Chapter 15
IEEE 802.15.4 Technologies for Smart Grids

Yasin Kabalci

Abstract In recent years, wireless sensor networks (WSNs) have received growing attention owing to their remarkable advantages, and they are widely being utilized in various metering and monitoring application areas such as Internet of things (IoT), smart grids, smart cities, smart homes, cloud computing, healthcare monitoring, military investigation, environmental surveillance systems. The most widely utilized standard in the WSN applications is IEEE 802.15.4 that is developed to enable short-range applications with low data rates and low power consumption features. This chapter aims to provide comprehensive information concerning of the WSNs, general specifications of the IEEE 802.15.4 standard, recently developed new technologies based on this standard, and several practical WSN applications performed for smart grid concept. This chapter firstly introduces the fundamentals, application areas, and advantages of the WSNs in a detail. Later, the chapter continues by explaining technical backgrounds of the WSNs where IEEE 802.15.4 standard is examined in terms of layer stacks. The physical (PHY) and media access control (MAC) layers of the IEEE 802.15.4 standard are comprehensively analyzed since these layers are the basis of new technologies such as ZigBee, WirelessHART, ISA100.11a, 6LoWPAN, and 6TiSCH. Afterward, these novel technologies are introduced and analyzed by considering open systems interconnection (OSI) reference model. Finally, practical examples of the WSNs regarding metering and monitoring applications of smart grids are presented at the end of this chapter.

Keywords Wireless communication systems · Wireless sensor networks
IEEE 802.15.4 · ZigBee · WirelessHART · ISA100.11a · 6LoWPAN · 6TiSCH
Smart grid · Metering and monitoring

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15.1 Introduction

Over the past decade, wireless sensor networks (WSNs) have gained increasing interest depend on their low-cost solutions provided for practical problems. A typical WSN contains a combination of many independent devices that are called wireless nodes. These nodes can be connected to each other for conveying small data packets where each node is linked to one or more sensors to monitor both several physical quantities and environmental variables. Movement, temperature, infrared, vibration, light, sound, pressure, and magnetism are several examples of physical quantities to be detected by sensors. The nodes of WSNs generally communicate with each other by employing wireless communication techniques, and the most widely utilized standard in the WSNs is IEEE 802.15.4[1] that is developed for short-range applications with low data rates and low power consumption. The WSNs are exploited in many popular application areas such as internet of things (IoT), smart environments, smart cities, smart grids (SGs) , smart homes, cloud computing, vehicular ad hoc networks (VANETs), machine-to-machine (M2M) communication, cyber physical systems (CPSs), healthcare monitoring, military investigation, environmental surveillance [1–7]. While the WSNs can be employed to monitor patients' status in healthcare systems, they can be used for observing volcanoes in real-time as an example of environmental surveillance applications. In addition, another popular application of WSNs is home management systems where home appliances are remotely controlled by mobile devices such as smart phones and tablets.

One of the most important application areas of WSNs is the SGs that are evolution of conventional power grids. The SGs that contain many smart meters (SMs) and sensors connected each other through WSNs have been recently developed in order to provide better quality power and satisfying increased power demands efficiently. In the SGs, generation, transmission, and distribution stages of power systems can be also managed without the need for human intervention because of the fact that the WSNs can offer several effective services. Conventional power generation systems mainly depend on the wired network structure. Therefore, the network can cover particular regions, while some areas cannot be covered due to limitations of wired networks. On the other hand, the WSNs can be implemented everywhere without any limitation. Another advantage of the use of WSNs in power systems is that WSN nodes inform control and management center by sensing various parameters of power generation systems such as temperature, vibration, light, sound, and pressure before undesirable faults happen. Therefore, service providers can take precautions before major problems arise that can cause to several important issues affecting power generation systems and power quality of users. Moreover, transmission and distribution sections of the power systems are also observed thanks to the WSNs in the SG concept. This provides several advantages to manage utility grids for efficiently covering demand management that is a crucial requirement for the SGs. The most important applications of WSNs in the SGs are preventing energy theft, fault

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[1] For simplicity, 802.15.4 term will be preferred instead of IEEE 802.15.4 after this part of the chapter.

detection, and insulation breakdown that highly improve managing and operating features of SGs when compared with conventional power grids [8].

The SGs combine information and communications technology (ICT) with power grids to present more secure, flexible, and efficient power grid structure that can be easily operated to monitor and manage energy generation systems and user demands [9]. The SMs and sensors are main components of the SGs which are spread from homes to management center all over the network and are also employed to detect peak values of electricity usage required for demand response management processes. Security is also very critical issue for the SGs, smart homes, and every smart environment. Therefore, use of the secure and effective communication technologies in smart environments is needed between users and system devices. However, real-time monitoring and device control can be accomplished by employing secure access gateways in home area networks (HANs) [10]. In addition to the coverage advantage of the WSNs, they also provide low-cost solutions for real-world problems that make WSNs more promising technology rather than other technologies. On the other hand, it is important to note that low energy consumption is one of the main requirements for massive network structures operating long term. IEEE 802.15 working group has developed 802.15.4 standard to present a communication infrastructure for the WSNs with low-cost, low-speed, low-energy consumption and wide coverage characteristics. In this standard, physical (PHY) and media access control (MAC) layers aim to provide energy-efficient transmission with low-rate and energy-saving operation by utilizing special scheduling protocols for sleep/wake up modes. In addition, this standard supports various network schemes such as peer-to-peer (P2P), cluster-tree, and star topology. Owing to these outstanding features, 802.15.4 standard has been one of the most important candidates for the WSNs and wireless control networks [11–14].

