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Technical Report

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Abstract

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Abstract

The IEEE 802.15.4 has been adopted as a communication protocol standard for Low-Rate Wireless Private Area Networks (LR-WPANs). While it appears as a promising candidate solution for Wireless Sensor Networks (WSNs), its adequacy must be carefully evaluated. In this paper, we analyze the performance limits of the slotted CSMA/CA medium access control (MAC) mechanism in the beacon-enabled mode for broadcast transmissions in WSNs. The motivation for evaluating the beacon-enabled mode is due to its flexibility and potential for WSN applications as compared to the non-beacon enabled mode. Our analysis is based on an accurate simulation model of the slotted CSMA/CA mechanism on top of a realistic physical layer, with respect to the IEEE 802.15.4 standard specification. The performance of the slotted CSMA/CA is evaluated and analyzed for different network settings to understand the impact of the protocol attributes (superframe order, beacon order and backoff exponent), the number of nodes and the data frame size on the network performance, namely in terms of throughput (S), average delay (D) and probability of success (Ps). We also analytically evaluate the impact of the slotted CSMA/CA overheads on the saturation throughput. We introduce the concept of utility (U) as a combination of two or more metrics, to determine the best offered load range for an optimal behavior of the network. We show that the optimal network performance using slotted CSMA/CA occurs in the range of 35% to 60% with respect to an utility function proportional to the network throughput (S) divided by the average delay (D).

1. Introduction

The recent advances in wireless communications triggered the development of standard protocols specifically designed for a particular range of applications. In that direction, the IEEE 802.15.4 protocol [1] has been recently proposed as a wireless communication standard for low-rate, low-power consumption Wireless Personal Area Networks (LR-WPANs). The power-efficiency and robustness of its Physical Layer (PhyL) with the flexibility of its Medium Access Control (MAC) sublayer, makes the IEEE 802.15.4 protocol a strong candidate to be a federating communication protocol for Wireless Sensor Networks (WSNs).

The IEEE 802.15.4 MAC protocol supports two operational modes that may be selected by a central node called *PAN coordinator* : (1) the non beacon-enabled mode, where the MAC is ruled by non-slotted CSMA/CA; (2) the beacon-enabled mode, where beacons are periodically sent by the PAN coordinator to identify its PAN, to synchronize nodes that are associated with it, and to delimit a superframe during which all transmissions must occur. During the contention access period of the superframe, the MAC is ruled by the slotted CSMA/CA mechanism.

In this paper, we evaluate the performance of slotted CSMA/CA for two main reasons. First, the beacon-enabled mode has more interesting features as compared to the non beacon-enabled mode, such as providing synchronization services using beaconing, and optionally a Contention Free Period (CFP) using the Guaranteed Time Slot (GTS) mechanism. Second, in contrast to the unslotted version, the slotted CSMA/CA mechanism defined in [1] has particular characteristics different from other well-known CSMA/CA schemes (e.g. DCF in IEEE 802.11) due to its slotted nature, its distinctive backoff algorithm and the *Clear Channel Assessment* (CCA) procedure.

Related work. The performance of the slotted CSMA/CA mechanism in IEEE 802.15.4 was recently evaluated using discrete time Markov chain models [2-4]. 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 behavior of the protocol in terms of throughput and access delays. However, the impact of the *Beacon Order* (*BO*), *Superframe Order* (*SO*) and *Backoff Exponent* (*BE*) was not addressed. In [5], the authors have proposed a different Markov chain model of the slotted CSMA/CA mechanism and computed the throughput and energy consumption in saturation conditions.

In this paper, we propose a comprehensive performance study using simulation, complementary to the work in [2-5]. We address the impact of the slotted CSMA/CA overheads, the IEEE 802.15.4 MAC attributes (*BO*, *SO*, and *BE*), the number of nodes and the frame size on the performance of slotted CSMA/CA in terms of throughput, average delay and success probability. We also introduce the concept of *utility*, which is defined as the combination of two or more metrics, enabling to determine the optimal offered load for achieving the best trade-off between all combined metrics.

Another particularity of this work is that it evaluates the performance of slotted CSMA/CA in case of broadcast transmissions, i.e. without acknowledgements. In [2-5], the analytic models were developed for acknowledged transmissions. The reason behind considering unacknowledged transmissions is that most WSNs rely on broadcast transmissions for data dissemination.

To our best knowledge, this is the first simulation study addressing the slotted CSMA/CA mechanism in IEEE 802.15.4. In [6], a general purpose simulation study of the IEEE 802.15.4 was presented using the NS-2 simulator. However, the performance of slotted CSMA/CA was only lightly addressed.

Contributions of this paper. The general contribution of this paper is providing a comprehensive analysis of the slotted CSMA/CA using simulation to assess the impact of the IEEE 802.15.4 attributes (*BO*, *SO* and *BE*), the number of nodes and the data frame size on the network performance in terms of throughput, success probability and average delay.

The motivation for this work is two-folded.

1. First, we aim to provide a practical understanding of the slotted CSMA/CA mechanism using a reliable simulation model for different settings of the IEEE 802.15.4 MAC protocol. This analysis permits to identify its limitations and may trigger the proposal of improved schemes for specific purposes (reducing average delays, improving the throughput …).

2. Second, we believe that the simulation work itself using a fine model provides an added value to the theoretical work in [2-5]. 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.).

The simulation model of IEEE 802.15.4 is presented in Section 3. We briefly describe the simulation tool that we have developed, then we present the simulation test-bed used in the simulation studies, and finally we present the performance metrics evaluated in this paper. We also define the utility function as a combination of two or more metrics to determine the range of offered loads that provides the best performance with respect to utility.

The first contribution is analyzing the impact of the slotted CSMA/CA overheads (backoff delay, contention window and CCA deference) on the saturation throughput, which is the maximum traffic generated by one node (without the effect of collisions) (Section 4). We analytically derive the probability of the CCA deference and the saturation throughput and compare these analytical results with those obtained by simulation. Our analytical model proves to be more accurate than a previous proposal, closely matching the results obtained by simulation.

The second contribution is to evaluate the impact of different network settings (*SO*, *BO*, *BE*, number of nodes and frame size) on network performance (Section 5).

As a general result, we show that slotted CSMA/CA achieves optimal performance in terms of average delay and throughput for offered loads comprised between 35% and 60% of the network capacity (250 kbps).

2. Relevant Features of IEEE 802.15.4

2.1. Overview of the IEEE 802.15.4 MAC protocol

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. 1). 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.

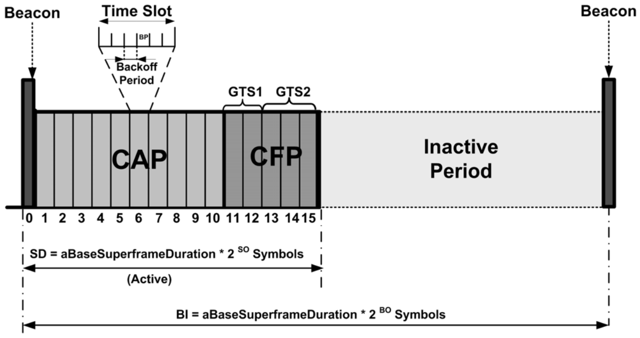


Fig. 1. Beacon interval and superframe concepts

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:

$$\begin{gathered} BI = aBaseSuperframeDuration \cdot 2^{BO} \\ for \ \ 0 \le BO \le 14 \end{gathered} \tag{1}$$

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

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

In Eqs.(1) and (2), *aBaseSuperframeDuration* denotes the minimum duration of the superframe, corresponding to $SO = 0$. This duration is fixed to 960 symbols [1] (a symbol corresponds to 4 bits) corresponding to 15.36 ms, assuming 250 kbps in the 2.4 GHz frequency band. In this paper, we will consider the features of the 2.4 GHz frequency range, which is supported by the MICAz motes from Crossbow Tech. [10], for example. In this case, when SO = 0, each time slot has a duration of $SD/16 = 15.36/16 = 0.96$ ms.

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 accessing the medium. The IEEE 802.15.4 protocol also offers the possibility of defining a *Contention-Free Period* (CFP) within the superframe (Fig. 1). 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 performance of the GTS mechanism is addressed in [13].

2.2. The slotted CSMA/CA mechanism

The slotted CSMA/CA algorithm is based on a basic time unit called *Backoff Period* (BP), which is equal to $aUnitBackoffPeriod = 80$ bits (0.32 ms) independently from *SO* and *BO*. Each operation of slotted CSMA/CA (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. 1).

The slotted CSMA/CA backoff algorithm mainly depends 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 $\left(2^{BE} - 1\right)$.
2. The *Contention Window* (*CW*) represents the number of backoff periods during which the channel must be sensed idle before accessing to the channel. The standard set the default initialization value to $CW = 2$ (corresponding to two CCAs). In each backoff period, channel sensing is done 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 [7]. In the latter, *CW* has a similar meaning to the time interval $\left[0,2^{\mathrm{BE}}\text{-}1\right]$. Fig. 2 presents the flowchart of the slotted CSMA/CA algorithm, which is briefly described next.

