From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things

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Abstract Wireless Sensor and Actuator Networks (WSANs) are expected to have a key role in the realization of the future Internet of Things that will connect to the Internet any kind of devices, living beings, and things. A number of standards have been released over the last years to support their development and encourage interoperability. In addition IETF has defined a set of protocols to allow the integration of sensor and actuator devices into the Internet. In this chapter we focus on the 802.15.4e, released by IEEE in 2012 to enhance and add functionality to the previous 802.15.4 standard, so as to address the emerging needs of embedded industrial applications. We describe how the limitations of the 802.15.4 standard have been overcome by the new standard, and we also show some simulation results to better highlight this point.

1 Introduction

In the future Internet of Things (IoT) a very large number of real-life objects will be connected to the Internet, generating and consuming information. IoT elements will no longer be only computers and personal communication devices, as in the current Internet, but all kinds of devices (e.g., cars, robots, machine tools), living beings (persons, animals, and plants) and things (e.g., garments, food, drugs, etc.). A key role in the realization of the IoT paradigm will be played by wireless sensor/actuator

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networks (WSANs) that will behave as a sort of digital skin, providing a virtual layer through which any computational system can interact with the physical world [1, 2].

A WSAN consists of a number of sensor and actuator devices deployed over a geographical area and interconnected through wireless links. Sensor devices gather information from the physical environment or a monitored system (e.g., temperature, pressure, vibrations), optionally perform a preliminary local processing of acquired information, and send (raw or processed) data to a controller. Based on the received information, the controller performs appropriate actions, through actuator devices, to change the behavior of the physical environment or the monitored system.

WSANs are already used in many application domains, ranging from traditional environmental monitoring and location/tracking applications to more constrained applications such as those in the industrial [3] and healthcare domain [4]. In the industrial field WSAN applications include factory automation [5], distributed and process control [6–8], real-time monitoring of machinery health, detection of liquid/gas leakage, radiation check [9] and so on. In the healthcare domain WSANs have been considered for the monitoring of physiological data in chronicle patients and transparent interaction with the healthcare system.

In many application domains *energy efficiency* is usually the main concern in the design of a WSAN. This is because sensor/actuator devices are typically powered by batteries with a limited energy budget and their replacement can be expensive or, even, impossible [10]. However, in some relevant application domains additional requirements need to be considered, such as *timeliness, reliability, robustness, scalability,* and *flexibility* [3, 11]. *Reliability* and *timeliness* are very critical issues for industrial and healthcare applications. If data packets are not delivered to the final destination, correctly and within a pre-defined deadline, the correct behavior of the system (e.g., the timely detection of a critical event) may be compromised. The maximum allowed latency depends on the specific application. Typical values ranges from tens of milliseconds (e.g., for discrete manufacturing and factory automation), to seconds (e.g., for process control), and even minutes (e.g., for asset monitoring) [11].

In recent years many standards have been issued by international bodies to support the development of WSANs in different application domains. They include IEEE 802.15.4 [12], ZigBee [13], Bluetooth [14], WirelessHART [15] and ISA-100.11a [16]. At the same time, the Internet Engineering Task Force (IETF) has defined a number of protocols to facilitate the integration of smart objects (i.e., sensor and actuator devices) into the Internet. The most important of them are the *IPv6 over Low power WPAN* (6LoWPAN) [17] adaptation layer protocol that allows the integration of smart objects into the Internet, the *Routing Protocol for Low power and Lossy networks* (RPL) [18], and the *Constrained Application Protocol* (CoAP) [19] that enables web applications on smart objects.

In this chapter we focus on the IEEE 802.15.4 standard [12] that defines the physical and Medium Access Control (MAC) layers of the OSI reference model and is complemented by the ZigBee specifications [13] covering the networking and application layers. The 802.15.4 standard was originally conceived for applications without special requirements in terms of latency, reliability and scalability. In order to overcome these limitations, in 2008 the IEEE set up a Working Group (named

802.15e WG) with the aim of enhancing and adding functionality to the 802.15.4 MAC, so as to address the emerging needs of embedded industrial applications [20]. The final result was the release of the 802.15.4e standard in 2012. In the following sections, after emphasizing the limitations and deficiencies of the 802.15.4 standard, we will show how they have been overcome in the new standard. Specifically, we will describe the new access modes defined by 802.15.4e, with special emphasis on the *Time Slotted Channel Hopping* (TSCH) mode. We will also present some simulation results to better highlight the performance limitations of 802.15.4 and show that they are overcome by 802.15.4e.

The remainder of this chapter is organized as follows. Section 2 describes the 802.15.4 standard. Section 3 highlights its main limitations and deficiencies. Section 4 describes the new functionalities provided by the 802.15.4e standard. Section 5 compares the performance of 802.15.4 and 802.15.4e in a simple scenario through simulation. Finally, Sect. 6 concludes the chapter.

