A Comprehensive Simulation Study of Slotted CSMA/CA for IEEE 802.15.4 Wireless Sensor Networks

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Abstract

In this paper, we analyze the performance limits of the slotted CSMA/CA mechanism of IEEE 802.15.4 in the beacon-enabled mode for broadcast transmissions in WSNs. The motivation for evaluating the beacon-enabled mode is due to its flexibility 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) on the network performance, namely in terms of throughput (S), average delay (D) and probability of success (Ps). 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 advent 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 IEEE 802.15.4 MAC attributes (*BO*, *SO*, and *BE*) 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. We have elaborated more results in [16] including the evaluation of the saturation throughput and the impact of the number of nodes and frame size on the performance of slotted CSMA/CA, which will not be presented in this paper due space limitation.

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.

The rest of this paper is organized as follows. Section 2 presents an overview of IEEE 802.15.4 and its slotted CSMA/CA mechanism. Section 3 highlights the simulation model. Section 4 presents the performance evaluation studies of slotted CSMA/CA under different settings, namely as a function of the couple (*BO*, *SO*) and the backoff exponent. Section 5 concludes the paper.

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.

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:

$$BI = aBaseSuperframeDuration \cdot 2^{BO} \quad for\ \ 0 \le BO \le 14 \qquad \textbf{(1)}$$

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

$$SD = aBaseSuperframeDuration \cdot 2^{SO} \quad for\ \ 0 \le SO \le BO \le 14 \qquad \textbf{(2)}$$

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, each time slot has a duration of $15.36/16 = 0.96$ 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 $aUnitBackoffPeriod = 80\text{ bits }(0.32\text{ ms})$. 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).

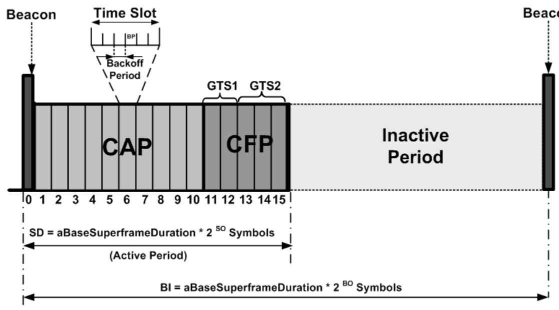

Fig. 1. Beacon interval and superframe concepts

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 $\left[0, 2^{BE}\text{-}1\right]$. 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(2, *macMinBE*) 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 [0, 2^{BE}-1] (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, provided that the remaining BPs in the current CAP are sufficient to transmit the frame and the subsequent acknowledgement. If not, the CCAs and the frame transmission are both deferred to the next superframe. This is referred to as *CCA deference*.

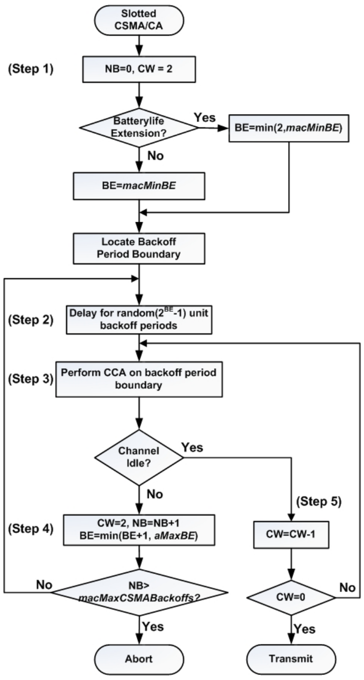

Fig. 2. The slotted CSMA/CA algorithm

Note that this algorithm is activated for each transmission of a new packet. 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] presented in Fig. 3.

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 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.

