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Technical Report

IEEE 802.15.4: a Federating Communication Protocol for Time-Sensitive Wireless Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) have been attracting increasing interests for developing a new generation of embedded systems with great potential for many applications such as surveillance, environment monitoring, emergency medical response and home automation. However, the communication paradigms in WSNs differ from the ones attributed to traditional wireless networks, triggering the need for new communication protocols. In this context, the recently standardised IEEE 802.15.4 protocol presents some potentially interesting features for deployment in wireless sensor network applications, such as power- efficiency, timeliness guarantees and scalability. Nevertheless, when addressing WSN applications with (soft/hard) timing requirements some inherent paradoxes emerge, such as power-efficiency versus timeliness, triggering the need of engineering solutions for an efficient deployment of IEEE 802.15.4 in WSNs. In this chapter, we will explore the most relevant characteristics of the IEEE 802.15.4 protocol for wireless sensor networks and present the most important challenges regarding time-sensitive WSN applications. We also provide some timing performance and analysis of the IEEE 802.15.4 that unveil some directions for resolving the previously mentioned paradoxes.

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Abstract

Wireless Sensor Networks (WSNs) have been attracting increasing interests for developing a new generation of embedded systems with great potential for many applications such as surveillance, environment monitoring, emergency medical response and home automation. However, the communication paradigms in WSNs differ from the ones attributed to traditional wireless networks, triggering the need for new communication protocols. In this context, the recently standardised IEEE 802.15.4 protocol presents some potentially interesting features for deployment in wireless sensor network applications, such as power-efficiency, timeliness guarantees and scalability. Nevertheless, when addressing WSN applications with (soft/hard) timing requirements some inherent paradoxes emerge, such as power-efficiency versus timeliness, triggering the need of engineering solutions for an efficient deployment of IEEE 802.15.4 in WSNs. In this technical report, we will explore the most relevant characteristics of the IEEE 802.15.4 protocol for wireless sensor networks and present the most important challenges regarding time-sensitive WSN applications. We also provide some timing performance and analysis of the IEEE 802.15.4 that unveil some directions for resolving the previously mentioned paradoxes.

Keywords: *Wireless Sensor Networks, IEEE 802.15.4, real-time communications, power efficiency*

1. Introduction

1.1. Context and motivation

Wireless Sensor Networks (WSNs) have revolutionized the design of emerging embedded systems and triggered a new set of potential applications. A WSN is typically composed of a large set of nodes scattered in a controlled environment and interacting with the physical world. This set aims the collection of specified data needed for the monitoring/control of a predefined area/region. The delivery of sensory data for process and analysis, usually to a control station (also referred as sink), is based on the collaborative work of the WSN nodes in a multi-hop fashion (Fig. x.1).

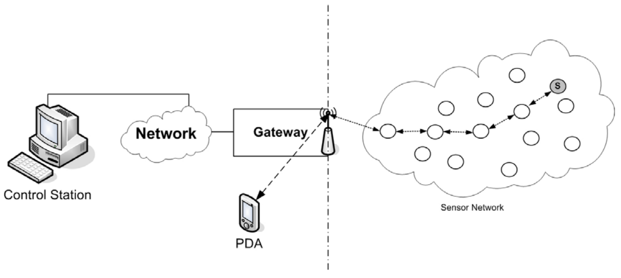


Fig. x.1. Typical topology of a Wireless Sensor Network

Hence, a WSN node is intended to act as:

- A *data source* with some basic capabilities, namely sensing (eventually other I/O), processing (and memory) and wireless communications, and that produces sensory data by interacting with the physical environment and collecting relevant physical parameters (e.g. temperature, humidity, pressure, movement).
- A *data router* that transmits data from one neighbour sensor node to another, towards the control station, which processes and analyses the data collected from the different sensors/nodes in the network.

This particular form of distributed computing raises many challenges in terms of real-time communication and coordination due to the large number of constraints that must be simultaneously satisfied, including limited power, CPU speed, storage capacity and bandwidth. These constraints trigger the need for new paradigms in terms of node/sensor design and network communication/coordination mechanisms. The design of wireless sensor networks is mainly concerned with power-efficiency issues, due to the severe limitation in terms of energy consumption (Aykildiz et al. 2002, Stankovic et al. 2003). However, the design complexity is even more significant when applications have, in addition, real-time and/or scalability requirements (Stankovic et al. 2003).

Several research initiatives, aiming at providing different design solutions for WSNs protocols, have recently emerged (Lu et al. 2002, Bandyopadhyay et al. 2003, He et al. 2003, Ye et al. 2004, Bacco et al. 2004). However, we believe that the use of standard technologies pushed forward by commercial manufacturers can speed up a worldwide utilization of WSNs. In this context, the IEEE 802.15.4 protocol (IEEE 802.15.4 Standard 2003), recently adopted as a communication standard for Low-Rate Wireless Local Area Networks (LR-WPANs), shows up itself as a potential candidate for such a deployment. This protocol provides enough flexibility for fitting different requirements of WSN applications by adequately tuning its parameters, even though it was not specifically designed for WSNs. In fact, low-rate, low-power consumption and low-cost wireless networking are the key features of the IEEE 802.15.4 protocol, which typically fit the requirements of WSNs. Moreover, the ZigBee specification (ZigBee Alliance 2005) relies on the IEEE 802.15.4 Physical and Data Link Layers, building up the Network and Application Layer, thus defining a full protocol stack for LR-WPANs (refer to Section 2.1).

More specifically, the IEEE 802.15.4 Medium Access Control (MAC) protocol has the ability to provide very low duty cycles (from 100% to 0.1 %), which is particularly interesting for WSN applications, where energy consumption and network lifetime are main concerns. Additionally, the IEEE 802.15.4 protocol also provides real-time guarantees by using the Guaranteed-Time Slot (GTS) mechanism, which is quite attractive for time-sensitive WSNs. In fact, when operating in beacon-enabled mode, i.e. beacon frames are transmitted periodically by a central node called the *PAN Coordinator* for synchronizing the network, the IEEE 802.15.4 protocol allows the allocation/deallocation of GTSs in a superframe for nodes that require real-time guarantees. Hence, the GTS mechanism provides a minimum service guarantee for the corresponding nodes and enables the prediction of the worst-case performance for each node's application.

In this chapter, we describe the most important features of the IEEE 802.15.4 protocol that are relevant for WSNs, and then discuss the ability of this protocol to fulfil the different requirements of WSNs and to resolve inherent paradoxes involving power-efficiency, timeliness guarantees and scalability issues.

1.2. Structure of the technical report

This report starts by presenting a technical overview on the most important features of the IEEE 802.15.4 protocol, in Section 2. While some relevant aspects on the protocol architecture, components, topologies, Physical Layer and network management are outlined, more focus is put on the MAC protocol, due to its importance in the context of this chapter. When addressing time–sensitive WSN applications (with soft/hard real-time requirements), some inherent paradoxes emerge, such as scalability vs. communication latencies and power consumption vs. timing efficiency. Section 3 tackles these paradoxes and addresses the most important results related to the performance evaluation and analysis of the beacon-enabled IEEE 802.15.4 MAC protocol, namely the slotted CSMA/CA and the GTS mechanisms for time-sensitive applications. In Section 4, we present some research trends and future challenges for the deployment of IEEE 802.15.4 in WSNs.

2. Overview of the IEEE 802.15.4 protocol

2.1. The IEEE 802.15.4/ZigBee protocol stack

The IEEE 802.15.4 protocol (IEEE 802.15.4 Standard 2003) specifies the MAC sub-layer and the Physical Layer for LR-WPAN (hereafter denoted as PAN). The IEEE 802.15.4 protocol is very much associated with the ZigBee protocol (ZigBee Alliance 2005) which specifies the protocol layers above IEEE 802.15.4 to provide a full protocol stack for low-cost, low-power, low data rate wireless communications. This layered architecture is depicted in Fig. x.2.

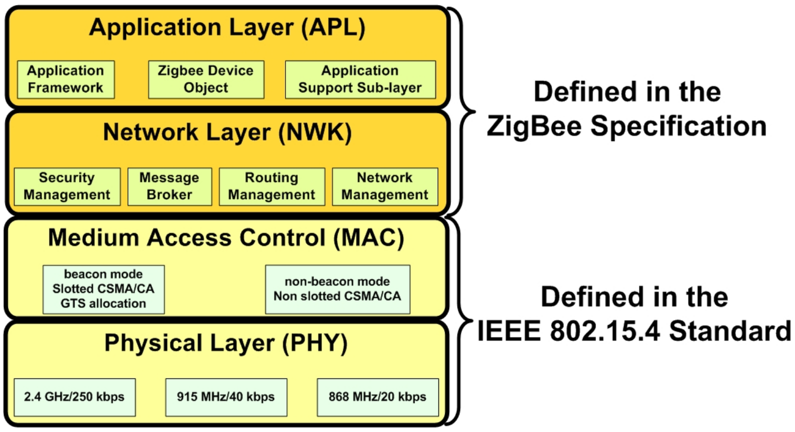


Fig. x.2. IEEE820.15.4/ZigBee protocol stack architecture

This protocol stack results from the joint effort within the ZibBee Alliance (ZigBee Alliance 2005), an organization with over 200 member companies that has been working in conjunction with IEEE (task group 15.4) in order to achieve a full protocol specification as well as to foster its use worldwide.

2.2. Network components and topologies

2.2.1. Network components

The IEEE 802.15.4 protocol basically defines three types of nodes.

- **PAN Coordinator.** It is the principal controller (Master) of the network, which identifies its PAN, and to which other nodes may be associated. It also provides **global** synchronization services to other nodes in the network through the transmission of beacon frames containing the identification of the PAN and other relevant information.

