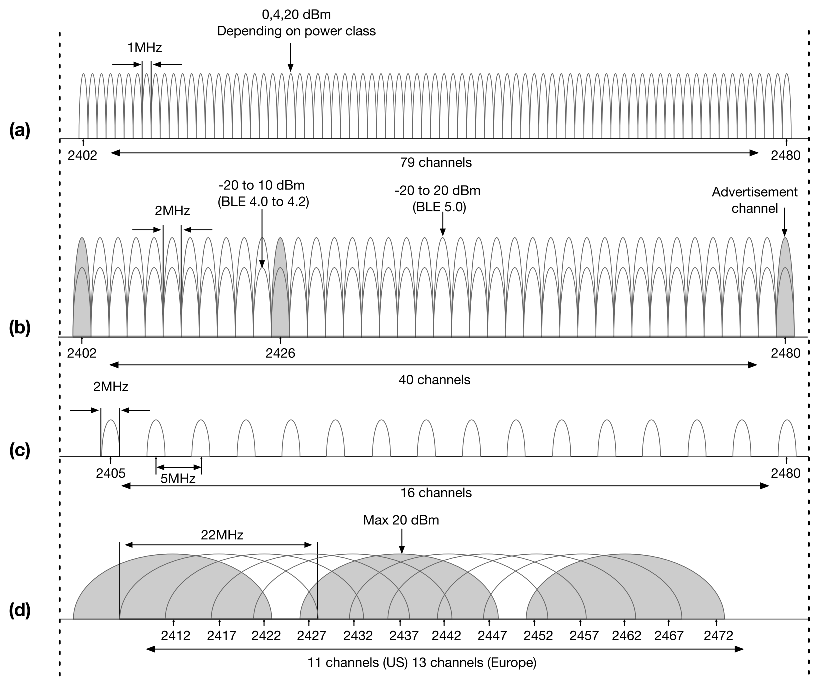


FIGURE 9. **BR/EDR, BLE, IEEE 802.15.4, and IEEE 802.11 sharing** 2.4 GHz **frequency band.**

required. After that, it reverts to primary BR/EDR radio to save power.

1) BR/EDR RADIO

The radio operates on the 2.4 GHz ISM band at frequencies between 2402 to 2480 MHz. It uses *Gaussian Frequency Shift Keying* (GFSK) modulation with three output power classes: class one has the maximum output power 100 mW and achieving communication range 100 m, class two and class three support output power 2.4 mW and 1 mW, respectively. The communication range of class two and class three is almost 10 m. Power classification improves energy efficiency and avoids interference with other networks by reducing the communication range. For example, a few meter communication ranges satisfy the user requirement for Bluetooth headphones and a smartphone. Lowering the signal propagation range reduces noise for other wireless networks in the vicinity. The physical channel is subdivided into 1, 3, or 5 time slots; each time slot is 625 μs and *Time Division Duplex* (TDD) provides full duplex transmission. In TDD, both the uplink and downlink can transmit information in the same frequency by using a synchronized time interval which resolves contention over the wireless channel. In BR/EDR, the frequency band is divided into 79 channels, and each channel is 1 MHz wide. Figure 9(a) shows the channel assignment of BR/EDR. The radio uses the *Frequency Hopping Spread Spectrum* (FHSS) technique to avoid interference from any coexisting Bluetooth devices with other technologies that share the same frequency band. In the FHSS technique, the radio switches the transmission channels 1600 times per second; therefore, if a transmission encounters noise on one channel, there is a chance that the next channel would be free of noise. In Bluetooth v1.2, AFH added a technique that blacklists the channels based on traffic load as good or bad channels. This minimizes the chance of collision by only performing transmission in the good channels.

2) NETWORK TOPOLOGY

In BR/EDR, devices communicate in a network called a *piconet*. A piconet is a star based topology, in which a node can only communicate with a central node called *master* and the others are called *slaves*. In the master node, the built-in clock is responsible for synchronizing master-slaves communication. The slave nodes receive an inquiry message from the master node to identify the address and clock phase. With this information, the slave nodes can compute the channel hopping sequence to identify when and on what channel to listen. The slaves can only initiate communication after receiving permission from the master node. There are two types of slave nodes: *active* and *parked*. In a piconet, one master, up to seven active slaves, and up to 255 parked slaves can coexist. Therefore, in order to address the active and parked slaves, three and eight bits are required respectively. The master node continuously polls the active slaves to see if they have data to transmit. If an active slave does not respond to the polling for a long period, it loses its three-bit active slave address and becomes a parked slave by obtaining an eight-bit address. For the parked slaves to rejoin the network, the master node periodically checks their status if they have any data to transmit. If so, the master node reassigns the three-bit active slave address.

Since each piconet uses its own frequency pattern that is generated by the master node, it would be possible for several piconets to coexist. As shown in Figure 10, neighboring

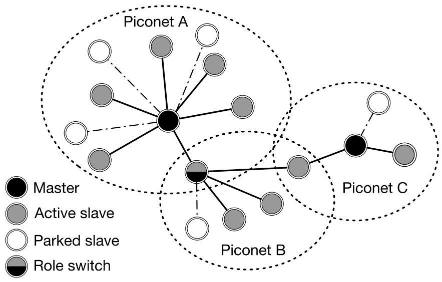


FIGURE 10. A sample of Bluetooth scatternet formation. Although Bluetooth is a star-based technology, node role switching enables connection establishment with other networks in vicinity.

piconets can join and construct a new network topology called a *scatternet*. A scatternet is a combination of two or more piconets through node sharing. With this, a slave can be shared by two piconets, or it can be a master in one piconet and a slave in another. In this way, by combining piconets, Bluetooth can extend the number of nodes in the network. For example, in Figure 10, the nodes are organized into three piconets: A, B and C. However, the piconets can communicate with each other using the shared nodes. The shared node between piconets A and B switches the roles from a slave in A to a master in B and vice versa. On the other hand, the shared node in piconets B and C remain as a slave in both.

3) LINK CONTROLLER

Bluetooth does not support the OSI model or the TCP/IP protocol stack because it has its own MAC protocol for communication management called the *link controller*. Figure 11 shows the state diagram of the link controller in BR/EDR. There are three primary states: *standby*, *connection*, and *park*. The standby state is the default state that waits for the connection event. It is designed to save power when the connection is not required. The connection state is when the BR/EDR radio turns on to discover devices in the vicinity and starts exchanging information if they are ready to communicate. Park mode is a deep sleep mode that helps to save power when the connection is not required for a long period. Only slaves can switch to this mode. They receive the synchronization packet periodically, and, once received, they can then join the network whenever it is needed. Before switching from the standby mode to the connection state, there are some sub-states such as *Device Discovery* and connection establishment. The connection establishment sub-state discovers the devices that are willing to initiate the connection. The Device Discovery sub-state has three sections. In the inquiry section, the device that attempt to initiate the connection hops among 32 out of the 79 channels, which are known as the *inquiry channels*, and broadcasts ID packets. For channel hopping, it uses the built-in clock and pseudo-random numbers to generate the pattern. On the other side, the device that is about to become discoverable switches to the inquiry scan state and waits for the expected ID packets in the inquiry channel. It listens for 1.28 s in every channel. It switches the channels slower than the device that broadcasts the ID packet

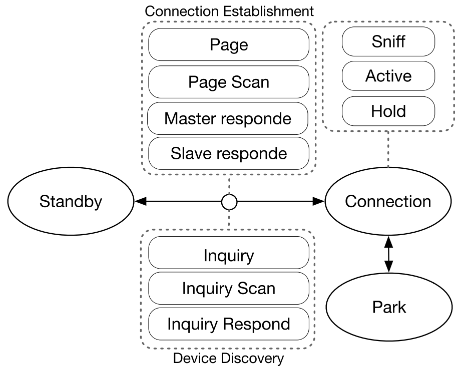


FIGURE 11. Link controller state for BR/EDR designed for communication establishment and power saving.

in order to increase the probability of handshake at the same time and the same channel. After receiving the ID packet, it replies in the inquiry response state with the Frequency Hop Synchronization (FHS) packet. The packet contains the node's address, the clock value, and value used for synchronization. After the devices are discovered and the packets have been exchanged, the connection establishment sub-state starts. This state is much faster than the inquiry state because both devices know each other's frequency and clock information. The previously discovering device changes to the page state and becomes the master node while the discovered device changes the state to page scanning and becomes the slave. After defining the roles, the connection state starts. The master polls the slaves and waits for the response from the slaves. During the connection state, the device can be in one of three modes: sniff, active and hold. In the active mode, the master node keeps scheduling the slaves by transmitting POLL packets. The packet exchange stops in the hold mode, and the master and slave nodes get informed about the duration of time that they need to hold. The sniff mode is designed to save the battery. In this mode, during the connection the device can be temporarily absent from the piconet. For example, a device that is not operating, such as a mouse or keyboard, puts itself in sniff mode and transitions to the active mode when needed.

4) LIMITATIONS OF BR/EDR

Two major limitations of BR/EDR are high power consumption and lack of scalability. Although BR/EDR uses the standby state, parked mode, and effective duty cycling to save energy, these techniques are not enough to guarantee the low-power consumption requirement of some IoT applications. A major disadvantage of BR/EDR is high power consumption. This is because of continuous polling of the slave nodes by the master node in the absence of data to transmit. Many studies address this problem and propose scheduling algorithms for polling the slave nodes such as, [112], [113], and [114]. Chakraborty *et al.* [115] proposed a solution for adaptive polling of slave nodes. In their method, the master node polls the slave based on the probabilistic scheduling estimation. This allows the node to reduce power consumption by extending its standby time. Also, in [116], the performance of different scheduling algorithms, such as pure round-robin, gated round-robin, and exhaustive round-robin for polling the slave nodes in BR/EDR have been evaluated using OPNET simulator.

The second reason behind the high power consumption of BR/EDR is the scanning of a large number of channels (32 channels) for Device Discovery. For example, Duflot *et al.* [117] pointed out the issue and proposed a probabilistic model to scan the inquiry channels. They also analyzed the power consumption performance of Device Discovery in the best and worst case scenarios. In [118], the effect of Device Discovery complexity on power consumption has been analyzed. They proposed the adaptive rendezvous protocol as a method of optimizing Device Discovery performance.

The lack of scalability and mesh networking are other weaknesses of BR/EDR. This version of Bluetooth only supports a maximum number of eight nodes, and slave nodes are not able to connect to each other directly because of the star-based topology. This standard has been primarily developed for the scenarios in which a computer plays a master node role, and a limited number of devices, such as a mouse, keyboard, and headset, are connected as slaves. Scatternet is one of the most highlighted solutions for performing mesh networking and improving the scalability of BR/EDR. Scatternet is a formation that is not natively supported by the core specification, but there is a huge amount of research that proposes scatternet-based solutions or improves on the scatternet formation. For example, Jedda *et al.* [119] mentioned the time efficiency problem in scatternet formation and proposed an algorithm to solve this challenge. They also compared the performance of other scatternet formation algorithms, such as BlueStars [120] and BlueMesh [121]. In [122], the problem with scatternet formation, specifically, was that the network overhead was caused by an increased number of bridges that were switching the piconets. This increases the probability of packet loss. Reference [123] analyzed the performance of algorithms for Bluetooth scatternet formation namely, BlueTrees [124], BlueStars and the BlueNet protocol [125], and revealed the problem of time-consuming Device Discovery in a scatternet network. In general, these works conclude that scatternet is not a reliable and robust solution for Bluetooth networking, specifically due to the discovery delay and routing challenges.