First, the number of backoffs and the contention window are initialized ($NB = 0$ and $CW = 2$) (Step 1). The backoff exponent is also initialized to $BE = 2$ or $BE = \min\left(2, macMinBE\right)$ depending on the value of the *Battery Life Extension* MAC attribute. *macMinBE* is a constant defined in the standard [1], which is by default equal to 3. Then, the algorithm starts counting down a random number of BPs uniformly generated within $\left[0..2^{\mathrm{BE}}\text{-}1\right]$ (Step 2). The count down must start at the boundary of a BP. When the timer expires, the algorithm then performs one CCA operation at the BP boundary to assess channel activity (Step 3). If the channel is busy (Step 4), *CW* is re-initialized to 2, *NB* and *BE* are incremented. *BE* must not exceed *aMaxBE* (default value equal to 5) [1]. 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. If the channel is sensed as idle, *CW* is decremented (Step 5). The CCA is repeated if $CW \neq 0$. This ensures performing two CCA operations to prevent potential collisions of acknowledgement frames. If the channel is again sensed as idle, the node attempts to transmit. Nevertheless, collisions may still occur if two or more nodes are transmitting at the same time.

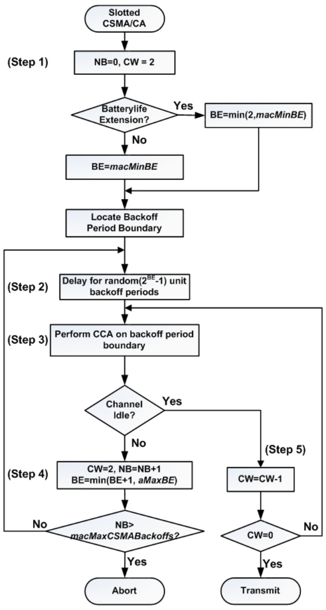
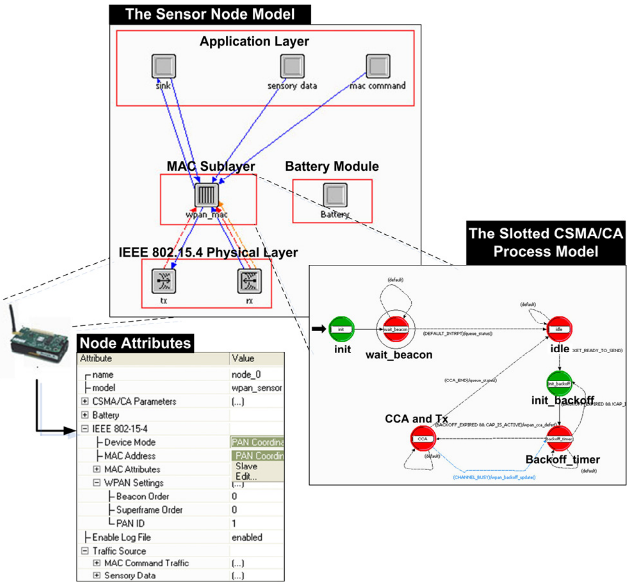


Fig. 2. The slotted CSMA/CA algorithm



Attribute	Value
name	node_0
model	wpan_sensor
CSMA/CA Parameters	(...)
Battery	
IEEE 802-15-4	
Device Mode	PAN Coordina
MAC Address	PAN Coordin Slave Edit...
MAC Attributes	
WPAN Settings	(...)
Beacon Order	0
Superframe Order	0
PAN ID	1
Enable Log File	enabled
Traffic Source	
MAC Command Traffic	(...)
Sensory Data	(...)

Fig. 3. Simulation model of an IEEE 802.15.4 sensor node

For more details on IEEE 802.15.4 and slotted CSMA/CA, the interested reader is referred to [8].

In this paper, since we are addressing the slotted CSMA/CA mechanism, the CAP is also referred to as the superframe (no CFP exists).

3. The Simulation Model

3.1 Simulation tool for IEEE 802.15.4

We have developed a simulation tool for the IEEE 802.15.4 slotted CSMA/CA mechanism using OPNET simulator [9]. Fig. 3 presents the simulation model used in our study.

The sensor node model is composed of four functional blocks: (1) The *physical layer* consists of a wireless transceiver (*rx* for reception and *tx* for transmission) compliant to the IEEE 802.15.4 specification operating at the 2.4 GHz frequency range, where each channel has a bandwidth of 2 MHz. The transmission power is set to 1 mW and the modulation scheme is *Quadrature Phase Shift Keying* (QPSK). (2) The *MAC sublayer* implements the slotted CSMA/CA. It is also responsible for generating beacon frames and synchronizing the network when used in a PAN coordinator node. (3) The *battery module* computes the consumed and remaining energy levels. The default values of current draws are set to those of the MICAz mote specifications [10]. (4) The *application layer* consists of two generators. The *sensory data* module generates unacknowledged frames and the *mac command* module generates acknowledged frames (not used in this paper). The *sink* module receives frames forwarded from lower layers and performs statistics.

Moreover, we use the default wireless models of OPNET library for emulating the background noise, propagation delay, radio interferences, received power, bit error rate, etc. In case of collisions, the reception result depends on the number of collided frames, received power and bit error threshold computed in the default receiver pipelines of the OPNET library.

3.2 Simulation test-bed

Our objective is to evaluate the performance of the slotted CSMA/CA mechanism as a MAC protocol for WSNs. We consider a typical wireless sensor network in a surface of $\left(100\text{ m} \bullet 100\text{ m}\right)$ with one PAN coordinator and 100 identical nodes (randomly spread) generating Poisson distributed arrivals, with the same mean arrival rate (Fig. 4). Note that the Poisson distribution is typically adopted by most simulation and analytical studies on CSMA/CA [2-6, 11].

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*.

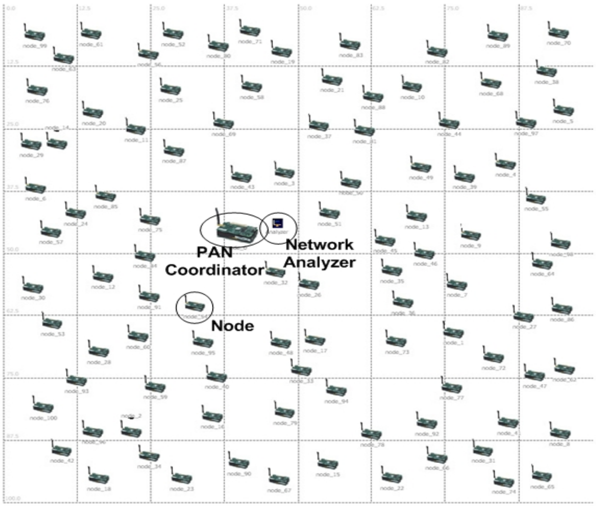


Fig. 4. Network topology (a PAN Coordinator, 100 Nodes and a Network Analyzer)

In WSNs, data dissemination is typically based on the diffusion of sensory data to all neighbors 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 terminal problem).

The slotted CSMA/CA attributes are set to their default values given by the standard [1] (*CW* = 2, *macMaxCSMABackoffs* = 5) and *macMinBE* = 2, unless explicitly specified.

We assume that the generated data frames have a constant size and are equal in all nodes. The default value in our simulations is 300 bits for data payload and 104 bits for the MAC header size (according to the standard specifications [1]). The global offered load (denoted as G) generated by all node's application layers depends on the inter-arrival times, which are exponentially distributed (Poisson arrivals). Basically, the performance of the slotted CSMA/CA mechanism will be evaluated as a function of the offered load G in the network.

We also denote G_{mac} as the offered load sent by the MAC sublayer. Note that G and G_{mac} can be different in case of an overflow in a node, when the frame arrival rate at the application layer (G) is higher than the output of the MAC sublayer (G_{mac}). In case of 100 nodes, based on our simulation tool we have $G \simeq G_{mac}$, for $G \leq 3$.

3.3 Performance Metrics and Utility

Since we propose to analyze the performance of the global network traffic, we have developed a *Network Analyzer* device (Fig. 4) operating in promiscuous mode (receiving all frames) for performing all required measurements and producing statistics.

The performance metrics analyzed in this paper are the following.