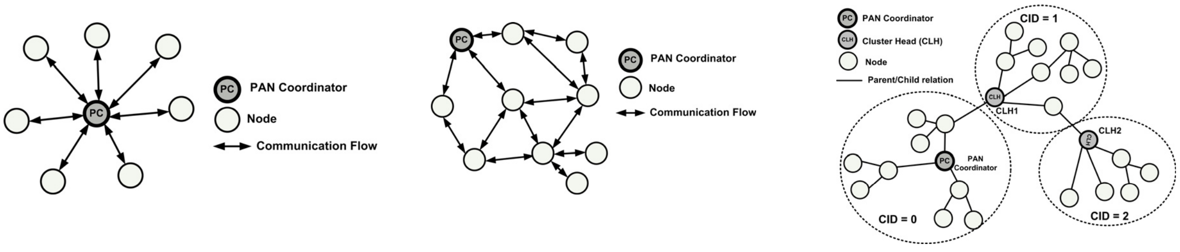
- **Coordinator**. It has the same functionalities as the PAN Coordinator with the exception that it does not create its PAN. A Coordinator is associated to a PAN Coordinator and provides **local** synchronization services to nodes in its range by means of beacon frame transmissions containing the identification of the PAN defined by the PAN Coordinator to which it is associated, and other relevant information.
- **Simple (Slave) node**. It is a node that does not have any coordination functionalities. It is associated as a slave to the PAN Coordinator (or to a Coordinator) for being synchronized with the other nodes in the network.

In (IEEE 802.15.4 Standard 2003), the first two types of nodes are referred to as *Full Function Devices* (FFD), which means that they implement all the functionalities of the IEEE 802.15.4 protocol for ensuring synchronization and network management. The third type is referred to as *Reduced Function Device* (RFD) meaning that the node is operating with a minimal implementation of the IEEE 802.15.4 protocol. Note that a simple node can also be an FFD.

Starting and maintaining PANs. Note that a PAN must include at least one FFD acting as a PAN Coordinator that provides global synchronization services to the network, and manages other potential Coordinators and slave nodes in its range. Once a PAN is started, it must be maintained by its PAN Coordinator by generating and sending beacons frames, managing association and dissociation of other nodes to the PAN, providing synchronization services, allowing GTS allocation and management, etc. More details on starting and maintaining PANs are available in (Koubâa et al. 2005a).

2.2.2. Network topologies

Two basic network topologies have been defined in the IEEE 802.15.4 specification: the *star* topology and the *peer-to-peer* topology. A third type of topology – the *cluster-tree* topology, can be considered as a particular case of a peer-to-peer topology.



a) Star Topology **b)** Peer-to-Peer Topology **c)** Cluster-Tree Topology

Fig. x.3. Network topologies in IEEE 802.15.4

The star topology (Fig. x.3.a)**.** In the star topology, a unique node operates as a PAN Coordinator. The communication paradigm in the star topology is centralized; that is, each node joining the network and willing to communicate with the other nodes must send its data to the PAN Coordinator, which will then dispatch it to the destination nodes. Due to the power-consuming tasks of the PAN Coordinator in the star topology, the IEEE 802.15.4 standard recommends that the PAN Coordinator should be mains-powered while other nodes are more likely to be battery-powered. The star topology seems to be not adequate for traditional wireless sensor networks for two reasons. First, a sensor node selected as a PAN Coordinator will get its battery resources rapidly ruined. A potential bypass to this problem is to have a dynamic PAN Coordinator based on remained battery supplies in sensor nodes, such as made in LEACH protocol (Heinzelman et al. 2000). However, this solution seems to be quite complex, since the dynamic election of a PAN Coordinator among a large number of sensor nodes is not always efficient. Second, the coverage of an IEEE 802.15.4 cluster is very limited while addressing a large-scale WSN, leading to a scalability problem. Nevertheless, the star topology may be promising in case of cluster-based architecture as it will be shown later in Section 3.1.

The peer-to-peer topology (Fig. x.3.b). This topology also includes a PAN Coordinator that identifies the entire network. However, the communication paradigm in this topology is decentralized, where each node can directly communicate with any other node within its radio range. This mesh topology enables enhanced networking flexibility, but it induces an additional complexity for providing end-to-end connectivity between all nodes in the network. Basically, the peer-to-peer topology operates in ad hoc fashion and allows multiple hops to route data from any node to any other node. However, these functions must be defined at the Network Layer and therefore are not considered in the IEEE 802.15.4 specification. Wireless Sensor Networks are one of the potential applications that may take advantage from such a topology. In contrast with the star topology, the peer-to-peer topology seems to be more power-efficient and the battery resource usage is fairer, since the communication process does not rely on one particular node (the PAN Coordinator).

The cluster-tree topology (Fig. x.3.c). In this topology, one (and only one) Coordinator is nominated as the PAN Coordinator, which identifies the entire network. However, any node may act as a Coordinator and provide synchronization services to other nodes or other Coordinators. The nomination of new Coordinators is in charge of the PAN Coordinator.

Actually, the standard does not define how to build a cluster tree network. It only indicates that this is possible, and may be initiated by higher layers. The cluster forming is performed as follows. The PAN Coordinator forms the first cluster by establishing itself as *Cluster Head* (CLH) with a *Cluster Identifier* (CID) equal to zero. It then chooses an unused *PAN Identifier* (PAN ID) and broadcasts beacons to neighbouring nodes. Nodes that are in the range of this CLH may request to be associated to the network at the CLH. In case of acceptance, the CLH adds the requesting node as a child node in its neighbour list, and the newly joined node adds the CLH as its parent in its neighbour list and begins transmitting periodic beacons. Other nodes can then join the network at the latter joined node. If for some reason the requesting node cannot join the network at the cluster head, it will search for another parent node.

For a large-scale sensor network, it is possible to form a mesh out of multiple neighbouring clusters. In such a situation, the PAN Coordinator can promote a node to become the CLH of a new cluster adjacent to the first one. Other nodes gradually connect and form a multi-cluster network structure (Fig. x.3.c). The Network Layer defined in the ZigBee specification uses the primitives provided by the IEEE 802.15.4 MAC sub-layer and proposes a cluster-tree protocol for either a single cluster network or a potentially larger cluster-tree network.

2.3. Physical Layer (PHY)

The IEEE 802.15.4 offers three operational frequency bands: 2.4 GHz, 915 MHz and 868 MHz. There is a single channel between 868 and 868.6 MHz, 10 channels between 902 and 928 MHz, and 16 channels between 2.4 and 2.4835 GHz (see Fig. x.4).

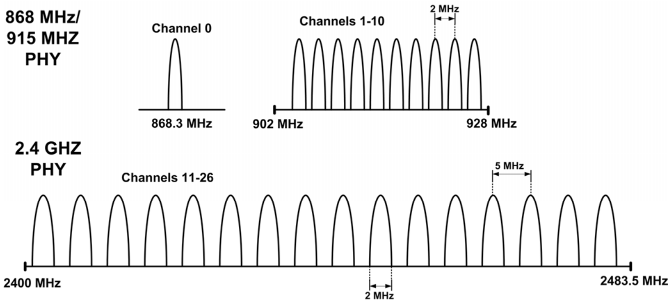


Fig. x.4. Operating frequency bands

The data rates are 250 kbps at 2.4 GHz, 40 kbps at 915 MHZ and 20 kbps at 868 MHz. Lower frequencies are more suitable for longer transmission ranges due to lower propagation losses. However, the advantage of high data rate transmission is the provision of higher throughput, lower latency or lower duty cycles.

All of these frequency bands are based on the *Direct Sequence Spread Spectrum* (DSSS) spreading technique. The features of each frequency band (modulation, chip rate, bit rate …) are summarized in Table 1. Note that one '*symbol*' is equivalent to four '*bits*'.

Table 1. Frequency Bands and Data Rates

Frequency Band (MHz)	Spreading Parameters		Data Parameters		
	Chip rate (kchip/s)	Modulation	Bit rate (kbps)	Symbol rate (ksymbol/s)	Symbols
868	300	BPSK	20	20	Binary
915	600	BPSK	40	40	Binary
2400	2000	O-QPSK	250	250	16-ary

In addition, the Physical Layer of the IEEE 802.15.4 is in charge of the following tasks.

- **Activation and deactivation of the radio transceiver**. The radio transceiver may operate in one of three states: *transmitting*, *receiving* or *sleeping*. Upon request of the MAC sub-layer, the radio is turned ON or OFF. The standard recommends that the *turnaround time* from transmitting to receiving states and vice versa should be no more than 12 symbol periods.
- **Receiver Energy Detection (ED)**. It is an estimation of the received signal power within the bandwidth of an IEEE 802.15.4 channel. This task does not involve any signal identification or decoding on the channel. The standard recommends that the energy detection duration should be equal to 8 symbol periods. This measurement is typically used to determine if the channel is busy or idle in the Clear Channel Assessment (CCA) procedure or by the Channel Selection algorithm of the Network Layer.
- **Link Quality Indication (LQI).** The LQI measurement characterizes the Strength/Quality of a received signal on a link. LQI can be implemented using the receiver ED technique, a signal to noise estimation or a combination of both techniques. The LQI result may be used by the higher layers (Network and Application layers), but this procedure is not specified in the standard.

- **Clear Channel Assessment (CCA).** The CCA operation is responsible for reporting the medium activity state: busy or idle. The CCA is performed in three operational modes:
    - *Energy Detection mode*. The CCA reports a busy medium if the received energy is above a given threshold, referred to as *ED threshold*.
    - *Carrier Sense mode*. The CCA reports a busy medium only if it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and which may be higher or lower than the ED threshold.
    - *Carrier Sense with Energy Detection mode*. This is a combination of the aforementioned techniques. The CCA reports that the medium is busy only if it detects a signal with the modulation and the spreading characteristics of IEEE 802.15.4 and with received energy above the ED threshold.
- **Channel Frequency Selection.** The IEEE 802.15.4 defines 27 different wireless channels. A network can choose to operate within a given channel set. Hence, the Physical Layer should be able to tune its transceiver into a specific channel upon the reception of a request from a Higher Layer.

There are already commercially available wireless sensor motes that are compliant with the IEEE 802.15.4 physical layer. For instance, the CC2420 transceiver (CC2420 datasheet 2004) from Chipcon Company provides the implementation of the IEEE 802.15.4 physical layer, operating at 2.4 GHz with a data rate of 250 kbps. This transceiver is widely used by many sensor network products such as MICAz from Crossbow Tech. (MICAz datasheet 2004).

