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Technical Report

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Abstract

In beacon-enabled mode, IEEE 802.15.4 is ruled by the slotted CSMA/CA Medium Access Control (MAC) protocol. The standard slotted CSMA/CA mechanism does not provide any means of differentiated services to improve the quality of service for timecritical events (such as alarms, time slot reservation, PAN management messages etc.). In this paper, we present and discuss practical service differentiation mechanisms to improve the performance of slotted CSMA/CA for time-critical events, with only minor add-ons to the protocol. The contribution of our proposal is more practical than theoretical since our initial requirement is to leave the original algorithm of the slotted CSMA/CA unchanged, but rather tuning its parameters adequately according to the criticality of the messages. We present a simulation study based on an accurate model of the IEEE 802.15.4 MAC protocol, to evaluate the differentiated service strategies. Four scenarios with different settings of the slotted CSMA/CA parameters are defined. Each scenario is evaluated for FIFO and Priority Queuing. The impact of the hiddennode problem is also analyzed, and a solution to mitigate it is proposed.

Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks

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In beacon-enabled mode, IEEE 802.15.4 is ruled by the slotted CSMA/CA Medium Access Control (MAC) protocol. The standard slotted CSMA/CA mechanism does not provide any means of differentiated services to improve the quality of service for time-critical events (such as alarms, time slot reservation, PAN management messages etc.). In this paper, we present and discuss practical service differentiation mechanisms to improve the performance of slotted CSMA/CA for time-critical events, with only minor add-ons to the protocol. The contribution of our proposal is more practical than theoretical since our initial requirement is to leave the original algorithm of the slotted CSMA/CA unchanged, but rather tuning its parameters adequately according to the criticality of the messages. We present a simulation study based on an accurate model of the IEEE 802.15.4 MAC protocol, to evaluate the differentiated service strategies. Four scenarios with different settings of the slotted CSMA/CA parameters are defined. Each scenario is evaluated for FIFO and Priority Queuing. The impact of the hidden-node problem is also analyzed, and a solution to mitigate it is proposed.

1. Introduction

Providing Quality of Service (QoS) support in Wireless Sensor Networks (WSNs) for improving their timing and reliability performance under severe energy constraints has attracted recent research works [1-3]. The standardization efforts of the IEEE Task Group 15.4 have contributed to solve this problem by the definition of the IEEE 802.15.4 protocol for *Low-Rate*, *Low-Power* Wireless Personal Area Networks (WPANs) [4]. In fact, this protocol shows great potential for flexibly fitting different requirements of WSN applications by adequately setting its parameters (low duty cycles, guaranteed time slots (GTS)). In beacon-enabled mode, the IEEE 802.15.4 protocol uses slotted CSMA/CA as a Medium Access Protocol (MAC). Even though the IEEE 802.15.4 protocol provides the GTS allocation mechanism for real-time flows, the allocation must be preceded by an allocation request message. However, with its original specification, the slotted CSMA/CA does not provide any QoS support for such time-sensitive events, including GTS allocation requests, alarms, PAN management commands, etc., which may result in unfairness and degradation of the network performance, particularly in high load conditions.

Related work. The improvement of CSMA/CA MAC mechanisms has drawn many research efforts. Particularly for the case of the IEEE 802.15.4 protocol, some recent research works have contributed to enhance the slotted CSMA/CA mechanism for achieving reduced (soft) delay guarantees and better reliability of time-critical events, as described next.

In [5], the authors modified the slotted CSMA/CA algorithm to enable fast delivery of high priority frames in emergency situations, using a priority toning strategy. Nodes that have high priority frames to be transmitted must send a tone signal just before the beacon transmission. If the tone signal is detected by the PAN Coordinator, an emergency notification is conveyed in the beacon frame, which alerts other nodes with no urgent messages to defer their transmissions by some amount of time, in order to privilege high priority frame transmissions at the beginning of the contention access period. In [6], the authors extend the previous schemes by allowing high priority frames to perform only one *Clear Channel Assessment* (CCA) operation instead of two, using a frame tailoring strategy, which aims to avoid collisions between data frames and acknowledgment frames when only one CCA is performed. These solutions seem to improve the responsiveness of high priority frames in IEEE 802.15.4 slotted CSMA/CA, but require a non-negligible change to the IEEE 802.15.4 MAC protocol to support the priority toning and frame tailoring strategies, thus turning them non-compatible with the standard.