B. BLUETOOTH LOW ENERGY (BLE)

BLE, introduced by SIG in 2011, was created for low-power wireless applications that did not require high throughput. To achieve low power consumption, the link layer, PHY layer, and packet formats were redesigned. In addition, while BR/EDR designed for only two-way communication, BLE devices are capable of acting only as either a transmitter or a receiver. For example, a remote control only needs to transmit a short command, and it does not need to receive a response. On the receiving side, a TV or lamp acts only as a receiver, waiting for a command to act. This results in design simplification, yielding higher power efficiency. In December 2013, SIG released the first update (v4.1) for the technology [126]. This update can be applied over the air, and no hardware change is required. In the first version of BLE, the devices were only able to establish a connection as master or slave. However, in the new update, the link layer is redesigned and allows devices to switch their roles when needed. One year later, SIG made noticeable changes and released version 4.2 [127]. In this new update, the actual payload size was increased from 27 Bytes to 251 Bytes. Increasing the payload size while keeping the same packet format increased the throughput up to 2.6 times more. This increase in the packet size also increased the feasibility of IPv6 support. Although version 4.2 does not support IPv6 in the core specifications, IETF published RFC (7668) [128] to provide IPv6 support over BLE with the adaptation of 6LoWPAN protocol stack. Bluetooth 5, introduced in December 2016, is the latest version of BLE [129]. Its main aim is to overcome the limitations of the older versions by increasing the range, size of advertisement payload, and throughput. The extension in range provides indoor application coverage and even enables building-to-building connectivity. In addition, advertisement extension was introduced in this version in order to increase the advertisement payload up to 8 times more by using data channels as secondary advertisement channels. This opened a new domain of applications for Bluetooth beacons. The last improvement was increasing the data rate by doubling the modulation rate, also called BLE high-speed mode. This mode helps lower power consumption because of the shorter radio operation time that is needed for transmitting the same amount of data. It also improves the coexistence of the technology with other devices through shorter occupancy of air time. An application of this mode is over-the-air-update of IoT devices.

1) RADIO

As Table 4 shows, the general transmit power range in BLE is between −10 dBm and 10 dBm. However, theoretically, version 5 supports output power up to 20 dBm. Similar to the classic version, the PHY layer in BLE operates in the 2.4 GHz frequency band. In contrast to BR/EDR, it has 40 channels, and each channel is 2 MHz wide. Among these channels, there are three special channels called *advertisement channel*s. As shown in Figure 9(b), these channels are placed in the center frequency of 2402 MHz, 2426 MHz, and 2480 MHz and are specified with a gray color. The reason for choosing these frequency centers is to avoid the most common cause of interference in the 2.4 GHz, which is IEEE 802.11b/g/n. Since IEEE 802.11 b/g/n channels are 22 MHz wide, they overlap. Therefore, the conventional technique is to use only none-overlapping channels which are channel 1, 6, and 11. Thus, advertisement channels are strategically located in places that have minimum interference with non-overlapping channels in IEEE 802.11 b/g/n [130].

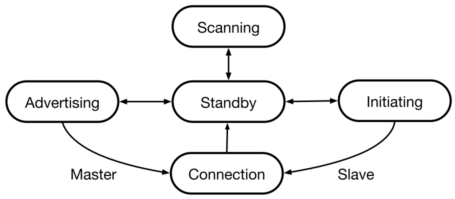


FIGURE 12. BLE link layer state has five states: *Standby*, *Scanning*, *Advertising*, *Initiating*, and *Connection*.

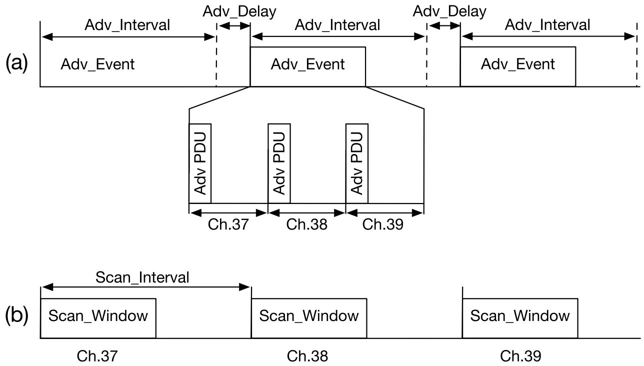


FIGURE 13. Advertisement and scanning process in BLE. (a) shows the advertising device, and (b) shows the process in a scanning device.

Advertisement channels are used for various purposes, such as Device Discovery, connection establishment, and broadcasting. In BR/EDR 32 channels are assigned for connection initiating which causes significant power consumption and delay. Where BLE reduced initiating links down to three advertisement channels that the receiving device needs to scan. By limiting the number of channels, connection establishment is faster and more power efficient compared to BR/EDR. Although both versions use the FHSS and AFH to cope with interference, only *data channels* are involved in frequency hopping in BLE. Data channels are channels that are reserved for information exchange. Please note that BLE 5 in advertisement extension mode uses data channels as secondary channels for advertisement. Before switching to data channels on the sender side, the device sends a special PDU in the advertisement channels and returns to sleep. In the receiver side, the device listens to these channels to pick up the PDU. Finally, GFSK modulation is used for radio transmission. The modulation rate is 1 Mbps, except in the BLE 5 high-speed which is 2 Mbps.

2) LINK LAYER

Compared to BR/EDR, the new link layer has been simplified to reduce the power consumption and provides a faster connection establishment [131]. BLE has only a single packet type, instead of the 17 types of packets that are used in the BR/EDR. In particular, BR/EDR has a specific packet format for different modulations and file or voice transmission, on the other hand, BLE omitted the voice streaming capability and only has GFSK modulation. This simplifies the processing of resource-constrained devices. Connection establishment only requires scanning advertisement channels. Subsequently, based on the PDU format received, it either switches to data channels or receives the broadcast data [132]. Figure 12 shows the state machine of BLE, which has five states.

- **Standby** is the initial or default state. This state is designed to save power, and no sending or receiving happens in this state. The device may switch to this state from any other state. For example, after advertising device returns to standby mode to save power.
- **Advertising** is the first step for any BLE connection. In the link layer, advertisement channels are responsible for broadcasting PDUs. Based on the reason for advertising, these PDUs are classified as either: non-connectable advertising, connectable advertising, discoverable advertising, directed advertising, scan request, scan response, or connect request [133]. Advertising may result in communication establishment or merely broadcasting data. Figure 13(a) shows the process in the advertising state. During the Adv_Interval, devices send the same PDU in the advertisement channels (channels number 37, 38, and 39), return to the standby state for the duration of Adv_Delay, and then repeat the process.
- **Scanning** state is divided into two parts: passive scan and active scan. In the passive scan, the receiver only listens to the advertised packets and does not respond. In the active scan, the receiver may respond the received packet to get more information in order to make the connection.
- **Initiating** happens when the initiator receives the packet from the advertiser, and it responds to the packets by sending initiating packets.
- **Connection** is only required when the devices need to switch to data channels and exchange information. The advertising device becomes the master node, and the initiating device becomes a slave node. Then, the advertisement channels hand over the responsibility to the data channels by employing the AFH. After the connection ends, the device is only allowed to transition to the standby state.

C. BLUETOOTH BEACON

The idea of Bluetooth beacons was first introduced by Apple and named as iBeacon [134]. A Bluetooth beacon is equipped with BLE and was designed to be an simple one-way communication channel. Due to the low-power consumption of BLE, these beacons can operate for several years with a small battery. The concept of beaconing in Bluetooth refers to the periodical broadcasting of small pieces of information, such as sensor data or marketing information. Bluetooth beacons have applications in many areas, such as train stations, smart parking, and indoor positioning in order to help people by providing a platform directly to their smartphones. Currently,

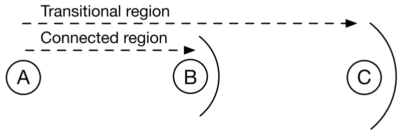


FIGURE 14. Connected region and transitional region in BLE 5 long range.

there are various types of BLE beacons are available in the market, such as Eddystone [135], which is developed by Google in 2015. Today, the availability of Bluetooth in smartphones allows people to interact with the technology easily. The maximum payload size for advertisement channels is 31 B. However, this is only enough to broadcast a short message with a limited number of characters. For example, in marketing applications, the packet size is not able to carry enough information to introduce the products. On the other hand, increasing the packet size creates other complications. For example, [136] shows that increasing the packet size in advertisement channels may result in significant interference in dense BLE environments. In Bluetooth 5, *advertisement extension* provided a solution to this problem.

D. BLUETOOTH 5

Bluetooth 5 added new features to the previous versions. As shown in Figure 9, channel allocation in this version is the same as the older versions. However, the maximum transmit power increased from 10 dBm to 20 dBm. As mentioned earlier, the boldest enhancements in this update are an increase in range by employing *Forward Error Correction* (FEC), utilizing advertisement extension by using the data channels as secondary channels, and increasing the throughput by doubling the modulation rate [142]. We explain these features as follow.

1) BLE CODED AND FEC

One of the major issues in IoT devices is the range limitation, and Bluetooth-enabled devices are not an exception. Generally, common solutions for range extension are mesh networking and increasing transmission power. Mesh networking and IPv6 extend communication range by routing packets to reach their destination. This causes network traffic and consumes power from other nodes as well. On the other hand, increasing transmission power to achieve more extended point-to-point connectivity causes higher power consumption in the transmitter. To avoid these problems, the FEC feature is added to BLE. Typically, wireless propagation of waves (transitional region) is much longer than the connected region. In BLE connected region is where the acceptable *Bit Error Rate* (BER) in the receiver side is less than 10^{-3} bits. For example, in Figure 14, node C can receive the signals from node A. However, due to path loss and interference, bits are corrupted, and data is not reliable.

In FEC, several bits represent a single bit. If the receiver bits get corrupted, it can identify and recover these bits based on the pattern that represents each bit. Therefore, using a higher number of redundant bits makes it easier to recover the bit. There are two options available in version 5 for coding: $S = 8$ and $S = 2$. This means that it replaces a single bit with 8 and 2 bits, respectively. This feature increases the range up to 4 times and enables Bluetooth 5 to cover an entire house or extended outdoor area. Due to the extra bits added to the packet, the actual bit rate per second drops from 1 Mbps down to 125 kbps in S=8 and down to 500 kbps in S=2 [143]. It is important to note that due to the extra bits, the larger packet is more sensitive to interference due to the longer transmission time.

