Simulative assessments of the IEEE 802.15.4 CSMA/CA with Priority Channel Access in Structural Health Monitoring scenarios

Luca Leonardi, Gaetano Patti, Filippo Battaglia, Lucia Lo Bello
Department of Electrical, Electronics and Computer Engineering
University of Catania, Catania, Italy
{luca.leonardi, gaetano.patti, fbattaglia, lobello}@unict.it

Abstract — Recently, wireless sensor networks (WSNs) are emerging in various application fields thanks to their low cost and ease of deployment. In particular, the rapid increase of critical monitoring applications encourages the study and evaluation of wireless communication protocols that can fulfill the requirements of such applications. Among the WSN standards, the IEEE 802.15.4 is very promising, as it provides critical messages with the support for prioritized channel access through the Priority Channel Access mechanism. The paper assesses the behavior of an IEEE 802.15.4 wireless sensor network implementing the Priority Channel Access mechanism in a realistic monitoring scenario, focusing on the impact on critical message transmissions. The assessments are based on OMNeT++ simulations.

Keywords — Wireless sensor networks; IEEE 802.15.4; IEEE 802.15.4k; Priority channel access; Structural health monitoring.

1. Introduction

Advances in wireless technology and embedded processing make wireless sensor networks an attractive alternative to wired data acquisition systems. In fact, wireless systems are usually easy to deploy and less expensive than their wired counterparts. For this reason, WSNs are increasingly used for monitoring applications, in which periodic and event-driven data are collected from a large number of devices.

Several works addressed medium access protocols and mechanisms to handle in a reliable way periodic flows with time and energy constraints in industrial WSNs [1], [2]. As structural health monitoring is looking into WSNs as low-cost replacements for the traditional wired monitoring systems, this paper deals with a realistic structural health monitoring scenario. In particular, this work addresses a scenario in which the network traffic consists of *regular messages*, i.e., periodic monitoring messages generated with long transmission periods, plus *critical* traffic flows that are dynamically generated by the occurrence of an event. These critical traffic flows, once started, are made up of periodic *critical messages* with very short periods and high priority, whose transmission has to continue until an intervention is made. Such critical traffic flows require a higher priority than the regular monitoring flows exchanged on the same network.

The IEEE grouped in a new revision of the IEEE 802.15.4 standard [3] several amendments. Among the novel features there is the prioritized channel access (PCA), that was formerly introduced by the IEEE 802.15.4k [4] amendment. This paper compares the performance of a wireless network supporting *both critical and regular periodic transmissions* through the carrier sense multiple access with collision avoidance (CSMA/CA) protocol with and without the PCA mechanism, respectively. For this purpose, an OMNeT++ simulator was implemented to simulate a realistic scenario for a structural health monitoring network. OMNeT++ was chosen as it provides network and protocol models that are widely used and accepted in academia [5] and in industry. In the following of the paper, the term regular messages will therefore refer to the periodic transmissions of non-critical monitoring messages, while the term critical messages refer to the periodic transmissions of high priority messages.

The paper is organized as follows. Section II summarizes related work, while Section III provides an overview of the IEEE 802.15.4 standard, with a particular focus on the prioritized channel access. Section IV addresses the requirements and constraints of structural health monitoring, while Section V describes the realistic application scenario in which the simulations were performed and discusses the results obtained. Finally, Section VI addresses conclusions and future works.

2. Related work

The standard IEEE 802.15.4 and its amendments, such as the IEEE 802.15.4k, were investigated in several application fields, including agriculture and critical infrastructure monitoring [6]-[8]. In fact, the usage of WSNs for structural health monitoring has recently attracted much interest, thanks to their advantages over traditional wired monitoring systems, i.e., low cost and ease to deploy, thus becoming one promising research domain with several research threads. For instance, in [9] a new data coding and transmission method is proposed to reduce the redundant information and enhance the transmission reliability of wireless structural health monitoring systems deployed on large civil infrastructures. The works [10], [11] address structural health monitoring systems in which wireless sensors are placed inside the concrete structure and present the design of customized embedded circularly polarized (CP) antennas able to work inside the concrete structure. The use of CP antennas is advantageous in WSN for their capability to establish reliable links regardless of the antenna orientation and is recommended in dedicated short range communications [12], [13]. The work in [14] targets the design of a distributed structural health monitoring algorithm able to achieve the same accuracy of a centralized one, but with lower wireless transmission costs.