- **Network Throughput (*S*)**. It is the fraction of traffic correctly received by the Network Analyzer normalized to the overall capacity of the network (250 kbps). The $S(G)$ analysis of CSMA-like mechanisms was first introduced in [12]. Note that the *Error Correction threshold*, which specifies the highest proportion of bit errors allowed in a frame, is equal to 1, assuming a perfect error correction model. This means that in case of collisions of many frames, the first received frame will be correctly received and contribute to the throughput, while the others will be rejected. We have opted to this choice to evaluate the maximum performance achievable by slotted CSMA/CA.
- **Average delay (*D*)**. It 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 denote by $D(G)$ the average delay as a function of the offered load G.
- **Success probability (*Ps*)**. This metric is computed as S divided by G_{mac}, i.e. $Ps = S / G_{mac}$. It reflects the degree of reliability achieved by the network for successful transmissions. We denote by $Ps(G)$ the success probability as a function of the offered load G.
- **Utility (*U*).** We define the utility of the network as a combination of two or more metrics. The motivation behind the definition of the utility is that there is a need to identify the best network settings that jointly optimize two or more metrics. For example, when increasing the offered load G injected into the network, the network throughput $S(G)$ increases and the probability of success $Ps(G)$ decreases. Then, we can consider the following utility function $U(G) = S(G) \cdot Ps(G)$. Hence, the optimal offered load G_{op} is the one that maximizes the utility function $U(G)$. It is also possible to define other utility functions depending on which metrics need to be jointly optimized. In our simulations, we aim to determine the optimal range of offered loads that maximizes the network throughput (S) and minimizes the average delay (D). For that purpose, since both S and D grow with G (from our experiments in Section 5), we consider the following utility function:

$$U(G) = S(G) \frac{D_{ref}}{D(G)} \quad \textbf{(3)}$$

Dref is a constant (e.g. 1 ms) that specifies an average delay reference so that the utility function will be without unit.

4. Impact of the slotted CSMA/CA overheads on the saturation throughput

4.1 The saturation throughput concept

The purpose of this section is to evaluate the impact of the slotted CSMA/CA overheads (backoff delay, contention window, i.e. CCA and CCA deference) on the saturation throughput.

The *saturation throughput* is defined as the maximum traffic generated by a node using slotted CSMA/CA as a MAC protocol when it operates in the saturation mode, i.e. it always has a frame to transmit. Thus, the maximum saturation throughput of one node is achieved when only this node sends its traffic to the network, i.e. no collision occurs, in saturation mode. Therefore, the simulations presented in this section consider one PAN coordinator that only sends beacon frames, one node that sends data frames and the network analyzer to sniff all generated traffic. Obviously, the maximum throughput cannot reach 100% even if no collision occurs. This is due to four factors.

1. The impact of the backoff delay, forcing one node to wait even if the channel is idle.
2. The impact of the contention window (two mandatory CCA operations).
3. The impact of the CCA deference, when the remaining backoff periods in the superframe are less than the number required to transmit the entire frame.
4. The beacon frame.

4.2 Computation of the saturation throughput

First, we analyze the first two factors (backoff delay, contention window) by assuming an infinite superframe length (Fig. 5.a). We then analyze the impact of the CCA deference (Fig. 5.b). We assume that the data frame size is constant and equal to L backoff periods. Note that since only one node is contending for medium access, the CCA operations always report an idle channel.

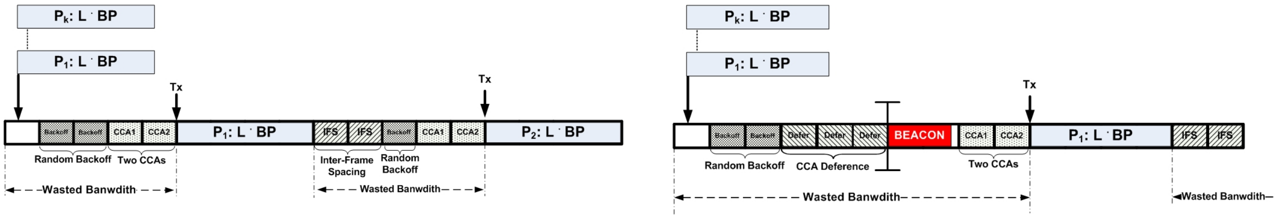


Fig. 5.a: Impact of the backoff algorithm on the Throughput

Fig. 5.b: Impact of the CCA Deference on the Throughput

Fig. 5. Impact of the backoff algorithm (5.a) and the CCA deference (5.b) on the saturation throughput of one node

The saturation throughput is the fraction of bandwidth used for successful data frame transmissions. In this case, it is the number of BPs used for data frame transmissions divided by the number of all BPs (used for data frame transmissions, backoff delay, CCAs, and CCA deference). Hence, if we assume that the superframe is infinite (no beacon frames, no CCA deference) (Fig. 5.a), each data frame transmission has an overhead including an inter-frame spacing, a random backoff delay and a contention period *CW* (corresponding to two CCAs). As a result, the saturation throughput assuming an infinite superframe length is expressed as:

$$S = \frac{L}{L + IFS + CW + \overline{n}_{BE}} \tag{4}$$

where $\overline{n}_{BE}$ is the mean backoff delay (expressed in BP) and IFS is the inter-frame spacing between two consecutive transmissions. For frame sizes greater than 144 bits, the minimum IFS is equal to 160 bits (0.64 ms = 2 BP), otherwise the minimum IFS is equal to 48 bits (0.192 ms = 0.6 BP).

However, the superframe length is actually limited, which forces the node to defer its transmissions if the number of remaining BPs is lower than the number needed to complete the transmission (Fig. 5.b). Hence, we can write:

$$S = \frac{L}{L + IFS + CW + \overline{n}_{BE} + \overline{n}_{deference}} \tag{5}$$

where $\overline{n}_{deference}$ is the mean number of BPs skipped due to CCA deference ***for each transmission***. It is then mandatory to compute $\overline{n}_{deference}$.

First, we determine the probability that a given transmission is deferred - $P_{deference}$. In [2-4], the authors proposed an expression of the CCA deference probability equivalent to:

$$P_{deference} = (L + CW)/SD \tag{6}$$

where *SD* is the superframe duration (Eq. (2)). This probability is independent from the beacon frame size and from the backoff delay. However, when the backoff delay increases the probability of CCA deference will obviously increase (this is also observed by simulation results).

For a given superframe duration, the number of data frame transmissions (when no collision occurs) is the following:

$$n_{tx} = \left\lfloor \frac{SD - L_{beacon}}{L + IFS + CW + \overline{n}_{BE}} \right\rfloor \tag{7}$$

where L_{beacon} is the beacon frame size. Note that n_{tx} comprises the transmission of one data frame deferred from the previous beacon interval (due to the saturation mode) (Fig. 5.b).The probability that a transmission is deferred to the next beacon interval after a backoff delay is:

$$P_{deference} = \frac{1}{n_{tx}} \tag{8}$$

Note that the probability of deference expressed in Eq. (8) depends on the beacon frame size and on the backoff delay, contrarily to Eq. (6). Actually, the probability of deference in Eq. (8) assumes that the backoff delay expires within the same superframe where it is started. However, in reality the backoff delay could be started in one superframe and resumed in the next superframe if the remaining BPs in the first superframe are lower than the backoff delay. Hence, this probability will be higher or equal to the real deference probability depending of the backoff delay. Thus, this probability holds the deference of both CCAs and backoff delays.

Thus, after the transmission of a data frame, a node would defer the transmission of the next data frame if the sum of the randomly generated backoff delay with the two CCAs and the data frame transmission time is higher than the remaining BPs. The skipped BPs in each superframe due to CCA deference is a random variable in between $\left[0,\ L + IFS + CW + \overline{n}_{BE}\right]$, whose distribution depends on the frame size, the backoff delay, and the beacon frame size. Assuming that n_{skip} is the mean number of skipped BPs due to a CCA deference, then $\overline{n}_{deference}$ is expressed as follows:

$$\overline{n}_{deference} = P_{deference} \cdot n_{skip} \tag{9}$$

In case of BE = 0, n_{skip} is a constant in each superframe since the backoff delay is constant and equal to 0.

In the following, we assume that the number of skipped BPs in each superframe is uniformly distributed in $\left[0,\ L + IFS + CW + \overline{n}_{BE}\right]$, therefore the mean number of skipped BPs in case of deference is $\left(L + IFS + CW + \overline{n}_{BE}\right)/2$.

4.3 Analytical vs. simulation results

In this example, we consider $BE = 3$, which leads to a mean backoff delay equal to $\overline{n}_{BE} = 3.5\ \text{BP}$.

Fig. 6 presents the probability of deference for different SO values. The deference probabilities are plotted using Eq. (6), Eq. (8) and by simulations. The simulator tool counts the number of all transmissions and the number of deferred transmissions and paused backoff delays. Then, it computes the average value that corresponds to the probability of deference.