2 IEEE 802.15.4 Standard

IEEE 802.15.4 [12] is a standard for low-rate, low-power, and low-cost Personal Area Networks (PANs). A PAN is formed by one PAN coordinator which is in charge of managing the whole network, and, optionally, by one or more coordinators that are responsible for a subset of nodes in the network. Regular nodes must associate with a (PAN) coordinator in order to communicate. The supported network topologies are *star* (single-hop), *cluster-tree* and *mesh* (multi-hop).

The standard defines two different channel access methods: a *beacon enabled* mode and a *non-beacon enabled* mode. The beacon enabled mode provides a power management mechanism based on a duty cycle. It uses a superframe structure (see Fig. 1) which is bounded by *beacons,* i.e., special synchronization frames generated periodically by the coordinator node(s). The time between two consecutive beacons is called *Beacon Interval* (BI), and is defined through the *Beacon Order* (BO) parameter ($\mathrm{BI} = 15.36 \cdot 2^{BO}$ ms, with $0 \leq \mathrm{BO} \leq 14$).[1] Each superframe consists of an active period and an inactive period. In the active period nodes communicate with the coordinator they are associated with, while during the inactive period they enter a low power state to save energy. The active period is denoted as *Superframe Duration* (SD) and its size is defined by the *Superframe Order* (SO) parameter ($\mathrm{SD} = 15.36 \cdot 2^{SO}$ ms, with $0 \leq \mathrm{SO} \leq \mathrm{BO} \leq 14$). It can be further divided into a *Contention Access Period* (CAP) and a *Contention Free Period* (CFP). During the CAP a slotted CSMA-CA algorithm is used for channel access, while in the CFP communication occurs in a Time Division Multiple Access (TDMA) style by using a number of *Guaranteed Time Slots* (GTSs), pre-assigned to individual nodes. In the non-beacon enabled mode there is no superframe, nodes are always active (energy conservation is delegated to

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[1] Throughout the chapter we assume that the sensor network operates in the 2.4 GHz frequency band.

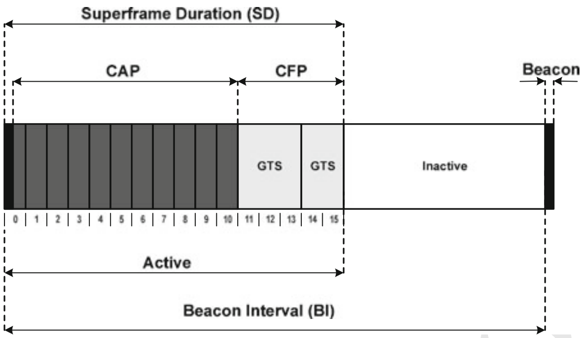

Fig. 1 IEEE 802.15.4 Superframe Structure

the layers above the MAC protocol) and use an unslotted CSMA-CA algorithm for channel access.

2.1 CSMA-CA Algorithm

The CSMA-CA algorithm is used in both the *beacon enabled* mode (during the CAP portion of the active period) and the *non-beacon enabled* mode. In the beacon-enabled mode a slotted scheme is used—i.e., all operations are aligned to backoff period slots (whose duration is $320\,\mu s$)—while in the non-beacon enabled mode there is no such alignment.

Upon receiving a data frame to be transmitted, the CSMA-CA algorithm performs the following steps.

1. A set of state variables is initialized, i.e., the contention window size ($CW = 2$, only for the slotted variant), the number of backoff stages carried out for the on-going transmission ($NB = 0$), and the backoff exponent ($BE = macMinBE$).
2. A random backoff time, uniformly distributed in the range $[0, 2^{BE} - 1] \cdot 320\,\mu s$, is generated and used to initialize a backoff timer. In the beacon-enabled mode, the starting time of the backoff timer is aligned with the beginning of the next backoff slot. In addition, if the backoff time is larger than the residual CAP duration, the backoff timer is stopped at the end of the CAP and resumed at the beginning of the next superframe. When the backoff timer expires, the algorithm proceeds to step 3.
3. A Clear Channel Assessment (CCA) is performed to check the state of the wireless medium.
    (a) If the medium is busy, the state variables are updated as follows: $NB = NB + 1$, $BE = min(BE + 1, macMaxBE)$ *and* $CW = 2$ (only for the slotted variant). If the number of backoff stages has exceeded the maximum admis-

sible value (i.e. $NB > macMaxCSMABackoffs$), the frame is dropped. Otherwise, the algorithm falls back to step 2.
   (b) If the medium is free and the access mode is unslotted, the frame is immediately transmitted.
   (c) If the medium is free and the access mode is slotted, then $CW = CW - 1$. If $CW = 0$ then the frame is transmitted.[2] Otherwise the algorithm falls back to step 3 to perform a second CCA.

It should be noted that, unlike the algorithm used in 802.11 WLANs, the 802.15.4 slotted CSMA-CA does not guarantee a transmission at the end of the backoff time after the channel is found clear. Instead, transmission occurs only if the wireless medium is found free for two consecutive CCAs. The complete CSMA-CA algorithm, both in the slotted and unslotted version, is depicted in Fig. 2.