IEEE 802.15.4/IEEE 802.11b coexistence problem. The deployment of IEEE 802.15.4 WPANs in the presence IEEE 802.11b WLANs triggers some inherent problems since they both operate in the 2.4 GHz frequency band. Coexistence between both technologies has become an important issue after the proposal of the IEEE 802.15.4 standard and has been subject of recent research works. In (Howitt et al. 2003), the authors analyzed the impact of an IEEE 802.15.4 network composed of several clusters on an IEEE 802.11b station communicating with a WLAN access point. An expression of the probability of an IEEE 802.11b packet collision due to the interference with IEEE 802.15.4 has been proposed. The authors conclude that the IEEE 802.15.4 network has little to no impact on the performance of IEEE 802.11b, unless the IEEE 802.11b station is very close to an IEEE 802.15.4 cluster with high activity level. A later work in (Shin et al. 2005) analyzed the packet error rate of IEEE 802.15.4 WPANs under the interference of IEEE 802.11b WLAN and proposed some coexistence criteria for both standards. The results of this work show that the interference caused by the IEEE 802.11b WLAN does not affect the performance of an IEEE 802.15.4 WPAN if the distance between the IEEE 802.15.4 nodes and the IEEE 802.11b WLAN is longer than 8 m. Moreover, if the frequency offset is larger than 7 MHz, the interference of IEEE 802.11b is has negligible effect on the performance of the IEEE 802.15.4. Another experimental work by Crossbow Tech. (Crossbow Tech. 2005) considered a set of three experiments using the MICAz motes, which implement the physical layer of the IEEE 802.15.4 and the Stargate single board computer compliant with IEEE 802.11b. The first experiment run with no WiFi interference and the other experiments run under IEEE 802.11 interference with two different power levels (standard level and 23 dBm). The packet delivery rate was analyzed. The experiment shows that high power transmissions of IEEE 802.11b packet reduce the packet delivery rate up to 80% for 23 dBm Wifi card.

In general, these results state that the coexistence of both IEEE 802.15.4 and IEEE 802.11b networks is generally possible with an acceptable performance, when nodes are not in a close proximity of each other and channels are adequately selected to prevent overlapping.

2.4. Medium Access Control Sub-Layer

2.4.1. General description

The MAC protocol supports two operational modes that may be selected by the PAN Coordinator (Fig. x.5).

- The *non beacon-enabled mode*, in which MAC is simply ruled by non-slotted CSMA/CA.
- The *beacon-enabled mode*, in which beacons are periodically sent by the PAN Coordinator to synchronize nodes that are associated with it, and to identify the PAN. A beacon frame delimits the beginning of a *superframe* (see Section 2.4.2) defining a time interval during which frames are exchanged between different nodes in the PAN. Medium access is basically ruled by slotted CSMA/CA. However, the beacon-enabled mode also enables the allocation of some time slots in the superframe, called Guaranteed Time Slots (GTSs) for nodes requiring guaranteed services.

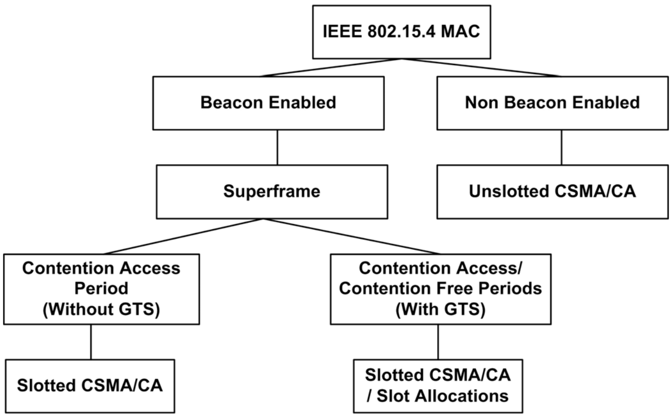


Fig. x.5. IEEE 802.15.4 MAC operational modes

Due to its importance in the context of this chapter, we address next the main characteristics of the beacon-enabled operational mode. We also describe the slotted and non-slotted versions of CSMA/CA, in Section 2.4.3.

The MAC sub-layer of the IEEE 802.15.4 protocol has many similarities with the one of the IEEE 802.11 protocol (IEEE 802.11 Specification 1999), such as the use of CSMA/CA (*Carrier Sense Multiple Access / Contention Avoidance*) and the support of contention-free and contention-based periods. However, the specification of the IEEE 802.15.4 MAC sub-layer is adapted to the requirements of LR-WPANs as, for instance, eliminating the RTS/CTS mechanism (used in IEEE 802.11), mainly due to the following reasons: (1) data frames in LR-WPANs are usually as small as RTS/CTS frames, and thus the collision probability would be the same with or without the RTS/CTS mechanism, (2) the exchange of RTS/CTS is energy consuming which is not adequate for LR-WPANs, (3) Sensor networks and potential LR-WPAN applications basically rely on broadcast transmissions, which do not use the RTS/CTS mechanism.

2.4.2. The superframe structure

In beacon-enabled mode, beacon frames are periodically sent by the PAN Coordinator to identify its PAN and synchronize nodes that are associated with it. The *Beacon Interval* (BI) defines the time between two consecutive beacon frames, and includes an active period and, optionally, an inactive period (Fig. x.6). The active period, called *superframe*, is divided into 16 equally-sized time slots, during which frame transmissions are allowed. During the inactive period (if it exists), all nodes may enter in a sleep mode, thus saving energy.

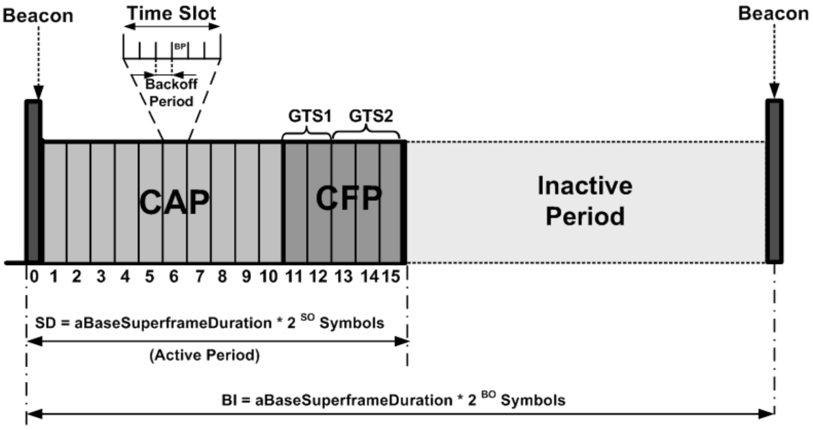


Fig. x.6. Beacon Interval and Superframe concepts

The Beacon Interval and the *Superframe Duration* (*SD*) are determined by two parameters, the *Beacon Order* (*BO*) and the *Superframe Order* (*SO*), respectively. The Beacon Interval is defined as follows:

$$BI = aBaseSuperframeDuration \cdot 2^{BO}, \quad for\ 0 \leq BO \leq 14 \tag{1}$$

The Superframe Duration, which corresponds to the active period, is defined as follows:

$$SD = aBaseSuperframeDuration \cdot 2^{SO}, \quad for\ 0 \leq SO \leq BO \leq 14 \tag{2}$$

In Eqs.(1) and (2), *aBaseSuperframeDuration* denotes the minimum duration of the superframe, corresponding to *SO* = 0. This duration is fixed to 960 symbols (IEEE 802.15.4 Standard 2003) (where a symbol corresponds to four bits) corresponding to 15.36 ms, assuming 250 kbps in the 2.4 GHz frequency band. In this case, each time slot has a duration of 15.36/16 = 0.96 ms. In this chapter, we will mainly consider the features of the 2.4 GHz frequency range supported by available COTS sensor network products (e.g. MICAz motes of Crossbow Tech. (MICAz datasheet 2004)).

By default, nodes compete for medium access using slotted CSMA/CA during the *Contention Access Period* (CAP). A node computes its backoff delay based on a random number of backoff periods, and performs two CCAs before transmitting. The IEEE 802.15.4 protocol also offers the possibility of defining a *Contention-Free Period* (CFP) within the superframe (Fig. x.6). The CFP, being optional, is activated upon request from a node to the PAN Coordinator for allocating *Guaranteed Time Slots* (GTS) depending on the node's requirements.

The information on Beacon Interval and the Superframe Duration is embedded in each beacon frame sent by the PAN Coordinator (or any other Coordinator in the PAN) in the *superframe specification* field. Therefore, each node receiving the beacon frame must correctly decode the information on the superframe structure, and synchronize itself with PAN Coordinator and consequently with the other nodes. Observe that the CAP starts immediately after the beacon frame and ends before the beginning of the CFP (if it exists). Otherwise, the CAP ends at the end of the active part of the superframe. During the CAP, nodes can communicate using slotted CSMA/CA while ensuring that their transactions (data frame + inter-frame spacing + acknowledgement if any exists) would finish before the end of the CAP; otherwise the transmission is deferred to the next superframe. Finally, note that the CFP starts immediately after the end of the CAP and must complete before the start of the next beacon frame. All the GTSs that may be allocated by the PAN Coordinator are located in the CFP and must occupy contiguous slots. The CFP may therefore grow or shrink depending on the total length of all GTSs. The transmissions in the CFP are contention-free and therefore do not use the CSMA/CA mechanism. Additionally, a frame may only be transmitted if the transaction (data frame + inter-frame spacing + acknowledgement if any exists) would finish before the end of the corresponding GTS.

2.4.3. The CSMA/CA mechanisms

The IEEE 802.15.4 defines two versions of the CSMA/CA mechanism.

1. The *slotted CSMA/CA* algorithm – used in the beacon-enabled mode.
2. The *non-slotted CSMA/CA* algorithm – used in the non beacon-enabled mode.