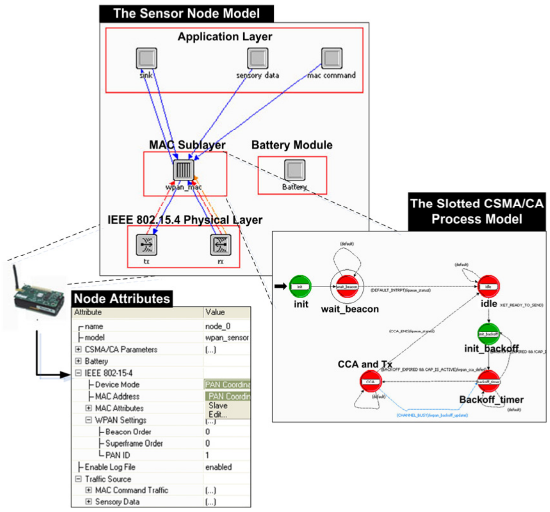

Fig. 3. Simulation model of an IEEE 802.15.4 sensor node

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. The following physical channel attributes are set as follows. The *transmit power* is set to 1 mW, the *path loss model* is set Free Space, for which the received power is inversely proportional to the square of the distance (d^2), and the antennas are considered to be isotropic. The sensing sensitivity is set to 0, thus enabling each node to detect the channel as busy if any frame is being transmitted (no hidden-node problem).

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 (100 m x 100 m) 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 $BO = SO$. The Beacon frame size is assumed to be constant and equal to 120 bits (MAC Header + Beacon Frame Header).

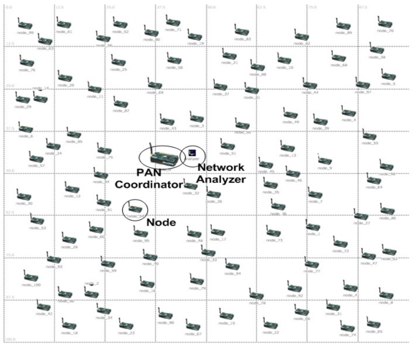

Fig. 4. Network topology (a PAN Coordinator, 100 nodes and a network analyzer)

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]). This choice is just an example of a small frame size. 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 average offered load (normalized to 250 kpbs) 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 $G \leq 300$ %. There is no loss in the queues.

The simulation duration is set to 50 s. We have verified that the results presented in this paper are equivalent to those obtained with higher simulation durations since the behavior of the evaluated network is stationary.

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 4), we consider the following utility function:

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

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

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

4.1 Study 1 – impact of *SO* and *BO*

Setting *BO* and *SO* is one of the most important tasks of the PAN coordinator. In this section, 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. 5, 6, (7, 9) and 10 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.

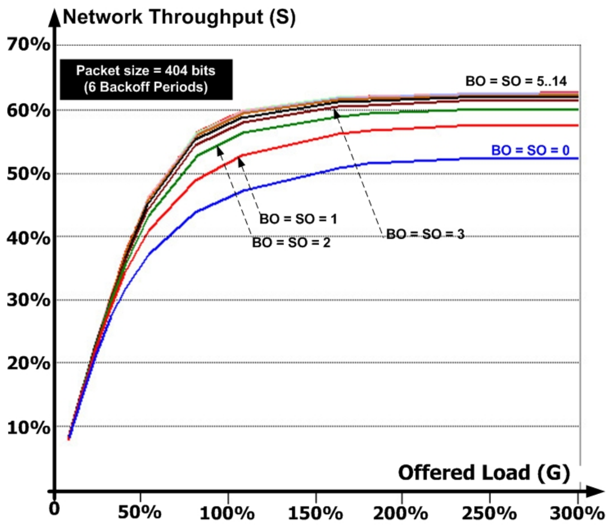

Fig. 5. The network throughput as a function of the offered load for different (*BO*, *SO*) values

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.

The increase in the superframe order from *SO* equal to 5 until 14 has little to no 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.

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. 6).