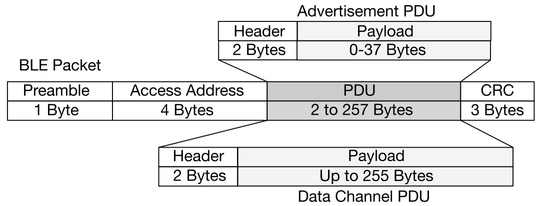


FIGURE 15. BLE 4.2 and 5 (LE1M, LE2M) packet format.

2) ADVERTISEMENT EXTENSION

Since only three advertisement channels are available in BLE, an increase in the payload size will increase the traffic in these channels. Because of this, advertisement extension only uses the advertisement channels to address the next packet in data channels. To initiate this feature, the device sends the first packet, which includes the pointer to the channel that is randomly selected from the 37 data channels. The randomly selected channel is known as the secondary channel for advertisement. Figure 15 shows the packet format in advertisement channels and the data channels. The transmitted packet in the main advertisement channels has a maximum payload of 37 B; however, the secondary advertisement channels can carry up to 255 B in their payload. Furthermore, it is also possible to extend the payload by adding the next packet address and making a chain for data streaming applications. Before this, frequency hopping was only applied in the connection mode. Since the data channels are randomly selected as the secondary channels in advertisement extension, the receiver needs to know the channel number and time to listen. Therefore, the primary packet broadcasted by the advertisement channels must contain the hopping pattern. Marco *et al.* [144] performed a simulation experiment to evaluate the performance of service ratio, communication delay, and battery life, when advertisement extension is used. They claim that advertisement extension offers better performance compared to the connection-oriented and the basic advertisement in BLE concerning the factors above. However, they also pointed out the issues of higher losses, in comparison with connection mode, and latency, compared to the basic advertisement.

3) BLUETOOTH 5 2 Mbps

In BLE 5 increasing the speed is an optional mode known as 2 Mbps version. This mode only operates on data channels

TABLE 3. Bluetooth 5 support SoC comparison.

	CC2640R2F [137]	**EFR32BG12** [138]	**nRF52840** [139]	**nRF52832** [140]	**EM9304** [141]
RF processor	Cortex-M0	Cortex-M4	Cortex-M4F	Cortex-M4F	ARC EM4
SoC processor	Cortex-M3	Cortex-M4	Cortex-M4F	Cortex-M4F	ARC EM4
Supply (V)	1.8 to 3.8	1.8 to 3.8	1.7 to 5.5	1.7 to 3.6	1.5 to 3.0
Max. power (dBm)	5	19	8	4	6
TX current @ 0 dBm (mA)	6.1	8.5	6.4	7.1	5.5
Peak RX current (mA)	6.1	10.8	12.9	6.5	3.5
Sleep current (μA)	1.1	1.5	1.3	1.9	0.9
RF sensitivity (dBm)					
125-kbps Coded	-103	NA	-103	NS	NA
500-kbps Coded	-101	NA	-99	NS	NA
1-Mbps	-97	-95.2	-96	-96	-96
2-Mbps	-92	-91.3	-92	-92	NA
RAM (KB)	20	256	256	64	136
ROM (KB)	128	1024	1024	512	48

(NS) No Support, **NA** Not Available

and increases the throughput by doubling the modulation rate. One of the applications for this mode is upgrading the IoT device's firmware over the air. In this case, higher speed helps saving energy by reducing the duty cycle, besides, shorter over the airtime minimizes the probability of the collision with other operating networks in the frequency band. Please note that BLE 5 maintained the 1 Mbps as the default mode to support backward compatibility with the older versions. Because every packet transmission requires a gap called *Inter-frame Space* (IFS) between packets and ACK to guarantee a successful transmission, the actual throughput in BLE is less than the modulation rate. In BLE IFS is defined as 150 μs for all the versions, but packet transmission and ACK periods vary based on the modulation rate. For example, as shown in Figure 16 although the packet size in v5 2 Mbps has one more octet, the transmit time is almost half of the v4.2 and v5 1 Mbps. This also explains the shorter period for ACK. $Packet\_Transmission\_Time = (Packet\_size \times 8)/Modulation\_rate$, however, in order to achieve the actual data rate only the payload of the packet has to be considered. Therefore, the actual throughput can be computed by Equation (1).

$$Throughput = \frac{L_{payload}}{T_{frame} + IFS + ACK + IFS} \quad (1)$$

Where, $Transmit\_packet + IFS + ACK + IFS$ are in μs and *Payload* is in bits. From the Equation, it can be observed that the actual payload for v5 2 Mbps is $(251 \times 8)/(1064 + 150 + 40 + 150) = 1.4Mbps$. Consequently, v5 2 Mbps is 1.7 and 4.6 times faster than v5 1 Mbps/4.2 and 4.0/4.1 respectively.

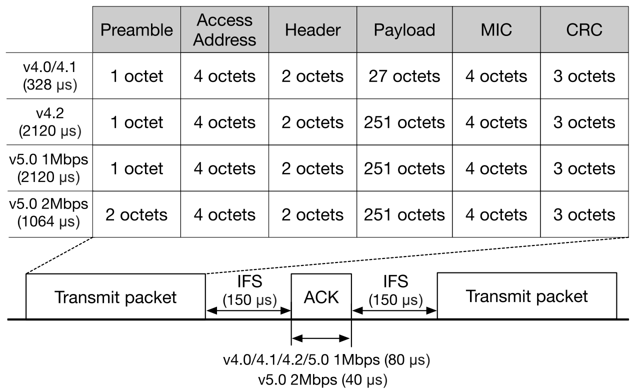


FIGURE 16. BLE packet transmission.

E. BLUETOOTH MESH

Draves *et al.* [148] showed the importance of mesh networking over WPAN. Although *Qualcomm* introduced a proprietary Bluetooth mesh known as *CSRMesh* [149], in the official Bluetooth mesh specification was later released by SIG in July 2017 [150]. Prior to this, Bluetooth suffered from shortcomings such as a single point of failure, limited network size, and range extension. Bluetooth mesh allows 3200 nodes to operate in a network. It enables a wide range of applications, such as in smart homes and industrial automation, where scalability is a major issue.

The new software stack supports the BLE versions 4.0 through to 5. The more nodes joining the network, the more robust and reliable the network will be due to the nature of mesh networking and the ability to have multiple available paths for routing. Nodes in Bluetooth mesh are divided into several types. The first type is the low-power nodes that mostly rely on battery power [151]. They have the responsibility of transmitting or receiving information and going back to sleep for the defined period. Another type is called the *friend* nodes. They are mostly connected to the main power grid. Due to the lack of power limitation, they can perform more complex tasks. Friend nodes store the incoming message for low-power nodes. BLE shares the radio and link layer with Bluetooth mesh in order to adopt any BLE-enabled devices to work with mesh networking.

F. LIMITATIONS OF BLE

Although BLE has many benefits, such as low-power consumption, beaconing, and availability in many devices, there are some issues associated with it. It still needs to rely on dual-mode devices and BR/EDR for audio streaming and bulky file transmission. There are studies in which researchers tried to

TABLE 4. Comparison of Bluetooth Standards.

	BR/EDR	BLE 4.0/4.1	BLE 4.2	BLE 5 [145]			
				LE Coded S=2	LE coded S=8	LE 1M	LE2M
Channels	79 (1 MHz)	40 (2 MHz)	40 (2MHz)	40 (2MHz)	40 (2MHz)	40 (2MHz)	40 (2MHz)
Advertisement Ch.	N/S	3	3	3 (P) 37 (Sc)	3 (P) 37 (Sc)	3 (P) 37 (Sc)	3 (P) 37 (Sc)
TX power (dBm)	0 to 20	-20 to 10	-20 to 10	-20 to 20	-20 to 20	-20 to 20	-20 to 20
RX sensitivity (dBm)	-93 [146]	-97 [147]	-97	-99	-103	-95	-89
Peak current (mA)	<30	<15	<15	<15	<15	<15	<15
Latency (ms)	100	<6	<6	<6	<6	<6	<6
Range (m)	10-100	10-100	10-100	40-400	20-200	10-100	10-100
Data rate (Mbps)	1, 3, 24	1	1	0.5	0.125	1	2
Max payload (byte)	1021	37	255	255	255	255	255
Max ADV payload (byte)	NS	37	37	255	255	255	255
Voice channels	3	NS	NS	NS	NS	NS	NS
Max active nodes	8	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
PDU format	Several	Single	Single	Single (coded)	Single (coded)	Single	Single

(N/S) No Support, **(P)** Primary, **(Sc)** Secondary channels

implement audio transmission over BLE. Gentili *et al.* [152] introduced BlueVoice and examined the feasibility of voice transmission over BLE. They also mentioned the requirements, such as using 64.3 kbps bandwidth to transmit voice quality of 16 kHz. In their experiment, they measure the power consumption, memory, and processing requirements. Another limitation is the lack of seamless IPv6 connectivity in the core specification. This leads to a dependency of BLE on other networks like *Wireless Local Area Network* (WLAN) or LTE to translate the Bluetooth packets to IP packets [131], [153], [154]. For example, a BLE-enabled smartwatch is unable to transmit heartbeat information directly to the Internet. It has to be done in two steps. First, this information has to be forwarded to a smartphone. Then, the smartphone converts the BLE packet to an IP packet to be routable over the Internet and transmits it via WLAN or LTE.

V. COEXISTENCE IN 2.4 GHZ SPECTRUM

Wireless networks are susceptible to radio interference. The impact of interference becomes even more deteriorated if they operate in the same frequency band because it causes disruptive effects in the transmission [155]. Interference can cause packet loss, latency, jitter, false alarms, and synchronization errors [155]. All of these adverse effects, in particular, cause severe problems for mission-critical applications. As the 2.4 GHz band is unlicensed globally, many technologies use this band for their devices throughout the world, thereby, making the band more crowded. In 2003, the IEEE 802.15.2 task group [156] published standards for the coexistence of WPAN with other wireless networks. However, raising awareness of the new techniques and technologies do not solve the entire coexistence issue.

The problem of coexistence among BR/EDR, BLE, IEEE 802.15.4, and IEEE 802.11 networks is causing major difficulties in terms of delay and power consumption in IoT networks. The issue of coexistence has gotten further momentum due to the fact the emerging standards like WirelessHART, ISA100.11a, and IEEE 802.15.4e share the same license-exempted ISM band, resulting in the 2.4 GHz frequency band being more crowded. Due to the massive proliferation of IEEE 802.15.4 and IEEE 802.11 networks, the possibility of interference would deteriorate application-specific QoS parameters. These networks exist in large numbers today and operate in close proximity to a number of application domains. Suitable interference avoidance solutions need to be adapted in order to maintain the required service.