In both cases, the CSMA/CA algorithm uses a basic time unit called *Backoff Period* (BP), which is equal to *aUnitBackoffPeriod* = 20 Symbols (0.32 ms). In slotted CSMA/CA, each operation (channel access, backoff count, CCA) can only occur at the boundary of a BP. Additionally, the BP boundaries must be aligned with the superframe time slot boundaries (Fig. x.6). However, in non-slotted CSMA/CA the backoff periods of one node are completely independent of the backoff periods of any other node in a PAN.

The slotted/non-slotted CSMA/CA backoff algorithms mainly depend on three variables:

1. The *Backoff Exponent* (*BE*) enables the computation of the backoff delay, which is the time before performing the CCAs. The backoff delay is a random variable between 0 and (2^{BE}-1).
2. The *Contention Window* (*CW*) represents the number of backoff periods during which the channel must be sensed idle before accessing the channel. The *CW* variable is only used with the slotted CSMA/CA version. The IEEE 802.15.4 standard set the default initialization value *CW* = 2 (corresponding to two CCAs). In each backoff period, channel sensing is performed during the 8 first symbols of the BP.
3. The *Number of Backoffs* (*NB*) represents the number of times the CSMA/CA algorithm was required to backoff while attempting to access the channel. This value is initialized to zero (*NB* = 0) before each new transmission attempt.

Observe that the definition of *CW* in IEEE 802.15.4 is different from its definition in IEEE 802.11 (IEEE 802.11 Specification 1999). In the latter, *CW* has a similar meaning to the time interval $[0, 2^{BE}-1]$.

Fig. x.7 presents the flowchart of the slotted and non-slotted CSMA/CA algorithms, which are briefly described next.

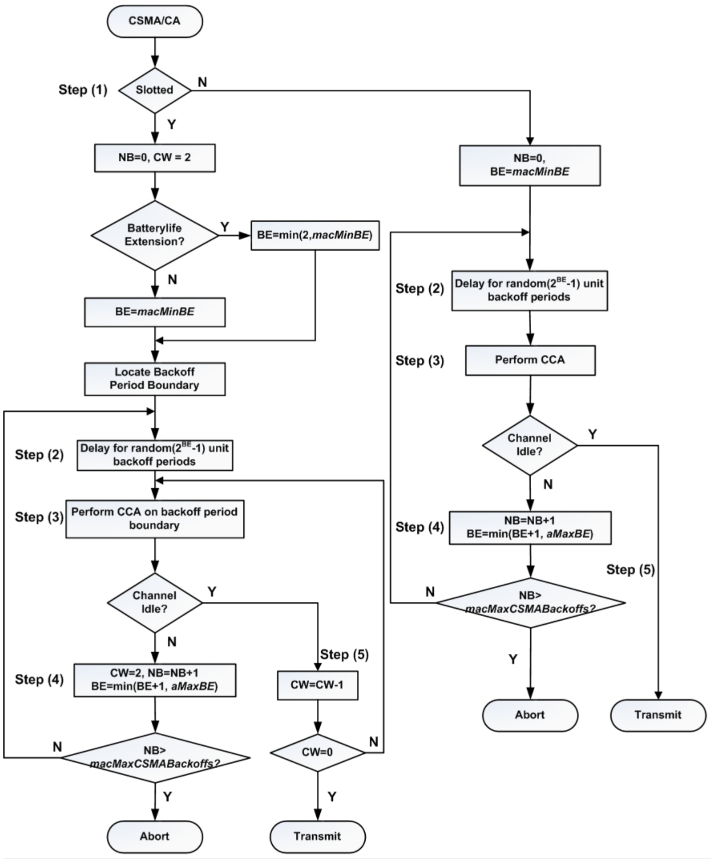


Fig. x.7. The slotted/non-slotted CSMA/CA algorithms

The slotted CSMA/CA can be summarized in five steps:

Step 1 - initialization of NB, CW and BE. the number of backoffs and the contention window are initialized ($NB = 0$ and $CW = 2$). The backoff exponent is also initialized to $BE = 2$ or $BE = \min(2, macMinBE)$ depending on the value of the *Battery Life Extension* MAC attribute. *macMinBE* is a constant defined in the standard, which is by default equal to 3. After the initialization, the algorithm locates the boundary of the next backoff period.

Step 2 - random waiting delay for collision avoidance. the algorithm starts counting down a random number of BPs uniformly generated within $[0, 2^{BE}-1]$. The count down must start at the boundary of a BP. To disable the collision avoidance procedure at the first iteration, *BE* must be set to 0, and thus the waiting delay is null and the algorithm goes directly to *Step 3*.

Step 3 - Clear Channel Assessment (CCA). When the timer expires, the algorithm then performs one CCA operation at the BP boundary to assess channel activity. If the channel is *busy*, the algorithm goes to *Step 4*, otherwise, i.e. the channel is idle, the algorithm goes to *Step 5*.

Step 4 - busy channel. If the channel is assessed to be *busy*, *CW* is re-initialized to 2, *NB* and *BE* are incremented. *BE* must not exceed *aMaxBE* (default value equal to 5). Incrementing *BE* increases the probability for having greater backoff delays. If the maximum number of backoffs ($NB = macMaxCSMABackoffs = 5$) is reached, the algorithm reports a failure to the higher layer, otherwise, it goes back to (*Step 2*) and the backoff operation is restarted.

***Step 5 - idle channel*:** If the channel is assessed to be *idle*, *CW* is decremented. The CCA is repeated if $CW \neq 0$ (Step 3). This ensures performing two CCA operations to prevent potential collisions of acknowledgement frames. If the channel is again sensed as idle ($CW = 0$), the node attempts to transmit. Nevertheless, collisions may still occur if two or more nodes are transmitting at the same time.

The non-slotted CSMA/CA is similar to the slotted version with a few exceptions.

Step 1. The *CW* variable is not used, since the non-slotted CSMA/CA has no need to iterate the CCA procedure after detecting an idle channel. Hence, in Step 3, if the channel is assessed to be idle, the MAC protocol immediately starts the transmission of the current frame. Second, the non-slotted CSMA/CA does not support *macBattLifeExt* mode and, hence, *BE* is always initialized to the *macMinBE* value.

Steps 2, 3 and 4. It is similar to the slotted CSMA/CA version. The only difference is that the CCA starts immediately after the expiration of the random backoff delay generated in Step 2.

Step 5. The MAC sub-layer starts immediately transmitting its current frame just after a channel is assessed to be *idle* by the CCA procedure.

The performance of the slotted CSMA/CA mechanism will be addressed in Section 4.1.

2.4.4. GTS allocation and management

As previously mentioned in Section 2.4.2, the IEEE 802.15.4 protocol offers the possibility of having a Contention-Free Period (CFP) within the superframe. The CFP, being optional, is activated upon request from a node to the PAN Coordinator for allocating a certain number of time slots. Hence, a node that wants to allocate time slots in the CFP for an exclusive use sends its request to the PAN Coordinator, which decides whether to accept this request or not, based on available resources.

Fig. x.8 shows the GTS characteristics field format sent within a GTS allocation request command frame by a requesting node to the PAN Coordinator.

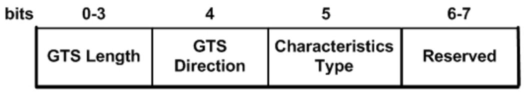


Fig. x.8. GTS characteristics field format in IEEE 802.15.4

The node explicitly expresses the number of time slots that it wants to allocate in the *GTS Length* field. Note that the GTS length can be up to 15 time slots. The *GTS Direction* field specifies if the GTS is in receive-only mode (value = 1), i.e. data is transmitted from the PAN Coordinator to the requesting node, or in transmit-only mode (value = 0), i.e. data is transmitted from the requesting node to the PAN Coordinator. The *Characteristics Type* field refers to a GTS allocation if it is set to one or a GTS deallocation if it is set to zero.

Upon receiving this request, the PAN Coordinator checks whether there are sufficient time-slots available in the superframe for this request. If the number of available time slots is smaller than the number requested, the GTS allocation request is rejected, otherwise it is accepted. The PAN coordinator must ensure that the CAP length remains always greater than *aMinCAPLength* equal to 7.04 ms according to the standard. In the former case, the corresponding node may still send its data frames during the CAP, but with no guarantee. If the GTS allocation request is accepted, the admitted node must keep track of beacon frames for checking which time slots have been allocated for that GTS in the current superframe. This information is located in the GTS descriptor field (Fig. x.9), which is embedded in each beacon frame. A beacon frame cannot have more than seven GTS descriptors, limiting the number of GTSs to seven.

Fig. x.9. GTS Descriptor Field Format in IEEE 802.15.4

The PAN Coordinator must also update the *final CAP slot* subfield of the *superframe specification* field of the beacon frame (IEEE 802.15.4 Standard 2003), which indicates the final superframe slot used by the CAP.

The explicit GTS allocation adopted by the standard has the advantage of being simple. However, it may be not efficient enough in terms of bandwidth utilization for flows with low arrival rates, which is typically the case in wireless sensor networks, since the guaranteed bandwidth of a GTS can be much higher than the arrival rates.

3. IEEE 802.15.4 for time-sensitive WSN applications

3.1. Tackling the scalability/latency paradox

3.1.1. Problem statement

Basically, peer-to-peer communications using flat routing protocols or broadcast transmissions is the commonly used paradigm in wireless sensor networks due to its data centric nature (Akyildiz et al. 2002, Stankovic et al. 2003). In that context, the IEEE 802.15.4 protocol can potentially fit such a paradigm, as it supports peer-to-peer topologies (refer to Section 2.2.2). On the other hand, most wireless sensor network applications are large-scale, which trigger the need to consider scalability issues in IEEE 802.15.4.

For such kind of networks, the non-beacon enabled mode seems to be more adapted to the scalability requirement than the beacon-enabled mode. In fact, when disabling the beacon-enabled mode, it is easier to construct a peer-to-peer network than when periodic beacons are sent, since in the former case all nodes are independent from the PAN Coordinator, and the communication is completely decentralized. In addition, the non-slotted CSMA/CA version in the non beacon-enabled mode will enable a better flexibility for a large-scale IEEE 802.15.4-compliant peer-to-peer network, since it does require any synchronization, contrarily to slotted CSMA/CA.