15.2 IEEE 802.15.4 Standard

As a result of demands for communication technologies that offer low power consumption advantage, 802.15.4 standard has been released in 2003. This standard developed by the IEEE 802.15.4 working group is the first one for low-rate wireless personal area networks (LR-WPANs). The main goal of the standard is to present a novel infrastructure that comes with up very important features such as energy-saving, low-cost, and low-complexity features for wireless network applications [15]. The 802.15.4 standard identifies both PHY and MAC layers as the lowest layers of the protocol stack where PHY layer performs signal processing operations such as data mapping, transmission, channel selection, and energy management, while MAC layer is responsible for minimizing collisions and managing frames. The other layers are specifically characterized by other standards such as ZigBee, 6LoWPAN, and WirelessHART.

Two different network node types, which are full-function device (FFD) and reduced-function device (RFD), can be created in the 802.15.4 standard. The FFD

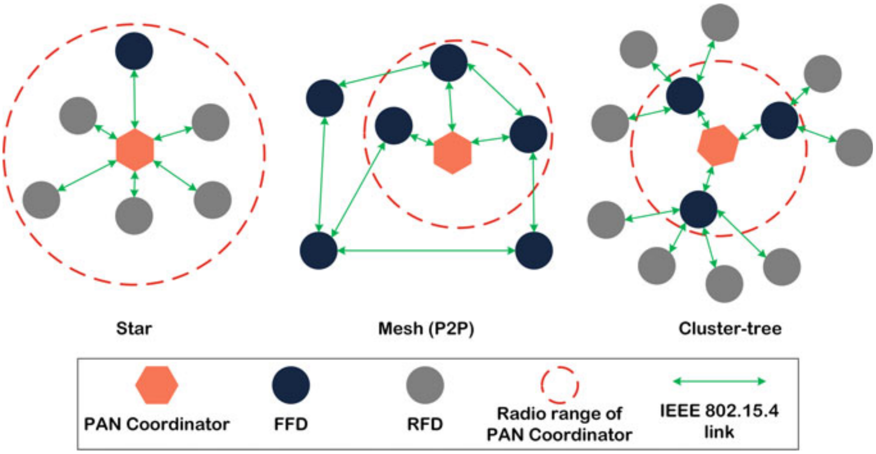


Fig. 15.1 Node topology examples utilized in 802.15.4-based WSNs

covers nodes that can completely ensure the standard since these nodes consist of all of the network capabilities. Therefore, the FFDs in the network can behave as a personal area network (PAN) coordinator, or as a local coordinator or as an end-device. It is important to note that at least one FFD should be absolutely defined as a network coordinator in any 802.15.4 network. The other network node type can behave merely as end-devices and creates fundamental nodes that are able to form only a certain part of the network capabilities because of processing and memory scarcities. Even though the RFDs have no ability to send messages to their final destinations, they can act as end-devices in the network. On the other hand, the local coordinator that should be combined with either a PAN coordinator or a formerly associated local coordinator supplies synchronization services thanks to transmission of beacons.

Three different node topologies that are star, mesh (P2P), and cluster-tree are supported in 802.15.4 standard as shown in Fig. 15.1. All of the devices contact with a PAN coordinator by employing master/slave network model in the star topology. In other words, one of the FFDs takes over the network coordinator role, and the other nodes composed of FFDs and RFDs merely communicate with the network coordinator. In mesh topology, nodes can form more complex network designs where all devices can freely contact with each other. However, the nodes that intend to contact with each other should firstly communicate with the PAN coordinator. On the other hand, cluster-tree scheme is regarded as a special case of mesh (P2P) network topology where the vast majority of devices are the FFDs. Communication range of the standard typically varies from 10 m to 75 m due to the environmental conditions and low-powered transmission feature. The coverage of the network can be expanded through the cooperative networking and multi-hop techniques where some of the nodes operate as a relay for other nodes as it is in a cluster-tree topology [16].

15.2.1 The PHY Layer of IEEE 802.15.4

The PHY layer of 802.15.4 carries out data processes such as data transmitting and data receiving by exploiting specific radio channels, modulation techniques, and spreading codes [17]. Even though this layer identifies various channels in different frequency bands, the most popular operation bands in applications are especially 868 MHz, 915 MHz, and 2.4 GHz frequency bands. The 2.4 GHz frequency band, which is also referred as industry, science, and medicine (ISM) band, is the most frequently utilized unlicensed band worldwide. Figure 15.2 depicts channel structures of these most popular bands in 802.15.4 standard. The 868 MHz frequency channel operates over one channel with 20 kbps data rate in Europe, while the 915 MHz operates over ten channels with 40 kbps data rate in North America. In addition, the other frequency bands serve in the 2.4 GHz ISM band with a very wide coverage over the world. The frequencies from 2.4 to 2.483 GHz are exploited by these band to offer 16 channels with 250 kbps data rate, and each channel space is specified as 5 MHz as can be seen from the Fig. 15.2. Furthermore, the PHY layer specifications of 802.15.4 are listed in Table 15.1. On the other hand, it is important to note that a transmitter structure must transmit at a power level of minimum −3 dBm (approximately 0.5 mW) according to specifications of this standard. However, transmitters need to propagate low power as soon as possible in order to prevent interference effects on other systems and devices. In addition, the maximum level of transmit power is specified by local regulators.