The 802.15.4 CSMA-CA algorithm also includes an optional retransmission mechanisms for improving reliability. When retransmissions are enabled, the destination node must send an acknowledgement whenever it correctly receives a data frame (the acknowledgement is not sent in case of collision and corrupted frame reception). On the sender side, if the acknowledgment is not (correctly) received within the pre-defined timeout, a retransmission is scheduled. The frame can be re-transmitted up to a maximum number of times, specified by the MAC parameter *macMaxFrameRetries*. Upon exceeding these value, the data frame is rejected and a failure notification is sent by the MAC sublayer to the upper layers.

3 Limitations of IEEE 802.15.4 MAC

The performance of the 802.15.4 MAC protocol, both in BE mode and NBE mode, have been thoroughly investigated in the past. As a result of this extended study, a number of limitations and deficiencies have been identified, the main of which are discussed below.

- *Unbounded Delay*. Since the 802.15.4 MAC protocol, both in BE mode and NBE mode, is based on the CSMA-CA algorithm it cannot guarantee any bound on the maximum delay experienced by data to reach the final destination. This makes 802.15.4 unsuitable for time-critical application scenarios where a low and deterministic delay is required (e.g., industrial and medical applications).
- *Limited communication reliability*. The 802.15.4 MAC in BE mode provides a very low delivery ratio, even when the number of nodes is not so high which make it unsuitable for critical application scenarios. This is mainly due to the random-access method (i.e., CSMA-CA algorithm) and the synchronization introduced by the periodic Beacon. A similar behavior also occurs in the NBE mode when

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[2] In the beacon-enabled mode, before starting the frame transmission, the algorithm calculates whether it is able to complete the operation within the current CAP. If there is not enough time, the transmission is deferred to the next superframe.

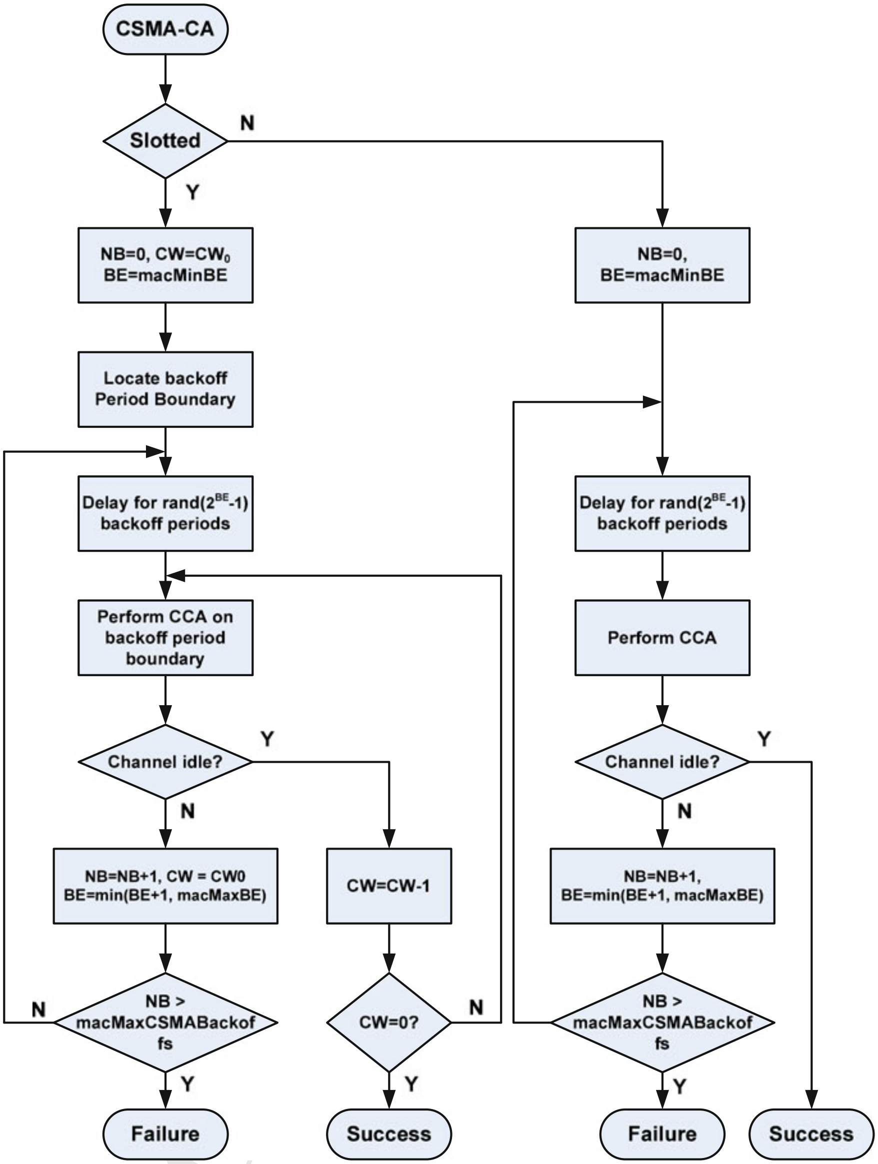


Fig. 2 CSMA-CA algorithm

a large number of nodes start transmitting simultaneously (e.g., in event-driven applications).