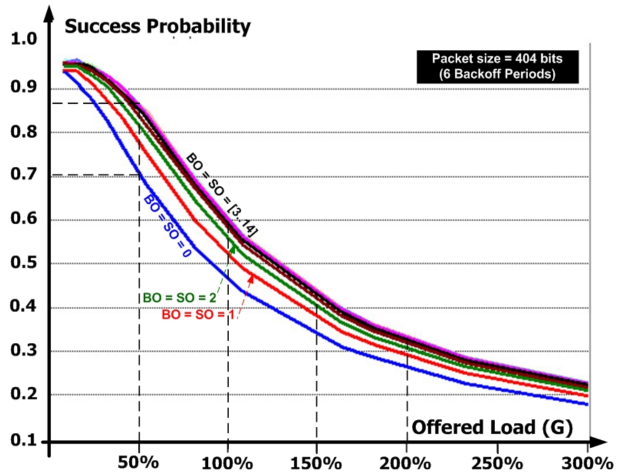

Fig. 6. Success probability as a function of the offered load for different (*BO*, *SO*) values

From Fig. 6, it can be observed that for an offered load *G* lower than 50%, the probability of success is higher than 80% for $SO \geq 1$ 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.

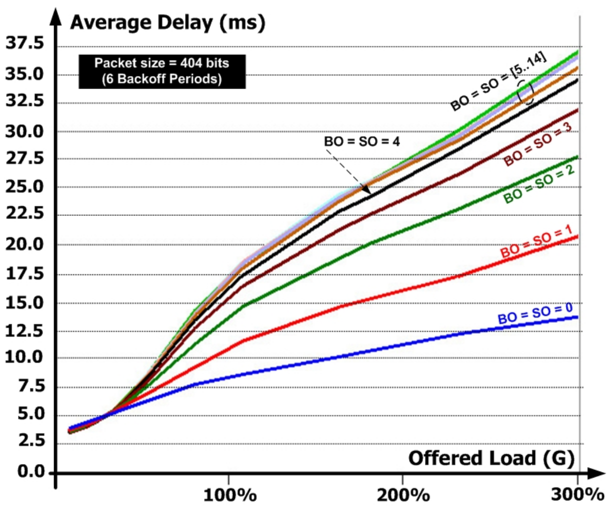

Fig. 7. The average delay as a function of the offered load for different (*BO*, *SO*) values

Fig. 7 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 *SO* values. 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.

This problem is illustrated in Fig. 8, where three data frame transmissions are deferred to the next superframe leading to a collision.

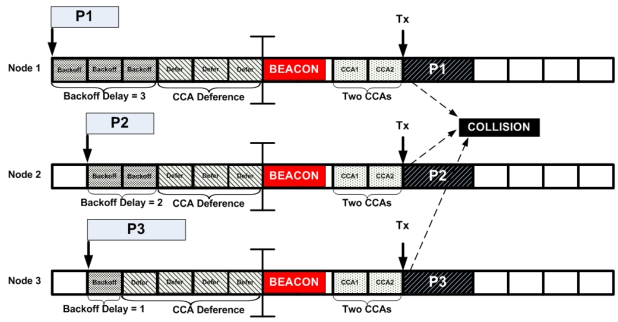

Fig. 8. Collision problem after a CCA deference

The situation presented in Fig. 8 will frequently happen with low *SO* values, which clearly explains the low network throughput observed in Fig. 5 for low *SO* values. Now, in the example of Fig. 8 if we consider greater superframe durations, 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. 9).