In this paper, we investigate other alternatives for improving slotted CSMA/CA without forcing fundamental changes to the MAC protocol. We particularly aim to assess different parameter settings of the protocol with some basic queuing strategies (FIFO and Priority Queuing) for each traffic priority. Note that in [5, 6], the toning mechanism imposes some changes to the hardware (using a tone signal transmitter) and also to the protocol itself, due to the frame tailoring strategy.

The motivation for proposing differentiated QoS support with only minor add-ons to the slotted CSMA/CA mechanism is to ensure backward compatibility with the standard. Also, we would like to assess if such a simple approach is sufficient to satisfy the requirements of time-critical messages. This proposal can be easily adopted in the IEEE 802.15.4b extension [7] of the standard.

The rest of the paper is organized as follows. Section 2 highlights the IEEE 802.15.4 features and its slotted CSMA/CA mechanism. Section 3 presents the proposed differentiation service strategies. Section 4 presents the simulation study and performance evaluation results. Section 5 concludes the paper.

2. IEEE 802.15.4 Slotted CSMA/CA MAC

In beacon-enabled mode, beacon frames are periodically sent by a central device, referred to as *PAN coordinator*, to identify its PAN and synchronize nodes that are associated with it. The PAN coordinator defines a superframe structure characterized by a *Beacon Interval* (*BI*) specifying the time between two consecutive beacons, and a *Superframe Duration* (SD) corresponding to the active period, defined as:

$$\begin{aligned} BI &= aBaseSuperframeDuration \cdot 2^{BO} \\ SD &= aBaseSuperframeDuration \cdot 2^{SO} \\ &for\ \ 0 \le SO \le BO \le 14 \end{aligned} \qquad \textbf{(1)}$$

BO and *SO* are called *Beacon Order* and *Superframe Order*, respectively. The Beacon Interval may optionally include an inactive period (for *SO* < *BO*), in which all nodes may enter into a sleep mode, thus saving energy. More details can be found in [4].

By default, nodes compete for medium access using slotted CSMA/CA during the *Contention Access Period* (CAP). The

IEEE 802.15.4 protocol also provides a *Contention-Free Period* (CFP) within the superframe, in which a node may request the PAN coordinator to allocate Guaranteed Time Slots (GTS). In this paper, we consider the physical layer operating in the 2.4 GHz frequency band and with a 250 kbps data rate.

The slotted CSMA/CA algorithm is based on a basic time unit called *Backoff Period* (BP), which is equal to $aUnitBackoffPeriod = 80 \text{ bits } (0.32 \text{ ms})$. The slotted CSMA/CA backoff algorithm mainly depends on three variables: **(1)** the *Backoff Exponent* (*BE*) enables the computation of the backoff delay, **(2)** the *Contention Window* (*CW*) represents the number of BPs during which the channel must be sensed idle before channel access, **(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. Fig. 1 presents the slotted CSMA/CA algorithm [4].

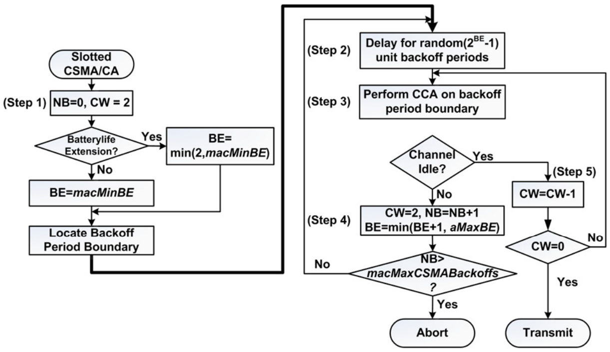

Fig. 1. The slotted CSMA/CA algorithm

First, the number of backoffs and the contention window are initialized ($NB = 0$ and $CW = CW_{init} = 2$) (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, 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 $CW_{init} = 2$, *NB* and *BE* are incremented. *BE* must not exceed *aMaxBE* (default value fixed to 5). Incrementing *BE* increases the probability for having greater backoff delays. If the maximum number of backoffs ($NB = macMaxCSMABackoffs = 5$) is reached, the algorithm reports a failure to the higher layer; otherwise, it goes back to (Step 2) and the backoff operation is restarted. The protocol allows $aMaxFrameRetries = 3$ after each failure. 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*.