- *No protection against interferences/fading*. Interferences and multi-path fading are very common phenomena, especially in application scenarios where sensor/actuator networks are expected to be used. Unlike other wireless network technologies (e.g., Bluetooth [14], ISA 100.11a [16] and WirelessHART [15]), the 802.15.4 MAC takes a single-channel approach and has no built-in frequency hopping mechanism to protect against interferences and multi-path fading. Hence, the network is subject to frequent instabilities and may also collapse. This make 802.15.4 unsuitable to be used in critical application scenarios (e.g., industrial or healthcare applications).

- *Powered relay nodes.* The 802.15.4 support both single-hop (star) and multi-hop (peer-to-peer) topologies. In principle, the BE mode could be used to form multi-hop PAN with a tree topologies where intermediate node do not need to stay active all the time. In practice, intermediate relay nodes in 802.15.4 networks (both with tree and mesh topologies) need to keep their radio on all the time, which leads to a large energy consumption.

4 IEEE 802.15.4e Standard

To overcome the limitations of the 802.15.4 standard, emphasized in the previous section, the 802.15e Working Group was created by IEEE in 2008 to redesign the existing 802.15.4 MAC protocol. The goal was to define a low-power multi-hop MAC protocol, capable of addressing the emerging needs of embedded industrial applications. The final result was the IEEE 802.15.4e MAC Enhancement Standard document [20], approved in 2012. Specifically, the 802.15.4e standard extends the previous 802.15.4 standard by introducing two different categories of MAC enhancements, namely *MAC behaviors* to support specific application domains and *general functional improvements* that are not tied to any specific application domain. In practice, 802.1.5.4e borrows many ideas from existing standards for industrial applications (i.e., WirelessHART [15] and ISA 100.11.a [16]), including slotted access, shared and dedicated slots, multi-channel communication, and frequency hopping.

The MAC behavior modes defined by the 802.1.5.4e standard are listed below. They will be described in the next section.

- *Radio Frequency Identification Blink (BLINK).* intended for applications such as item and people identification, location, and tracking;
- *Asynchronous multi-channel adaptation (AMCA).* targeted to application domains where large deployments are required (e.g., process automation/control, infrastructure monitoring, etc.);
- *Deterministic and Synchronous Multi-channel Extension (DSME).* aimed to support industrial and commercial applications with stringent timeliness and reliability requirements;
- *Low Latency Deterministic Network (LLDN).* intended for applications requiring very low latency requirement (e.g., factory automation, robot control)
- *Time Slotted Channel Hopping (TSCH).* targeted to application domains such as process automation.

The general functional enhancements, not specifically tied to a particular application domain, are as follows.

- *Low Energy (LE).* This mechanism is intended for applications that can trade latency for energy efficiency. It allows a device to operate with a very low duty cycle (e.g., 1 % or below), while appearing to be *always on* to the upper layers. This mechanism is extremely important for enabling the Internet of Things paradigms as Internet protocols have been designed assuming that hosts are always on. However, it may be useful also in other applications scenarios (e.g., event-driven and/or infrequent communications, networks with mobile nodes).
- *Information Elements (IE).* The concept of IEs was already present in the 802.15.4 standard. It is an extensible mechanism to exchange information at the MAC sublayer.
- *Enhanced Beacons (EB).* Extended Beacons are an extension of the 802.15.4 beacon frames and provide a greater flexibility. They allow to create application-specific beacons, by including relevant IEs, and are used in the DSME and TSCH modes.
- *Multipurpose Frame.* This mechanism provides a flexible frame format that can address a number of MAC operations. It is based on IEs.
- *MAC Performance Metrics* are a mechanism to provide appropriate feedback on the channel quality to the networking and upper layers, so that appropriate decision can be taken. For instance the IP protocol running on top of 802.15.4e MAC may implement dynamic fragmentation of datagrams depending on the channel conditions.
- *Fast Association (FastA).* The 802.15.4 association procedure introduces a significant delay in order to save energy. For time-critical application latency has priority over energy efficiency. The FastA mechanism allows a device to associate in a reduced amount of time.

4.1 802.15.4e MAC Behavior Modes

In this section we describe the MAC behavior modes that have been introduced in the previous section. The description is necessarily brief for the sake of space. The reader can refer to [20] for details.

The *Radio Frequency Identification Blink (BLINK)* mode is intended for application domains such as item/people identification, location, and tracking and is, thus, very relevant in the perspective of Internet of Things. Specifically, it allows a device to communicate its ID (e.g., a 64-bit source address) to other devices. The device can also transmit its alternate address and, optionally, additional data in the payload. No prior association is required and no acknowledgement is provided to the sending device. The BLINK mode is based on a minimal frame consisting only of the header fields that are necessary for its operations. The BLINK frame can be used by “transmit only” devices to co-exist within a network, utilizing an Aloha protocol.

