

Chapter 2

Key Standards and Industry Specifications

A vast number of sensors exists in the sensor industry that can be used to measure physical parameters, such as temperature, pressure, humidity, illumination, gas, flow rate, strain, and acidity. Standardized sensor interfaces, data formats, and communication protocols are required to enable effective integration, access, fusion, and the use of sensor-derived data. The goal is to allow sensors from different manufacturers to work together without human intervention and customization.

Standards have several advantages and safeguards compared to proprietary technologies. The technology has the support from industry, thus bolstering customer confidence and allowing larger markets. Also, a standard allows future proofing as the technology is not dependent on a single vendor. The public availability of specifications draws research from multiple sources. This ensures that the standard technologies are continually improving in their performance, and expanding into new areas and applications.

Existing wireless standards, such as IEEE 802.11 [4] WLAN or GSM standards, can be used in conjunction with the sensor networks. However, these are not designed for WSNs and do not take account for their unique characteristics. Thus, this section considers only the communication standards that are specifically targeted for low power WSNs.

The operating frequency band, nominal data rate, and protocol support of WSN communication standards are listed in [Table 2.1](#). The support for PHYsical (PHY), Medium Access Control (MAC), Network (NWK), and Transport (TRP) protocols denotes that a standard defines the layer in question. Application Support (APS) defines application profiles detailing the services, message formats, and methods required to access applications, therefore allowing interoperability between devices from different manufacturers. For security, Access Control Lists (ACLs) allow only certain nodes to participate in the network while data encryption prevents unauthorized use of data. The listed standards use 128-bit Advanced Encryption System (AES) for data encryption.

Table 2.1 The properties of WSN communication standards.

Standard	Frequency (MHz)	Data rate (kbps)	Protocol layers					Security	
			PHY	MAC	NWK	TRP	APS	ACL	Encryption
IEEE 802.15.4	868	20	●	●	○	○	○	●	●
	915	40	●	●	○	○	○	●	●
	2400	250	●	●	○	○	○	●	●
ZigBee ¹	-	-	○	○	●	●	●	●	●
6LoWPAN ¹	-	-	○	○	●	○	○	●	●
WirelessHART ²	2400	250	●	●	●	●	●	●	●
ISA100.11a ²	2400	250	●	●	●	●	●	●	●
Z-Wave	865	40	●	●	●	○	●	○	○
	915	40	●	●	●	○	●	○	○
Bluetooth									
Low Energy	2400	1000	●	●	●	●	●	●	●
ANT/ANT+	2400	1000	●	●	●	○	●	●	○
ONE NET	868/	38.4	○	●	●	○	○	●	●
	915	230	○	●	●	○	○	●	●
DASH7	433	27.8	●	●	○	○	○	○	○
IEEE 1902.1 RuBee	0.131	1.2	●	●	○	○	○	○	○

¹ Uses IEEE 802.15.4 as PHY and MAC layers² Uses IEEE 802.15.4 as PHY layer

2.1 IEEE 802.15 Standard Family

IEEE 802.15 family defines several standards targeted at WPANs:

- *802.15.1*: lower layers of Bluetooth 1.x protocol stack
- *802.15.2*: methods to improve coexistence of WPANs with other wireless devices in unlicensed frequency bands. The proposed methods include adaptive frequency hopping, power control, and techniques to avoid same frequencies
- *802.15.3*: high speed WPAN for multimedia applications with data rates from 55 MB/s up to several GB/s
- *802.15.4*: Physical (PHY) and Medium Access Control (MAC) layers for Low-Rate Wireless Personal Area Networks (LR-WPANs)
- *802.15.5*: mesh networking functionality for WPANs
- *802.15.6*: Body Area Network (BAN) which operate in and around the human body
- *802.15.7*: PHY/MAC for Visible Light Communications (VLC)

In the standard family, IEEE 802.15.4 [5] and IEEE 802.15.5 standards are the most relevant for the resource constrained WSNs.

IEEE 802.15.4 is relatively popular standard and has therefore been used as a basis for other standards. Fig. 2.1 presents how different standards build on top of the IEEE 802.15.4. While few standards, such as IEEE 802.15.5 and ZigBee[13], use the IEEE 802.15.4 as a whole, other presented standards reuse the PHY layer. The

motion is to save money by using compatible transceivers that are already popular and on the market.