Similar to the other wireless signals, 802.15.4 signals are also influenced by both noise and several interferences while they are propagating through a wireless medium that is able to decrease the performance of communication system significantly. Spread spectrum (SS) techniques such as direct sequence SS (DSSS) and parallel sequence SS (PSSS) are utilized in the 802.15.4 standard to ensure harmony of this standard with other standards using the ISM band. For instance, IEEE 802.11 wireless local area networks (WLANs) also operate in this frequency band and are more spread than that of the 802.15.4-based systems. However, the impact of the WLAN

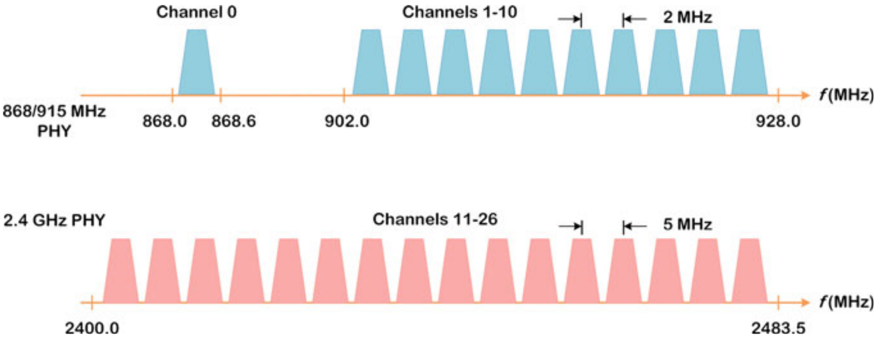


Fig. 15.2 Channel structures for different frequency bands of 802.15.4

Table 15.1 Physical layer specifications of 802.15.4 standard

Frequency range (MHz)	Spreading parameters		Data parameters		
	Chip rate (kchips/s)	Modulation	Bit rate (kbps)	Symbol rate (ksymbol/s)	Symbols
868–868.6	300	BPSK	20	20	Binary
868–868.6	400	ASK	250	12.5	20-bit PSSS
868–868.6	400	O-QPSK	100	25	16-ary quasi-orthogonal
902–928	600	BPSK	40	40	Binary
90–928	1600	ASK	250	50	5-bit PSSS
902–928	1000	O-QPSK	250	62.5	16-ary quasi-orthogonal
2450–2483.5	2000	O-QPSK	250	62.5	16-ary quasi-orthogonal

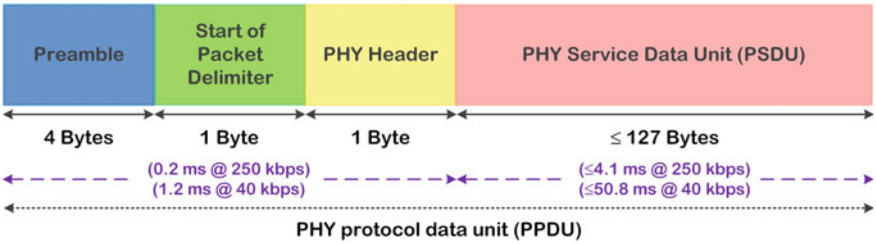


Fig. 15.3 IEEE 802.15.4 packet structure

on the 802.15.4 signals is merely considered as a broadband interference since the standard utilizes dissimilar SS techniques. In the event of IEEE 802.15.1 (Bluetooth) networks in the ISM band are considered, the effects of the Bluetooth are regarded as a narrowband interference on 802.15.4-based systems due to the narrowband structure of the Bluetooth. Therefore, the SS techniques utilized in 802.15.4-based communication systems ensure robustness against such disruptive effects. On the other hand, a general packet scheme is adapted to PHY layers to allow identification of a common MAC interface. The packet structure of the standard is also referred as PHY protocol data unit (PPDU) which is composed of four main parts such as preamble, packet delimiter, PHY header, and PHY service data unit (PSDU). A general packet structure utilized in PHY layer is presented in Fig. 15.3.

The PHY layer of the 802.15.4 has several important properties such as activation/deactivation of transceivers, link quality indication (LQI), energy detection (ED), channel frequency selection, and clear channel assessment (CCA). These features can be briefly explained as follows.

- *Activation/Deactivation of Transceivers*: According to the standard, transceivers need to support three different operating modes such as transmitting, receiving, and sleeping. The transceiver is switched on or off according to demand of MAC layer. The turnaround time between transmission and receiving processes or vice versa is specified as less than 12 symbol periods.

- *Energy Detection (ED)*: This parameter is exploited to predict power level of received signal in the bandwidth. In this process, there is no additional operation such as decoding, demodulation, or signal identification. The ED time is defined as a period of eight symbols in the standard. The obtained ED result is generally exploited on the network layer either for channel selection algorithm or for CCA process. If the value of ED is equal to zero, this shows that power of received signal is at least 10 dB above minimum value of receiver sensitivity.
- *Link Quality Indication (LQI)*: This measurement method is handled for each received packet and defines a quality metric for received packets. Whereas the measurement process can be performed by several methods, the most popular methods are employing receiver ED or using signal-to-noise ratio (SNR) estimation or both of these methods together. It is important to note that the standard does not define how the LQI parameter will be utilized neither on network layer nor on application layer. The minimum and maximum values of the LQI parameter indicate the range of the quality based on perceptible signals by the receiver units. In addition, distribution of the LQI values must be uniform within these upper and lower bounds.
- *Clear Channel Assessment (CCA)*: This process can be carried out in four different ways which are called as ED, carrier sense, a combination of ED and carrier sense methods, and *ALOHA*. In ED technique, the channel is taken into account as busy when an energy level is perceived above of the predefined threshold value. In carrier sense method, the CCA notifies a busy channel if it perceives a mapped signal having spreading features of the standard. Energy level of the detected signal is not important in this method. In third way, the CCA informs a busy channel when it detects a mapped signal with spreading properties of the standard and energy level of perceived signal is higher than predefined threshold value. In last mode, in *ALOHA*, the CCA will always notify an idle channel.
- *Channel Frequency Selection*: Although the standard offers 27 different wireless channel options, each network can exploit only a portion of the options. Therefore, the PHY layer should be able to adjust its radio in a flexible way.