The *Asynchronous multi-channel adaptation (AMCA)* mode is targeted to application domains where large deployments are required, such as smart utility networks, infrastructure monitoring networks, and process control networks. In such networks using a single, common, channel for communication may not allow to connect all the devices in the same PAN. In addition, the variance of channel quality is typically large, and link asymmetry may occur between two neighboring devices (i.e., a device may be able to transmit to a neighbor but unable to receive from it). The AMCA mode relies on asynchronous multi-channel adaptation and can be used only in non Beacon-Enabled PANs.

The *Deterministic and Synchronous Multi-channel Extension (DSME)* mode is intended for the support of industrial applications (e.g., process automation, factory automation, smart metering), commercial applications (such as home automation, smart building, entertainment) and healthcare applications (e.g., patient monitoring, telemedicine). This kind of applications requires low and deterministic latency, high reliability, energy efficiency, scalability, flexibility, and robustness [20]. As mentioned in Sect. 2, the 802.15.4 standard provides *Guaranteed Time Slots (GTSs)*. However, the GTS mode has a number of limitations. It only includes up to seven slots and, thus, it is not able to support large networks. In addition, it relies on a single frequency channel. DSME enhances GTS by grouping multiple superframes to form a multi-superframe and using multi-channel operation. Like GTS, DSME runs on Beacon-enabled PANs. All the devices in the PAN synchronize to multi-superframes via beacon frames. A multi-superframe is a cycle of superframes, where each superframe includes the beacon frame, the Contention Access Period, and Contention Free Period (i.e., GTS slot). A pair of nodes wakes up at a reserved GTS slot to exchange a data frame and an ACK frame. In order to save energy, DSME uses CAP reduction, i.e., the Contention Access Period (CAP) is only in the first superframe of the multi-superframe, while it is suppressed in subsequent superframes.

The *Low Latency Deterministic Network (LLDN)* mode is mainly targeted to industrial and commercial applications requiring low and deterministic latency. Typical application domains addressed by LLDN include factory automation (e.g., automotive manufacturing), robots, overhead cranes, portable machine tools, milling machines, computer-operated lathes, automated dispensers, cargo, airport logistics, automated packaging, conveyors. In this kind of applications typically there are a large number of sensors/actuators observing and controlling a system, e.g., a production line or a conveyor belt. In addition, applications have very low requirements in terms of latency (transmission of sensor data in 5–50 ms, and low round-trip time) [20]. To guarantee stringent latency requirements of target applications LLDN only supports the star (i.e., single hop) topology, and uses a *superframe*, based on timeslots, with small packets. Keeping the size of packets (and, hence, timeslots) short leads to superframes with short duration (e.g., 10 ms). Obviously, the number of timeslots in a superframe determines the number of devices that can access the channel. Since the number of devices may very large (there may be more than 100 devices per PAN coordinator) LLDN allows the PAN coordinator to use multiple transceivers on different channels. In the LLDN mode each superframe consists of a *beacon timeslot*, *management timeslots* (if present), and a number of *base timeslots* of equal size. Base timeslots include uplink timeslots and bidirectional timeslots. There are two categories of base timeslot, namely *dedicated* and *shared group* timeslots. Dedicated timeslots are assigned to a specific node (owner) that has the exclusive access on them, while shared group timeslots are assigned to more than one device. The devices use the slotted CSMA-CA algorithm described in Sect. 2 to contend for shared group timeslots. In addition, they use a simple addressing scheme with 8-bit addresses in. The LLDN mode includes a *Group ACK* (GACK) function to reduce the bandwidth overhead. GACK is sent by the PAN coordinator in a superframe to stimulate the retransmission of failed transmission in uplink timeslots.

The *Time Slotted Channel Hopping (TSCH)* mode is mainly intended for the support of process automation applications with a particular focus on equipment and process monitoring. Typical segments of the TSCH application domain include oil and gas industry, food and beverage products, chemical products, pharmaceutical products, water/waste water treatments, green energy production, climate control [20]. TSCH combines *time slotted access*, already defined in the IEEE 802.15.4 MAC protocol, with *multi-channel* and *channel hopping* capabilities. Time slotted access increases the potential throughput that can be achieved, by eliminating collision among competing nodes, and provides deterministic latency to applications. Multi-channel allows more nodes to exchange their frames at the same time (i.e., in the same time slot), by using different channel offsets. Hence, it increases the network capacity. In addition, channel hopping mitigates the effects of interference and multipath fading, thus improving the communication reliability. Hence, TSCH provides increased network capacity, high reliability and predictable latency, while maintaining very low duty cycles (i.e., energy efficiency) thanks to the time slotted access mode. TSCH is also topology independent as it can be used to form any network topology (e.g., star, tree, partial mesh or full mesh). It is particularly well-suited for multi-hop networks where frequency hopping allows for efficient use of the available resources.

4.2 Time Slotted Channel Hopping (TSCH) Mode

Among the various access modes defined by the 802.15.4e standard, *TSCH* is certainly the most complex and interesting one. Hence, in the following we will provide a more detailed description of it.