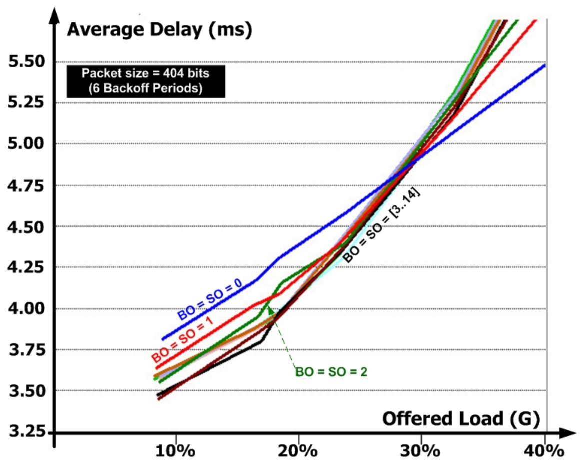

Fig. 9. The average delay as a function of the offered load for different (*BO*, *SO*) in the range G = [0, 40%]

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. 10 shows that, according to the utility function defined in Eq. (3), the optimal offered load range is located in between [35%, 60%] 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.

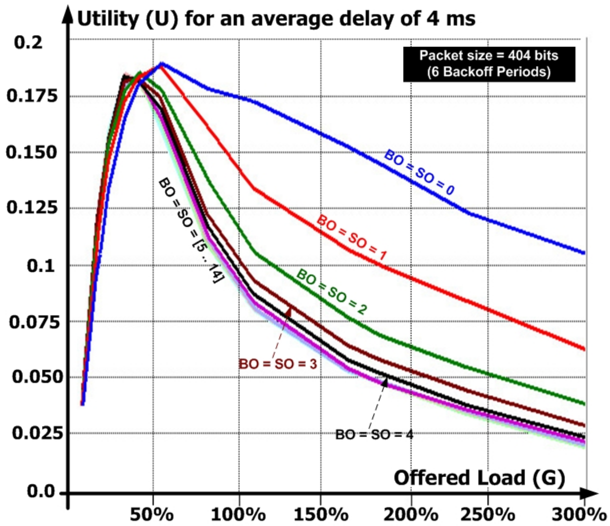

Fig. 10. Utility (*U*) as a function of the offered load (*G*) for different (*BO*, *SO*) values

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 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.

4.2 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.

In Fig. 11, it is observed that the network throughput is completely independent from the initial value of the backoff exponent *macMinBE*. Similarly, in Fig. 12 the probability of success is independent from *macMinBE*. We recall that in case of 100 nodes, we have $G = G_{mac}$, for $G \leq 300$ %.

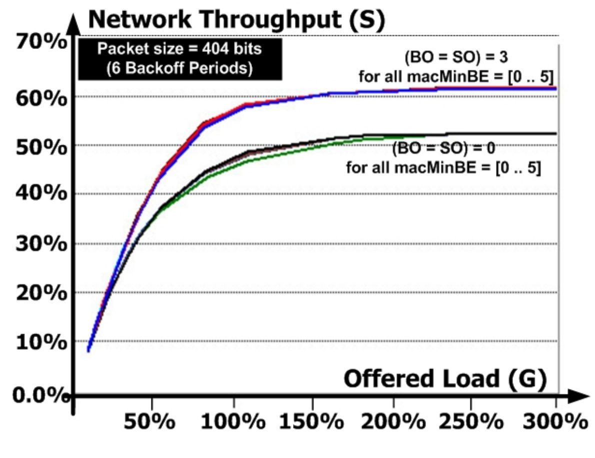

Fig. 11. The network throughput as a function of the offered load for different *macMinBE* values

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 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 [0, $2^{macMinBE}$-1]. 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 [0,31] 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*.

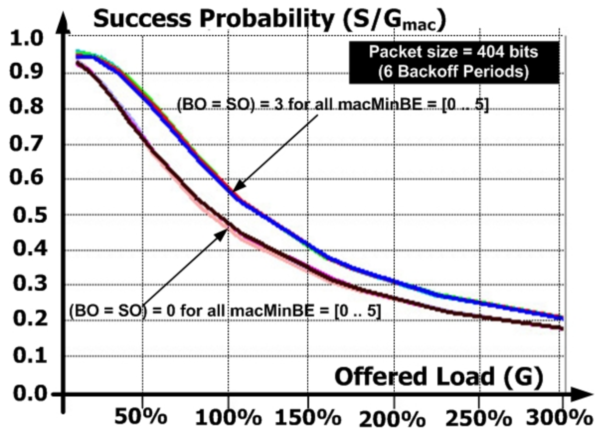

Fig. 12. The success probability as a function of the offered load for different *macMinBE* values

It is clear that a critical limitation of slotted CSMA/CA is that the upper limit of the backoff delay interval is limited to 2^5-1 = 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. 13 presents the corresponding network throughput as a function of the offered load for different *macMinBE* values with 10 competing nodes.