15.2.2 The MAC Sublayer of IEEE 802.15.4

The MAC sublayer is composed of two services that are MAC data service and MAC management service. The first one of these services authorizes MAC protocol data units (MPDUs) to receive and/or to transmit data across the PHY data service. The main properties of the MAC sublayer can be sorted as beacon management, guaranteed time slot (GTS) management, frame validation, acknowledged frame delivery, channel access, association, and disassociation. Furthermore, the MAC layer offers opportunities to implement suitable security structures for applications.

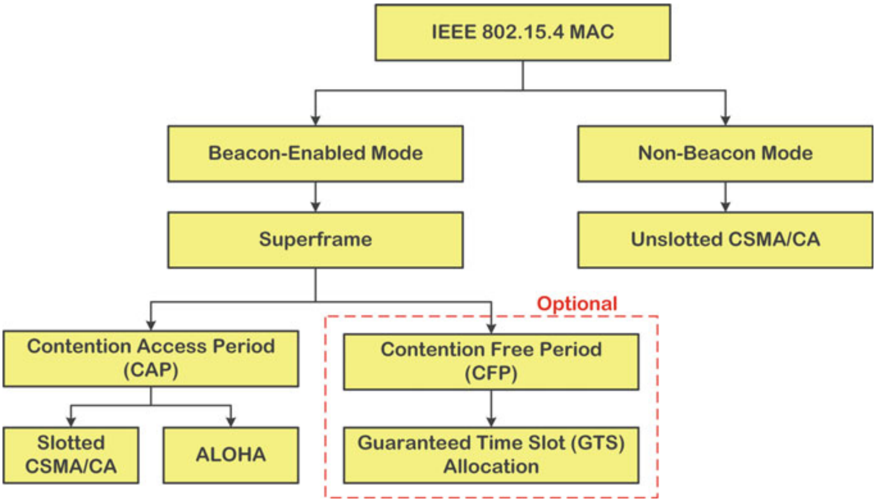


Fig. 15.4 IEEE 802.15.4 operational modes

Two difference channel access techniques, which are *beacon-enabled mode* and *non-beacon mode*, are allowed in the 802.15.4 standard. In the event of unslotted carrier sense multiple access with collision avoidance (CSMA/CA) is exploited, the standard operates in a non-beacon mode. On the other hand, if the slotted CSMA/CA is employed, the standard runs in a beacon-enabled mode in which PAN coordinator transmits beacon frames systematically to all of the end-devices available in the network. The beacons are exploited for three important goals as providing a synchronization between devices, defining PAN infrastructure and identifying superframe structures that are used in beacon-enabled mode to coordinate communication in the wireless channel. The beacon interval (BI) is characterized as the time interval between two beacons and consists an active period and an optional inactive period. In the time of the inactive period, nodes may be remained in low-power mode (sleep mode) for preserving their power sources. The active period part of the superframes is entitled as superframe duration (SD), and each SD includes 16 time intervals with equal lengths. In addition, active periods contain contention access period (CAP) and contention-free period (CFP) sections. The CFP, which is controlled by the PAN coordinator, is typically employed for low-latency applications and comprises up to seven GTSs. In the time of CAP between beacon frames, nodes can communicate with each other by using a slotted CSMA/CA or *ALOHA*. The operational modes of 802.15.4 MAC sublayer are summarized in Fig. 15.4.

The PAN coordinator defines the superframe structure that is characterized based on *macBeaconOrder* (BO) and *macSuperframeOrder* (SO) values. While the BO identifies the time period, the SO defines period of active part and beacon frame. A typical superframe structure is depicted in Fig. 15.5 by considering the beacon-

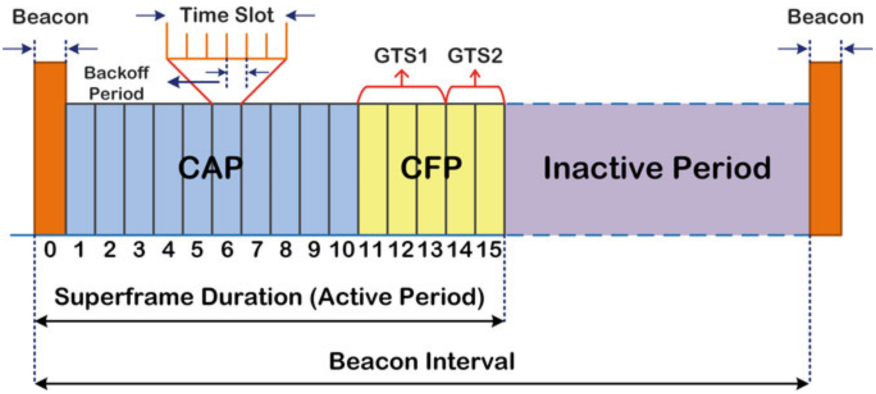


Fig. 15.5 A typical superframe example of IEEE 802.15.4 standard

enabled mode. In addition, the relation between BI and BO parameter can be expressed as

$$\mathrm{BI} = \mathrm{aBaseSuperframeDuration} \times 2^{\mathrm{BO}} \text{ symbols, for } 0 \le \mathrm{BO} \le 14 \qquad (15.1)$$

When the value of BO is equal to 15, the value of SO is neglected and beacon frames are not transmitted unless a special request comes. In addition, the relation between SO and SD can be expressed as

$$\mathrm{SD} = \mathrm{aBaseSuperframeDuration} \times 2^{\mathrm{SO}} \text{ symbols, for } 0 \le SO \le BO \le 14 \qquad (15.2)$$

When the value of SO is equal to 15, the superframe will not continue active mode after the beacon. In the event of value of the BO is equal to 15, the value of SO will be neglected in this case. The responsibilities of the MAC sublayer can be summarized as follows.