As presented in Figure 9 the different wireless technologies operating in the 2.4 GHz band. In Figure 9(a), BR/EDR is operating between 2402 MHz to 2480 MHz. It divides the frequency into 79 (1 MHz wide) channels and uses AFH to avoid collisions. Figure 9(b) shows BLE, which has 40 channels that are 2 MHz wide and also uses AFH. The only difference is that the advertising channels (specified with the gray color) have the responsibility of initiating the connection in connectable mode, and they are not involved in the frequency hopping. As mentioned in Table 4, to achieve longer coverage, the maximum transmit power in BLE 5 is increased from 10 dBm to 20 dBm, compared to the earlier version of BLE. Figure 9(c) shows channel assignment for the IEEE 802.15.4 standard. Channels from 1 to 10 for the 868 − 868.6 MHz and 902 − 928 MHz bands are defined for lower frequency ranges, whereas the channels from 11 to 26 are operating in 2.4 GHz band. Each channel is 2 MHz wide, and the center of each channel is 5 MHz apart. Figure 9(d) depicts the channel assignment of the IEEE 802.11b standard in the US. There are 11 channels, each 22 MHz wide. These channels overlap with each other, and in the best case scenario, we can only have three non-overlapping channels: channel 1, 6, and 11. However, the IEEE 802.11 standards have several versions, and the channel assignment differs in some countries.

A. COEXISTENCE OF IEEE 802.15.4 AND IEEE 802.11

IEEE 802.11, more widely known as WiFi, is the ubiquitous technology defining standards for WLANs. Today, WiFi devices are everywhere, and they are causing severe interference with IEEE 802.15.4 networks. Unlike

IEEE 802.15.4 devices, IEEE 802.11 devices operate at a high transmit power, high data rate, and long range. Since they are unable to sense IEEE 802.15.4 devices, they create strong interference with them. In terms of channel bandwidth, both IEEE 802.15.4 and IEEE 802.11 channels are asymmetric, i.e., each IEEE 802.15.4 and IEEE 802.11 channel has bandwidth 5 MHz and 22 MHz, respectively. This causes overlapping of the four IEEE 802.15.4 channels, as shown in Figure 9. In most cases, IEEE 802.15.4 is vulnerable to interference [157], however, in certain cases, it does cause interference [158].

In order to improve network performance and support coexistence, these technologies inherently utilize specific techniques that help to promote coexistence. For example, IEEE 802.15.4 employs a number of inherent mechanisms such as DSSS, CSMA/CA, CCA, low transmit power, low duty cycle, channel alignment, ED, and LQI as explained in Section III. DSSS promotes coexistence and protects against interference by spreading the signal to a wider frequency through chipping code. Chipping code is achieved by mapping the bit pattern of the signal into a higher data rate bit sequence. As the signal is spread over a larger bandwidth, the narrowband interferer blocks a small overall percentage of the signal. The receiver is able to easily recover the signal [159]. CSMA/CA works on a "listen before talk" principle, where the transmitting devices PHY continuously samples the channel and notifies the receiving device when it is clear to transmit. In this way, it is less likely to cause collision and interference with other signals. The radio turnaround time for IEEE 802.15.4 is 192 μs, while the turnaround time of the DIFS (Distributed Interframe Space) of IEEE 802.11 is 50 μs. This can cause IEEE 802.11 devices to easily preempt the channel access while the IEEE 802.15.4 device is still in the process of radio state switching. Acknowledged transmission and retries further ensure reliability, where the receiver acknowledges a successful data reception. If the receiver does not send an ACK in a stipulated time, the sender assumes failure and retransmits data by using its retry limit. This can be particularly useful when the IEEE 802.15.4 device is encountering interference when coexisting with Bluetooth. Bluetooth may interfere with the first transmission, but then it would hop to another channel. A retry helps the IEEE 802.15.4 device to make a successful transmission on the second attempt. However, studies in [160] show that the timing mechanism employed in CCA mechanism of IEEE 802.15.4 is much longer than that of IEEE 802.11 b/g, and it causes IEEE 802.15.4 to be in an adverse situation in terms of channel access competition.

IEEE 802.15.4e TSCH mode uses channel hopping to promote coexistence. Every transmission happens on a different channel. This helps to further counter the effects of interference from other co-located networks. Likewise, WirelessHART utilizes channel hopping in combination with channel blacklisting to deal with interference effectively. With this method, a channel that is continuously causing transmission problems is eliminated from the list of available channels. ISA100.11a employs adaptive frequency hopping using slow hopping, fast hopping, and a hybrid combination of both.

Although these techniques avoid interference to some extent, the rising penetration of these networks in different domains prompts the need for more advanced and sound interference avoidance techniques in order to help these technologies coexist constructively. Especially for mission critical applications, the issue of interference in a coexisting environment becomes more challenging due to the real-time characteristics of these applications which always require bounded latency and high throughput.

The issue of coexistence between IEEE 802.15.4 and IEEE 802.11a/b/g has been discussed in [157], [158], and [160]. For instance, in [160], it is shown how severely an IEEE 802.11 network can interfere with an IEEE 802.15.4 network and degrade its performance. This performance degradation can lead to adverse consequences for application QoS requirements. For example, consider a fire detection application based on IEEE 802.15.4. If there is a substantial packet loss due to massive IEEE 802.11 interference, the fire extinguisher may not trigger within the set latency bounds, leading to catastrophic consequences. Angrisani *et al.* [155] experimentally studied the coexistence of ZigBee and WLAN. The experiment was conducted by varying different characteristics, such as packet size, packet rate, and SINR, under different topologies. The authors confirmed that ZigBee and WLAN could coexist but to the detriment of packet loss rate and throughput. Guo *et al.* [161] conducted experimental tests to assess the interference from an IEEE 802.11 transmitter, Bluetooth transmitter, and microwave ovens sources on the link reliability of IEEE 802.15.4 devices. Through their results, the authors show that these interference sources (ISs) cause significant packet error rate (PER). The value of PER varies from 2% with no IS to an upward 25% depending upon the distance between receiver, transmitter, and IS.

B. COEXISTENCE OF BLUETOOTH WITH OTHER WIRELESS TECHNOLOGIES

After version 1.2, Bluetooth employed AFH with the pseudo-random FH technique. As random frequency hopping suffered from certain complications, such as repeating the transmission in busy channels. Pust and Burda [162] performed a comparison between the FH and AFH mathematical models and proved that AFH has a better performance in avoiding interference. The basic idea of AFH is to classify the channels as good or bad channels. Nodes are only allowed to transmit in good channels. To avoid interference, AFH restricts transmission on busy channels by labeling them as bad channels. Transmission in a good channel helps Bluetooth to establish a reliable connection and leave busy channels for other technologies. However, the number of channels should not be less than a specific number. Otherwise, the good channels would be more sensitive to interference. For example, in BR/EDR, the good channels can be reduced down to only

20 channels [163]. In AFH the device is not aware of the other devices and their transmission status. In order to identify the traffic condition in a channel for classification, there are two main methods: *Received Signal Strength Indication* (RSSI) and the *Packet Error Rate* (PER) [164]. Channel noise is one of the factors which has an impact on signal strength. In the RSSI technique, the receiver side measures the signal strength and informs the transmitter about the channel condition. On the other hand, in PER, the transmitter measures channel noise based on the number of lost packets. In order to update the channel map, the validity of classification needs to be checked periodically. Apart from all of the benefits of the AFH, there are also disadvantages to its use. For instance, in order to check the channel quality over time, AFH has to periodically scan and classify the channels, which increases the duty cycle. Moreover, reducing the number of available channels may cause more sensitivity to interference. Lee and Lee [165] simulated packet delivery ratio performance in BR/EDR by combining AFH and adaptive transmit power. They considered an environment with IEEE 802.11b and a number of BR/EDR piconets. They compared the proposed method with the basic AFH in term of interference mitigation in different distances. They showed that adaptively controlling the transmit power significantly decreases the PER. Another study in [166] analyzed the impact of interference of other sources on BLE and ZigBee. The authors monitored the power consumption of BLE and ZigBee and showed that BLE is more energy efficient in terms of the number of transmitted bytes per Joule. The study presented in [167] tested the performance of BLE. They analyzed the probability of BLE network failure in different environments and presence of interference. The results showed that, with the use of AFH, BLE has a lower probability of failure even in high interference. Bronzi *et al.* [168] presented the application of BLE for robust Inter-vehicular communications. They examined the impact of IEEE 802.11g on BLE. The experimental results showed that BLE can be a reliable solution when compared to IEEE 802.11p if the high data rate is not required. The performance of the advertisement channels in BLE was analyzed in [136]. Based on the experiment, in a dense environment, authors claimed that when multiple devices are scanning in the same channels, it is not feasible to increase packet size to above 31 bytes for the advertisement channel.

C. OTHER SOURCES OF INTERFERENCE

Microwave ovens use electromagnetic waves in the 2.4 GHz band. Although they are covered by a Faraday cage, there is still some leakage that occurs around the doors. These waves increase the motion in water molecules and heat up food [169]. According to the US Department of Energy (DOE), more than 90% of houses have microwave ovens [170]. They also share the same spectrum and cause interference for networking devices based on WLAN, Bluetooth, and IEEE 802.15.4. Microwave ovens normally generate 60 dBm signal power and operate in a different range in 2.4 GHz (model dependent). Results show that the radiation from microwave ovens that operate in the vicinity of WSN networks can cause up to 92% packet loss [171] in WSN. This increases further interference for wireless networking devices in the 2.4 GHz band. Kim *et al.* [160] investigated the coexistence of WLAN and ZigBee networks in the presence of microwave ovens. The experimental results show that the microwave oven is a dominant interferer and it significantly increases ZigBee's PER. Rondeau *et al.* [172] analyzed the characteristics of microwave ovens and their effect on BR/EDR. The experimental results show that the AFH mechanism enables BR/EDR to be able to tolerate a high level of interference at a distance of one meter.

Cordless phones are available almost everywhere. Most of them operate in the 2.4 GHz band like microwave ovens. They use DSSS or FHSS to overcome interference and achieve better voice quality. Generally, the DSSS method changes the channel manually, while the FHSS method automatically changes the channel. Similar to microwave ovens, the frequency range and the technique used in these devices are model dependent, and there is no global standard for them.

VI. Z-WAVE

Z-wave is a low-power wireless technology that is specifically designed for control applications in residential areas. It supports full mesh networking. The technology was developed by Zensys, which is a company for home automation applications such as *Heating, Ventilation, and Air Conditioning* (HVAC), *Smart Lighting Control* (SLC) and access control [173]. The main feature of the Z-wave technology is that it operates in the sub-1 GHz band, which allows the signal to avoid any interference with the 2.4 GHz working technologies. Moreover, it has the advantage of full interoperability with other z-wave enabled devices compared to other wireless technologies. This means regardless of product type, brand and manufacturer all Z-wave devices are able to join one network and help grow the mesh network. For example, a BLE enabled thermostat from one company might not connect to BLE smart sensor with other brand but in the Z-wave network, all the devices are cooperating with one another. The standard is proprietary and is available under a non-disclosure agreement. The point-to-point communication range between nodes is about 30 meters.