However, when addressing WSN applications with timing requirements, the peer-to-peer paradigm becomes controversial. In fact, with the inherently limited characteristics of wireless sensor nodes, timeliness guarantees (as well as reliability) are far from being granted. One of the problems is the use of the (non-slotted) CSMA/CA mechanism which does not provide any guarantee for a time-bounded delivery. To illustrate the scalability/latency paradox in peer-to-peer WSNs, let us consider a typical scenario of data delivery in WSNs (Fig. x.10).

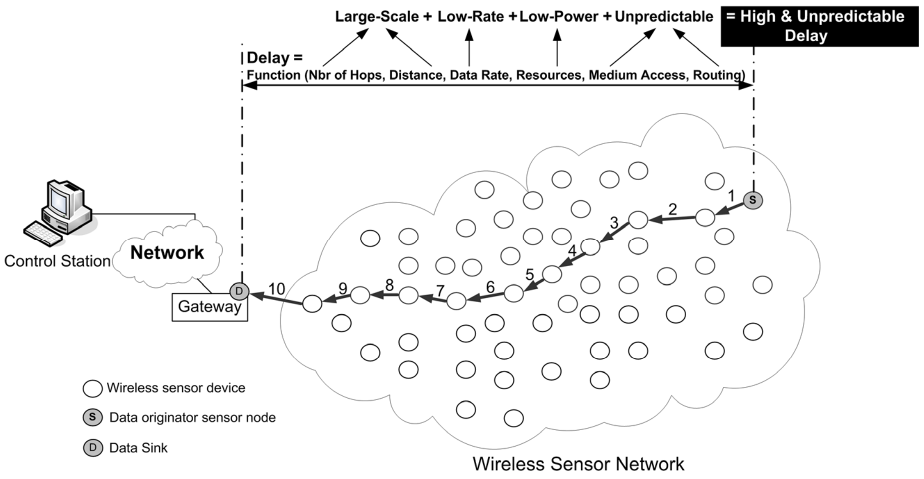


Fig. x.10. Timing performance limitations in peer-to-peer wireless sensor networks

Observe that the sensory data originated from sensor node *S* toward the data sink *D* is routed in a multi-hop ad-hoc fashion. Hence, the end-to-end delay experienced by such a data packet is basically a function of the number of hops, the distance, data rate, resources, medium access and routing protocols. On the other hand, in large-scale WSNs, the number of intermediate hops and the distance from source to data sink may be significantly high. Moreover, due to the low data rate and the need for low-power consumption, processing and transmission delays are far to be negligible, when compared to those in other types of communication networks. Adding to these facts the unpredictable behaviour of the communication protocols (e.g. the MAC sub-layer typically deploys contention-based MAC protocols, dynamic topological changes due to node failures), the end-to-end delay in large-scale WSNs is inevitably high. Even with the provision of very efficient communication protocols, the real-time performance is still limited due to the stringent resource constraints and to the unreliability of individual sensor nodes.

On the other hand, in beacon-enabled mode, the IEEE 802.15.4 enables the provision of real-time guarantees by using its GTS mechanism. Unfortunately, the use of GTSs is limited to direct communications between the PAN Coordinator and the nodes within its radio coverage, since GTS allocations are only granted by the PAN Coordinator. As a consequence, to benefit from the GTS mechanism, a node must be in the transmission range of the PAN Coordinator, which limits the configuration of the WPAN to a star topology. However, the star topology is not scalable and therefore is not adequate for large-scale wireless sensor networks, since only a small subset of WSN nodes would be in the range of their PAN Coordinator. The protocol also allows a cluster-tree topology to increase the network coverage, but still the GTSs cannot be used outside the range of the PAN Coordinator.

In what follows, we present some guidelines to tackle scalability versus timing performance paradox.

3.1.2. A two-tiered cluster-based architecture for IEEE 802.15.4-based WSNs

The previously referred limitation has been tackled by means of a two-tiered architectural approach, where an upper tier Wireless Local Area Network (WLAN) serves as a backbone to a large-scale WSN (Koubâa 2005b, Koubâa 2005c). In (Koubâa 2005b), the authors have presented the concept of the two-tiered architecture with some important design goals. However, no communication protocol has been investigated for both tiers. Then, (Koubâa 2005c) proposed ART-WiSe, a two-tiered cluster-based architecture for real-time communications in large-scale WSNs based on the IEEE 802.15.4 protocol.

The ART-WiSe architecture provides a solution for supporting real-time communications in large-scale WSNs while coping with the limited network coverage of IEEE 802.15.4 in beacon-enabled mode. This is achieved by organizing a “traditional” WSN in two interoperable networks arrayed in a hierarchical manner (Fig. x.11): tier-1 and tier-2.

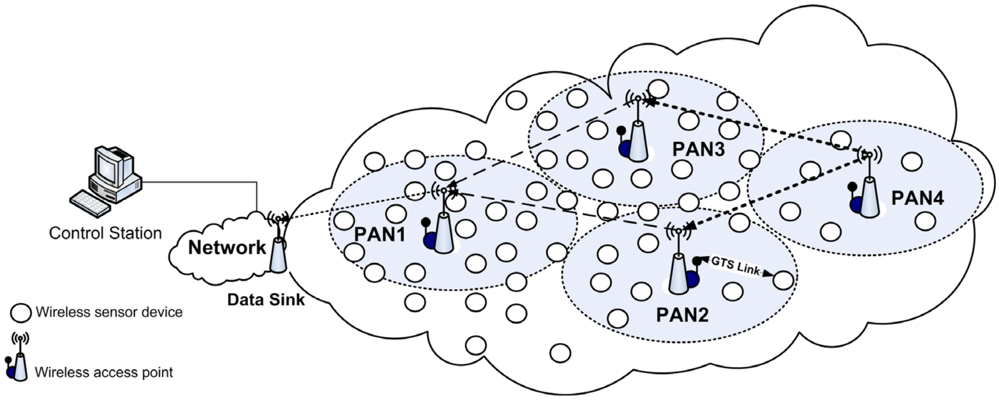


Fig. x.11. ART-WiSe architectural approach

The Tier-1 network is a basic IEEE 802.15.4-compliant WSN interacting with the physical environment to collect sensory data. This network is characterized by a low data rate (250kbps), a short transmission range (10-70 m) and severe energy constraints, resulting in limited communication capabilities. The WSN is partitioned into several clusters, where each cluster is an independent WPAN managed by a node (access point) of the Tier-2 network. For time-sensitive applications, real-time communications are achieved with the IEEE 802.15.4 beacon-enabled mode, through the GTS mechanism inside one IEEE 802.15.4 cluster of tier-1. This mechanism provides applications with predictable minimum service guarantees, enabling to predict the worst-case real-time performance of the network (Koubâa et al. 2006a), as it will be presented in Section 3.2.

The Tier-2 network (or the *overlay network*) is a wireless network acting as a backbone for the underlying WSN. It is composed of a set of special nodes called *access points*, which act as an interface between the WSN and the overlay network. The Tier-2 network is dedicated to relaying sensory data from the sensor network to the data sink. Each node (access point) in the Tier-2 network acts as a unique PAN Coordinator of the PAN cluster that it manages. Even though the architecture is independent from the federating communication protocols, the use of IEEE 802.11b as an overlay network is envisaged since it is a mature, widely used and cost-effective solution with significant bandwidth (11 Mbps up to 54 Mbps) and long transmission ranges (>100 m). Although the basic IEEE 802.11 does not provide any Quality of Service (QoS) guarantees, it has been shown that it performs well under lightly loaded networks (Bharghavan et al. 1998, Zheng et al. 2003). In ART-WiSe, it is expected that the overlay network will not be subject to high traffic load, since the difference between data rates in the WSN (250 kbps) and in the overlay wireless network (> 11 Mbps) is quite high. However, it is still possible to use the IEEE 802.11e extension (IEEE 802.11e Standard 2001) that provides additional QoS guarantees to the IEEE 802.11 protocol. Another important option for the overlay wireless network is the on-going extension of IEEE 802.15.4 made by the TG4a working group and which envisages a new physical layer based on Ultra Wide Band Impulse Radio enabling low-power consumption and high data rate.

Relying on the coexistence of IEEE 802.15.4 under IEEE 802.11 in the same network imposes some further investigation, at the light of existing studies referred in Section 3.2.

3.2. Tackling the power/timing efficiency paradox

3.2.1. Problem formulation

With the emergence of new WSN applications under reliability and timing constraints, the provision of real-time guarantees may be more crucial than saving energy during critical situations. The IEEE 802.15.4 protocol presents the advantage to fit different requirements of potential applications by adequately setting its parameters. Real-time guarantees can be achieved by using the GTS mechanism in beacon-enabled mode. The allocation of a GTS by a node provides it with a minimum service guarantee, enabling the prediction of the worst-case timing performance of the network. On the other hand, power-efficiency can be achieved by operating at low duty cycles (down to 0.1%). However, power-efficiency and timeliness guarantees are often two antagonistic requirements in wireless sensor networks.

This issue has been addressed in (Koubâa et al. 2006b). We have analyzed and proposed a methodology for setting the relevant parameters of IEEE 802.15.4-compliant WSNs that takes into account an optimal trade-off between power-efficiency and delay bound guarantees. To tackle this challenge, we have proposed an accurate model of the service curve provided by a GTS allocation as a function of the IEEE 802.15.4 parameters, using Network Calculus formalism. We then evaluated the delay bound guaranteed by a GTS allocation and expressed it as a function of the duty cycle. Based on the relation between the delay requirement and the duty cycle, we proposed a power-efficient superframe selection method that simultaneously reduces power consumption and enables meeting the delay requirements of real-time flows allocating GTSs. In what follows, we present the most relevant results presented in (Koubâa et al. 2006b) for showing a potential solution of the power/timing efficiency paradox.

We consider an IEEE 802.15.4 cluster with a unique PAN Coordinator, and a set of nodes within its radio coverage. The network operates in beacon-enabled mode, thus the PAN Coordinator periodically sends beacon frames. The Beacon Interval (*BI*) and the Superframe Duration (*SD*) are defined by Eq. (1) and Eq. (2), respectively. Let C be the total data rate of the channel. In our case, the data rate is fixed to $C = 250$ kbps.