3. Service Differentiation Strategies for Slotted CSMA/CA

Observe that the behavior of slotted CSMA/CA is affected by four *initialization* parameters, which are: (1) the minimum backoff exponent (*macMinBE*), (2) the maximum backoff exponent (*aMaxBE*), (3) the initial value of the *CW* (CW_{init}) and (4) the maximum number of backoffs (*macMaxCSMABackoffs*).

Changing the value of any of these parameters will have an impact on the performance. For instance, a performance evaluation study in [8] has shown that the average delay of broadcast frames increases with *macMinBE*, whereas the probability of success remains independent of *macMinBE* in large-scale WSNs. However, the probability of success increases for high *macMinBE* values, in small-scale WSNs. Based on those observations, we propose to offer differentiated services for time-critical messages. In this paper, our service differentiation mechanisms are particularly based on the *macMinBE*, *aMaxBE* and CW_{init} parameters.

Note that IEEE 802.15.4 defines two frame types: (1) *data traffic*, which typically represents sensory data broadcasted to the network (without using acknowledgments), (2) and *command traffic*, which comprises critical messages (such as alarm reports, PAN management messages and GTS requests) sent by sensor nodes to the PAN Coordinator. Due to their importance, command frames are sent using acknowledged transmissions to ensure the reliability of their transfer, and require a particular QoS support to be delivered to their destination in a bounded time interval. In this paper, we consider command frames as the *high priority service class* and data frames as the *low priority service class*.

The differentiated service strategies are presented in Fig. 2.

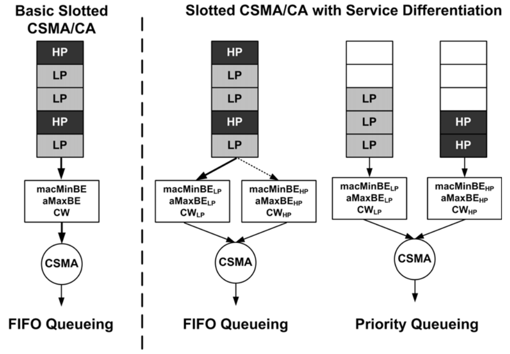

Fig. 2. Differentiated service strategies

The idea is simple. Instead of having the same CSMA/CA parameters for both traffic types, we assign each class its own attributes. We denote [$macMinBE_{HP}$, $aMaxBE_{HP}$] and CW_{HP} the backoff interval and the contention window initial values for high priority traffic related to command frames, and [$macMinBE_{LP}$, $aMaxBE_{LP}$] and CW_{LP} the initial values for low priority traffic related to data frames. While, the slotted CSMA/CA described in Section 2 remain unchanged, the adequate initial parameters that correspond to each service class must be applied.

In addition to the specification of different CSMA/CA parameters, Priority Queuing can be applied to reduce queuing delays of high priority traffic (Fig. 2). In this case, slotted CSMA/CA uses priority scheduling to select frames from queues, and then applies the adequate parameters corresponding to each service class. Note that if a low priority frame is selected, i.e. the high priority queue is empty, then the backoff process corresponding to this frame will not be preempted, if a high priority frame arrives during that service time, until this frame is sent, or rejected if the maximum number of backoff is reached.

The heuristics for adequately setting the CSMA/CA parameters are the following. Intuitively, a first differentiation consists in setting CW_{HP} smaller than CW_{LP}. It results that low priority traffic has to assess the channel to be idle for a longer time before transmission. A second differentiation is related to the backoff interval. Providing lower backoff delay values for high priority traffic by setting $macMinBE_{HP}$ lower than $macMinBE_{LP}$ would improve its responsiveness without degrading its throughput, as it has been observed in [8]. These intuitive heuristics are evaluated in the next section.