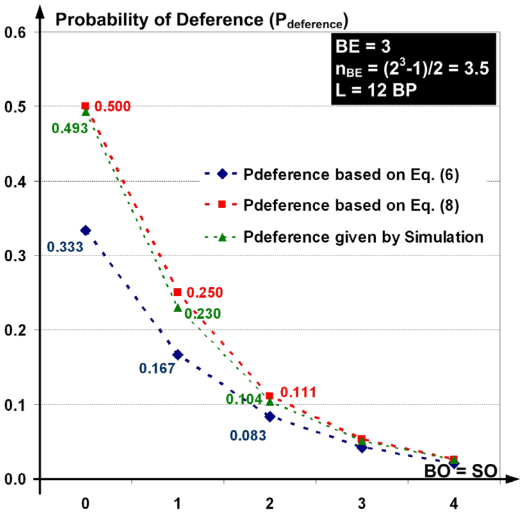


Fig. 6. CCA deference probability as a function of *SO* and *BO*

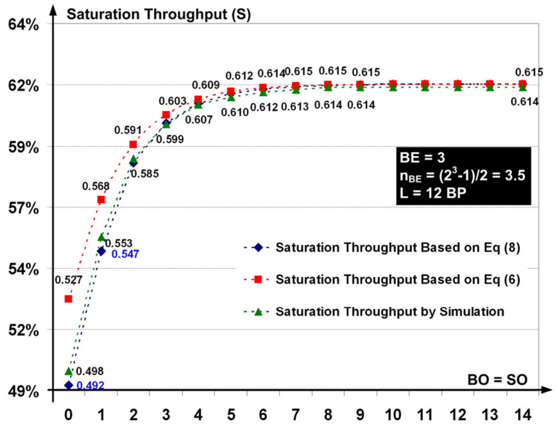


Fig. 7. Saturation throughput as a function of *SO* and *BO*

Fig. 7 presents the saturation throughput (S) for different superframe orders. The three curves are obtained by simulations and analytically using Eq. (5), where the probabilities of deference are computed using Eq. (6) and Eq. (8).

Similarly to the observation of Fig. 6, Eq. (8) leads to more accurate results than Eq. (6) as compared with simulation results. A first conclusion is that the slotted CSMA/CA mechanism introduces a significant amount of overheads (approximately 50%) for $SO = 0$. This is due to the fact that many backoff periods are wasted due to CCA deference and more frequent beacon frames. The throughput would be even worse for shorter data frames. Note that for short data frames the deference probability will be lower. However, the backoff delay (namely with high *BE* values) will have a more negative impact on the throughput, since the fraction of BPs used by the backoff delay and both CCAs would be higher than that used by data frame transmissions. This result can also be observed by Eq. (5).

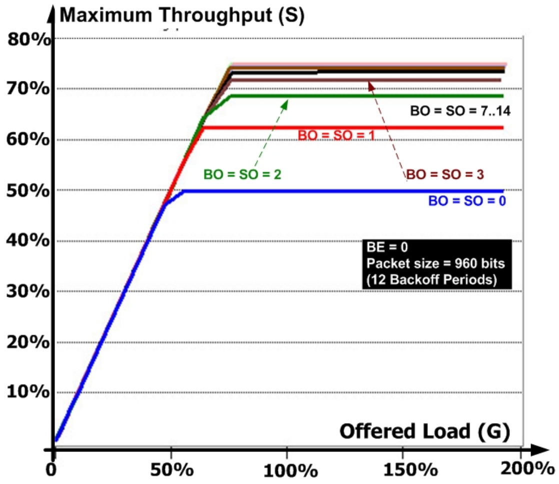


Fig. 8. Saturation throughput as a function of the offered load with a data frame size *L* = 12 BPs

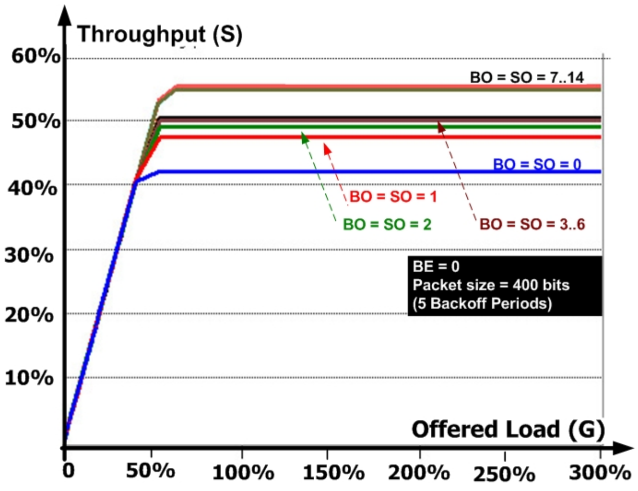


Fig. 9. Saturation throughput as a function of the offered load with a data frame size *L* = 5 BPs

Figs. 8 and 9 present the saturation throughputs as a function of the offered load (*G*) for a data frame size equal to 12 BPs and 5 BPs, respectively, for *BE* = 0. Note that since the medium is always sensed idle, *BE* will not be incremented (is always equal to 0). We observe that the throughput for low offered loads (≤ 50%) is independent from *SO*. Observe also, that the saturation throughput for *L* = 5 BPs is only 55% compared to 75% for *L* = 12 BPs.

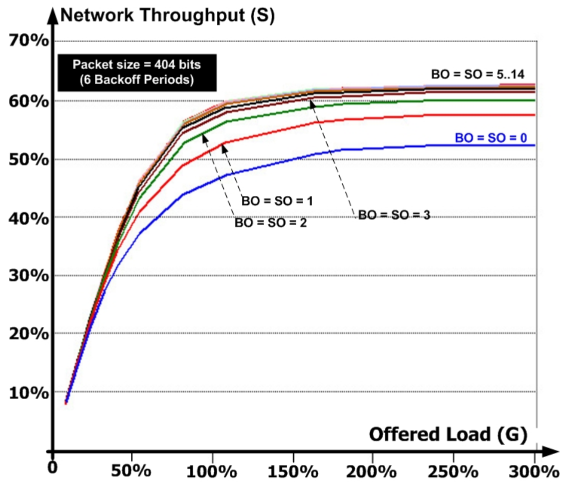
The impact of the frame size on the network throughput will be further investigated in a more generic perspective in Section 5.4.

5. Performance evaluation of slotted CSMA/CA under different settings

5.1 Study 1 – impact of *SO* and *BO*

Setting *BO* and *SO* is one of the most important tasks of the PAN coordinator. It has been shown in [8] that low *SO* values (equal to 0, 1, 2) provide the best timing performance compared to high *SO* values, when using the GTS mechanism in the CFP. In this paper, we analyze the impact of *BO* and *SO* on the performance of slotted CSMA/CA.

We run the simulation test-bed, described in Section 3.2, for different values of *SO* (and *BO* = *SO*). For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads, assuming a constant packet size (see Section 3.2). Each curve corresponding to (*SO, BO*) couple is obtained for thirteen different inter-arrival times (hence, thirteen *G* values). Figs. 10, 11, (12, 14) and 15 present the network throughput, the success probability, the average delay, and the utility (as defined in Eq. (3)), respectively, as a function of the offered load *G* for different *SO* values.



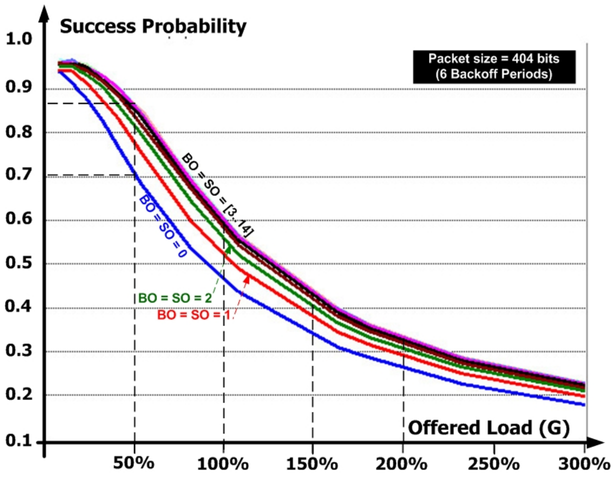


Fig. 10. The network throughput as a function of the offered load for different (*BO*, *SO*) values

Fig. 11. The success probability as a function of the offered load for different (*BO*, *SO*) values

Observe that, as expected, low SO values produce lower throughput due to the reasons explained in Section 4.3.

Comparing Figs. 9 and 10, we observe that the saturation throughput (for high offered loads $G \geq 1.5$) is practically the same in both cases (1 node in case of Fig. 9 and 100 nodes in case of Fig. 10). The impact of collisions on the network throughput is more visible for low offered loads ($G \leq 100\%$), since for a given load G, the network throughput is lower in case of 100 nodes due to collisions. The impact of the number of nodes will be analyzed in Section 5.3.

The increase in the superframe order from SO equal to 5 to 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 of multiple nodes, and thus leads to higher network throughputs.

Note that for high offered loads, the network throughput reaches a stable saturation throughput (around 62%). However, the success probability is quite low when the offered load increases (see Fig. 11).

From Fig. 11, it can be observed that for an offered load G lower than 50%, the probability of success is higher than 80% for SO>1 and 70% for SO = 0, which might be acceptable as an average guarantee for broadcasts in WSNs, since WSN nodes generate traffic at low rates. Hence, if the entire offered load is restricted to 50% (125 kbps), then each of the 100 nodes should generate data frames at a rate of 1.25 kbps, which is likely to be adequate in real WSNs. An important advantage of the IEEE 802.15.4 protocol is that it provides a capacity of 250 kbps, which is higher than the capacity of other protocols generally operating below 40 kbps (e.g. MICA2 motes [10]). Hence, even by restricting the network at 50% of its capacity, the protocol will still offer a significant bit-rate of 125 kbps.