In this case, the network throughput depends on the initialization value *macMinBE*, but, contrarily to what is 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. 14.

Fig. 14 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.

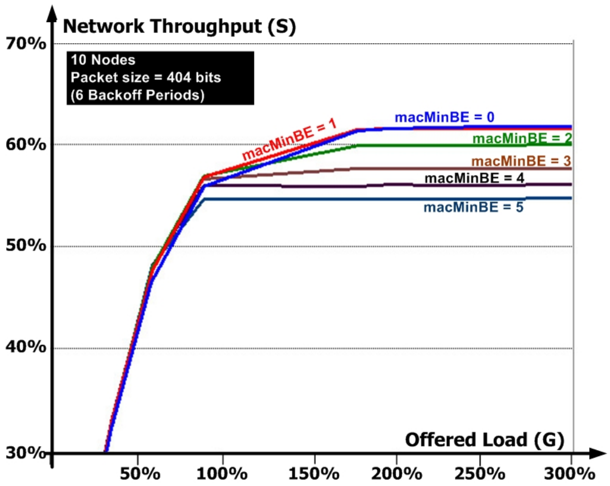

Fig. 13. The network throughput as a function of the offered load for different *macMinBE* values with 10 nodes

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. 15.

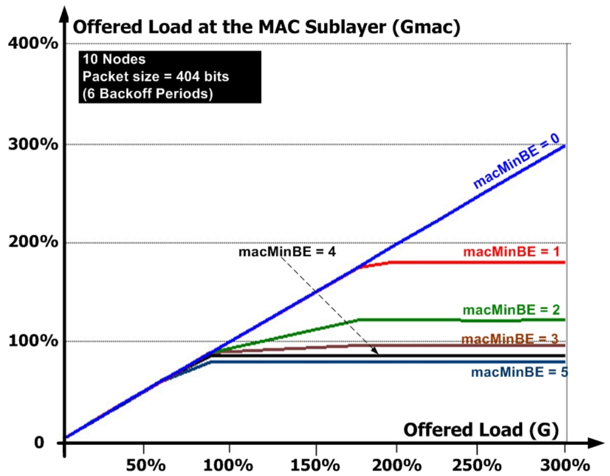

Fig. 14. *Gmac* as function of the offered load for different *macMinBE* values with 10 nodes

Fig. 15 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.

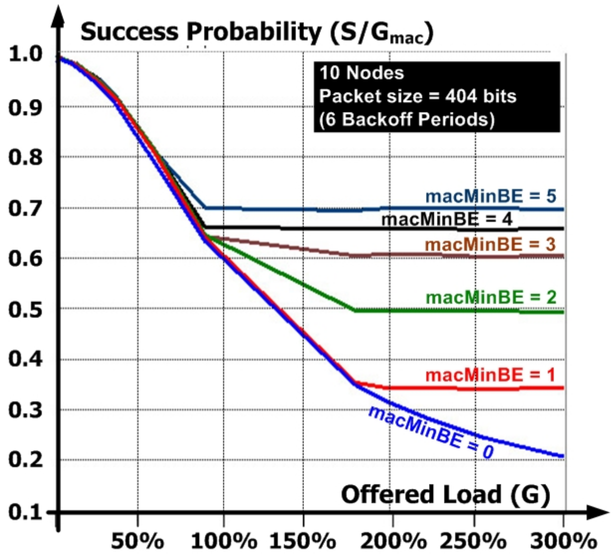

Fig. 15. The success probability as a function of the offered load for different *macMinBE* values with 10 nodes

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 [11,15] 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.