4. Performance Evaluation

4.1 Simulation Workload and scenarios

We present a simulation study based on an accurate model of IEEE 802.15.4 using OPNET simulator [9], to assess the impact of differentiated services in slotted CSMA/CA. We consider a WSN in a surface of 100 m x 100 m with one PAN coordinator, $BO = SO = 3$ and 100 identical nodes (randomly spread) generating *low priority* (*data*) *traffic* with Poisson distributed arrivals with the same mean arrival rate. The data frame size is fixed to 404 bits (300 bits of data payload + 104 bits of MAC header). These nodes also generate *high priority* (*command*) *traffic* with an inter-arrival time exponentially distributed with a mean value equal to 1 second. The command frame size is fixed to 304 bits (200 bits of data payload + 104 bits of MAC header). Frame size values are chosen as illustrative examples of short frame sizes. Command frames are sent from nodes to the PAN Coordinator using acknowledged transmissions. Data frames are simply broadcasted to the network. The maximum number of backoffs *macMaxCSMABackoffs* is equal to 4 and the maximum number of retries *aMaxFrameRetries* is by default equal to 3. The transmission power is equal to 0.1 mW.

The simulation study consists in varying the intensity of data traffic, while the command frames remain exponentially generated with the average of 1 frame/second in each node, and analyzing the performance of command frames in terms of average delay (D), probability of success ($S/Gapp$) and power efficiency. S denotes the throughput of command frames and $Gapp$ denotes the offered load of command frames generated by the application layers of 100 nodes. In this study, $Gapp$ is approximately equal in average to 31.5 kbps (= 100 * 304 bits per second), which represents 12.5% of the overall network capacity (250 kbps).

Note that there is a difference between $Gapp$ and $Gmac$. The latter is defined as the offered load generated by the MAC layers due to the transmissions of original command frames and the retransmissions of their copies in case of non successful delivery. Hence, the power efficiency is reflected by the $Gmac$ performance metric, i.e. fewer retransmissions (lower $Gmac$) results in a better power efficiency.

In this paper, the performance of data frames is also analyzed in terms of average delay and probability of success $\left(S_{data}/G_{mac}^{data}\right)$, which reflects the degree of reliability achieved by the network for successful transmissions of data frames. In case of data traffic, the probability of success is measured by the throughput of data frames S_{data} divided by the offered load of data frames generated by the MAC layers (G_{mac}^{data}). Since there is no retransmissions in case of a transmission failure of a data frame (unacknowledged transmissions), G_{mac}^{data} is at most equal to G_{app}^{data}, which is the data traffic generated by the application layer. This is because, at a given time, it may happen that some data frames are still waiting for service in the queue. Note that in our scenario with 100 nodes, we have verified that $G_{mac}^{data} = G_{app}^{data}$, for all network loads (G) considered in this simulation study (no buffer overflow for data frames). The network load (G) represents all command and data frames generated by the MAC layers of 100 nodes.

We consider four different scenarios, presented in Table 1. Each scenario is simulated with FIFO and Priority Queuing scheduling policies (refer to Fig. 2).

Table. 1. Simulation scenarios

Scenario	[macMinBE$_{HP}$, aMaxBE$_{HP}$]	[macMinBE$_{LP}$,aMaxBE$_{LP}$]	CW$_{HP}$	CW$_{LP}$
Sc1	[2,5]	[2,5]	2	2
Sc2	[2,5]	[2,5]	2	3
Sc3	[0,5]	[2,5]	2	2
Sc4	[0,5]	[2,5]	2	3

4.2 Case of a fully connected network (no hidden-node problem)

First, we consider a fully connected network, where all nodes hear each other.

Fig. 3 clearly shows the impact of the first differentiation scheme related to the initial contention window size on the success probability. As it was intuitively expected, setting CW_{LP} greater than CW_{HP} notably results in higher throughputs for high priority command frames, either for FIFO or Priority Queuing. The success probability remains satisfactory even in high load conditions for Sc2 and Sc4 (up to 80%). However, the effects of *macMinBE* and scheduling policies are negligible on $S/Gapp$ since Sc1 and Sc3 have the same throughput (similarly to Sc2 and Sc4) for different *macMinBE* values. This confirms the result in [8].