Fig. 12 shows that the average delays significantly increase with SO for a given offered load G higher than 50% as explained next. The high probability of CCA deference results in having collisions of many data frames in 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 should be higher.

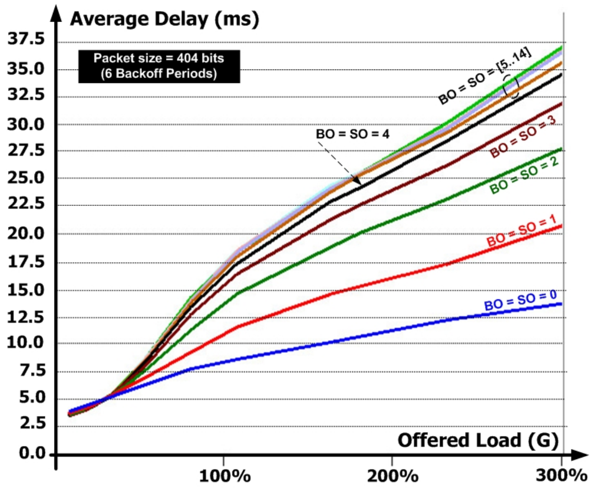


Fig. 12. The average delay as a function of the offered load for different (*BO*, *SO*) values

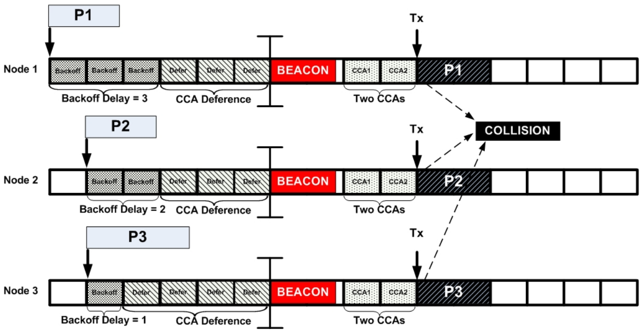


Fig. 13. Collision problem after a CCA deference

This problem is illustrated in Fig. 13, where three data frame transmissions are deferred to the next superframe leading to a collision.

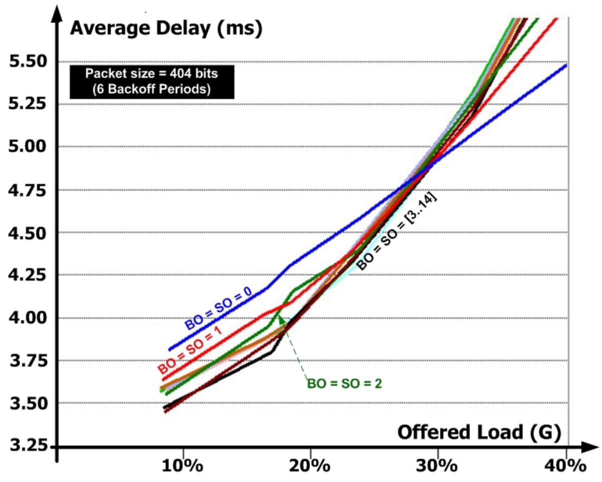
The situation presented in Fig. 13 will frequently happen with low SO values, which clearly explains the low network throughput observed in Fig. 10 for low *SO* values. Now, in the example of Fig. 13 if we consider that the superframe duration is greater, node 3 can start its transmission before nodes 1 and 2 wake up. These latter nodes will then sense the channel busy (since node 3 is transmitting), and thus go to backoff with higher backoff delay value (after increasing *BE*). This fact clearly explains the higher average delay value obtained with high superframe orders.

Now, let us consider the average delay for offered loads lower than 50% (Fig. 14).

We observe that, in this case, higher delays are experienced with lower *SO* values. The reason is that with low offered loads, the impact of the CCA deference on the network throughput is reduced as compared with high offered loads (we can observe in Fig. 10 that the network throughput is the same with all *SO* values for $G \leq 50\%$), hence, less collisions will occur. However, due to more successful transmissions after the CCA deference, the average delay is more affected by the time spent waiting for the next superframe, which increases for lower superframe orders. The backoff delay will not have a great impact on the performance since with low offered load, the channel will be sensed as idle more often and thus the backoff delay will remain low.

Fig. 15 shows that, according to the utility function defined in Eq. (3), the optimal offered load range is located in between $\left[35\%,60\%\right]$ of the network capacity, i.e. the best tradeoff between delay guarantee and network throughput is achieved in this range. The peak is generally achieved around 40% of offered load, except for *SO* = 0 and SO = 1, where the peak is reached for around 60% of offered load.

Observe also that the utility peak value is almost the same for all *SO* values. However, for higher offered loads, the utility is higher for lower superframe orders.



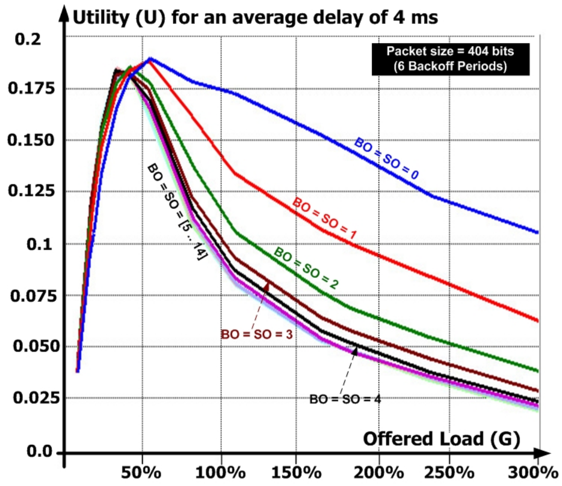


Fig. 14. The average delay as a function of the offered load for different (*BO*, *SO*) in the range *G* = [0, 40%]

Fig. 15. The Utility (U) as a function of the offered load (G) for different (*BO*, *SO*) values

Summary. It has been shown that high superframe orders provide better network throughput than low superframe orders due to their increased immunity against the CCA deference symptom. On the other hand, low *SO* values result in lower average delays in case of high offered loads. This is mainly because backoff delays remain low due to frequent collisions after the CCA deference. With low offered loads, the average delays with higher *SO* values are smaller due to low fractions of CCA deference backoff periods.

It can be understood that the CCA deference presents two different limitations depending if it is with high or low offered loads.

1. With high offered loads, it causes lower network (saturation) throughputs due to the collisions resulting from of multiple simultaneous transmissions after the deference, at the beginning of a new superframe.
2. With low offered loads, it causes an increase in the average delay due to the wasted amount of backoff periods during the CCA deference.

Hence, one of the important challenges for improving slotted CSMA/CA is to reduce the probability of collisions after the CCA deference, by avoiding multiple transmissions in the next superframe. One idea is to go again into a backoff delay at the beginning the next superframe instead of immediately starting transmissions after two CCAs.

5.2 Study 2 – impact of *macMinBE*

The Backoff Exponent (*BE*) is an important parameter in the backoff algorithm of slotted CSMA/CA. It enables the computation of the random backoff delay before trying to access the channel. Note that this behavior is particularly different from the backoff algorithm of the DCF in IEEE 802.11 [7]. The initial value, denoted as *macMinBE*, is set to 3 by default [1], but can be set differently by the MAC sublayer in the range [0,5]. Setting *macMinBE* to 0 would disable collision avoidance during the first iteration of the algorithm.

The purpose of this section is to study the impact of the initialization value *macMinBE* on network performance.

We run the simulator (described in Section 3.2), for different values of *macMinBE* - from 0 to 5. For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads with a constant packet size (see Section 3.2). Each curve corresponding to a given *macMinBE* is obtained for thirteen different inter-arrival times. Figs. 16, 17, 18 and 19 present the network throughput, success probability, average delay, and utility (as defined in Eq. (3)), respectively, as a function of the offered load for different *macMinBE* values. Figs. 16 and 17 are plotted for two *SO* values (0 and 3).

In Fig. 16, it is observed that the network throughput is completely independent from the initial value of the backoff exponent *macMinBE*. Similarly, in Fig. 17 the probability of success is independent from *macMinBE*. We do remember that in case of 100 nodes, we have $G = G_{mac}$, for $G \leq 3$.