The work in [15] addresses how to modify some carrier sensing parameters of the IEEE 802.15.4 standard to make it suitable for low-power industrial wide area networks. In [15], the performance of popular Clear Channel Assessment (CCA) methods, obtained through simulations in a low-power wide area network based on the IEEE 802.15.4k standard, are presented and some hints are provided about how to select the appropriate CCA method according to the channel quality.

This work focuses on the Priority Channel Access mechanism. The impact of the Priority Channel Access on the Direct Sequence Spread Spectrum (DSSS) physical layer is dealt with in the work [16], which addresses a network that adopts a slotted Aloha with PCA at the MAC layer. The results described in [16], obtained through OPNET simulations in non-saturated traffic conditions, show that the PCA significantly improves the delay performance of the critical messages.

The contribution of this work is that here we assess the impact of the PCA on the unslotted CSMA/CA, while in [16] the authors assess the impact of the PCA on the slotted Aloha MAC layer.

3. Overview of the 802.15.4 standard

The goal of the IEEE 802.15 Working Group was to produce a standard to enable very low-cost and low-power communications. The latest revision of the IEEE 802.15.4 standard [3] includes the amendments approved after the 2011 revision of the standard, being the IEEE 802.15.4k one of them. Among the added features there are prioritized channel access, low-power mechanisms, a variety of new physical modulation, coding, and band options to support a broad spectrum of application requirements. The standard [3] defines the physical layer and medium access control (MAC) sublayer specifications for low-rate wireless personal area network (LR-WPAN). The standard provides for ultra-low complexity, ultra-low cost, ultra-low power consumption, and for low data rate wireless connectivity among inexpensive devices. When a personal area network (PAN) works in the nonbeacon-enabled mode, the nodes access the channel using a multiple access protocol.

The IEEE 802.15.4 standard supports conventional MAC protocols, such as, CSMA/CA with and without PCA, and ALOHA with PCA. The MAC layer uses normal and priority channel access to transmit regular messages and critical messages, respectively. The devices can use PCA to prioritize their traffic while accessing the medium, thus providing a notion of quality of service. The algorithms with PCA, called PCA backoff algorithms, on average, provide shorter backoff delays during priority access than during normal access.

As it was shown in [17], an IEEE 802.15.4-based network working in non-beacon enabled mode achieves smaller mean end-to-end delays and higher reliability (i.e., a lower packet loss percentage) than the ones obtained working in the beacon-enabled mode. For this reason, this work focuses on the nonbeacon-enabled mode of the IEEE 802.15.4 standard. In this work, for comparison purposes, the devices adopt as medium access protocols the plain unslotted CSMA/CA (i.e., without PCA) and the unslotted CSMA/CA with PCA.

a. *Unslotted CSMA/CA*

The plain unslotted version of the CSMA/CA algorithm is implemented using time units called backoff periods. In the plain unslotted CSMA/CA, the backoff periods of one device are not related in time to the backoff periods of any other device in the PAN. Each device maintains two variables for each transmission attempt, i.e., NB (number of backoff periods) and BE (backoff exponent). NB is the number of times the CSMA-CA algorithm is required to back off while attempting the current transmission. This value is initialized to zero before each new transmission attempt. BE is the backoff exponent, which is related to how many backoff periods a device must wait before attempting to assess a channel through the Clear Channel Assessment (CCA) procedure. In unslotted systems, BE is initialized to the value of macMinBe [3]. If macMinBe is set to zero, collision avoidance will be disabled during the first iteration of the algorithm. Note that during the CCA part of the algorithm, the device may discard any frame received during this time interval, although the receiver of the device is enabled. Fig. 1 illustrates the steps of the CSMA-CA algorithm. If the algorithm ends with success, the MAC layer transmits the frame, otherwise, the algorithm terminates with a channel access failure.