- *Beacon Generating for Coordinator*: A coordinator is able to decide that it will operate in beacon-enabled mode or non-beacon mode. In the beacon-enabled mode, it operates by employing superframe structure that is limited by network beacons. Each active portion of superframes is composed of 16 equally spaced slots (*aNumSuperframeSlots*). In addition, coordinators transmit network beacons regularly so as to synchronize devices connected to the network and defining the network.
- *Providing Synchronization between End-Device and PAN Coordinator*: An end-device committing in beacon-enabled mode is able to pursue beacons for providing synchronization to the PAN coordinator. The synchronization is very crucial issue for detecting status of other devices in the network and energy-saving operations.

- *Association and Disassociation*: MAC sublayer provides association and disassociation features for enabling automatic setup and self-configuration in star and mesh network type.
- *Using CSMA/CA Technique for Channel Access Process*: CSMA/CA technique is exploited as channel accessing method in 802.15.4 standard similar to other popular protocols modeled for wireless networks. Nevertheless, request-to-send (RTS) and clear-to-send (CTS) mechanisms are not employed in 802.15.4 standard.
- *Guaranteed Time Slot (GTS) Mechanism*: As the beacon-enabled mode is active, coordinator can assign some parts of the effective superframe into a device. These assigned parts are entitled GTSs, and they also contain CFP of the superframe.
- *Ensuring Secure Link among MAC Entities*: In order to improve link reliability among MAC entities, several mechanisms such as CSMA/CA, re-transmission, frame acknowledgment, and CRC data verification are exploited by the MAC sublayer.

15.3 Popular Technologies Based on IEEE 802.15.4 Standard

The 802.15.4 standard has been the basis of many wireless technologies so far. As mentioned before, the 802.15.4 standard only addresses first two layers, PHY and MAC layers, while upper layers are specified by other wireless technologies such as ZigBee [18], WirelessHART [19], ISA100.11a [20], 6LoWPAN [21], and 6TiSCH [22]. The first implementation of 802.15.4 standard is ZigBee technology that is developed by ZigBee Alliance as a wireless network protocol where ZigBee Alliance specified network layer and application layer on top of the 802.15.4 MAC layer. While the routing process is performed by network layer, appropriate frameworks for several application types are accomplished by application layer of the ZigBee. It employs 2.4 GHz or 868/915 MHzunlicensed ISM bands to enable star-, mesh-, or cluster-tree-based network topologies in the WSNs. There are three kinds of devices in a ZigBee network with respect to their role which are coordinator, router, and end-device. While a coordinator manages all processes of the ZigBee network, a router device transfers information between nodes. An end-device is only responsible for fulfilling coordinator commands. In addition, a router may contain more than one node in a ZigBee network, while an end-device cannot include other nodes. After the first technology called ZigBee, ZigBee Pro has been announced in 2007 that is turned into a common technology. ZigBee Pro offers several advantages such as easy network establishing, supporting of a large number of nodes, providing flexible network structures and ensuring low power consumption to implement low-powered radio systems. Therefore, it has been widely preferred in many practical applications, especially for the purpose of control and monitoring applications.

WirelessHART is another 802.15.4 standard-based wireless networking technology that is developed by HART Communication Foundation as an open standard. After ZigBee Pro has been thoroughly exploited in many applications, WirelessHART is confirmed by International Electrotechnical Commission (IEC) as an international and industrial wireless communication standard with IEC 62591 in 2010. The major elements of a WirelessHART system are network manager, gateway, access points, field devices, and mobile devices. The field devices are established at the industrial plants to perform data acquisition and routing operations, and acquired data are conveyed to gateways by means of access points. In addition, network manager is responsible for arranging and managing communications between devices available on the network. This technology can also support star, mesh, and a combination of star-mesh network topologies. This technology operates as a standalone system like ZigBee systems. In other words, unless a special gateway is employed between networks having different standards, WirelessHART cannot communicate with different networks.

The Internet Engineering Task Force (IETF) 6LoWPAN working group has focused on to enable IPv6 over IEEE 802.15.4 networks in 2005 and developed IPv6 over low power wireless personal area networks (6LoWPAN) IPv6 over low power WPAN. This technology aims to implement a new approach where 802.15.4 networks will communicate with other devices over an IP network directly. Therefore, 6LoWPAN describes an adaptation layer that is located on the 802.15.4 MAC layer, and this layer is responsible for providing requirements of IPv6. There are two essential tasks of 6LoWPAN which are preparing the packet size among 802.15.4 network and IPv6 network and adjusting address resolution between these networks. In addition, 6LoWPAN is compatible with transport layer and network layer of ISA100.11a. The 6LoWPAN uses an alternative way than other low-powered WSN technologies, and this provides a significant advantage for this technology. However, the 6LoWPAN technology is not yet as popular as the others. When considering the development of systems using packet data, it is foreseen that this technology will become a widespread technology in the near future.

International Society of Automation (ISA) introduced ISA100.11a in 2009 that is confirmed as IEC 62734 standard in 2014. In spite of the previously proposed wireless standards, ISA100.11a intends to present novel perspectives in terms of coverage, flexibility, reliability, security, and connectivity features. The network and transport layers of ISA100.11a are improved on the basis of IPv6, 6LoWPAN, and User Datagram Protocol (UDP) standards, while data link layer is designed as an individual layer in the ISA100.11a where the layer carries out frequency hopping, graph routing, and time-slotted time division multiple access (TDMA) processes [20]. In this standard, two main devices are available called field devices and infrastructure devices. While the field devices comprise routers, data acquisition devices, and mobile devices, infrastructure devices contain gateways, backbone routers, and security devices [23, 24]. The use of backbone routers makes the ISA100.11a standard unique among other standards, and backbone routers offer several advantages such as decreasing latency, improving throughput, development of network reliability, and reduction of traffic congestion. The protocol characteristics of 802.15.4-based popular technologies are detailed shown in Fig. 15.6. The layer structures of these technologies are summarized by taking into account seven-layer OSI reference model in which the blanks mean that standards do not contain related protocol(s).