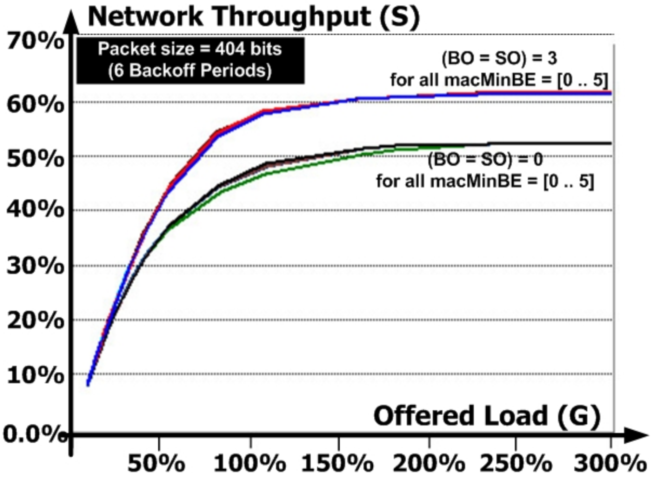


Fig. 16. The network throughput as a function of the offered load for different *macMinBE* values with 100 nodes

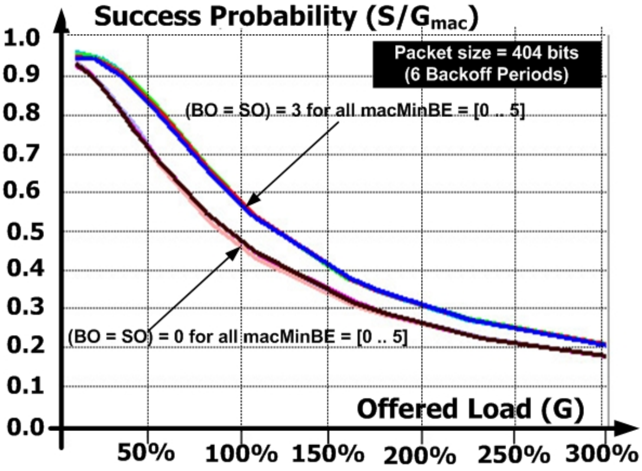


Fig. 17. The success probability as a function of the offered load for different *macMinBE* values with 100 nodes

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 behavior 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 $\left[0..2^{\text{macMinBE}}\text{-}1\right]$. Independently from *macMinBE*, the lower limit of the backoff delay interval is always 0 and 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 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 of other nodes. Thus, the backoff interval will tend to $\left[0{,}31\right]$ in all remaining nodes waiting to access the medium and, as a result, the backoff delay distribution will not depend too much on the initialization value of *macMinBE*.

It is clear that a critical limitation of slotted CSMA/CA is that the upper limit of the backoff delay interval is limited to $2^5\text{-}1\text{=}31$ BPs. This value is too small (e.g. as compared to 1024 in IEEE 802.11) to reduce the impact of collisions in a WSN of with a significant number of nodes. In fact, let us consider a scenario with ten competing nodes. Fig. 18 presents the corresponding network throughput as a function of the offered load for different *macMinBE* values.

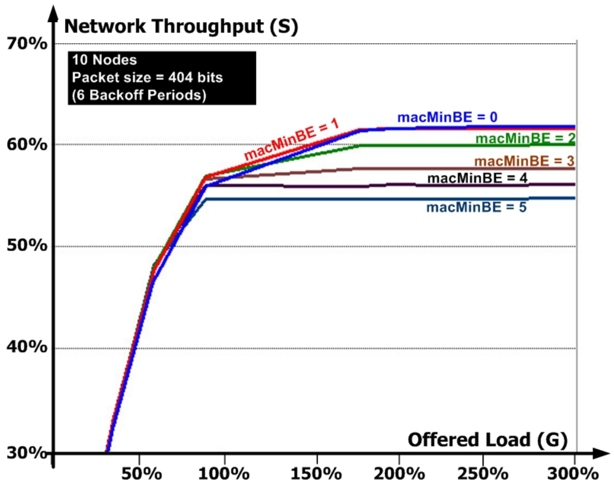


Fig. 18. The network throughput as a function of the offered load for different *macMinBE* values with 10 nodes

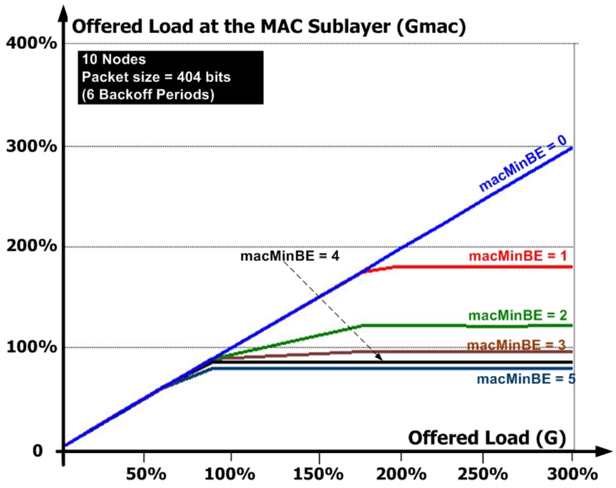


Fig. 19. *Gmac* as a function of the offered load for different *macMinBE* values with 10 nodes

In this case, the network throughput depends on the initialization value *macMinBE*, but, contrarily to what should be expected, the network saturation throughput decreases when increasing the *macMinBE*. However, this does not mean a worse behavior for higher *macMinBE*. In fact, the *macMinBE* has an important influence on the amount of traffic sent to the network by the MAC sublayer (G_{mac}), as it is shown in Fig. 19.

Fig. 19 presents the offered load produced by the MAC sublayer (G_{mac}) as a function of the offered load of the application layer (G). The remaining part of the traffic $\left(G - G_{mac}\right)$ is still queued waiting for service or dropped in case of limited buffer sizes.

Inversely to the case of 100 nodes, where $G = Gmac$ for all *macMinBE*, in a small-scale network with only ten nodes, the increase of *macMinBE* reduces the load effectively transmitted in the network. This is because high backoff delays will cause more wasted backoff periods not used by any of the competing nodes. This is explained by the small number of competing nodes in the network. This result has a positive impact on the success probability (S/G_{mac}), as depicted in Fig. 20.

Fig. 20 presents the success probability as a function of the offered load (G). As it is expected, increasing the backoff delay interval (starting with high *macMinBE*) results in a better success probability, while avoiding collisions in small-scale WSNs. Most of the traffic sent is correctly received for high *macMinBE*s.

This behavior is different from the CSMA/CA version defined in IEEE 802.11 [7]. In fact, in IEEE 802.11 the backoff delay is chosen within an interval $\left[CW_{\min}..CW_{\max}\right]$ where $CW_{\min}$ and $CW_{\max}$ are the lowest and highest values of the backoff delay interval, respectively. These limits can be set in the range of $\left[0,1024\right]$. It has been shown in [13-14] that $CW_{\min}$ has the most critical impact on the saturation throughput.

Hence, by analogy, in case of the slotted CSMA/CA, the impact of *macMinBE* on the network throughput is limited, since it only affects the higher limit of the backoff delay interval , while the lower limit is always equal to 0. This is likely to be a limitation in the slotted CSMA/CA backoff algorithm of IEEE 802.15.4, since the standard does not allow changing the lower limit of the backoff delay interval. This limitation mainly reduces the flexibility of the slotted CSMA/CA to have different ranges for the backoff delay.

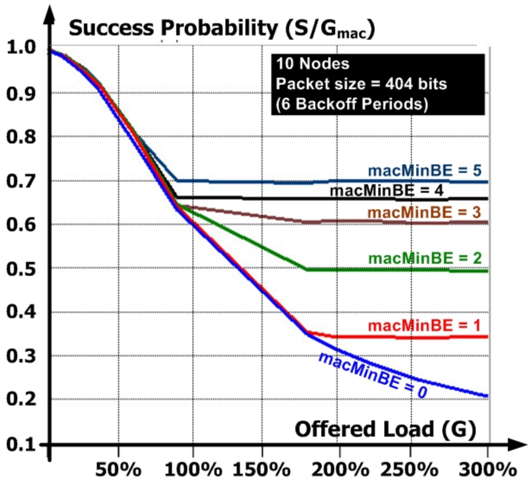


Fig. 20. The success probability as a function of the offered load for different *macMinBE* values with 10 nodes

In Fig. 21 (100 nodes), observe that the average delay increases with *macMinBE* for a given offered load. 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 ($G \le 50\%$), 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 $G \ge 50\%$, the impact of *macMinBE* is significantly more visible. For instance, for G = 300%, the average delay is higher than 110 ms (344 BPs) for *macMinBE* = 5, whereas it is does not exceed 8 ms (25 BPs) in case of *macMinBE* = 0.