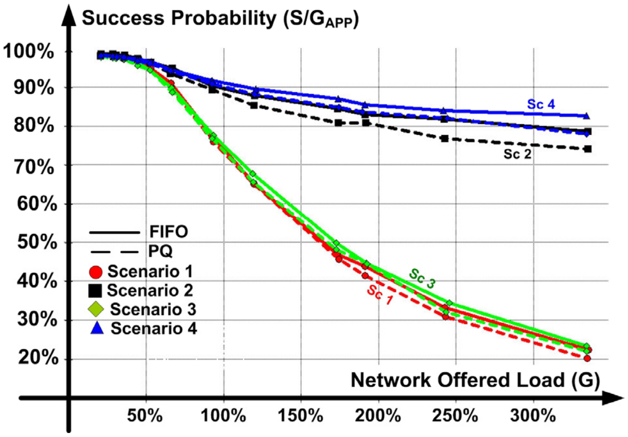

Fig. 3. Success probability of command frames without hidden nodes

Fig. 4 shows the average delays for all scenarios. Sc1 is only comparable to Sc3, whereas Sc2 is comparable to Sc4, due to the success probability results in Fig. 3 (it is not logical to compare delays for scenarios with different success probabilities).

Observe that lower *macMinBE* for high priority frame leads to lower average delays, since the backoff delays are reduced. The beauty of this result is that lower *macMinBE* does not degrade the throughput, as shown in Fig. 3. The advantage of using Priority Queuing in reducing average delays is also observable in Fig. 4.

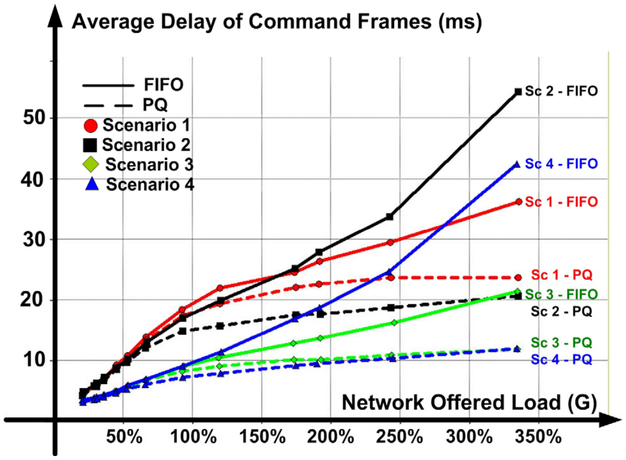

Fig. 4. Average delay of command frames (ms) without hidden nodes

As for power efficiency (Fig. 5), setting CW_{LP} greater than CW_{HP} clearly results in lower energy consumption, since fewer retransmissions are needed in Sc2 and Sc4. Priority Queuing seems also to be advantageous for improving energy efficiency.

The impact of *macMinBE* on *Gmac* depends on the values of CW_{LP} and CW_{HP}. If both are equal (Sc1 and Sc3), higher *macMinBEs* are more energy efficient. However, if $CW_{LP} < CW_{HP}$ (Sc2 and Sc4) lower *macMinBEs* are more energy efficient. This is because retransmissions are mostly due to collisions with data frames. Since Sc4 provides more differentiation to high priority frames than the other scenarios, it presents the best performance for all metrics.