The PHY layer in Z-wave is designed for remote control applications, where most of their requirements are just a single end-to-end message. For example, turning on and off a light requires a very low data rate. The technology operates in the 908.42 MHz band in the US and the 868.42 MHz band in Europe, employing the *Frequency Shift Keying* (FSK) modulation. By operating in this band, Z-wave avoids collision in 2.4 GHz frequency band. The radio has a data rate of up to 40 kbit/s [174].

In the MAC layer, Z-wave uses the CSMA/CA. The retransmission technique is based on ACKs. There are two types of Z-wave devices: controller and slaves. The controller has the responsibility of initiating the control commands and sending them to other nodes. On the other hand, slave nodes are responsible for replying and executing the commands. It is also possible for the slave to forward the command to other nodes. A Z-wave network can support 232 nodes, including multiple controllers [175]. The controller node, which creates the Z-wave network, becomes the primary controller. There is only one central controller in a Z-wave network. The other controllers are the secondary controllers. Controllers can communicate with all the slaves. However, just the primary controller can add and remove the nodes from the network. Aside from the controller, there are some slave nodes in a Z-wave network that are only responsible for performing an action or routing the controller's messages.

VII. 802.11AH

WLAN is a worldwide available technology. However, this technology suffers from a limited range and high power consumption, which are key elements in IoT. In October 2013, IEEE P802.11-TASK GROUP AH [176] provided the standard specification over WLAN to overcome these limitations. In the specification, MAC and PHY are inherited from IEEE 802.11ac. Additionally, sub-1 GHz frequency operation is added to provide better coverage, obstacle penetration, and lower power consumption. As explained in Section V, most of the wireless technologies opt for operating in the unlicensed 2.4 GHz band. This makes the frequency band more and more crowded. Operating in sub-1 GHz is an advantage for IEEE 802.11ah to avoid interferes in the 2.4 GHz frequency band. On the other hand, while technologies such as Bluetooth and ZigBee are targeting WPAN, IEEE 802.11ah aims for up to 1 km coverage to be used for applications in *Low Power Wide Area Networks* (LPWAN). Adaptation of IEEE 802.11ah in smart homes, wearables, agriculture monitoring, animal tracking, industrial automation, and smart cities eliminates many existing wireless communication limitations. For example, a smartwatch can directly communicate with an IEEE 802.11ah *Access Point* (AP) to transmit the information without needing to connect to a smartphone, or a single AP in a smart building can manage all the connected devices.

A. PHY LAYER

As discussed above, IEEE 802.11ah, like IEEE 802.11ac, employs *Orthogonal Frequency Division Multiplexing* (OFDM) modulation in order to achieve high throughput and more extended coverage among low-power wireless networks. The difference between IEEE 802.11ac and IEEE 802.11ah is that the channel widths are ten times clocked down. Instead of 20, 40, 80, and 160 MHz in IEEE 802.11ac, IEEE 802.11ah uses 2, 4, 8, and 16 MHz in addition to an extra 1 MHz channel to extend the range. The 1 MHz and 2 MHz bandwidths are intended for applications that require low data rates and power, such as WSN. Furthermore, a new modulation and coding scheme, MCS10, has been designed for the 1 MHz channel. MCS10 is more reliable than the other modulation and coding schemes, and it can provide a coverage range up to 1 km. However, employing all the channels in different regions is not possible because of the licensing limitations. Table 5 shows the global available unlicensed bands in sub-1 GHz with *Emitted Radiated Power* (ERP) and *Channel Bandwidth* (CBW) [178].

TABLE 5. Worldwide availability of IEEE 802.11ah frequency range [177].

Country	RF Range (MHz)	ERP (mW)	CBW (MHz)
US	902-928	1000	1-20
South Korea	917.5-923.5	3; 10	1,2,4
Europe	863-868	10	1,2
China	755-787	5; 10	1
Japan	916.5-927.5	1,20,250	1
Singapore	866-869, 920-925	500	1,2,4

B. MAC LAYER

The IEEE 802.11ah MAC layer is designed to support scalability while keeping the power consumption low. Theoretically, the standard is able to support up to 6000 nodes. In order to support this amount of connected nodes to a single AP, IEEE 802.11ah uses the *Restricted Access Window* (RAW) mechanism. An AP defines RAW by first grouping the clients. The RAW is a time slot assigned to a group and the AP. The group is only allowed to communicate in that specified time slot window. In each group, nodes are competing for channel access. Up to 64 slots are supported [179]. In addition, IEEE 802.11ah introduced *Target Wake Time* (TWT) to save power. TWT assigns access time to the clients that need to wake up and access the channel. Clients and the AP exchange information about the channel access time and connection duration.

VIII. LoRa

LoRa is a radio frequency transmission method for wide area network applications. It was developed by Cycleo of Grenoble and acquired by Semtech [180]. It is a low-power and low data rate technology that covers up to 10 kilometers for wireless communication. It operates in the sub-1 GHz spectrum and follows the previously mentioned unlicensed band for every region in the world (see Table 5). The frequency band is divided into 8 or 15 channels, depending on the operation region. The transmission power is limited from 2 to 14 dBm in Europe and from 5 to 20 dBm in the U.S. LoRa has three bandwidth classes for communication: 125, 250, and 500 KHz. Although high bandwidth has the advantage of high data rate, it consumes more energy, reduces the communication range, and increases the possibility of interference due to operating in the broader spectrum. In LoRa, modulation is based on spread-spectrum techniques and a variation of *Chirp Spread Spectrum* (CSS). In particular, it has the *spreading factor* (SF) of 7 to 12, which represents the number of bits encoded per symbol. The larger SF increases the transmission range in the expanse of higher power consumption. The CSS does not distinguish the noise in the channel like DSSS or AFH, but it has the advantage of using the entire allocated bandwidth, making it resistant to channel noise, Doppler effect, and multi-path fading. Normally, FSK modulations can only detect signals that are 8 to 10 dB above the noise floor, however, using CSS features enables the LoRa to detect signals that are 19.5 dB below the noise floor. Together with CSS LoRa uses FEC for error correction with the code rate of 4/5, 4/6, 4/7, and 4/8 to increase the robustness of the channel. More redundancy bits for error correction helps to extend the range and robustness of the link by recovering the corrupted bits that are caused by path loss or interference. However, the overhead consumes more energy. The LoRa network architecture uses the star-of-stars topology, which consists of end nodes and gateways. End nodes are usually battery powered devices and act as slave devices, while gateways are potent devices that are connected to AC power source and are responsible for collecting the data from the end nodes. In the LoRa network, several gateways can receive the information that is transmitted by the end node, and multiple receptions increase the reliability of the network.

Long Range Wide Area Network (LoRaWAN) is a layer on top of the LoRa that defines roles for communication introduced by the LoRa Alliance [181]. It is one of the most adopted, low-power wireless technologies for low data rate and long-range connectivity. It has advantages over cellular technologies, since cellular technologies are battery hungry and not suitable for low-power applications. For example, a soil moisture sensor in agricultural monitoring needs to sense the humidity level every few days, and the battery has to last for a few years. LoRaWAN extended the network functionality by adding a network server and defining different device classes for each application. The network server is responsible for managing the communication, filtering the multiple copies from one packet received by different gateways and scheduling the communication. For example, the network server decides the gateway that should communicate with certain end nodes and when to change the data rate. LoRaWAN has a bidirectional-employing adaptive data rate and transmission power. This adaptive control optimizes the power consumption and performance of the network. As presented in Figure 17 LoRaWAN has three device classes that are specified for each application.

- Class A is the default class and uses pure ALOHA to access the link for transmission. In this class, the end node wakes up periodically and transmits a packet. Then, it waits for the downlink to respond in the same channel and the same SF. If it does not receive the packet, it waits for the second packet in a different frequency and with different SF. After receiving a response from the gateway, the end node switches to sleep mode. On the gateway side, the device is only able to transmit information once, exactly after receiving the packet from the end node. Therefore, if the gateway needs to send more than one packet, it has to wait for hours or days to send the next packet in the queue. This class has the advantage of having the lowest power consumption due to the extended sleep period. Meanwhile, it is not suitable for real-time applications. This class is mostly used for non-critical sensors with long battery life requirements.
- Class B is designed for applications with more frequent connectivity requirements compared to class A. This class is a combination of class A and C. Devices in this class wake up whenever the gateways have information to transmit. A beacon that is transmitted by the gateway schedules the wake-up time for the end node. Frequent access ensures the connection establishment when it is required, however, the overhead due to the beacons and the frequent wake-up time reduces the battery life. Valves for irrigation are one of the examples of uses cases for devices in this class.
- Class C is normally implemented in devices that are connected to an AC power source, where energy consumption is not a concern. In this class, devices are continuously listening to the channel, except when they are transmitting information. Therefore, they are ideal for real-time applications. Devices such as street lights that are connected to the AC power are an example of this class and can act as gateways as well.

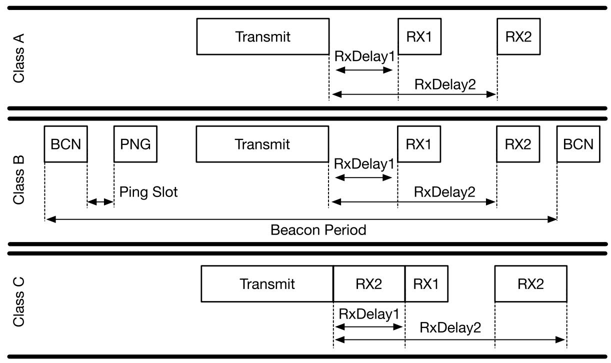


FIGURE 17. **LoRaWAN communication classes.**

IX. APPLICATIONS

In this section, we present an overview of the important IoT applications in the home, healthcare, industry, and city domain. These applications utilize different wireless technologies and standards. First, we summarize the requirements of each application and their traffic characteristics. Second, we discuss the suitability of each wireless standard pertaining to each type of application. We critically point out the standards that are suitable for each application category. Additionally, we identify the drawbacks of each standard based on the requirements of the applications.

A. SMART BUILDING

The basic goal of a smart building is to provide a better living environment in order to make our life more comfortable and more efficient while also making it safer and pleasant. It is reported that we spend more than 87% of our time in indoor environments, including home and commercial buildings [182]. In 2016, the global market for smart homes was valued at \$39.93 billion and predicted to reach up to \$79.57 billion by 2022 with a Compound Annual Growth Rate (CAGR) of 11.3% [183].

However, the concept of the smart building is not only about controlling lights or other devices with voice commands or a simple point to point remote control. The main idea is to have an *Ambient Intelligence* (AmI) using M2M communication in order for a device in the building to make smart decisions based on real-time conditions [184].