In the *TSCH* mode nodes synchronize on a periodic slotframe consisting of a number of timeslots. Figure 3 shows a slotframe with 4 timeslots. Each timeslot allows a node to send a maximum-size data frame and receive the related acknowledgement (Fig. 4). If the acknowledgement is not received within a predefined timeout, the retransmission of the data frame is deferred to the next time slot assigned to the same (sender-destination) couple of nodes.

One of the main characteristics of TSCH is the multi-channel support, based on channel hopping. In principle 16 different channels are available for communication. Each channel is identified by a *channelOffset* i.e., an integer value in the range.

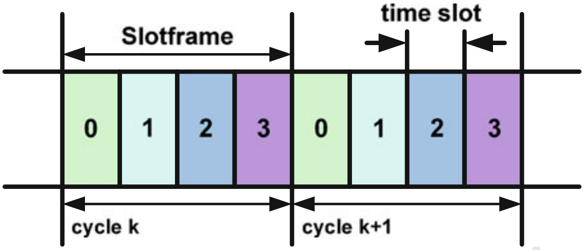


Fig. 3 Slotframe

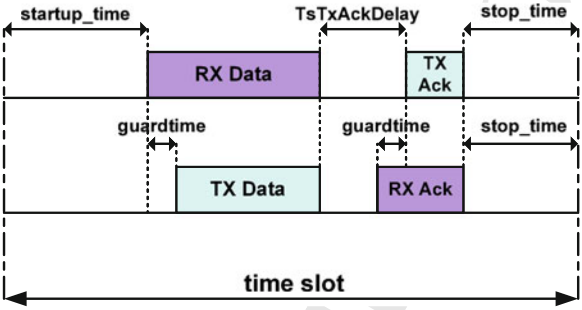


Fig. 4 Timeslot

However, some of these frequencies could be blacklisted (because of low quality channel) and, hence, the total number of channels $N_{channels}$ available for channel hopping may be lower than 16. In TSCH a link is defined as the pairwise assignment of a directed communication between devices in a given timeslot on a given channel offset [20]. Hence, a link between communicating devices can be represented by a couple specifying the timeslot in the slotframe and the channel offset used by the devices in that timeslot. Let denote a link between two devices. Then, the frequency f to be used for communication in timeslot of the slotframe is derived as follows.

$$f = F[(ASN + channeloffset) \,\%\, N_{channels}] \tag{1}$$

where is the *Absolute Slot Number*, defined as the total number of timeslots elapsed since the start of the network (or an arbitrary start time determined by the PAN coordinator). It increments globally in the network, at every timeslots, and is thus used by devices as timeslot counter. Function F can be implemented as a lookup table. Thanks to the multi-channel mechanism several simultaneous communications can take place in the same timeslot, provided that different communications use different channel offsets. Also, Eq. 1 implements the channel hopping mechanism by returning a different frequency for the same link at different timeslots.

Figure 5 shows a possible link schedule for data collection in a simple sensor network with a tree topology. We have assumed that the slotframe consists of four

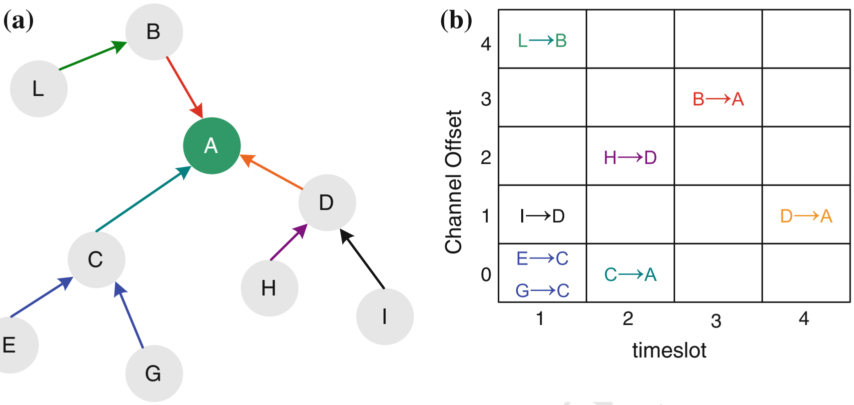


Fig. 5 A sensor network with a tree-topology (**a**) with a possible link schedule for data-collection (**b**)

timeslots and there are only five channel offsets available. We can see that, thanks to the multi-channel approach used by TSCH, eight transmissions have been accommodated in a time interval corresponding to four timeslots. In the allocation shown in Fig. 5 all links but one are *dedicated* links, i.e., allocated to a single device for communication. The 802.15.4e standard also allows *shared* links, i.e., links intentionally allocated to more than one device for transmission. This is the case of the link [1,0] allocated to both nodes E and G.