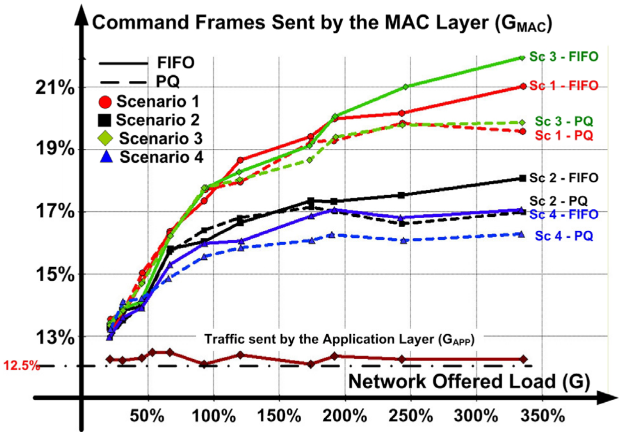

Fig. 5. Command traffic sent by the MAC layer without hidden nodes

As for the performance of low priority data frames, Figs. 6 and 7 present the success probability and the average delay, respectively. In Fig. 6, it is shown that setting CW_{LP} greater than CW_{HP} (Sc2 and Sc 4) results in relatively lower throughputs for low priority data frames, due to the privileges given to the high priority frames, as it can be observed in Fig. 3. However, the improvement of this differentiation scheme to the throughput of high priority command frames is more significant than the degradation of the throughout of low priority data frames, which further demonstrates the efficiency of this differentiation mechanism.

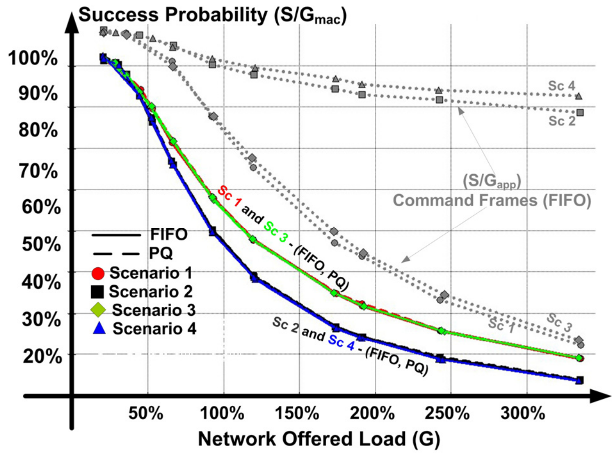

Fig. 6. Success probability of data frames without hidden nodes

In Fig. 7, observe that setting CW_{LP} greater than CW_{HP} results in greater average delays for data frames. This is because low priority data frames have a smaller probability to access the medium than high priority command frames when CW_{LP} increases, leading to return more often to the backoff process. This results in additional queuing and backoff delays (BE increases each time the channel is sensed busy) for data frames.

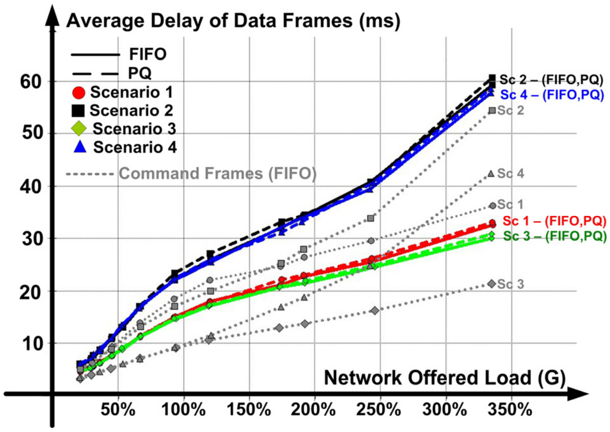

Fig. 7. Success probability of data frames without hidden nodes

Note that the Priority Queuing scheduling mechanism does not degrade the average delays of data frames even though they receive a low priority service. This is due to the fact that, in these simulation scenarios, command frames only use 12.5% (31.5 kbps) of the network capacity. The degradation would be more significant if command frames were generated at a higher rate. This behavior is typical for many WSNs, since command frames are likely to be generated with lower rate than data frames.

Another interesting observation is that the average delays of command frames are lower than those of data frames in all scenarios, except in Sc1 which does not provide any kind of differentiation. As a result, it is clearly shown that using one or both differentiation strategies (*CW* and/or *macMinBE*) always results in an improved performance for high priority frames.

4.3 Case of partially connected network (hidden-node problem)

We consider a partially connected network (we adjust the sensing sensitivity of the nodes to limit their communication range), to evaluate the impact of the hidden-node problem on the performance of slotted CSMA/CA with differentiated services. The sensing and receiving sensitivities are set such that the transmission range of each sensor node is limited to 32 m (command and data frames are sent with a transmission power equal to 0.1 mW). Beacon frames are sent by the PAN Coordinator at a transmission power equal to 1 mW, which is sufficient to reach all the nodes in the WSN. No routing protocol is used. Frames are simply broadcasted to the network (1) since most WSNs rely on broadcast transmissions and (2) we would like to provide results independent from any routing protocol.