According to Gartner, a typical family home will have 500 smart devices by 2022 [185]. This future requires a scalable wireless technology. As we discussed in Section V, with the increasing number of smart objects that communicate with each other using the same frequency band, interference becomes a severe issue.

Furthermore, issues related to Internet connectivity, mobility, availability, energy consumption, and reliability need to be addressed. There are many consumer-oriented IoT smart home applications. Some of the major use cases and their communication requirements are discussed below.

One of the common use cases in buildings is *Smart Lighting Control* (SLC) that provides more comfort and convenience for the owners and has a direct impact on saving cost and energy. The Gartner's report estimated that SLC cloud reduce the energy cost by 90%, and its market will grow from 46 million units in 2015 to 2.54 billion units in 2020 [187]. SLCs are performed by employing relays, motion sensors, daylight sensors, timers, dimmers, and switches. In order to perform efficient wireless controlling for this hardware, it requires mobility and scalability. For example, a large number of lamps or LEDs may exist and need to be accessible from different locations of the building. The mesh networking capability can support these to increase the coverage. A person who is moving in the building must be able to access the lights.

Another key use case is the privacy and safety of the buildings. A typical solution for providing safety in buildings is the use of video surveillance. However, many users are reluctant to surveillance cameras because of privacy concerns, installation costs, lack of real-time responses, power consumption issues, and massive storage requirements. A better alternative to video surveillance is to use low-cost and low-power sensors that are able to detect and perform actions immediately and prevent disasters. For example, in the case of a fire in the building, smoke detectors can reliably prevent hazardous situations in a promptly manner.

According to the U.S. Energy Information Administration, *Heating, Ventilation, and Air Conditioning* (HVAC) is the largest contributor to the energy bills in a home. It contributes to 48% of the total energy consumption of U.S. homes [188]. In many cases, the cost of power consumption changes based on the operation hours. Consequently, load balance controlling systems can help in scheduling the operation during off-peak periods [189]. The benefits of using smart HVAC are not only limited to providing comfort and a pleasant environment,

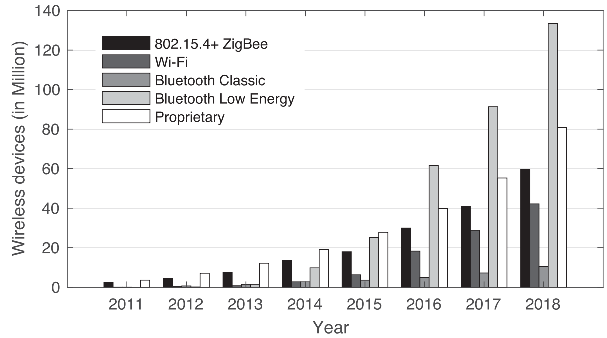


FIGURE 18. **Comparison of major wireless technology demands for smart home predicted by 2018 (The CAGR is from 2016 to 2021) (source: [186]).**

TABLE 6. **Smart building requirements and available technologies.**

	BR/EDR	BLE	ZigBee	Thread	Z-wave	Wi-Fi (TCP-IP)
IP-support	○	○	○	●	○	●
Mobility	●	●	◓	◓	◓	●
Availability	●	●	◓	◓	◓	●
Scalability	◓	●	●	●	●	◓
Energy	◓	●	●	●	●	○
Relability	◓	●	●	●	◓	◓

○ No support ◓ Partial support ● Full support

but they also have direct impacts on people's well-being. Smart controlling of HVAC requires employing smart thermostats, control valves, heating and cooling coils, dampers, actuators, pumps, fans, and vents. In order to access HVAC from anywhere, the timers, sensors, and actuators are required to be connected to the Internet and support scalability.

Interoperability is desirable among sensors and actuators from different vendors in order to collaboratively communicate to make decisions. For example, a central heating or cooling system must be able to collect information about window shades, humidity, temperature, or absence of residents.

Entertainment is one of the more compelling applications in smart buildings and homes that covers the access of multimedia contents such as music and home theaters. These applications require high throughput for streaming audio and video contents on the go. Since these devices rely on batteries, they require low-power consumption.

Figure 18 shows the forecasting provided by ABI research for the future of wireless technologies in smart homes [190]. The numbers prove that technologies like WiFi and Bluetooth dual mode will have less share of the market, and low-power and low rate devices will be more desired. Table 6 summarizes the general requirements and shows the major technologies that support these requirements in smart buildings. A detailed discussion about smart building requirements is presented in [191].

BR/EDR and BLE are available technologies in almost every smartphone, laptop, and tablet. This feature enables smart buildings to be controlled using these devices. Statistics show that nearly 73% of people would like to receive smartphone alerts from their home security system [192]. Compared to other low-power technologies, this availability along with lower-power consumption are advantages for BLE. As shown in Figure 18, it can be predicted that the BLE market will surpass other technologies. BLE's AFH algorithm and usage of advertising channels have reduced interference with most of the common operating wireless technologies in the 2.4 GHz band, such as IEEE 802.11. This feature makes BLE a suitable option for an environment that is full of wireless devices that operate in that band. The aforementioned features also help to reduce battery consumption and provide reliability. By increasing the range up to four times more in Bluetooth 5, the signals can cover an entire building. For example, the user is able to access the door lock from anywhere in the building. Another advantage of BLE is the recently added mesh networking feature, which increases the network scale, reliability, and coverage. Countless amounts of research has been done on Bluetooth applications in smart buildings [193]–[196]. For example, Putra *et al.* [197] compared the energy consumption of WiFi and BLE devices in smart home applications. The result showed the possibility of occupancy data transmission via BLE with 30% less battery consumption. Aside from academic publications on the application of BLE in smart buildings, there are some companies such as UniKey [198], BOLT [199], and Emerson [200] that are working on home automation devices based on Bluetooth. Beaconing is one of the unique features of BLE that is used in many applications, such as indoor positioning. For example, by tracking the users inside the building, the AmI can perform desired actions like turning on or off the lights or playing one's favorite music [201]. As shown in the Figure 18, the Bluetooth beacon market will have the highest market compared to other Bluetooth-enabled technologies in 2021. While Bluetooth has its benefits, it does have some limitations that are associated with it. For example, there is a lack of scalability support in BR/EDR and IPv6 connectivity in both BLE and BR/EDR [202]. Incorporating other technologies with Bluetooth will increase the demand.

ZigBee is another candidate for smart home applications. One of the major advantages of ZigBee is that as an open global wireless standard, it provides the open source software stack for developers to freely access the network and application layer. It employees mesh networking to eliminate the single point of failure and expand the reach of the network. Additionally, in the star topology in WLAN, sharing a single node between a large numbers of connected devices has the problem of increasing the delay in the entire network. The ZigBee network supports more than 400 connected nodes, which will be necessary for the future of smart homes, based on the Gartner report's prediction. With mesh networking increasing the number of the devices, the robustness of the network is also increasing due to redundancy and decentralization [204]. A self-organizing network is optimal for a more scalable network architecture that incorporates reliability and adaptivity. ZigBee enables a variety of smart home applications by connecting the sensors and actuators. Additionally, ZigBee is a low-power wireless standard that allows the battery to operate for several years. It can also run without a battery by utilizing harvested energy. For example, a keychain flashlight gets its power by a simple push of a button.

Internet connectivity is one of the significant characteristics of an ideal wireless network for home automation applications. Although ZigBee natively does not support Internet connectivity in the protocol stack, the 6LoWPAN technology adopted the IPv6 connectivity based on the 802.15.4 standard [47]. This adoption allows the nodes to be independent of the translation gateway in order to access the Internet.

Compared to Bluetooth, the main limitations of ZigBee-based smart buildings are the lack of support by smartphones and the low communication throughput. Similar to Bluetooth, there is an ample amount of research that has been done on the application of ZigBee in smart buildings [205] [206].

Zigbee also has products on the market that are used for smart building applications. Companies such as Control4 [207] and Phillips Hue [208] are designing their products based on ZigBee technology.

Thread is a recently developed wireless technology targeted for home automation. It is IPv6 enabled and supports mesh networking, thereby all devices can be addressed locally or globally. Mesh networking support allows the network to cover the entire building, and it improves the robustness of the network and avoids issues such as single point of failure. SLC is one of the main applications of a Thread network, and scalability is one of the requirements for the SLC applications. A Thread network supports up to 200 connected nodes. In addition, operating on MAC and PHY layers of IEEE 802.15.4 allows the technology to get the benefit of low-power consumption.

In addition to Bluetooth and ZigBee, several proprietary standards target building automation applications. Standards such as Z-wave [209], INSTEON [210], and EnOcean are particularly designed to meet the requirements in home automation applications. Z-Wave specifically targets control applications such as SLC and access control. A thermostat is one of the examples of these applications and has over 2100 certified products. The products are supported by 600 companies like Intermatic [211], Hawking Technology [212], Wink [213], and Aeotec [214]. As previously mentioned in Section VI, Z-wave has the advantage of using the sub-1 GHz frequency band. However, this can also be a disadvantage when the products need to be distributed globally and used in other countries that have different rules for operating in the sub-1 GHz band. INSTEON Alliance was launched in 2005 by Smartlabs company [215]. The technology combined powerline and wireless mesh technology. Devices can support wireless technologies, wired technologies, or both. Wireless devices use FSK modulation and operate at 904 MHz with a data rate of 38.4 kb/s [216], [217]. INSTEON has applications in SLC, thermostats, smart

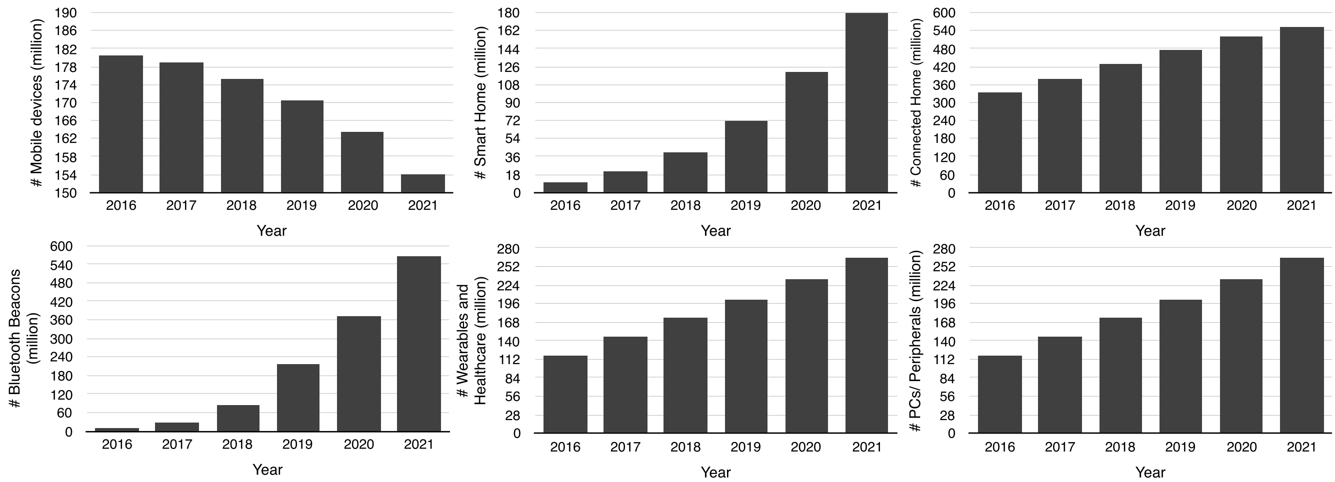


FIGURE 19. **Comparison of major Bluetooth applications market predicted by 2021 (source: [203]).**

sensors, and remote controls. EnOcean [218] is a wireless technology developed for smart homes and standardized by the international standard ISO/IEC 14543-3-10 [219]. It aims to use harvested power sources from the environment for wireless technology [220]. Devices such as smart plugs, SLC, and HVAC can be controlled by EnOcean. Like Z-wave and INSTEON, it operates in the sub-1 GHz band with a data rate of up to 125 kbps.