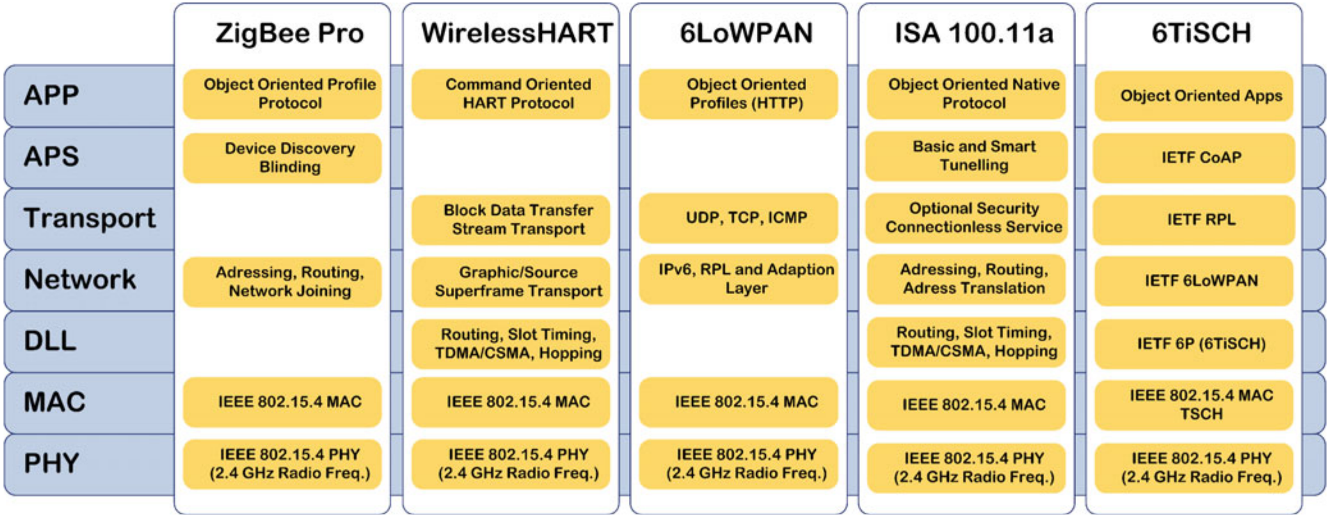
The developments on time-slotted channel hopping (TSCH) and deterministic and synchronous multichannel extension (DSME) methods, which are defined by IEEE 802.15.4e in 2012, supported the use of IPv6 in industrial networks, and this is adopted by IETF 6TiSCH working group [22]. The 6TiSCH is an emerging and alternative standard to ZigBee Pro, WirelessHart, 6LoWPAN, and ISA100.11a [23, 25, 26]. The 6TiSCH intends to enable IPv6 communication over TSCH by linking MAC sublayer with network layer. In addition, the 6TiSCH aims to improve a new standardizing concept that is able to support several resource scheduling methods. The operation sublayer of 6TiSCH achieved to complete deficiencies shown in scheduling and managing the network traffic that could not be carried out by IEEE 802.15.4e standard. Therefore, the 6TiSCH allows IPv6 to transform long 6LoWPAN packets to short 802.15.4 packets.

The fundamental methods employed IEEE 802.15.4 e TSCH such as the integration of channel hopping and time synchronization are very much alike with methods utilized in ISA100.11a and WirelessHART standards. Therefore, it is foreseen that the scheduling methods to be adapted in the 6TiSCH standard may be compatible with these standards. There are three popular wireless devices (RIOT, OpenWSN, and Contiki) which encourage the use of 6TiSCH in wireless networks [25, 26].

15.4 ZigBee Technology Applications for Smart Grids

The SG is a novel and popular concept utilized to define control and communication capabilities attached to traditional power grids in recent years. The main contribution of SGs to traditional power grids is providing bidirectional flow of energy and communication signals. The communication and control infrastructures of SGs enable them to react immediately to changes in any part of energy generation, transmission, distribution, and user section. This capability is based on the fact that they can observe the entire network through sensor networks in their structure. Furthermore, this ability provides a good advantage, such as the opportunity to determine source and load side demands for managing energy flow situations [27–32]. Smart metering system that measures energy consumption and other related parameters for billing process at predefined intervals is one of the most important components of the SGs. The measured data are mapped according to communication protocol to be utilized in SGs and are conveyed to management center either wired or wireless networks. Advanced metering infrastructure (AMI) is supposed as an advanced version of automated meter reading (AMR) and automatic meter management (AMM) systems. AMI comprises several advanced technologies such as SMs, HANs, wide area networks (WAN) and neighbored networks [27].

Recently, several smart metering and monitoring systems employing ZigBee technology have been developed for SGs [30, 33–36]. The advantages provided by ZigBee technology for SG applications such as fault location detection, monitoring of trans-



	ZigBee Pro	WirelessHART	6LoWPAN	ISA 100.11a	6TiSCH
APP	Object Oriented Profile Protocol	Command Oriented HART Protocol	Object Oriented Profiles (HTTP)	Object Oriented Native Protocol	Object Oriented Apps
APS	Device Discovery Blinding			Basic and Smart Tunelling	IETF CoAP
Transport		Block Data Transfer Stream Transport	UDP, TCP, ICMP	Optional Security Connectionless Service	IETF RPL
Network	Adressing, Routing, Network Joining	Graphic/Source Superframe Transport	IPv6, RPL and Adaption Layer	Adressing, Routing, Adress Translation	IETF 6LoWPAN
DLL		Routing, Slot Timing, TDMA/CSMA, Hopping		Routing, Slot Timing, TDMA/CSMA, Hopping	IETF 6P (6TiSCH)
MAC	IEEE 802.15.4 MAC	IEEE 802.15.4 MAC	IEEE 802.15.4 MAC	IEEE 802.15.4 MAC	IEEE 802.15.4 MAC TSCH
PHY	IEEE 802.15.4 PHY (2.4 GHz Radio Freq.)	IEEE 802.15.4 PHY (2.4 GHz Radio Freq.)	IEEE 802.15.4 PHY (2.4 GHz Radio Freq.)	IEEE 802.15.4 PHY (2.4 GHz Radio Freq.)	IEEE 802.15.4 PHY (2.4 GHz Radio Freq.)