Each sensor node in the range of the PAN Coordinator runs an application that generates a data flow. We consider that each data flow has a cumulative arrival function $R(t)$ upper bounded by the linear arrival curve $\alpha(t) = b + r.t$ with b denoting the maximum burst size, and r being the average arrival rate. We assume that each flow has a delay requirement D.

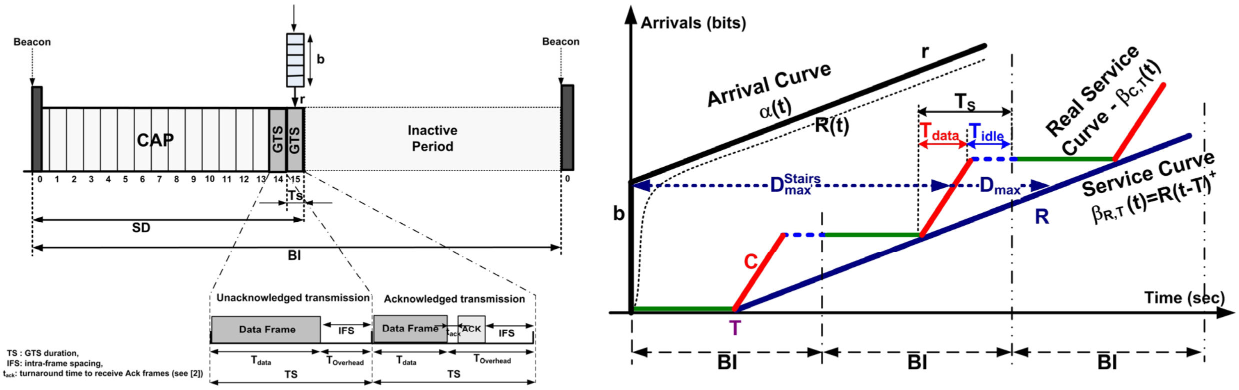
The main challenge is the following. *Given a set of data flows within an IEEE 802.15.4 cluster, where each data flow has a delay requirement D, what is the most efficient network setting (BO and SO pair) that satisfies the delay requirement of each data flow, allocating one time slot GTS, and minimizes the energy consumption?*

Hence, the purpose of our analysis is to derive an expression for the delay bound as a function of the duty cycle to evaluate the trade-off between energy consumption and delay guarantee.

3.2.2. Delay Bound Analysis of a GTS allocation

With the Network Calculus theory, the delay bound can be easily computed for a given flow constrained by an arrival curve $\alpha(t) = b + r.t$, if the service curve granted for this flow is known. The *service curve* defines the minimum amount of transmitted data at a given time. Obviously, the allocation of a GTS provides a minimum guaranteed bandwidth R with a maximum latency T, which is typically known as the rate-latency service curve, denoted as $\beta_{R,T}(t) = R.(t-T)^+$, with $(x)^+=\max(0,x)$. The first part of the work consists in determining the average bandwidth guaranteed by a GTS allocation and its maximum latency, which define the service curve of the GTS allocation.

The guaranteed service of a GTS allocation is depicted in Fig. x.12.



a) The GTS service time and transmission modes

b) Service curve of a GTS allocation and the corresponding delay bound

Fig. x.12. The GTS allocation guaranteed service

It can be observed in Fig. x.12.a that only a part of an allocated time slot can be used for data transmission. The remaining part of the time slot will be idle (due to Inter-Frame Spacing (IFS)) or used by a potential acknowledgement frame. We denote by T_{data} the maximum duration used for data frame transmissions inside a GTS. T_{idle} is the sum of idle times spent inside a GTS due to protocol overheads (IFS and/or Ack frames).

As a result, a node allocating a time slot of length Ts will be able to transmit data at a rate C during T_{data} for each Beacon Interval (BI). Hence, the maximum service latency is then equal to $T = BI - Ts$. This behaviour is captured by the stair service curve $\beta_{C,T}^{stair}(t)$ presented in Fig. x.12.b. In (Koubâa et al. 2006b), we have proved that:

$$\beta_{C,T}^{stair}(t) = \sum_k \beta_{C,T}^k(t) \qquad \forall t$$

$$\text{with } \beta_{C,T}^k(t) = \begin{cases} (k-1)\cdot C\cdot T_{data} + C\left(t-(k\cdot BI - Ts)\right)^+ \\ \quad \forall t,\ (k-1)\cdot BI \le t \le k\cdot BI - T_{idle} \\ \\ 0 \qquad \text{Otherwise} \end{cases} \tag{3}$$

In addition, a simplified approximation $\beta_{R,T}(t)$ of the stair service curve has been proposed, which has the form of a simple rate-latency service curve expressed as (see Fig. x.12.b):

$$\beta_{R,T}(t) = R\cdot(t-T)^+$$
$$\text{where } R = \frac{T_{data}}{BI}C \text{ and } T = (BI - TS) \tag{4}$$

Using the formulations of these service curves corresponding to a GTS allocation, the delay bound is simply the maximum horizontal distance between the arrival curve $\alpha(t) = b + r.t$ and the service curve received by the flow.

Hence, if considering the approximated service curve $\beta_{R,T}(t)$, the delay bound experienced by a data flow with an arrival curve $\alpha(t) = b + r.t$, which has allocated one time slot GTS, is computed as follows:

$$D_{\max} = \frac{b}{\frac{T_{data}}{BI} \cdot C} + \left(BI - Ts\right) \tag{5}$$

A more accurate delay bound can be obtained using the real service curve $\beta_{C,T}^{stair}\left(t\right)$ as depicted in Fig. x.12.b. We show that for a burst size *b* such that $k \cdot C \cdot T_{data} < b \leq \left(k+1\right) \cdot C \cdot T_{data}$, the delay bound of a data flow with an arrival curve $\alpha(t) = b + r.t$, which has allocated one time slot GTS is:

$$\begin{aligned} &D_{\max}^{stair} = \frac{b}{C} + \left(k+1\right) \cdot BI - Ts - k \cdot T_{data} \\ &\text{if } k \cdot C \cdot T_{data} < b \leq \left(k+1\right) \cdot C \cdot T_{data} \end{aligned} \tag{6}$$

3.2.3. Duty cycle evaluation as a function of the delay bound

At start-up, the PAN Coordinator of a given WPAN cluster must choose a superframe structure. The choice of the superframe structure affects the timing performance as well as the energy consumption in the cluster. Saving energy requires superframe structures with low duty cycles, whereas improving the timing performance requires higher duty cycles. A trade-off must be achieved by choosing the lowest duty cycle that still satisfies the timing constraints of the data flow. Hence, we investigate the following question.

> *Given a set of data flows within a PAN cluster, where each data flow has a maximum burst size b and a per-hop delay requirement D, what is the most efficient superframe structure, i.e. the combination of SO and BO, that satisfies the delay requirement of each data flow when it allocates one time slot GTS and minimizes the energy consumption?*

To evaluate the trade-off between energy consumption and delay guarantee, we derive the expression of the duty cycle as a function of the delay bound. For a given Superframe Order *SO* and Beacon Order *BO*, the duty cycle is defined as:

$$DC = \frac{SD}{BI} = 2^{SO-BO} \tag{7}$$

where *BI* is the Beacon Interval (Eq. (1)) and *SD* is the Superframe Duration (Eq. (2)).

As a result, based on Eqs. (1), (2) and (5), we show that the duty cycle can be expressed as a function of the delay requirement as follows:

$$DC = \frac{SD}{D + \lambda \cdot SD} \cdot \left(\frac{b}{T_{data} \cdot C} + 1\right) \tag{8}$$

where λ = 1/16.

According to Eq. (7), the minimum valid value of the duty cycle is then:

$$DC = 2^{IO} \text{ where } IO = \left\lfloor \log_2\left(\frac{SD}{D - \lambda \cdot SD} \cdot \left(\frac{b}{T_{data} \cdot C} + 1\right)\right) + 1 \right\rfloor \tag{9}$$

Eqs. (8) and (9) reflect the relation between energy consumption and the delay guarantee. From Eq. (9), it is possible to determine the lowest duty cycle that satisfies the delay requirement *D* of the flows, as it will be explained in the next section.

3.2.4. GTS Performance evaluation

Based on the aforementioned analysis, it is possible to evaluate the performance of a GTS allocation and capture the energy/delay trade-off.

Fig. x.13 presents the guaranteed bandwidth (*R* expressed in Eq. (4)) for different superframe orders with 100 % duty cycle ($SO = BO$) with unacknowledged transmissions. This figure is important to understand the effective bandwidth guaranteed while considering the impact of IFS. Note that if IFS = 0, we would have a constant guaranteed bandwidth, independently of *SO* values, equal to $Ts.C/BI$ = 15.625 kbps for 100% duty cycle.

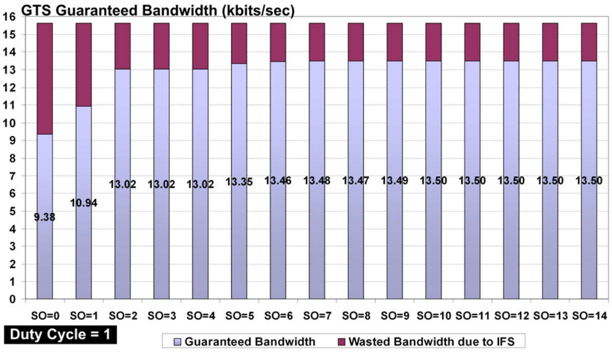


Fig. x.13. Guaranteed bandwidth (kbps) per one GTS allocation

We observe that the guaranteed bandwidth is slightly above 13 kbps, except for low superframe orders. The guaranteed bandwidth for $SO = 0$ and $SO = 1$ is relatively low compared to the others, due to more important impact of IFS, since the time slot durations are too small for sending high amount of data.

Our problem is to evaluate the impact of the delay bound on the duty cycle for a given superframe order *SO* and a given burst *b*. Fig. x.14 shows the variation of the duty cycle as a function of the delay bound for different values of *SO*. The burst size is equal to 200 bits.