B. SMART HEALTHCARE

Improving the health quality for individuals prompts a need to provide advanced systems for diagnosing, treating, and preventing diseases. A robust healthcare system can be divided into two generally classified categories: *prevention of illness* and *post illness monitoring*. Monitoring the blood pressure, *Electrocardiogram* (ECG), *Electroencephalogram* (EEG), *Electromyogram* (EMG), glucose level, cholesterol level, pulse oximetry, and toxins in the body can help early-stage detection in order to prevent fatal diseases, such as cancer or heart attacks [221]. The rapidly increasing population and longer life expectancies raise the importance of mechanisms for children and elderly health monitoring, artificial organ implementation and drug delivery. According to the *World Health Organization* (WHO), global life expectancy increased from 66.4 years in 2000 to 71.4 years in 2015 [222]. As the global life expectancy is increasing, the size of the geriatric population is also increasing. The number of people over 60 years old increased from 607 million to 901 million by a 48% increase. Also, it is predicted that by 2030, this number will grow by 56% to 1.4 billion and reach to 2.1 billion in 2050 [223]. It is also clear that the risk of chronic diseases like neurological conditions, diabetes, heart diseases, and strokes increase with age. The other concern is the cost of healthcare, which can include hospitalization, home nursing, and medicines. It is estimated that in the U.S., healthcare expenses are more than $2 trillion annually [224]. This leads to the need to provide an advanced healthcare system for diagnosing, treating, and preventing disease. The desired system must be inexpensive, accessible, harmless, reliable, and must not restrict the daily activities, mobility, or quality of life.

IoT, in combination with medical engineering, has the great potential to provide this system through wirelessly monitoring and recording medical data. Providing the Internet connectivity allows the physician to monitor the health condition of the patients. Thus, 41% of the IoT is marketed for healthcare applications by 2025 [228]. There are a large number of researchers who are focusing on the cure, prevention, and prediction of diseases using IoT and wireless technologies [229]–[232]. In IoT-based healthcare systems, smart homes can replace hospitals, and bulky, attached-to-the-body monitoring systems can be changed to tiny, implanted sensors. Table 7 shows the QoS requirements for a wireless network, including the data rate, timeliness, acceptable error rate, and required battery life.

It is important to provide a platform that does not limit the normal activities and quality of life of patients. For example, bulky attached sensors that are connected to wires are hard to carry and restrict the mobility of a patient [25]. Besides, providing *Ambient Assisted Living* (AAL) is important in monitoring health conditions. Smart homes or smart hospitals are examples of AAL. For instance, a smart home can receive the information from the wearable sensors of the patient in order to manage the temperature. Wireless sensors can be placed inside or outside of the body as wearables. These sensors can detect changes faster than highly equipped laboratories, especially for people who have a history of cancer or other diseases which can be inherited. However, this constant monitoring leads to high battery consumption. This increases the risk of nonavailability of these sensors in critical moments. Latency in bio-medical sensor applications is soft real time. Normally, in critical scenarios such as during a heart attack, a few seconds of latency is still acceptable.

TABLE 7. QoS requirements for smart healthcare (sources: [225]–[227]).

Application	Data rate	Latency	Bit Error Rate	Battery life
Deep brain stimulation	<320 kbps	<250 ms	$<10^{-10}$	>3 years
Capsule endoscopy	1 Mbps	<250 ms	$<10^{-10}$	>24 hours
ECG	72 kbps	<250 ms	$<10^{-10}$	>1 week
EEG	86.4 kbps	<250 ms	$<10^{-10}$	>1 week
EMG	1.536 Mbps	<250 ms	$<10^{-10}$	>1 week
Glucose monitor	<1 kbps	<250 ms	$<10^{-10}$	>1 week
Temperature	120 bps	<250 ms	$<10^{-4}$	>1 week
Motion sensor	35 kbps	<250 ms	$<10^{-4}$	>1 week
Drug delivery	<16 kbps	<250 ms	$<10^{-10}$	>24 hours
Video/med imaging	<10 Mbps	<100 ms	$<10^{-3}$	>12 hours
Voice	50-100 Mbps	<100 ms	$<10^{-3}$	>24 hours
Audio streaming	1 Mbps	<20 ms	$<10^{-5}$	>24 hours

In [233], they implemented real-time and low-power ECG and EEG Bluetooth based sensors. They introduced the compressed sensing method, which saves the battery up to 37.1% more. In [234], the feasibility of applying dual mode Bluetooth in vital monitoring was analyzed. Authors implemented the ARM CPU based sensors, such as ECG, body temperature, and motion sensors. Reference [235] reviewed the available commercial Bluetooth-based healthcare devices in the market, which are composed of sensors such as activity tracking, ECG, EEG, EMG, and glucose monitoring. A BLE-based ECG monitoring using a smartphone is implemented in [236], and the result shows that power consumption is highly reduced. In addition to reducing power consumption, an equally important aspect of using sensors is that the patient is being continuously monitored in both indoor and outdoor locations like their home, hospital, and outside. Elderly patients are penitent when they feel that they are in danger and need to be continuously monitored. Reference [237] proposed a BLE-based indoor positioning system for patients who have Alzheimer.

There are several commercial products like wearable devices on the market. Jawbone [238], Apple Watch [239], Samsung Gear [240] and most of the smartwatches are using Bluetooth and Wi-Fi technology to send the health sensor information. Heart rate monitoring with ECG, activity tracking, sleep monitoring, and other forms of health data are implemented in these wearables.

However, Bluetooth is not the only low-power wireless technology for healthcare applications. ZigBee and 6LoWPAN are other candidates in this area. In [241] and [242], ZigBee-based ECG and pulse oximetry sensors are implemented by the authors, and the results showed that ZigBee meets the QoS requirements for these healthcare applications. Coexistence is also important in healthcare applications due to the WiFi-enabled smartphones that are operating close to the wireless technologies such as ZigBee. In [243], the impact of WiFi near the ZigBee wearables has been analyzed.

Although 6LoWPAN and ZigBee share the same PHY and MAC, the IPv6 capability of 6LoWPAN makes the devices addressable via the Internet. This allows for the opportunity to remotely monitor health conditions or keep health records in the cloud. 6LoWPAN-based real-time health monitoring is proposed in [244]. They tested the performance of ECG monitoring sensor data for remote healthcare using a 6LoWPAN edge router. Doukas and Maglogiannis [245] presented the cloud platform in which sensors are connected to the Internet using 6LoWPAN technology.

C. INDUSTRIAL AUTOMATION

During the last decade, wireless technology has been increasingly utilized in industries, leading to the Industrial Internet of Things (IIoT), where *Industrial Wireless Sensor Network*s (IWSNs) play a central role of behaving like a digital skin for the IoT. IWSNs can monitor critical parameters and control industrial processes and then inform the industrial personnel of this information promptly. IWSNs offer flexibility, self-organization, rapid deployment, and low-cost. They have the ability to make processes autonomous, resulting in the minimal human intervention [246] when compared to their wired counterpart. The shift from wired to the wireless networks dramatically helps to reduce huge capital expenditures of installation and maintenance of wires. Moreover, wired networks are rigid and fixed in nature. This makes it difficult to adapt to changes in industrial environments. In addition, certain industrial applications require mobile robots, which becomes a huge challenge with wired networks. However, wireless networks can easily support such mobility scenarios. Although IoT seems to revolutionize the industries, it is only if it satisfies the strict requirements and challenges that are put in place by the industrial applications. Such challenges include: extremely high reliability, low latency, robustness, fault tolerance, massive scalability, interoperability, and energy efficiency. Reliability against interference is highly indispensable because industries encompass several wireless networks, heavy machinery, and co-located communication systems that can interfere with IWSNs [246]. This can negatively impact wireless connectivity and result in link unreliability issues. Besides, most low-power wireless standards operate in the ISM band which can make them highly vulnerable to interference. Certain applications in industries, such as closed-loop control systems are extremely delaying sensitive. They tend to require low latency so that the

TABLE 8. Different classes of industrial applications as defined by ISA.

Category	Class	Application	Description
Safety	0	Emergency action	Always critical
Control	1	Closed-loop regulatory control	Often critical
	2	Closed-loop supervisory control	Usually non-critical
	3	Open-loop control	Human in loop
Monitoring	4	Alerting	Short-term operational consequence
	5	Logging and downloading/uploading	No immediate operational consequence

control system can function smoothly. Furthermore, low power IWSNs have limited battery resources. When the devices run out of battery life and die, it leads to network failures. Therefore, the network needs to be fault tolerant so that failure of one device or a group of devices does not cause the entire network to fail. Scalability is also a challenge with wireless networks. The industries require dense networks that consist of hundreds and thousands of nodes. Efficient and fair distribution of limited resources in such dense networks causes trade-off complexities for several performance metrics. As time passes, certain devices and functionalities are removed, and new ones may be added. This requires the network to be scalable enough to accommodate such changes without compromising performance. Currently, wired networks are already prevalent in industries and used to support many processes and operations. The use of new wireless standards and solutions should seamlessly work with the legacy systems. This requires interoperability among the standards and solutions.

Table 8 shows the different classes of industrial applications, ranging from process monitoring, control, safety, and emergency operations as defined by ISA [37]. The traffic categories are listed according to traffic priority with 0 as the highest priority traffic and 5 as the lowest priority traffic. Each application category generates a different kind of data traffic. In comparison to user-generated traffic on the Internet, the traffic generated by the industrial applications has different characteristics.

Most of the processes in industries are periodic in nature, meaning that they do not require frequent data transmission. The long idle periods in between data transmission makes lower power networks more suitable in comparison to traditional cellular or next generation wireless networks.