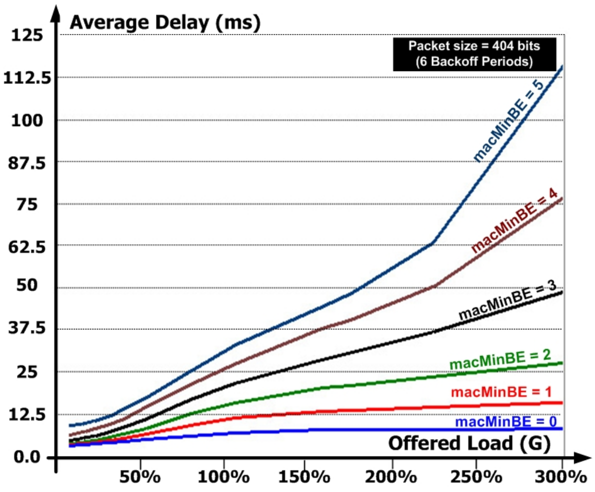


Fig. 21. The average delay as a function of the offered load for different *macMinBE* values with 100 nodes

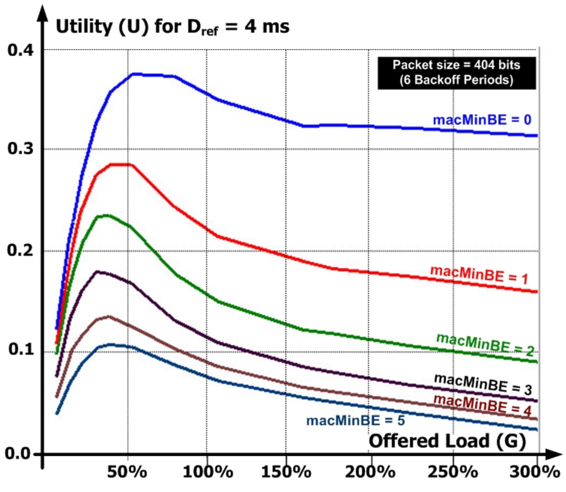


Fig. 22. The Utility (Eq. 3) as a function of the offered load for different *macMinBE* values with 100 nodes

In case *macMinBE* = 0, the average delay is almost independent from the offered load in the range $G \in$ [100%, 300%] (there is only 2 ms of average delay variation). The variation of the average delay is more visible for higher *macMinBE*, in the range $G \in$ [100%, 300%].

In Fig. 22, it is clear that the lowest *macMinBE* provides the best network throughput/delay tradeoff. This is because the network throughput is almost the same for all *macMinBE*s, while the lowest average delay is met with *macMinBE* = 0.

Observe that the utility reaches its peak value in the range of offered loads $G \in$ [35%, 60%], similarly to the previous study. The same conclusions also hold in this case.

Summary. In this study, we have shown that the network throughput is independent from the initial value of the backoff exponent *macMinBE* for a "large-scale" WSN. This is because the lower limit of the backoff delay interval [0, 2^{BE}-1] is not affected by the choice of *macMinBE*. However, the impact of *macMinBE* on the network throughput is quite important in small scale networks. In fact, increasing *macMinBE* will lead to relatively lower network throughput (since the capacity of the network (250 kbps) is not entirely used for high *macMinBE*), but to significant higher success probability thanks to more efficient collision avoidance.

In conclusion, the collision avoidance mechanism is not efficient in case of a large-scale WSN. However, the choice of *macMinBE* has a significant impact on average delays. In fact, for a given offered load *G*, the average delay experimented in the network increases with *macMinBE*. The variance is quite important for high offered loads. Based on the utility results, *macMinBE* = 0 is the best configuration for an optimal network throughput/average delay tradeoff. For all *macMinBE* values, the best tradeoff is achieved for $G \in$ [35%, 60%] similarly to the results in Study 2.

5.3 Study 3 – impact of the number of nodes

The number of nodes in a WSN can differ from one application to another (large-scale, medium-scale or small-scale WSNs). The purpose of this section is to evaluate the impact of the number of nodes in the network on the performance of the slotted CSMA/CA mechanism.

We run the simulation test-bed, described in Section 3.2, for different number of nodes in the network (10, 25, 50, 100, 200). For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads with a constant packet size (see Section 3.2). Each curve corresponding to a given number of nodes is obtained for thirteen different inter-arrival times. Figs. 23, 24, 25 and 26 present the network throughput, success probability, average delay, and utility (as defined in Eq. (3)), respectively, as a function of the offered load for different number of nodes.

Fig. 23 shows that the network throughput is almost independent from the number of nodes generating a given offered load *G* for a large scale network (number of nodes ≥ 50). The offered load is a bit lower for a ten node network. This is because the network throughput in small-scale networks is shown to be dependent of *macMinBE* value, which is set to 2 in this situation (same interpretation as in Section 5.2). The offered load generated by the MAC sublayer is lower than that generated by the application when the number of nodes is low.

The network throughput only depends on the offered load *G* whatever it is generated by 10, 25, 50, 100 or 200 nodes. However, for a given offered load *G*, the load generated by each node is obviously inversely proportional to the number of nodes. Hence, the number of competing nodes does not have any impact on the network throughput if the offered load in the network is the same.

As a result, if we assume that slotted CSMA/CA ensures fairness among all competing nodes in terms of throughput, the per-flow throughput will decrease when the number of nodes increases.

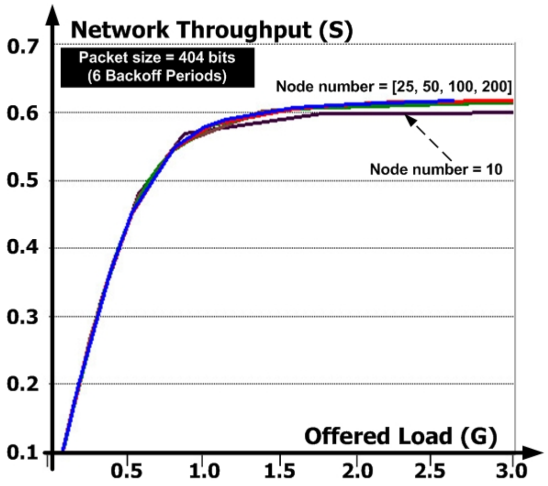


Fig. 23. The network throughput as a function of the offered load for different number of nodes

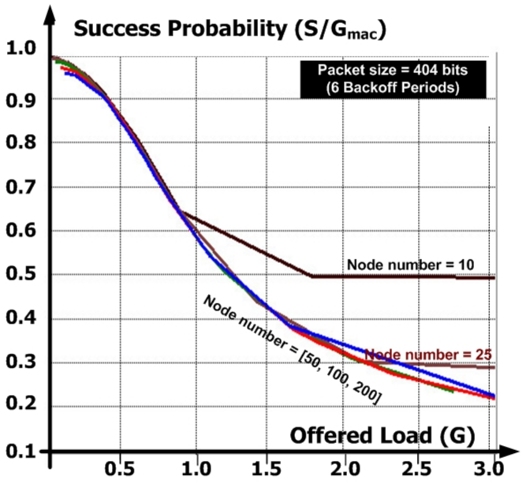


Fig. 24. The success probability as a function of the offered load for different number of nodes

Fig. 24 shows that the success probability in small and medium scale networks (with 10 and 25 nodes) is better than that in larger-scale networks. This means that the collision avoidance mechanism is much better for a small number of competing nodes, as we have discussed in Section 5.2, since the backoff delay is limited to 31 BPs. However, this is not priceless. In fact, based on Fig. 25, the average delays are shown to be quite high for networks with 10 and 25 nodes as compared to larger-scale networks (50, 100 and 200 nodes) in case of high offered loads. This is due to higher queuing delays in small-scale networks, since the per-node offered load is high in this case (it is inversely proportional to the number of nodes). There will be more frames that arrive from the application layer than those effectively sent to the network. This impact can be reduced by using *macMinBE* = 0, as it has been shown in Section 5.2.

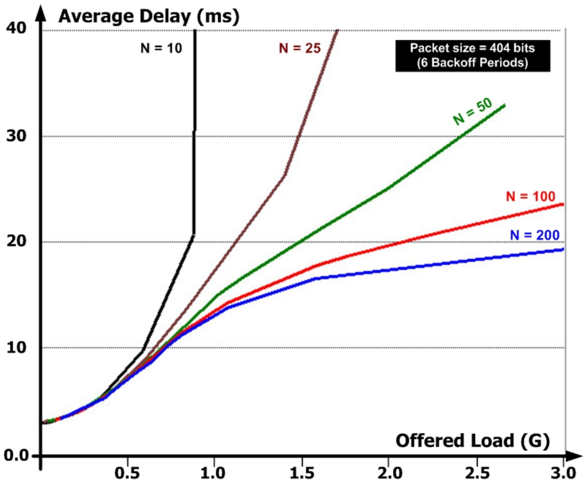


Fig. 25. The average delay as a function of the offered load for different number of nodes

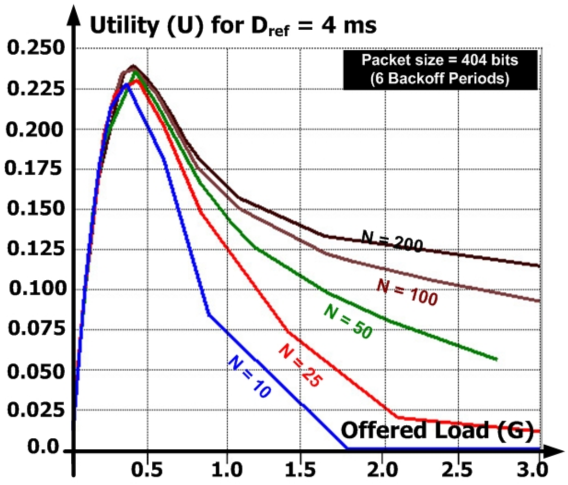


Fig. 26. The Utility as a function of the offered load for different number of nodes

Fig. 26 presents the utility function and shows that the optimal offered load range that ensures the best trade-off between average delay and network throughput is $G \in$ [35%, 60%]. Observe that, in this range, the tradeoff is achieved similarly for the different node numbers (almost the same value of utility) with a small exception when the number of nodes is equal to 10 (due to higher average delays), where the optimal range is limited to $G \in$ [35%, 60%].