IEEE 802.15.4 network supports three types of network devices: a Personal Area Network (PAN) coordinator, coordinators, and devices. The PAN coordinator initiates the network and operates often as a gateway to other networks. Coordinators collaborate with each other for data routing and network self-organization. Devices do not have data routing capability and can communicate only with coordinators.

IEEE 802.15.4 defines two types of devices, a Full Function Device (FFD) that can act as a router and a Reduced Function Device (RFD) that can communicate only with a FFD. Thus, a RFD is intended for simple use, e.g. to act as an light switch, and cheaper to implement as it requires less memory and processing capability. A 802.15.4 network always has one FFD device that act as a PAN coordinator. The PAN coordinator initiates the network and operates often as a gateway to other networks. The relation between FFDs and RFDs, and the supported star and peer-to-peer (mesh) topologies are show in Fig. 2.2.

IEEE 802.15.4a extension to the standard defines two optional high-rate PHYs, Ultra Wide Band (UWB) PHY operating in the sub-gigahertz band and in 3 GHz to 10 GHz frequency band and Chirp Spread Spectrum (CSS) operating in the 2.4 GHz band. Boths PHYs enhance robustness via resistance to multipath fading while operating with low power (0 dBm). The UWB PHY has the nominal over-the-air data rate of 851 kbit/s, and the optional data rates of 110 kbit/s, 6.81 Mbit/s, and 27.24 Mbit/s. Utilizing the unique capabilities of UWB waveforms, the UWB PHY can be used for precision ranging (1 m accuracy) between devices. The CSS PHY has the nominal data rate of 1000 kbit/s and optionally can support 250 kbit/s data

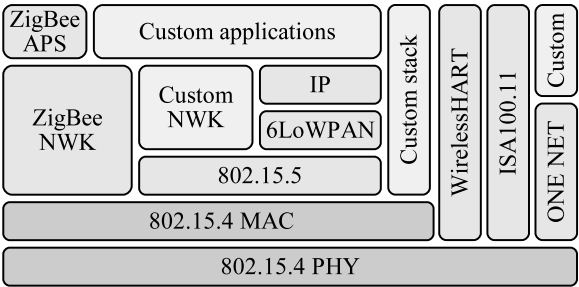


Fig. 2.1 IEEE 802.15.4 related protocols.

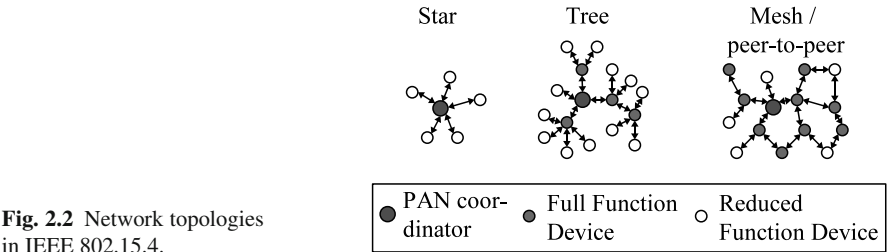


Fig. 2.2 Network topologies in IEEE 802.15.4.

rate. The CSS PHY has long link range allowing the support for mobile devices moving at higher speeds.

IEEE 802.15.5 defines two mesh network frameworks, a high-rate framework for IEEE 802.15.3 and a low-rate framework for IEEE 802.15.4. Both frameworks define procedures for topology formation and data routing. In addition, the low-rate framework describes mobility support (e.g. route maintenance), the practical use of power saving modes of IEEE 802.15.4, and a trace route service to monitor the status of a route.

2.2 ZigBee

ZigBee standard defines network and application layers on top of the IEEE 802.15.4 [13]. These layers comprise of several sub-layers as shown in [Fig. 2.3](#). ZigBee defines a wide range of application profiles targeted at home and building automation, remote controls, and health care.

The ZigBee network layer connects application objects with end points that allow distinguishing between applications, and are akin to the TCP/UDP ports in IP networking. A network can use star, peer-to-peer, or cluster-tree topologies. A network has always one device referred to as a ZigBee coordinator that controls the network. The coordinator is the central node in the star topology, the root of the tree in the tree topology, and can be located anywhere in the peer-to-peer topology. To reduce interference, ZigBee uses a network wide frequency agility mechanism where an individual device can report the interference and instruct network coordinator to change the network wide used channel.