Fig. 15.6 Comparison of IEEE 802.15.4 standard-based novel technologies over OSI reference model (APP: Application layer, APS: Application support sublayer, DLL: Data link layer)

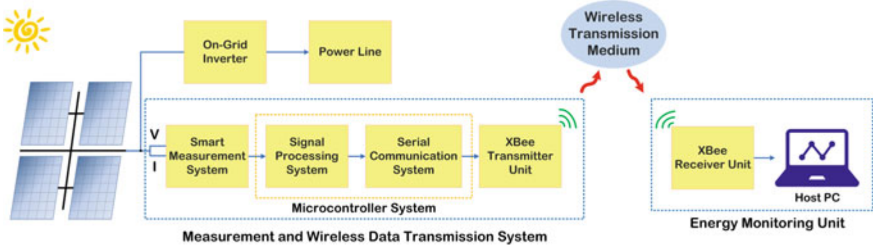


Fig. 15.7 The block diagram of AMI infrastructure for SGs [30]

mission lines, and metering applications in HANs are reported in [33]. A remote monitoring system for observing offshore wind turbines is proposed in [34] where the WSN of the designed system is established by a hybrid system based on GPRS and ZigBee technology. The proposed system is capable of to observe environmental, electrical, and mechanical parameters such as rotor speed, pitch angle, wind speed, and electrical power. In another study, in [35], different performance analyses of ZigBee systems are examined for various indoor and outdoor SG environments. Design and implementation of an AMI system for single-phase power grids are reported in [30]. The designed AMI system includes measurement, monitoring, and communication components of SG management system. The proposed AMI system is utilized to measure output current and voltage values of a microgrid constituted by photovoltaic (PV) panels. The acquired current and voltage results are transmitted to energy monitoring unit by means of wireless communication methods. Communication infrastructure of the system is realized by ZigBee technology. In addition, an energy monitoring software is coded to track measurement results. The block scheme of the reported AMI system is illustrated in Fig. 15.7. As can be seen from the scheme, the microgrid formed by PV panels is fed to grid over an on-grid inverter. In order to accomplish current and voltage measurement processes, special designed measurement systems [37, 38] are employed in the reported system.

The analog signal obtained after the measurement process is fed to microcontroller-based circuit that performs calibration and analog/digital conversion transactions. Measured data converted to the digital signal are transferred from microcontroller to XBee module by serial communication. XBee modules are widely used wireless communication modules based on the ZigBee technology. The data are wirelessly conveyed to energy monitoring unit by means of XBee module. The receiver module in the energy monitoring unit demodulates received data and then transfers data to energy monitoring software. This software has several important tasks such as arranging received measurement data, saving measurement data to the database, and displaying measurement results in real time. A screenshot of energy monitoring software is shown in Fig. 15.8.

In another ZigBee-based SG application, a wireless metering and monitoring feature-enabled solar string inverter is reported in [36]. The physical background of an AMI system is composed of metering section that covers both sensors and elec-

Fig. 15.8 A screenshot of ZigBee-based remote energy monitoring system [30]

tronic components. The metering section supports several systems such as time of use pricing, data management, and AMR system. Many regulations, standards, and recommendations for SMs have been reported worldwide up to the present. They generally focused on the accuracy, resolution requirements, sampling rate, security, and reliability of SMs owing to complexity of power measurement process. Since voltage and current sensors are very efficient on the measurement accuracy, they are widely included for both power sensing and power monitoring applications. An analog front end (AFE) which comprises current and voltage sensors of the SMs supplies measurement results to a microcontroller unit (MCU) so that it carries out sampling, analog-to-digital conversion (ADC), filtering, and other advanced signal processing processes. After these signal processing operations are performed, the MCU transfers processed measurement data to other systems that include various communication, displaying and monitoring systems. The block diagram of the reported AMI structure including wireless metering and monitoring features is illustrated in Fig. 15.9.

The designed system based on solar string inverter structure can support PV strings with double maximum power point tracking (MPPT) controller. The metering and monitoring part of the reported system is also carried out to meet the relevant stan-