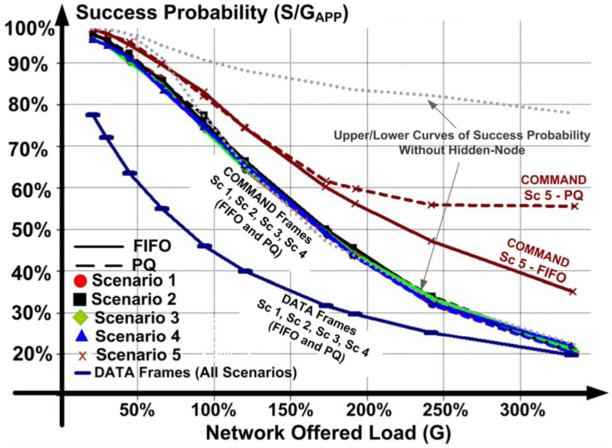

Fig. 8. Success probability of command/data frames with hidden nodes

It can be observed in Figs. 8, 9, 10 and 11 that the differentiated service strategies of the four scenarios defined in Table 1 have practically no impact on the performance metrics for both command and data frames, with an exception for the average delays. As shown in Fig. 9, lower *macMinBEs* slightly reduce the average delays of command frames. On the other hand, observe in Fig. 10 that greater CW_{LP} only results in a non significant increase of the average delays of low priority frames (difference around 1 ms). The success probabilities of command frames, as well as of data frames, remain closely insensitive to the differentiation service strategies in the four scenarios. In addition, The Priority Queuing scheduling policy has no impact on the improvement of the performance of high priority command frames.

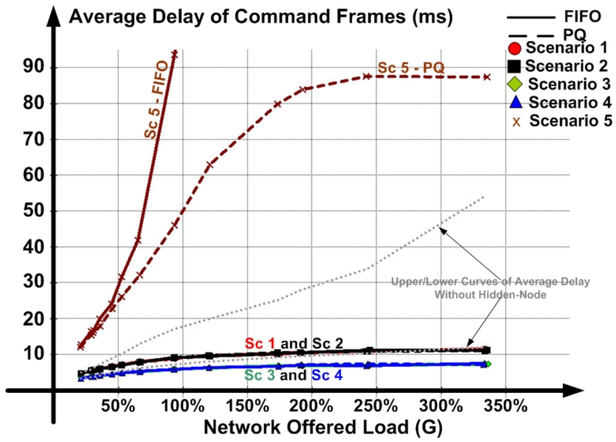

Fig. 9. Average delay (ms) of command frames with hidden nodes

These results clearly infer the severe impact of the hidden-node problem on the degradation of the performance of slotted CSMA/CA. Since nodes cannot hear each other, multiple hidden-node collisions occur independently of the differentiation schemes.

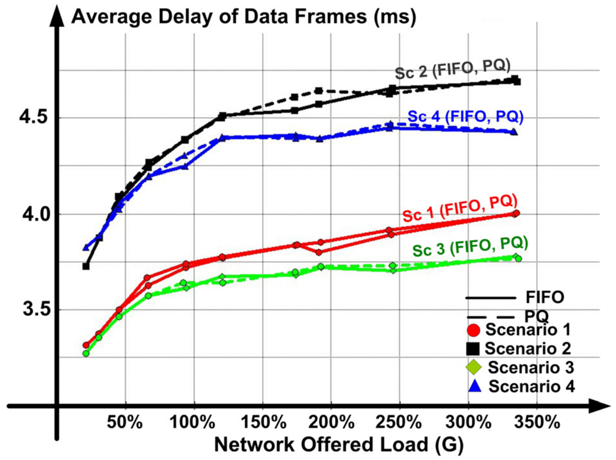

Fig. 10. Average delay (ms) of data frames with hidden nodes

The hidden-node impact is mainly a result of the small backoff interval duration. Note that with *aMaxBE* value equal to 5, the maximum backoff delay is equal to 31 BPs, which is not sufficient to avoid hidden-node collisions. One option to mitigate the hidden-node problem is to increase the backoff delay, such that competing nodes wait longer. Hence, other nodes would have more chance to successfully transmit their frames without facing hidden-node collisions. To illustrate this intuition, we propose the following additional scenario Sc5.