Application Support (APS) sub-layer provides common services for applications. It allows matching and binding devices together based on their services and needs, this way allowing data exchange between the devices. Also, APS includes fragmentation, reassembly, and reliable transport services and group addressing to enable multicast functionality. ZigBee Device Object (ZDO) component manages network by defining the role of the device within the network (a coordinator or an end device), discovers other devices and determines which application services they provide, and establishes a secure relationship between network devices. ZigBee Security Service Provider (SSP) defines methods for data encryption, key generation, key distribution, and authentication.

ZigBee defines two stack profiles, ZigBee and ZigBee Pro. Both stack profiles support full mesh networking and work with all application profiles. The ZigBee profile has less mandatory features, allowing implementation with less memory and processing power. ZigBee Pro mandates many features that are optional in the ZigBee stack profile, e.g. network wide encryption via Symmetric-Key Key Exchange (SKKE). In addition, ZigBee Pro provides additional features that aim to improve network scalability and performance. A stochastic address assignment improves address allocation over the default tree-based assignment, thus improving

network scalability. Many-to-one routing support improves routing efficiency when a network has only few data collecting sinks.

2.3 6LoWPAN

IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) [7] defines the transmission of IP packets over IEEE 802.15.4 networks. This way, the sensor network can act seamlessly as a part of the global Internet, thus enabling the use of wide range of existing IP-based applications and technologies. The standard does not define any routing protocols but relies on other specifications, such as e.g. IEEE 802.15.5, for mesh layer routing. 6LoWPAN is described in detail in Chapter 6.

2.4 Z-Wave

Z-Wave [12] is targeted at building automation and entertainment electronics and has been developed by over 120 companies including Zensys, Intel and Cisco. A Z-Wave network comprises controlling devices (e.g. remote controller) and AC powered slave nodes (e.g. television). Slave nodes can act as routers. As routers continuously listen to the wireless medium for incoming transmission, they need to be mains powered in practice. Controllers are active on demand and can be battery powered. The protocol operation is simple, a controller hosts a routing table to the entire network. If a packet needs to be routed over multiple hops, the controller embeds the route to the forwarded packet. The maximum number of nodes in a network is 232, although Z-wave networks can be inter-connected via gateways.

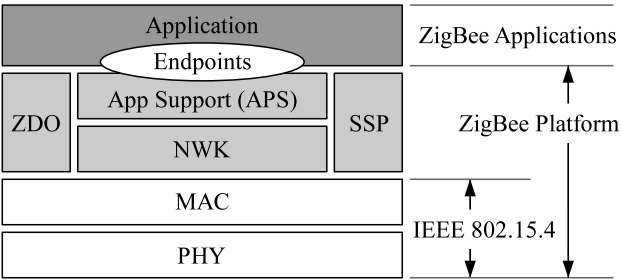


Fig. 2.3 ZigBee defines network and application layers on top of IEEE 802.15.4 standard.

2.5 WirelessHART and ISA100.11a

WirelessHART and ISA100.11a [6] are targeted at process industry applications where process measurement and control applications have stringent requirements for end-to-end communication delay, reliability, and security. Although the exact communication formats are different, the standards have similar operating principle. The convergence of the standards is planned in ISA100.12.

Both standards build on top of the IEEE 802.15.4 physical layer and utilize a TDMA MAC that employs network wide time synchronization, channel hopping, channel blacklisting. The Time Division Multiple Access (TDMA) based operation allows accurately determining bounds for latency and throughput, therefore being predictability which is important for industrial applications. A centralized network manager is responsible for route updates and communication scheduling for entire network. However, the centralized control of TDMA schedules limits the network size and the tolerance against network dynamics, thus limiting the usability of the standards to static WSNs.

2.6 Bluetooth Low Energy

Bluetooth Low Energy (BLE) [1] is an extension to the Bluetooth technology aimed at low energy wireless devices. The first defined applications comprise watch, Human Interface Device (HID), and sensor profiles. Despite the name, BLE is not compatible with the traditional Bluetooth due to different link layer protocol. Compared to the traditional Bluetooth, the main functional differences are the use of variable packet length, entering power save mode automatically when a device is not transmitting, and the exchange data in attribute/value pairs. These changes aim at minimizing transceiver's active time. To ease resource constrained implementation, the complexity of the protocol is reduced by decreasing the number of different connectivity states and message formats.