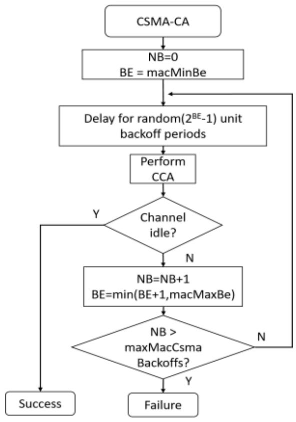

Fig. 1. CSMA-CA algorithm.

b. *Unslotted CSMA/CA with Priority Channel Access*

To transmit critical messages, the unslotted CSMA/CA with PCA algorithm is adopted. The steps of the algorithm are shown in Fig. 2.

The MAC sublayer is responsible for maintaining a variable, called Temporary Backoffs (TB), which indicates the number of remaining backoff periods since the start of the CSMA-CA with PCA backoff algorithm. Differently from the CSMA/CA, PCA does not use the NB variable. The backoff exponent BE is initialized to the maximum value between *macMaxBE-1* and *1* prior to the first transmission attempt (note that in [4], as opposed to [3], BE is set to the maximum value between *macMinBE-1* and *1*) and it remains constant in the subsequent retransmissions. TB is initialized to a random value between *0* and 2^{BE}*-1*. The PCA backoff algorithm follows a persistent CSMA mechanism, meaning that the device continues to monitor the channel and decrements TB by one every time the channel is sensed idle during a backoff period, in order to gain the channel access in a timely manner.

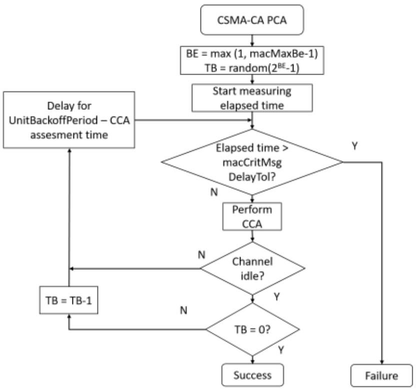

Fig. 2. CSMA-CA with PCA.

When the PCA-enabled operation mode is allowed, nodes may use PCA or not, depending on the type of the messages that they generate. The appropriate backoff has therefore to applied in each case.

Summarizing, the CSMA/CA with PCA algorithm differs from the plain CSMA/CA in two aspects:

1) In the plain CSMA/CA the backoff window grows exponentially every time the channel is found busy. Conversely, in the CSMA/CA with PCA the backoff time is increased of one aUnitBackoffPeriod every time the channel is found busy, thus allowing, on average, a shorter backoff than the plain CSMA/CA.

2) In the plain CSMA/CA the transmission attempts are limited to a maximum number (i.e., macMaxCsmaBackoffs), while in the CSMA/CA with PCA the transmission attempts are limited within a time interval. This feature, combined with the shorter backoff, provides a higher transmission probability than the plain CSMA/CA.

4. Requirements and constraints of SHM

Structural health monitoring is the process of assessing the state of health of any infrastructure using sensors (e.g. accelerometers, inclinometers, etc.) that are permanently placed on a structure in order to collect data that provide real-time information on its condition. The goal of SHM is to improve the safety and reliability of infrastructures by detecting any damage before it can determine a critical state for the structure. SHM also allows a rapid post-event assessment. Through on-going analysis of the collected data, SHM allows civil engineers and building inspectors to detect any change in the health of the structure. This detection enables operators to better plan and prioritize their maintenance programs, so as to ensure that the structures be able to accomplish their functions safely and efficiently. This form of inspection and monitoring is as good as its ability to uncover potential issues in a timely manner, so the timeliness and reliability of the communication system are of crucial importance.