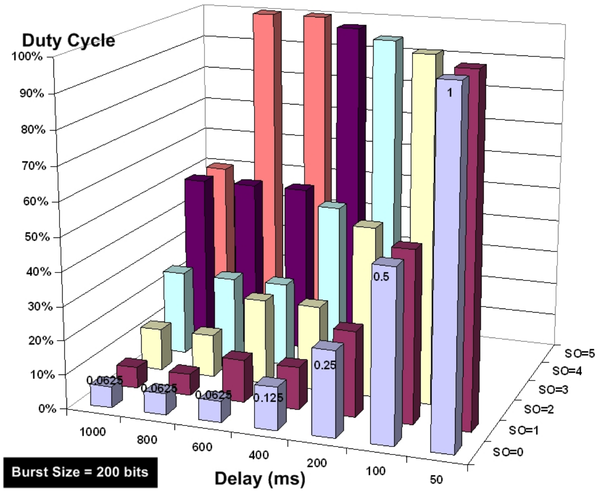


Fig. x.14. Duty cycle versus delay bound

Observe in Fig. x.14 that decreasing the delay requirement does not automatically increase the duty cycle. For instance, delay values in the range of [600, 1000] ms have the same 6.25% duty cycle for *SO* = 0. This fact is due to the slotted behaviour of the superframe structure defined in Eqs. (1) and (2). Hence, in some cases, relaxing the delay requirement will not automatically lead to a lower duty cycle for some IEEE 802.15.4 superframes. It is also observed from Fig. x.14 that the number of possible superframe structure configurations (alternatives for *BO* and *SO*) increases with the delay. Hence, for low delay requirements, only the lower superframe orders (*for low burst size*) can meet these delay bounds, if it is possible, due to the increased latency for large *SO* values (that also leads to larger *BO* values).

An other interesting problem is to determine the adequate superframe order reducing the duty cycle and still meeting a delay bound *D* for a given burst *b*. Fig. x.15 shows the variation of the duty cycle as a function of the superframe order for different values of the burst size. The delay bound requirement is assumed to be 3 seconds.

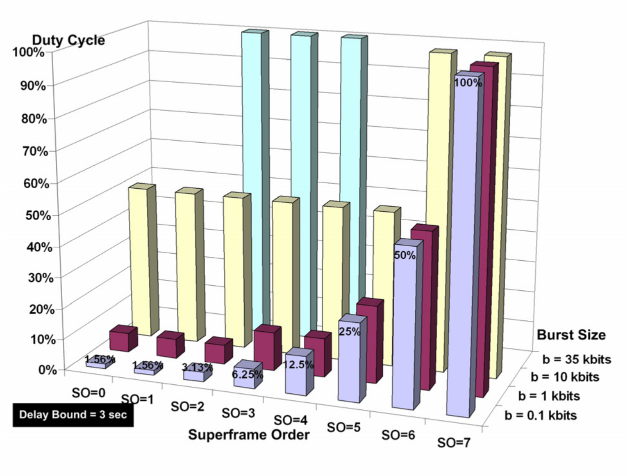


Fig. x.15. Duty cycle versus superframe order

Observe that for relatively low burst sizes (0.1 kbits, 1 kbits) the minimum duty cycle required to satisfy the delay bound increases with the superframe order. For a burst size equal to 10 kbits, there is no advantage of using low superframe orders for $SO \in \{0, 1, 2, 3, 4\}$. The duty cycle remains the same, since lower superframe orders have lower latencies whereas higher superframe orders provide higher guaranteed bandwidths.

However, for a burst size *b* = 35 kbps, only superframe orders $SO \in \{2, 3, 4\}$ can satisfy the delay bound of 3 s, with a full duty cycle. This is because the guaranteed bandwidth has the most significant impact on the delay bound.

3.3. Performance limits of the slotted CSMA/CA mechanism

3.3.1. Related work

The slotted CSMA/CA mechanism has attracted more attention from the research community as compared to the non-slotted version. This is typically due to two reasons: (1) The beacon-enabled mode has more interesting features as compared to the non beacon-enabled mode, such as providing synchronization services using beacon transmissions, and optionally a Contention Free Period (CFP) using the GTS mechanism. (2) In contrast to the non-slotted version, the slotted CSMA/CA mechanism has particular characteristics that are different from other well-known CSMA/CA schemes (e.g. DCF in IEEE 802.11) due to its slotted nature and its distinctive backoff algorithm using two *Clear Channel Assessments* (CCA).

The performance of the slotted CSMA/CA mechanism in IEEE 802.15.4 was recently evaluated using discrete time Markov chain models (Mišic et al. 2005a, Mišic et al. 2005b, Park et al. 2005, Pollin et al. 2005). Those papers presented analytic models of the slotted CSMA/CA mechanism in both saturation and non saturation modes, and provided steady state solutions. These analytical models are interesting for capturing the behaviour of the protocol in terms of throughput and access delays.

Other research trends focused on improved schemes for slotted CSMA/CA to achieve higher efficiency in terms of power consumption and (soft) delay guarantees. In (Kim et al. 2005a), the authors proposed a new scheme for slotted CSMA/CA to enable fast delivery of high priority packets in emergency situations, using a priority toning strategy. The idea is: nodes that have high priority information to be transmitted must send a tone signal just before the beacon transmission. If the tone signal is detected by the PAN Coordinator, an emergency notification is conveyed in the beacon frame, which alerts other nodes with no emergent messages to defer their transmissions by some amount of time, in order to privilege high priority packet transmissions at the beginning of the CAP. This solution seems to improve the responsiveness of high priority packets in IEEE 802.15.4 slotted CSMA/CA, but requires a non-negligible change to the IEEE 802.15.4 MAC protocol to support the priority toning strategy. In another paper (Kim et al. 2005b), the authors proposed a priority-based scheme of slotted CSMA/CA also for reducing the delivery delay of high priority packets. High priority packets are allowed to perform only one CCA operation instead of two. A frame tailoring strategy was proposed to avoid collisions between data frames and acknowledgment frames when only one CCA is performed before the transmission of high priority data frames. In addition, they combine the priority toning scheme proposed in (Kim et al. 2005a) with frame tailoring to define their improved slotted CSMA/CA scheme. Also here, a non-negligible modification of the standard is needed to implement this medium access technique.

One of the interesting challenges regarding the improvement of slotted CSMA/CA is to enhance this mechanism by adequately tuning its parameters without imposing changes to the protocol, to ensure backward compatibility with the standard.

3.3.2. Performance evaluation of slotted CSMA/CA

In (Koubâa 2006c), we have evaluated the performance of slotted CSMA/CA using simulations, as a complementary work to the aforementioned analytic studies. We believe that the simulation work itself, using a fine model, provides an added value to the theoretical work in (Mišic et al. 2005a, Mišic et al. 2005b, Park et al. 2005, Pollin et al. 2005). It also presents results without doing restrictive assumptions and taking into account some realistic features of the physical layer (propagation delays, fading, noise effect, etc.).

We consider a typical wireless sensor network in a (100 m x 100 m)surface with one PAN Coordinator and 100 identical nodes (randomly spread) generating Poisson distributed arrivals, with the same mean arrival rate. Note that the Poisson distribution is typically adopted by most simulation and analytical studies on CSMA/CA. The frame size is equal to 404 bits corresponding to 300 bits of data payload and 104 bits of the MAC header according to the standard.

The PAN Coordinator periodically generates beacon frames according to the *BO* and *SO* parameters. Unless it is mentioned differently, *BO* and SO are both equal to 3. Throughout the analysis, we always assume that *SO* = *BO* (100% duty cycle). Hereafter, when it is mentioned that the superframe order changes means that the beacon order is also changed and satisfies the equality *BO* = *SO*.

In WSNs, data dissemination is typically based on the diffusion of sensory data to all neighbours using broadcast transmissions. Therefore, in this study we consider unacknowledged transmissions, since broadcast transmissions do not use acknowledgements. In order to focus on the performance analysis of the slotted CSMA/CA algorithm, we assume that the network is fully connected, i.e. all nodes hear each other (no hidden-node problem).

In our simulation study, we consider the following two performance metrics: (1) The ***Network Throughput*** (*S*) is the fraction of traffic correctly received by the network analyzer (a device in promiscuous mode hearing all the traffic in the network) normalized to the overall capacity of the network (250 kbps). (2) The ***Average delay*** (*D*) is the average delay experienced by a data frame from the start of its generation by the application layer to the end of its reception by the analyzer.

We evaluate both metrics as a function of the offered load *G*, defined as the global load generated by all node's application layers. The offered load *G* depends on the inter-arrival times of the flows, which are exponentially distributed (Poisson arrivals).

First, we present the impact of *BO* and *SO* values on the network throughput (Fig. x.16) and the average delay (Fig. x.17).

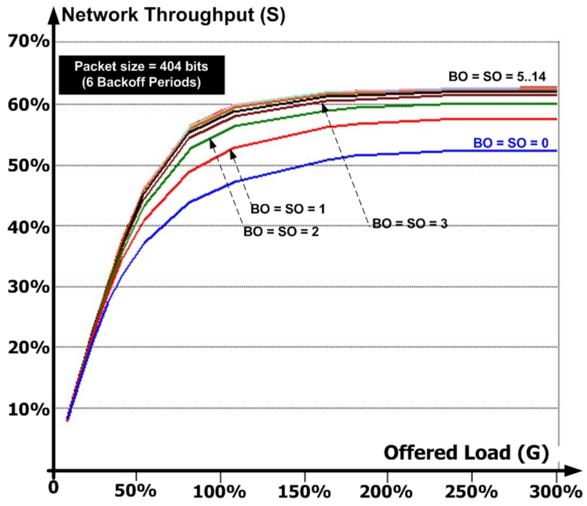


Fig. x.16. The network throughput as a function of the offered load for different (BO, SO) values

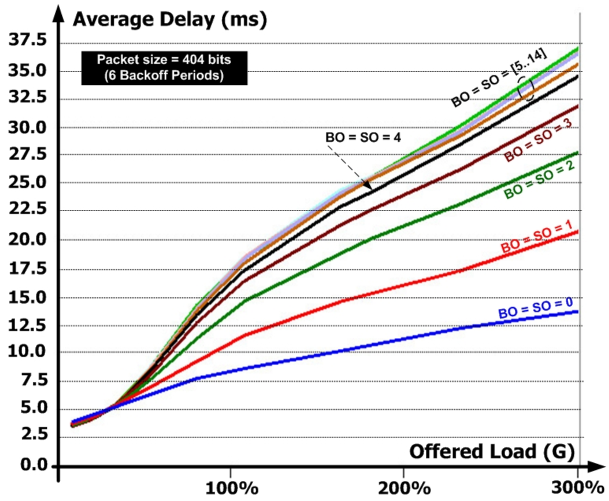


Fig. x.17. The average delay as a function of the offered load for different (BO, SO) values

Observe that, as expected, low *SO* values produce lower network throughput. This is basically due to two factors. First, the overhead of the beacon frame is more significant for lower *SO* values, since beacons are more frequent. Second, CCA deference is also more frequent in case of lower *SO* values, leading to more collisions at the start of each superframe.