Since shared links can be accessed by more than one transmitter, collisions may occur that result in a transmission failure. To reduce the probability of repeated collisions, the standard defines a retransmission backoff algorithm. The latter is invoked by a sending device whenever a data frame is transmitted on a shared link and the related acknowledgment is not received. The data frame will be retransmitted in the next link assigned to the sending device and with the same destination, which may be either a shared link or a dedicated link. The retransmission algorithm relies on a backoff delay and works as follows. The retransmission backoff only applies to the transmission on shared links, whereas dedicated links are accessed without any delay. The retransmission backoff is calculated using an exponential algorithm analogous to that described in Sect. 2 for CSMA-CA (it is still based on *macMaxBE* and *macMinBE*). However, in TSCH the backoff delay is expressed in terms of number of shared links that must be skipped. The backoff window increases for each consecutive failed transmission in a shared link, while it remains unchanged when a transmission failure occurs in a dedicated link. A successful transmission in a shared link resets the backoff window to the minimum value. The backoff window does not change when a transmission is successful in a dedicated link but there are still other frames to transmit (the transmission queue is not empty). The backoff window is reset to the minimum value if the transmission in a dedicated link is successful and the transmit queue is then empty.

A key element in TSCH is the link schedule, i.e., the assignment of links to nodes for data transmissions. Of course, neighboring nodes may interfere and, hence, they should not be allowed to transmit in the same timeslot and with the same channel offset. The multi-channel mechanism makes the link scheduling problem easier with respect to the traditional scenario where a single channel is used. However, finding out an optimal schedule may not be a trivial task, especially in large networks with multi-hop topology. The problem is even more challenging in dynamic networks where the topology changes over time (e.g., due to mobile nodes). It may be worthwhile emphasizing here that the derivation of an appropriate link schedule is out of the scope of the 802.15.4e standard. The latter just defines mechanisms to execute a link schedule, however, it does not specify how to derive such a schedule. This is left to upper layers.

A number of link scheduling algorithms have been specifically proposed for TSCH [21–23]. Also previous solutions for slotted multi-channel systems can be easily adapted to TSCH. Link scheduling algorithms can be broadly classified into two different categories, namely *centralized* and *distributed* algorithms. In centralized solutions [22] there is a specific node in the network (typically, the PAN coordinator) that is in charge of creating and updating the link schedule, based on information received by network nodes (about neighbors and generated traffic). Since the PAN coordinator has a global knowledge of the network status, in terms of network topology and traffic matrix, it can create very efficient link schedules. However, the link schedule has to be re-computed each time the network conditions change. Hence, the centralized approach is not very appealing for dynamic networks (e.g., networks with mobile nodes), where a distributed approach is typically more suitable. In a distributed link scheduling algorithm [21, 23] each node decide autonomously which link to activate with its neighbors, based on local and, hence, partial, information.

5 Performance Comparison

To measure the potential performance improvements that can be achieved when using IEEE 802.15.4e, instead of IEEE 802.15.4, we performed a set of simulation experiments using the ns2 simulation tool [24]. Specifically, we considered the 802.15.4 MAC in Beacon Enabled (BE) mode and Non Beacon Enabled (NBE) mode, and compared its performance to that of the 802.15.4e MAC in TSCH mode. To make the comparison fair and, also, to better emphasize the performance improvements that can be achieved with 802.15.4e, in TSCH we did not consider the multi-channel and frequency hopping mechanisms, i.e., we assumed a single channel frequency. Under this assumption TSCH reduces to a simple TDMA scheme.

In our analysis we considered a sensor network with star topology, where the sink node acts as the PAN coordinator and sensor nodes are placed in a circle centered at the PAN coordinator, 10 m far from it. The transmission range was set to 15 m, while the carrier sensing range was set to 30 m (according to the model in [25]). We considered a periodic reporting application where data acquired by sensors have to be reported periodically to the PAN coordinator. Time is divided into communication periods of duration T and each sensor node generates one data packets every T seconds.

To evaluate the performance of the different access modes, we derived the following performance indices.

- *Latency*, defined as the average time from when the packet transmission is started at the source node to when the same packet is correctly received by the PAN coordinator. It characterizes the *timeliness* of the system.
- *Delivery ratio*, defined as the ratio between the number of data packets correctly received by the PAN coordinator and the total number of data packets generated by *all* sensor nodes. It measures the network *reliability* in the data collection process.
- *Energy per packet*, defined as the total energy consumed by each sensor node divided by the number of data packets correctly delivered to the PAN coordinator. It measures the *energy efficiency* of the system.

The energy consumed by a sensor node was calculated using the model presented in [26], based on the Chipcon CC2420 radio transceiver [27]. This model supports the following radio states: *transmit*, *receive*, *idle* (the transceiver is on, but it is not transmitting nor receiving, i.e., it is monitoring the channel) and *sleep* (the transceiver is off and can be switched back on quickly).

The operating parameter values used in our experiments are shown in Table 1. The acknowledgement mechanism was always enabled in all the considered modes. When using the 802.15.4 BE mode the communication period corresponds to the Beacon period. We set BO = 6, which corresponds to a Beacon period of approximately 1 s (0.983 s to be precise). To make the comparison fair we used the same T value also for NBE and TSCH. In our experiments, for each simulated scenario, we performed 10 independent replications, where each replication consists of 1000 communication periods. For each replication we discarded the initial transient interval (10 % of the overall duration) during which nodes associate to the PAN coordinator node and start generating data packets. The results shown below are averaged over all the different replications. We also derived confidence intervals through the independent replication method. However, they are so small that they cannot be appreciated in the figures below.