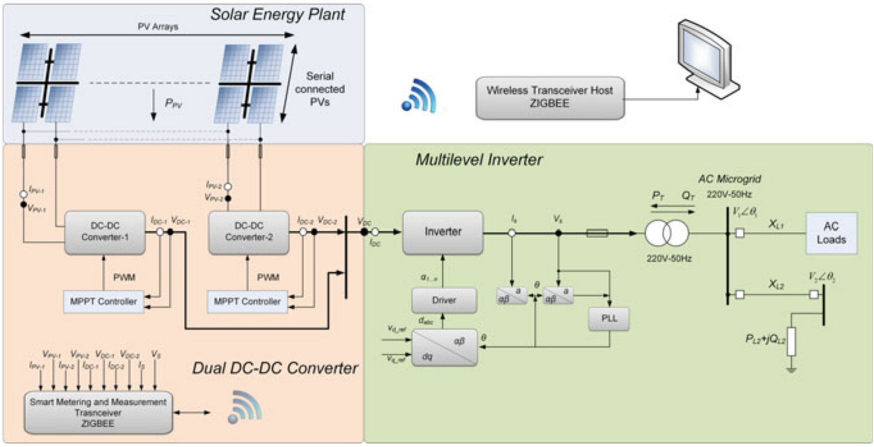
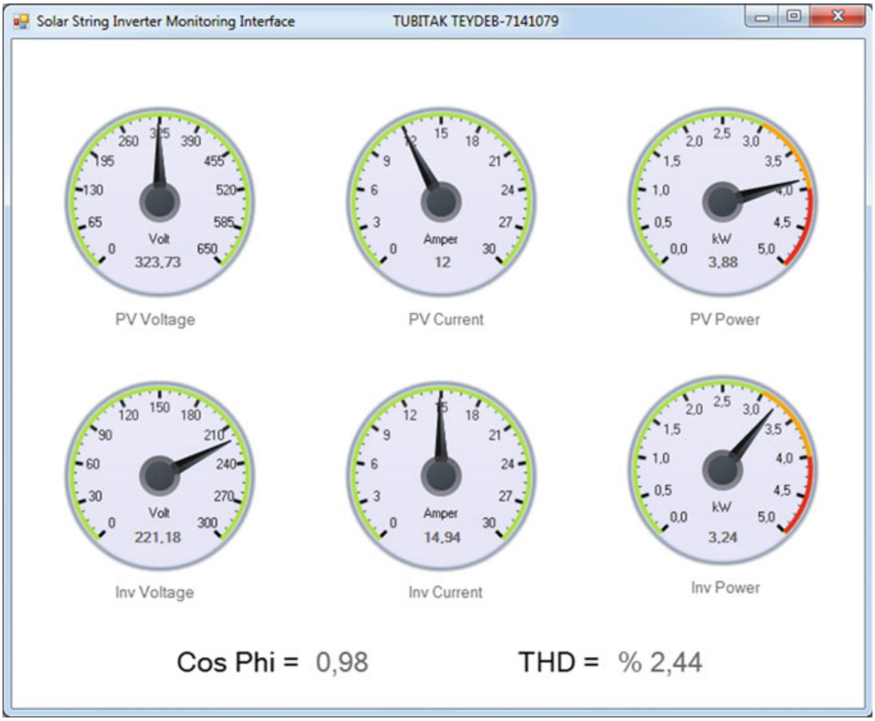


Fig. 15.9 Block diagram of wireless metering and monitoring systems designed for SG applications [36]

dards and recommendations required for SG systems. The host PC situated in the monitoring unit which collects and stores transmitted measurement data is depicted on the upper right-hand side of the block diagram. In order to compare designed system with other systems in terms of efficiency, accuracy, and cost, various designs based on Hall effect sensors are realized in measurement parts of the system. Different measurement stations at both the input and output of converter and inverter systems are specified in the block diagram where black circles stand for voltage measurement stations, while white circles show current measurement stations. The obtained measurement values are fed to ADC ports of the MCU to transform analog waveforms into the digital data. By the following ADC process, the acquired measurement data are transferred to serial communication ports of the MCU, and transmitter unit operating according to ZigBee standard transmits measurement data to the monitoring unit. A PIC18F4620 microcontroller, which provides several important advantages for metering process, is employed in the design. This MCU offers 64 KB flash program memory, a powerful ADC structure with 10-bit resolution and 13 independents channel features. Another advantages provided by this MCU can be listed as low power consumption, enhanced universal synchronous asynchronous receiver transmitter (EUSART) modules, advanced capture–compare–PWM module and supporting various operating modes.

The reported AMI system is composed of three main sections that are AFE of metering system, ZigBee-based wireless communication system, and the data acquisition and remote monitoring interface. The metering system contains four different measurement systems for sensing AC and DC signals. Two of them are responsible for sensing DC voltage and current signals at input of PV strings. The third one is tasked at output of DC-DC converter, while the last one is located at the inverter output. As specified earlier, the signal processing operations are performed by MCU



Cos Phi = 0,98

THD = % 2,44

Fig. 15.10 An example of measurement results obtained by reported wireless metering and monitoring system [36]

unit and the transmitter unit is based on the ZigBee standard. When the monitoring center is considered, the receiver unit performs data acquisition and demapping processes before sending received data to the host PC via USB port. An infrastructure to monitor obtained measurement results that are coded by C# programming language is also designed in the reported system. A measurement example of the designed system is given in Fig. 15.10. The indicators placed on the upper line of figure stand for current, voltage, and power measurements of converter system, while other indicators are related to inverter system. The instantaneous power value of the inverter is computed according to system power factor. In addition, all measurement results are saved to the database at intervals of ten seconds. The accuracy and stability tests are shown that the designed system accomplish metering and monitoring process by providing more than 97% correct values.

15.5 Conclusions

This chapter introduces the WSNs, fundamentals of 802.15.4 standard, and novel technologies improved based on the 802.15.4 standard. The 802.15.4 standard, which is developed for enabling short-range applications with low energy consumption and low cost, is one of the most widely utilized standard in the WSNs. Even though there are several novel technologies improved on the basis of 802.15.4 standard, all of them exploit PHY and MAC layers defined by this standard and they specify upper layers according to their standard definitions. The ZigBee technology that is one of the most popular technologies among the developed technologies is intensively preferred in several application areas since it provides significant advantages in real-world applications such as easy network constructing, providing flexible network structures, supporting of a large number of nodes, and ensuring low power consumption to implement low-powered radio systems. On the other hand, WirelessHART, ISA100.11a, and 6LoWPAN are generally being applied to the industrial applications. In addition, the 6TiSCH is a new technology that continues to evolve similar to other new technologies. Unlike the ZigBee and WirelessHART technologies; ISA100.11a, 6LoWPAN, and 6TiSCH technologies are compatible with IPv6 protocols. As a final remark, the presented applications in this chapter related to metering and monitoring processes clearly shown that the ZigBee technology can be exploited in the AMI systems of SGs in an efficient and reliable way.

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