Note that the increase in the superframe order, from *SO* equal to 5 until 14, has a reduced impact on the network throughput. In fact, for high *SO* values (≥ 5), the probability of deference is quite low, which reduces the amount of collisions due to simultaneous CCA deference in multiple nodes, and thus leads to higher network throughputs.

Fig. x.17 shows that the average delays significantly increase with *SO* for a given offered load *G* higher than 50 %, as explained next. In fact, for low *SO* values, the high probability of CCA deference results in having more frequent collisions of data frames at the beginning of a new superframe. Hence, the backoff delays will not increase too much due to this frequent collision in case of low superframe orders. However, for high superframe orders the backoff algorithm will be less exposed to this problem, and then nodes will go into additional and higher backoff delays, since the backoff exponent is increased each time the channel is sensed as busy.

Second, we present the impact of the initialization value of the backoff exponent *macMinBE* on the network throughput (Fig. x.18) and on the average delay (Fig. x.19).

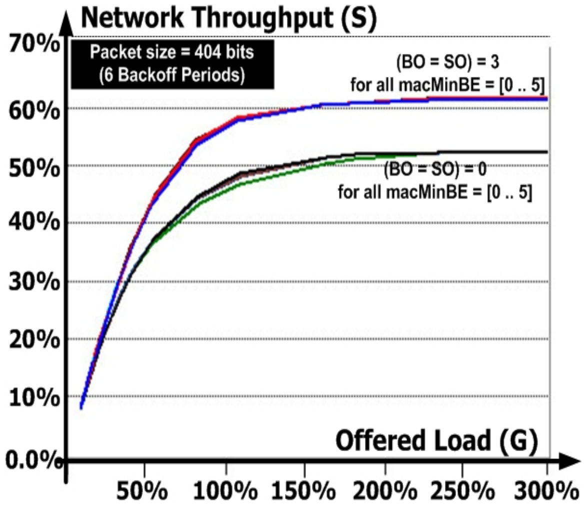


Fig. x.18. The network throughput as a function of the offered load for different *macMinBE* values

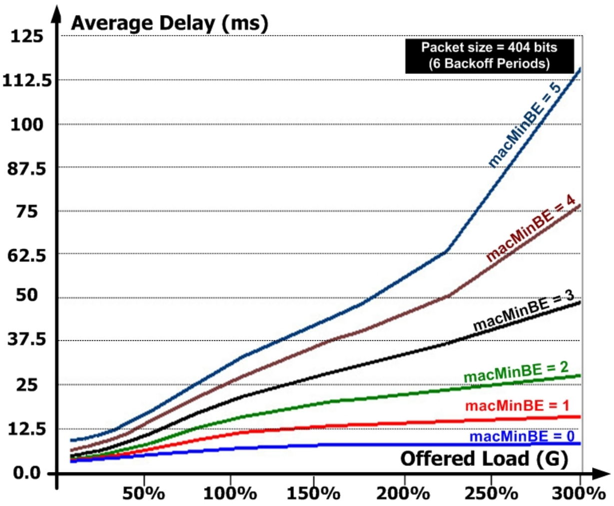


Fig. x.19. The averagedelay as a function of the offered load for different *macMinBE* values

Intuitively, it could be expected that the network throughput would be improved with higher *macMinBE* since the backoff interval would be larger. However, this is not the case in this example. This result is due to the backoff algorithm behaviour of slotted CSMA/CA. In fact, for a given *macMinBE*, the interval from which the backoff delay is randomly generated at the first iteration is [0, $2^{macMinBE}$ -1]. Independently from *macMinBE*, the lower limit of the backoff delay interval is always 0 while the upper limit will be incremented each time the channel is sensed busy. Since the number of nodes is high (100 nodes), the probability that a medium is busy is also high, which leads to increasing *BE* for improved collision avoidance in the next iterations. *BE* cannot exceed *aMaxBE* = 5 and this value is reached by the competing nodes at most after 5 transmissions from other nodes. Thus, the backoff interval will tend to [0, 31] in all remaining nodes waiting for medium access and, as a result, the backoff delay distribution will not depend too much on the initialization value of *macMinBE*.

On the other hand, observe that the average delay increases with *macMinBE* for a given offered load (Fig. x.19). Lower *macMinBE* values provide lower average delays with the same network throughputs. This is because the average backoff delays are higher for large [0, 2^{BE} -1] intervals. Observe that for low offered loads (G < 50 %), the variance of the average delays for different *macMinBE* is not significant (around 10 ms from *macMinBE* from 0 to 5). However, for high offered loads $G \geq 50$ %, the impact of *macMinBE* is significantly more visible. For instance, for *G* = 300%, the average delay is higher than 110 ms for *macMinBE* = 5, whereas it is does not exceed 8 ms in case of *macMinBE* = 0.

4. Research trends and challenges of the IEEE 802.15.4 protocol

Since its proposal in 2003, the IEEE 802.15.4 protocol has been attracting more and more research work envisaging its deployment in wireless sensor networks. It is expected that many commercial manufacturers of wireless sensor technologies will shift towards this standard solution due to its low-cost and improved performance. However, there are still some challenges that must be addressed to tune this COTS technology for WSN applications. In this section, we present some hints on potential research trends and future challenges for the use of IEEE 802.15.4 in wireless sensor networks.

One of the challenges is the deployment of the beacon-enabled mode in a multi-hop network with several Coordinators. The main problem is to find adequate synchronization schemes for different Coordinators in the same range, to avoid beacon collisions. In such kind of networks, beacon frames of a given Coordinator may collide with beacon frames of other Coordinators (which lead to permanent collisions) or data/control frames (which lead to occasional collisions). Loosing beacon frames will lead to synchronization failures of associated nodes in the network. This problem was analysed in (Ha et al. 2005), where the authors derived the probability of beacon frame collisions with other beacons, and the probability of beacon frame collisions with data/control frames. The analytical results and experiments show that, when the starting time of the first beacon frame generated by each Coordinator is uniformly distributed, multi-hop beacon enabled networks are feasible for *BO* values higher than 1, and for evenly distributed Coordinators. In such conditions, they show that synchronization failures may be less that 1%. An interesting extension of this work is to propose improved synchronization schemes for several Coordinators operating with beacon orders equal to 0 and 1, since these modes provides better performances in terms of delay guarantees, as it has been shown in Section 3.3. In addition, it is important to propose a deterministic synchronization scheme that ensures that no collisions will disturb beacon frame transmissions to reach 0 % of synchronization failure.

Another open issue is to resolve the hidden-node problem in IEEE 802.15.4, since its MAC protocol does not use any RTS/CTS mechanism. This problem may be serious in large-scale wireless sensor networks, which typically use broadcast transmissions to disseminate data. In such conditions, the hidden-node problem would have a negative impact on the network throughput. This issue was addressed in (Hwang et al. 2005), in which the authors proposed a grouping strategy to solve the IEEE 802.15.4 hidden-node problem without using the RTS/CTS mechanism. This strategy groups nodes according to their hidden-node relationship such that all nodes in each group are not hidden to each other. Then, this technique allocates to each group guaranteed time slots, in which slotted CSMA/CA is used by different nodes in the group to access the channel. The PAN Coordinator is in charge of detecting the hidden-node situation and performing grouping procedure if necessary.

Concerning time-sensitive sensor networks, the improvement of the GTS mechanism is still an open issue. In fact, the protocol only supports explicit GTS allocations, i.e. a node allocates a number of time slots in each superframe for exclusive use. The limitation of the explicit GTS allocation is that GTS resources may quickly disappear, since a maximum of seven GTSs can be allocated in each superframe, preventing other nodes to benefit from guaranteed service. Moreover, the GTSs may be only partially used, resulting in a wasted bandwidth. To overcome this limitation, one possible solution is to share the same GTS between multiple nodes, instead of being exclusively dedicated to one node, if a certain schedule that satisfies the requirements of all requesting nodes exists. Sharing a GTS by several nodes means that the time slots of this GTS are dynamically allocated to different nodes in each superframe, according to a given schedule.

Another important issue regarding the deployment of IEEE 802.15.4 is the adequacy of the Zigbee routing layer for wireless network applications. In fact, the IEEE 802.15.4 protocol is intended to operate on the bottom of the Zigbee network/application stack. It is therefore quite important to analyze the suitability of Zigbee solutions, namely in terms of routing protocols and network services, with the requirements of wireless sensor networks, which are typically data centric contrarily to traditional wireless networks. One of the problems is that the full Zigbee stack seems to be heavy to be implemented in tiny sensor devices. It is also interesting to propose localization mechanisms based on the IEEE 802.15.4 MAC services, since most WSN applications rely on location-awareness, which is not provided in the IEEE 802.15.4/Zigbee stack.

In conclusion, we believe that the IEEE 802.15.4 protocol is a promising enabling technology for low-cost, low-rate and low-power consumption WSNs due to its flexibility to fulfil different requirements of various application patterns, when adequately tuning its parameters.

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