In BLE, devices advertise their presence with periodic beacons, while listening to the channel briefly for incoming connection or data requests after each advertisement. BLE uses 3 advertising channels and 37 data channels. The protocol employs frequency hopping within the data channels to reduce the impact of interference. Advertisements can also contain data and connections are established fast (less than 3 ms), therefore avoiding the need to stay in connected state and enabling devices to save energy in standby states.

2.7 ANT and ANT+

ANT [2] defined by Dynastream Innovations Inc. is used e.g. by Suunto and Garmin in their performance monitoring products. Its communication model is based on vir-

tual channels that are defined by operating frequency and message rate parameters. The medium is accessed with TDMA where time slots are repeated on configured message intervals. As a result, several channels may operate on the same physical frequency.

Each channel has a single master device and slave devices. The channel itself can be unidirectional from a master to a slave, unidirectional from a slave to a master, or bidirectional. Further, the channel can be configured as a broadcast channel, use optional acknowledgments, or have burst support. As each node may act both as a master and a slave on different channels, ANT allows forming very complex topologies. However, considering that to build optimal TDMA schedules, traffic characteristics must be known a priori. Thus, ANT is best suited for relatively small networks.

ANT+ is an extension to the ANT protocol that uses the same communication method but includes profiles defining data formats and channel parameters.

2.8 ONE-NET

ONE-NET is an open source WSN specification that uses IEEE 802.15.4 compatible transceivers while specifying MAC and routing layers [11]. The protocol operates with the basic data rate of 38.4 kbit/s, although the specification allows up to 230 kbit/s data rates. In ONE-NET, all transmissions are encrypted with XTEA2 algorithm. Other security features include user key management. ONE-NET supports low duty cycling for battery powered devices but routing nodes must keep their transceivers active thus necessitating mains power. ONE-NET has limited APS with generic message formats for applications, but these do not define formats for specific applications to guarantee compatibility between implementations.

2.9 DASH7

DASH7 [10] technology based on ISO 18000-7 standard is targeted at very low rate data applications. Its main cited benefit stems from the 433 MHz operating frequency, which provides longer communication ranges and less crowded wireless channel than the typical 2.4 GHz frequency band [8]. DASH7 has the nominal communication range of 250 m at 0 dBm transmission power level, compared to 75 m of ZigBee and 10 m of Bluetooth (High Rate variant) [8].

2.10 IEEE 1902.1

IEEE 1902.1 (RuBee) [3] [9] fills the gap between WSN and Radio Frequency Identification (RFID) technologies. Unlike other listed technologies, signal does not include electric field component but uses magnetic dipole antennas. Thus, signal is unaffected by water and metals either enhance or do not affect the signal. RuBee nodes, referred to as tags, can be very simple identity tags or use 4-bit MCU, 0.5 kB-2 kB Static Random Access Memory (SRAM), optional sensors, signal processing firmware, displays and buttons [9]. The nominal data rate is small, 1.2 kbps, limiting the applicability of RuBee.

2.11 IEEE 1451

IEEE 1451 standard family defines a set of open, network-independent communication interfaces for connecting transducers (sensors and actuators) to microprocessors, instrumentation systems and networks. In IEEE 1451, a single sensor, an actuator, or a module comprising several transducers and any data conversion or signal conditioning (e.g. signal amplification or filtering) is referred to as a Transducer Interface Module (TIM). As a key element, the standard family defines Transducer Electronic Data Sheet (TEDS) to store transducer identification, calibration, correction data, and manufacturer related information. It also defines a set of commands to control and read data from the TIM. In practice, TEDS can be a software module integrated within a TIM. TEDS practically eliminates error prone, manual entering of data and system configuration, and allows transducers to be installed, upgraded, replaced or moved by plug-and-play principle.

IEEE 1451.0 and IEEE 1451.1 standards define generic methods to access transducers, and define transducer related interfaces and services. In addition, IEEE 1451 provides interfaces for several standardized communication protocols in IEEE 1451.2-1451.6 standards. IEEE 1451.2 defines wired point-to-point communication. IEEE 1451.3 defines distributed multi-drop system, where a large number of TIMs may be connected along a wired multi-drop bus. IEEE 1451.4 specifies mixed-mode communication protocols, which carry analog sensor values with digital TEDS data. IEEE 1451.6 defines a high-speed Controller Area Network (CAN) bus.

IEEE 1451.5 standard defines wireless sensors and thus, it is most closely related with WSNs. Supported communication technologies are IEEE 802.11a/b/g, IEEE 801.15.1, and IEEE 802.15.4.

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