In general, a monitoring system consists of four main elements, i.e., a network made up of various types of sensors permanently placed on a structure, a system for collecting and transmitting the working data, a data analysis procedure, and a decision-making system able to alert emergency management.

The sensors regularly sample the structure response and transmit the data to a central device that implements a SHM algorithm to detect damage. In real-time monitoring systems, a SHM algorithm measures the response of a structure both in normal service conditions and before, during and after the occurrence of a natural or man-made disaster.

When a critical event occurs, e.g., when a sensor node detects a value that exceeds its alarm threshold, this node begins to transmit critical messages. These messages shall be sent periodically, with short periods, until an intervention is made.

5. Simulative assessment

The purpose of this simulative assessment is to evaluate the network behavior when, upon the occurrence of a critical event, one or multiple nodes start generating critical messages, with much shorter sending periods than regular messages, to be delivered within a specific time interval.

Simulations were run using OMNeT++. The INETMANET framework was used to implement the IEEE 802.15.4 physical layer. The MAC layer relies on the classic CSMA/CA to enable/disable the channel access in priority mode simply setting a parameter. On top of this, a generic application layer was customized to perform specific measures.

The comparative assessment shows the performance obtained by the CSMA/CA with and without the priority channel access mechanism. The performance metrics used to evaluate the system are the Packet Loss Ratio (PLR) and the End-to-end Delay (E2E delay). The PLR is defined as the ratio between the number of lost or corrupted packets and the overall number of packets transmitted by the sensor nodes at the application layer, expressed in percentage, according to Eq. (1),

$$PLR = \left(1 - \frac{NumRxMsg}{NumTxMsg}\right) * 100. \quad (1)$$

The application packets will be henceforth called messages (here, the mapping between application messages and MAC layer messages is 1 to 1), therefore, in Eq.1, NumRxMsg is the number of correctly received messages, while NumTxMsg is the overall number of messages transmitted by the sensor nodes.

The E2E delay is the time that a message takes since its generation at the source node application level up to its arrival to the sink application level, calculated according to Eq. (2)

$$EDEDelay = ArrivalTime - GenTime \quad (2)$$

The processing delays are excluded from the simulations as they are implementation-dependent.

c. Simulated scenario

The assessment refers to a structural health monitoring application for a building (one of the case studies considered in the Smart Concrete national project, funded by the Italian Ministry of Research). The simulated network topology, shown in Fig. 3, consists in a nonbeacon-enabled PAN of 48 sensors distributed in the monitored structure, in which one PAN coordinator, located in the center of the structure to ensure the maximum coverage range, acts as the sink for all the data sent from the sensors.

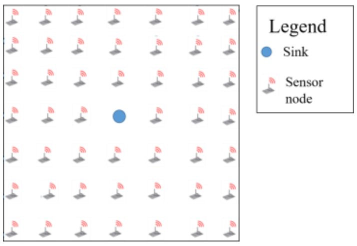

Fig. 3. Simulation topology.

Different kinds of sensors, taken from realistic monitoring scenarios, are considered, i.e., pressure and temperature sensors, accelerometers, and inclinometers. The sensor nodes generate regular messages to report their status, but their sending periods may vary, in case critical events have to be reported (thus originating critical messages). All the nodes are stationary and are placed in a sensing area of 30 x 30 meters, within the radio coverage of the coordinator, which is directly connected to them.

The simulation parameters for the MAC layer are summarized in Table I. The other parameters that are not shown here are set to the default values specified in [3]. The application layer payload is 64 bytes.

TABLE I. MAC PARAMETERS

Parameter	***Value***
aCcaTime	8 symbols (128 us)
aTurnaroundTime	12 symbols (192 us)
aUnitBackoffPeriod	32 us
macMinBE	3
macMaxBE	5
macMaxFrameRetries	3
maxMacCsmaBackoffs	0-5

To assess the impact of the priority channel access, we simulated a monitoring scenario where 5 nodes, upon detection of a critical event, start transferring critical messages.

The two considered cases studies (corresponding to different configurations in the same scenario) consist of 43 sensor nodes that send a regular message every 10s and 5 sensor nodes that send a critical message (high priority) every 2s.