Summary. In this section, we have shown that slotted CSMA/CA does not scale well with the size of the network. This is basically due to the limitation of its backoff algorithm. The basic advantage of slotted CSMA/CA for small scale networks is to provide high success probability.

However, small scale networks cannot deal with high offered load efficiently since they experience high delays.

5.4 Study 4 – impact of the frame size

The purpose of this section is to evaluate the impact of data frame size on the performance of slotted CSMA/CA.

We run the simulation test-bed, described in Section 3.2, for data frame sizes of 300, 500, 700, 900 bits. For each configuration, we vary the inter-arrival times of the flows in each node to have different offered loads (see Section 3.2). Each curve corresponding to a given number of nodes is obtained for thirteen different inter-arrival times (13 *G* values). Figs. 27, 28, 29 and 30 present the network throughput, success probability, average delay, and utility (as defined in Eq. (3)), respectively, as a function of the offered load G for different data frame sizes.

It can be conducted from Fig. 27, that the network throughput is better for longer data frames in high offered load conditions. This is because the slotted CSMA/CA overheads (backoff delay, CCA and CCA deference) have more impact on shorter frames, as it has been explained in Section 4. In fact, a successful transmission of a 900-bit data frame utilizes the channel more efficiently than three successful transmissions of 300-bit data frames due to slotted CSMA/CA overheads.

Fig. 28 shows that the success probability is higher for longer frames. This is a consequence of having better network throughput for longer frames. Observe that in most WSN applications, nodes transmit small amounts of data, which typically results in small data frames. Based on these results, we conclude that it is very efficient to perform data aggregation and send longer frames. The other advantage of aggregation is to reduce the amount of the protocol overheads (MAC header, backoff delays and CCA), by sending one frame instead of two or three.

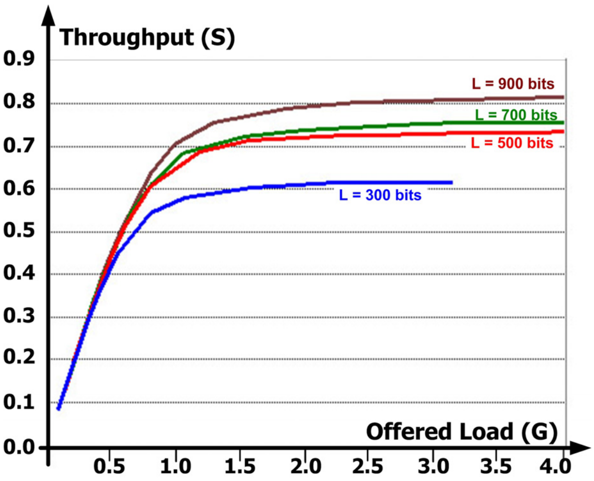


Fig. 27. The network throughput as a function of the offered load for different frame sizes

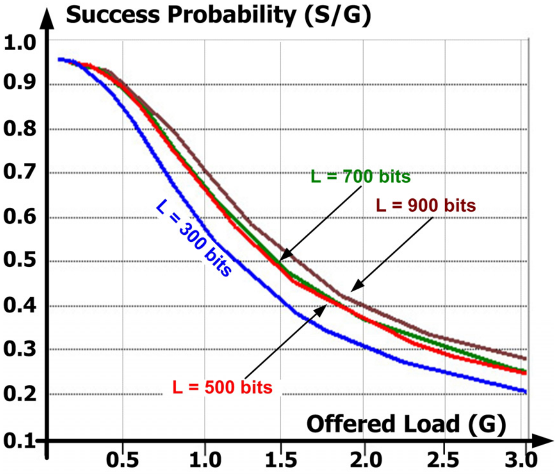


Fig. 28. The success probability as a function of the offered load for different frame sizes

In Fig. 29, it can be observed that the average delay experimented by long frames is a little bit higher. This is because longer frames have longer transmission times than shorter frames. However, the variation is not significant even for high offered load (less than 10 ms). In fact, during the transmission of a long frame, other nodes waiting for channel access will go to backoff more often than with the transmission of a small frame, since the channel occupancy period in the former case is higher. This results in higher backoff delays since the backoff exponent will increase leading to higher average backoff delays.

Observe in Fig. 30 that the offered load corresponding to utility peaks slightly differs with the frame size. The optimal offered load increases with the frame size. In this case also the range of offered load $G \in [35\%, 60\%]$ is the most suitable for a best trade-off between delay and network throughput.

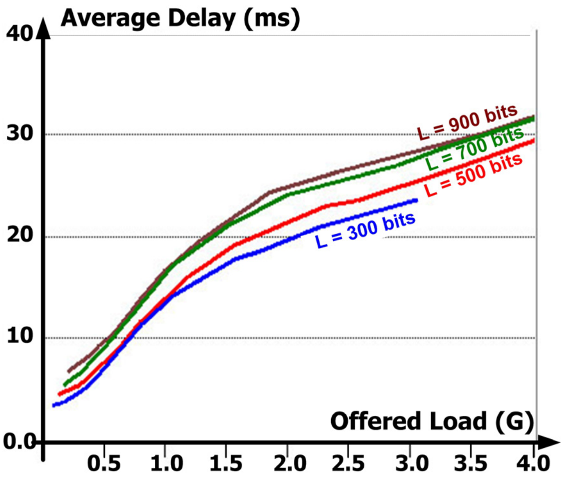


Fig. 29. The average delay as a function of the offered load for different frame sizes

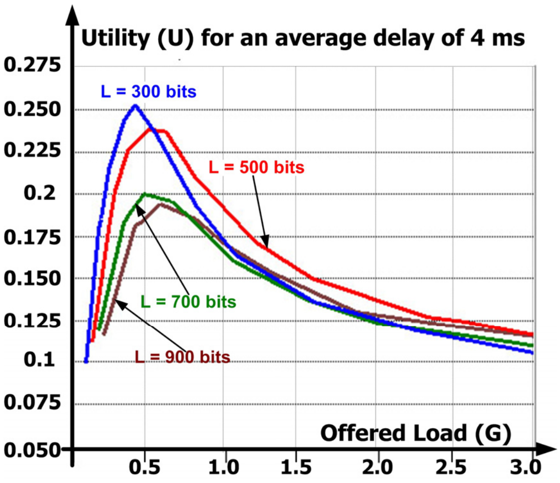


Fig. 30. The Utility as a function of the offered load for different frame sizes

For low offered loads, short frames lead to a better trade-off between network throughput and average delays, (greater utility). However, for higher offered loads, the trade-off is achieved similarly for all the frame sizes.

Summary. In WSNs, if the global load of the network is lower than 60%, aggregation may be useless for ensuring higher reliability since short frames have the advantage to produce similar throughput with lower average delays. In case of higher offered loads, it is more convenient to send long frames by using aggregation.

6. Conclusions

In this paper we have proposed a comprehensive performance evaluation and analysis of the slotted CSMA/CA medium access mechanism deployed by the IEEE 802.15.4 protocol in beacon-enabled mode.

We built a simulation tool to evaluate the impact of the following parameters on the performance of slotted CSMA/CA: (1) the slotted CSMA/CA overheads, (2) the beacon order and the superframe order, (3) the initialization value of the backoff exponent, (4) the number of nodes in the network (5) and finally the frame size.

We have studied the application of slotted CSMA/CA for broadcast transmissions in wireless sensor networks. The basic conclusions are the following.

- The backoff algorithm of slotted CSMA/CA is not flexible enough for large-scale sensor networks since the lower limit of the backoff delay is always 0, preventing specific ranges for the backoff delays, and its upper limit cannot not exceed 31 BP, which is not sufficient to avoid collisions in large scale sensor networks;
- The optimal range of offered load that makes the best trade-off between network throughput/average delay (utility) is, in general, $G \in \left[35\%, 60\%\right]$.
- Lower superframe orders introduce additional overheads due to more CCA deference and collisions after deference. It is important to propose a solution for recovering from this simultaneous collisions with low superframe orders in order to improve the throughput;
- Data aggregation is suitable in case of high offered load $G \geq 50$ % for providing high throughput, and thus improving the reliability (success probability) without increasing too much the average delay.

Finally, this work paves the way for a full understanding of the slotted CSMA/CA mechanism and its efficient use in WSNs. It also essential to improve the performance of this mechanism by introducing priority mechanisms and proposing some add-ons to turn slotted CSMA/CA more flexible and fair for large-scale sensor networks.

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