In Fig. 16 (with 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 ($G \leq 50\%$), 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 (344 BPs) for *macMinBE* = 5, whereas it is does not exceed 8 ms (25 BPs) in case of *macMinBE* = 0.

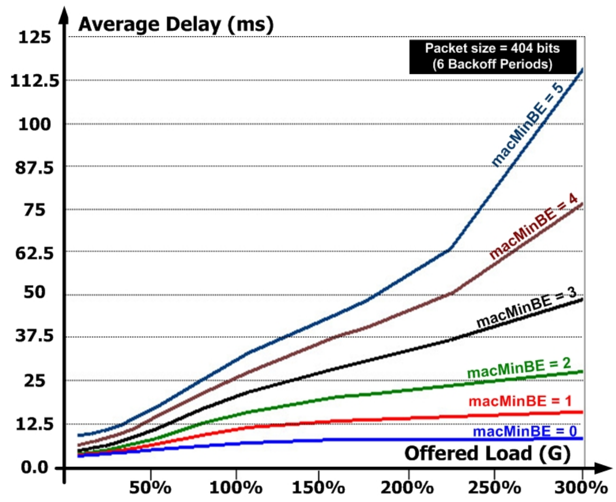

Fig. 16. The average delay as a function of the offered load for different *macMinBE* values with 100 nodes

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 $G \in [100\%, 300\%]$.

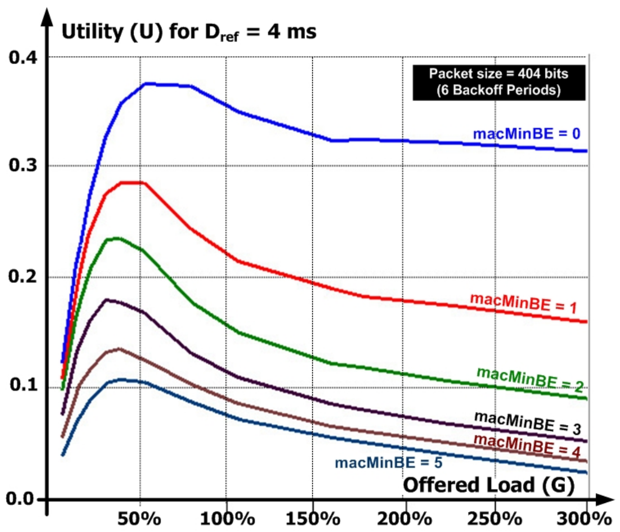

Fig. 17. The Utility (Eq. 3) as a function of the offered load for different *macMinBE*

In Fig. 17, 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 $[0, 2^{BE}\text{-}1]$ 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 1.

5. 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 beacon order and the superframe order, (2) the initialization value of the backoff exponent.

We have studied the application of slotted CSMA/CA for broadcast transmissions in wireless sensor networks. The reason is that broadcast is commonly used in most of WSN applications.

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 BPs, 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, $G \in [35\%, 60\%]$.
- 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;

In addition, in [16] we have elaborated more results related to the impact of the number of nodes and frame size on the performance of slotted CSMA/CA, but were not presented in this paper due to space limitation.

Finally, this work paves the way for a full understanding of the slotted CSMA/CA mechanism and its efficient use in WSNs. It is 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.

In our future work, we will first extend our simulation model to consider the hidden-terminal problem for evaluating its impact on the performance metrics and particularly on the throughput degradation. We are also conducting simulation studies of the presented scenarios using Network Simulator NS-2 [14], which has already proposed an implementation of the IEEE 802.15.4 protocol, to compare the results obtained by our simulation tool with those obtained by NS-2. The objective of such a comparison is to assess the confidence of the results obtained by different simulation tools.

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