Table. 2. Hidden-node avoidance scenario

Scenario	[macMinBE$_{HP}$, aMaxBE$_{HP}$]	[macMinBE$_{LP}$,aMaxBE$_{LP}$]	CW$_{HP}$	CW$_{LP}$
Sc5	[4,6]	[7,8]	2	10

By increasing *macMinBE* and *aMaxBE* for both high priority and low priority traffics, the backoff delay will clearly increase for both traffic classes. Observe also that CW_{LP} is set to 10 and CW_{HP} is set to 2, to give more privileges to high priority frames.

It can be observed in Fig. 8 that the configuration of Sc5 noticeably improves the throughput of command frames, by reducing hidden-node collisions. With Priority Queuing in Sc5, the success probability reaches more that 55% even in high load conditions. However, reporting to Fig. 9, the average delays can be very large with FIFO scheduling, but are more steady using Priority Queuing (less than 90 ms).

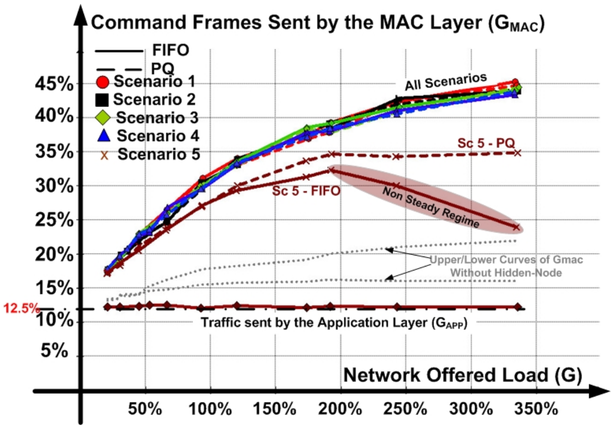

Fig. 11. Command traffic sent by the MAC layer with hidden nodes

Note that in Sc5 with FIFO, the network operates in a non steady regime (Fig. 11) in high load conditions, due to overloaded queues, which explains the expansion of average delays. The same behavior occurs for low priority data frames, both with FIFO and Priority Queuing. This is due to the blocking of high priority command frames by low priority data frames, which must wait for 10 CCA before transmission. However, with Priority Queuing, Sc5 is more energy efficient since fewer retransmissions than is other scenarios are performed.

5. Discussions

We have proposed a simple differentiated service scheme for slotted CSMA/CA in IEEE 802.15.4 to improve the performance of time-sensitive messages. It has been shown that tuning adequately the parameters of slotted CSMA/CA may result in an improved QoS for time-critical messages. This practical proposal can be easily adopted in the IEEE 802.15.4b extension of the standard since it only requires minor add-ons and ensures backward compatibility with the existing standard.

We have run the same simulation scenarios [10] using the implementation of the IEEE 802.15.4 protocol in the NS-2 simulator [11], for (1) comparative purposes, (2) the validation of our simulation results. The results obtained using NS-2 show a similar behavior to the results presented in this paper, thus confirming the validity of the approach. However, the values of the average delays observed in NS-2 results are greater than those obtained with our OPNET model. Also, NS-2 produces lower throughputs than those obtained with OPNET. To our understanding, this is mainly due to the amount of additional overheads introduced by the NS-2 simulator, since it imposes the use of a UDP (User Datagram Protocol) agent in each node for generating data, and also the generation of ARP (Address Resolution Protocol) frames. This is mainly because NS-2 was originally developed for IP (Internet Protocol) networks and then extended for IEEE 802.11 wireless networks. According to our personal experience, we strongly believe that the current version of the NS-2 simulator is not accurate for the simulation of wireless sensor networks, even though existing modules can be reused in this context. Our OPNET model implements more accurately the IEEE 802.15.4 protocol without these unnecessary overheads, turning its results more reliable than those obtained with NS-2.

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