Figures 6, 7 and 8 show the performance of the different MAC modes, for an increasing number of sensor nodes, in terms of delivery ratio, average latency, and energy efficiency, respectively. As expected, TSCH outperforms both BE and NBE for all the considered indices. Specifically, it performs a 100 % delivery ratio, with low (and fixed) latency and minimal energy consumption. In addition, its performance do not depend on the number of sensor nodes, at least until this number is less than or equal to the number of timeslots in the slotframe. Conversely, the 802.15.4 BE mode exhibits very poor performance, even when the number of sensor nodes is relatively high (e.g., with 20 nodes). This is because in BE mode nodes synchronizes to the periodic beacon emitted by the PAN coordinator. Hence, *all* sensor nodes having data to transmit compete for channel access at the beginning of the beacon

Fig. 6 Delivery ratio versus number of nodes

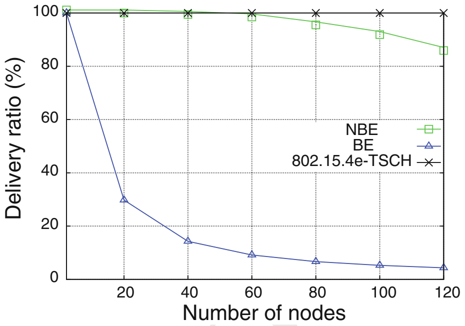


Table 1 Operating parameters

Parameter	Value
Communication Period (T)	0.983 s
Data frame size	127 bytes
ACK frame size	11 bytes
macMaxFrameRetries	3
macMaxCSMABackoffs	4
macMaxBE	5
macMinBE	3
P_{rx}	35.46 mW
P_{tx}	31.32 mW
P_{idle}	0.77 mW
P_s	36 μW

period. This maximizes the competition among nodes and results in high latencies and energy consumption. Also, a large percentage of frames is discarded due to exceeded number of backoff trials [28]. The NBE mode performs better than BE because, unlike BE, there is no synchronization and sensor nodes access the channel asynchronously, when they have a data packet ready for transmission. This reduces the competition among nodes even if conflicts can still occur. Hence, NBE performs similarly to TSCH when the number of nodes is low and there are no conflicts, while the performance gap between NBE and TSCH increases very quickly as the number of nodes grows up. It must be emphasized that, while TSCH provides a deterministic latency, thanks to its *slotted* access scheme, NBE is not able to guarantee a bounded latency, even when the number of nodes is low, since it implements a *contention-based* access scheme. For the same reasons, it is not able to guarantee a 100 % delivery ratio when the number of nodes is large or under high traffic conditions. Hence, NBE is not suitable for application scenarios where low and deterministic latency and/or high reliability are required. On the other side, being based on contention-based access, NBE does not require any preliminary link schedule to work and is, thus, more flexible and easy to manage, especially in network with dynamic topology.

Fig. 7 Average latency versus number of nodes

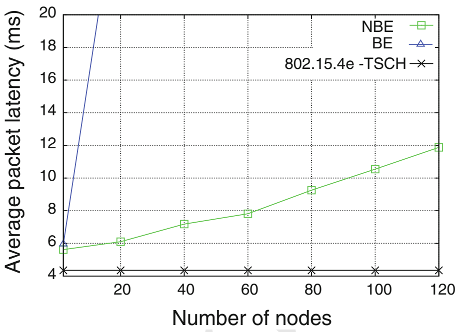
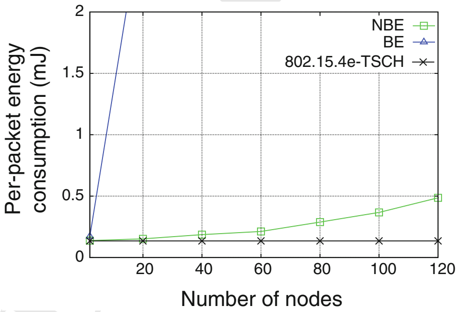


Fig. 8 Energy per packet versus number of nodes



Therefore, it can be preferred to TSCH in all application scenarios where latency AQ1 and/or reliability requirements are not so stringent.

6 Conclusions

In this chapter we have focused on the 802.15.4e standard, recently released by IEEE to enhance and add functionality to the 802.15.4 standard so as to address the emerging needs of embedded industrial applications. The 802.15.4 standard was conceived for applications without special requirements in terms of timeliness, reliability, robustness, and scalability. Therefore, it is unsuitable for application domains such as applications in the industrial and healthcare fields. We have highlighted the main limitations and deficiencies of the 802.15.4 standard and shown how these limitations have been overcome in the new standard. We have also presented some simulation results to better highlight the performance improvements allowed by the new standard.

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