Essentially, the industrial environment is heterogeneous as shown in Table 9, i.e., certain traffic is an extremely high priority, while the other requires less priority. The high priority traffic requires immediate response to certain events, i.e., they need the right response at the right time, otherwise, the system can run into catastrophic situations. Below, we discuss some of the well-known low power standards and technologies developed over the years that promise to fulfill the requirements of industrial automation and help to realize IIoT.

1) ZIGBEE

ZigBee offers low power consumption. It supports several topologies that make it suitable for industrial monitoring and control. However, it is unable to provide high reliability and robustness [248].

ZigBee does not employ any frequency-agility protection against interference and fading effects. Moreover, the static nature of the channel will create a bottleneck for ZigBee communication if other wireless LANs operate in close proximity. This also impacts the delay and energy consumption because frequent packet losses will cause retransmissions, which will lead to an increase in delay and energy consumption. ZigBee uses IEEE 802.15.4 MAC, which renders the delay to be unbounded (cf Section III-C). This causes problems for real-time transmission, especially for control applications in process automation.

2) WIRELESSHART

WirelessHART is developed to cater to monitoring and control in industries. It improves upon the drawbacks of ZigBee. The standard is robust and provides secure communication by implementing features such as channel hopping and channel blacklisting in order to avoid interference. In the case of transmission failures, retransmission occurs on a different channel. This improves reliability in harsh industrial environments. It supports mesh networking together with graph routing, which offers path redundancy and self-healing features that help in case of broken links [248]. The MAC protocol works on TDMA and provides multiple features, as discussed in Section 7.

The standard employs a dedicated security manager, which implements the necessary encryption and security policies. Although WirelessHART is suitable in many aspects compared to ZigBee, it lacks public key encryption and the ability to connect to other networks without a gateway [249].

3) IEEE 802.15.4E

IEEE 802.15.4e defines six MAC modes. In particular, its TSCH MAC mode is important because it implements a deterministic TDMA mechanism and has channel hopping features in order to avoid the inevitable interference. The MAC protocol is multi-channel and offers many improvements as discussed in Section III-E3. Although TSCH offers high reliability for industrial automation, it lacks a scheduling entity to compute the schedule of nodes based on the traffic requirements of the application. TSCH defines the schedule, but how the schedule is built and maintained is unknown.

Furthermore, 6TiSCH and 6LoWPAN standards emerged in order to provide an IP network that is capable of enabling low-power wireless standards as discussed in Section III-G and Section III-H, respectively. In this way, they promote interoperability among the latest and the traditional IP networks.

TABLE 9. Industrial applications and their typical requirements (source: [18], [247]).

	Applications	Delay	Range (m)	Battery	Update Frequency
Monitoring and supervision	Vibration sensor	seconds	100	3 years	seconds - days
	Pressure sensor	milliseconds	100	3 years	1 second
	Temperature sensor	seconds	100	3 years	5 seconds
	Gas detection sensor	milliseconds	100	3 years	1 second
Closed loop control	Control valve	milliseconds	100	> 5 years	10 - 500 ms
	Pressure sensor	milliseconds	100	> 5 years	10 - 500 ms
	Temperature sensor	milliseconds	100	> 5 years	500 ms
	Flow sensor	milliseconds	100	> 5 years	10 - 500 ms
	Torque sensor	milliseconds	100	> 5 years	10 - 500 ms
	Variable speed drive	milliseconds	100	> 5 years	10 - 500 ms
Interlocking and control	Proximity sensor	milliseconds	100	> 5 years	10 - 250 ms
	Motor	milliseconds	100	> 5 years	10 - 250 ms
	Valve	milliseconds	100	> 5 years	10 - 250 ms
	Protection relays	milliseconds	100	> 5 years	10 – 250 ms

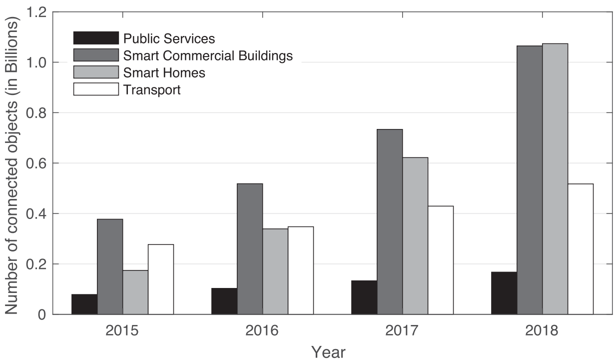


FIGURE 20. Comparison of major applications based on the number of connected devices in smart cites (source: [250]).

D. SMART CITY

The concept of a smart city envisions a city where information and communication technologies offer viable solutions to collect, analyze, and smartly distributes information in order to transform the services offered to the citizens, enhance operational efficiency, and help the public administration make better decisions [251], [252]. One of the promising projects for a smart city is the Smart Santander Project [50], conducted in the Spanish port city, Santander. It proposes a smart city where sensors, actuators, cameras, and screens are deployed around the city to help citizens better utilize information [253]. The smart city promises to manage and optimize the plethora of public services, such as monitoring structural health, air quality and noise, as well as traffic management, smart parking, managing city energy consumption, waste management, smart lighting, and the automation of public buildings [254]. This vision can be realized by utilizing the telecommunication infrastructure, as well as several technologies like as WSN, M2M, and *Vehicular to Vehicular* (V2V) communication. A smart city integrates several emerging technologies with existing information and communication infrastructure in order to exhibit the successful evolution of IoT. The environment is heterogeneous, i.e., it encompasses different types of devices and generates different types of data traffic. Such an environment vastly depends on the networking connectivity, which demands high reliability, availability, low latency, and, at the same time, satisfies the requirements of all levels of applications. The major barrier is the interoperability among the several heterogeneous technologies to be able to work together to achieve a common goal. In such a scenario, providing reliable connectivity is a huge challenge not only because of the coexistence of a large number of devices that comply with different technologies but also because these devices can face severe interference. In such scenarios, impaired network connectivity can result in catastrophic situations for the wide variety of offered services and applications.

In looking at the requirements that are defined by the smart cities, low-power standards, such as ZigBee, Bluetooth, IEEE 802.11ah, NFC, and Z-Wave, can fulfill their demands, but they are unable to provide high throughput and extended transmission range [255]. Furthermore, the advanced technologies, such as 3GPP, WiMAX, LTE, and LTE-Advanced, are not suitable due to their high power consumption because most of the smart city applications require small sensors that will be deployed everywhere and run on batteries. In order to realize the smart city concepts, low-power standards have to promote interoperability. A massive number of devices will be installed and need to work together efficiently, so scalable protocols are necessary.

X. RELATED SURVEYS

There exist various survey papers that discuss the characteristics, technologies, standards, and applications of IoT [21], [256]–[259]. Unfortunately, these studies did not cover the recent wireless technologies and their suitability for each IoT application. In particular, a comprehensive study on MAC and PHY layers in these technologies is missing. A recent study in [257] focuses on exploring the network architectures of IoT. The authors discuss the classification of IoT architectures and outline future architectural requirements. However, the paper does not cover aspects such as low-power standardization or well-known infrastructure protocols for IoT. Another survey in [21] provides an excellent, holistic discussion of IoT with respect to its architecture, common standards, elements, technologies, infrastructure protocols, applications, and market opportunities. It is more of a general overview of the various aspects of IoT, however, it does not cover the in-depth technical details, pitfalls, and limitations of MAC protocols of low-power standards. The survey paper in [258] provides a sound analysis of recent advances in IoT. The authors focus the paper on the standardized protocol stack and examine the IETF standardization efforts and protocols. The paper provides a profound, technical discussion on the application, MAC, routing and transport layers, as well as low-power radio characteristics. However, it does not cover their applicability and limitations in different IoT application domains. The IoT survey paper in [256] examines the IETF current standards and protocols and explores open questions, limitations, opportunities, and future challenges. However, it discusses only the defacto standards. Besides, some surveys focus on a single IoT application and its requirements as well as the suitability of each wireless technology for it. For example, Yuehong *et al.* [229] explored the application of IoT in health care. The study provides a general overview of a system architecture for IoT-based smart health care. It is a general overview, and the specific requirements for applications are not mentioned. Similarly, Domingo [260] studied the research trend to improve the quality of life for individuals with disabilities. The study shows the possible solutions to overcome the limitations of some disabilities by using connected sensors and positioning technologies. The adaptability of optimal wireless technology for each scenario has been reviewed as well. The study lacks a larger pool of individuals and ignores the challenge of providing a low-power network. In [261] WBANs for medical and non-medical applications have been reviewed. The authors explained the uniqueness of this network because of the high mobility and placement of some sensors inside the human body. The scope of this is limited to the WBANs, and challenges, such as the coexistence of the wireless network, have not been taken into consideration.

As was mentioned earlier, smart homes are another potential application of IoT. Alaa *et al.* [262] reviewed the research trend focusing on IoT-based smart homes. The study helps researchers to find out the challenges and demands of the desired smart homes. However, the study only classifies the number of researchers and directions and does not explain the technical specifications.

The study in [204] only focuses on home automation.

Raza *et al.* [263] reviewed the LPWAN for long-range communication networks such as SigFox and LoRaWAN. They explained the available technologies of these networks and applications. Due to the operation of LPWAN in the sub-1 GHz frequency and the requirement of having a different unlicensed band for every country, these technologies are not able to operate globally.

In contrast with single application surveys, some other reviews only explain a single wireless technology. For instance, Gomez *et al.* [107] and Darroudi and Gomez [264] review the BLE standard from a protocol stack point of view and research to provide a BLE mesh network, respectively. On the other hand, surveys like [67], [265], and [266] only focus on IEEE 802.15.4 based standards. Blanckenstein *et al.* [267] reviewed low-power transceivers and suitability for each application. However, due to the novelty of technologies like BLE 5, they did not cover the latest transceivers. Additionally, the survey only reviews the hardware requirements for low-power networks.

XI. CONCLUSION

Emerging IoT applications impose several constraints in terms of reliability, timeliness, scalability, and energy efficiency. The purpose of our study was to provide a thorough discussion about existing low-power wireless standards, technologies, and protocols, and examine their suitability in diverse IoT application domains. We presented the requirements of different applications such as smart healthcare, industrial automation, and smart cities, and analyzed the potentials of existing standards in meeting such requirements. Our survey focused on the PHY and MAC layers because they directly influence the aforementioned constraints. In our attempt to explore their suitability, we highlighted several drawbacks of the MAC protocols. We also discussed the interference issue among the coexisting, low-power wireless networks, which is a major challenge that degrades the network performance for reliability and latency. We analyzed how the inherent schemes employed by the standards cope with the interference issues.

Lastly, we presented the application domains of the IoT and the requirements for each scenario. Additionally, we introduced the optimal wireless solution for each application based on the demands.

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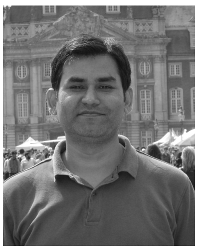

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