In the first configuration mode (case *a*) all nodes use the plain unslotted CSMA/CA to send both regular messages and critical messages.

Conversely, in the second configuration mode (case *b*) the five nodes that detect a critical event run the CSMA/CA with the PCA enabled to send critical messages (as described in Fig. 2).

The difference between the two configurations therefore lies in the MAC protocol that is used for transmitting critical messages. In case *a*, critical messages are transmitted using the plain unslotted CSMA/CA, while in case *b* they are transmitted using CSMA/CA with PCA. These nodes set the *macCritMsgDelayTol* to 2s, i.e., to a value equal to the message generation period, as each periodic message has to be delivered before the next message is generated, otherwise the first message shall be dropped.

d. Simulation results

The duration of each simulation run was set to 3600s in order to collect a significant number of data (slightly less than 25.000 messages). Moreover, the simulations were repeated ten times, varying the seed for the random number generator that influences the application start times of the nodes and the values of the backoff algorithm variables. Not only the mean values, but also their confidence intervals at the 95% were calculated, to provide the statistical significance of the results. Initially, in the simulations the free-space propagation model (i.e., an ideal environment) was adopted to highlight the effect on the performance of the MAC layer alone. Once the performance of the channel access algorithm was assessed, the simulations were run using the second configuration (case *b*) and adopting the log-normal shadowing propagation model with the propagation parameters for an indoor environment estimated as in [18].

Table II summarizes the results of the evaluation of the impact of the *macMaxCsmaBackoffs* parameter (the maximum number of CSMA/CA backoff attempts) on the PLR and how these results vary by changing the configuration mode (case *a* and case *b*) using a free space propagation model. The values reported in Table II represent the mean PLR percentage values with their confidence intervals (C.I.) at the 95%.

The PLR results in Table II show that using the configuration mode *a* the PLR improves with increasing macMaxCsmaBackoffs values, as the number of transmission attempts allowed before dropping a message also increases.

TABLE II. PLR - FREE SPACE PROPAGATION MODEL

macMax Csma Backoff	*Configuration mode a*				*Configuration mode b*			
	Critical		**Regular**		**Critical**		**Regular**	
	PLR %	C.I.	PLR %	C.I.	PLR %	C.I.	PLR %	C.I.
0	17.79	±4.76	34.84	±2.69	0.04	±0.02	37.63	±2.12
1	15.90	±4.53	33.29	±2.70	0.04	±0.02	35.73	±2.45
2	13.53	±4.26	30.41	±2.67	0.04	±0.02	32.70	±2.72
3	12.86	±3.90	26.81	±2.91	0.04	±0.02	28.88	±2.84
4	11.97	±2.93	24.02	±2.95	0.04	±0.02	25.33	±2.95
5	10.54	±1.92	21.96	±2.74	0.04	±0.02	22.75	±2.80

In fact, when the maximum number of possible backoff periods that a message can repeat is exceeded, the message is dropped. This is a significant problem especially for the critical messages.

The results obtained using the configuration mode *b* (i.e., when the PCA backoff algorithm is used for the critical messages) show that the CSMA/CA with PCA provides significantly lower PLR than the plain CSMA/CA. In fact, the number of critical messages that are not delivered becomes almost null (the reason for the very few undelivered messages is that they were still ongoing when the simulation was stopped). Conversely, the PLR of regular messages does not significantly change comparing with the configuration mode *a*.

To assess the performance of PCA, we also compared the end-to-end delay of the regular messages (transmitted using the plain CSMA/CA) and of the critical messages (transmitted using CSMA/CA with PCA) using the configuration mode *b*. In particular, we considered the extreme cases for the *macMaxCsmaBackoffs* value, i.e., 0 (Fig. 4a-b) and 5 (Fig. 4c-d), to obtain both the best and the worst case. In Fig. 4 the regular messages are represented in blue (Fig. 4a-4c), while the critical ones in red (Fig. 4b-4d).

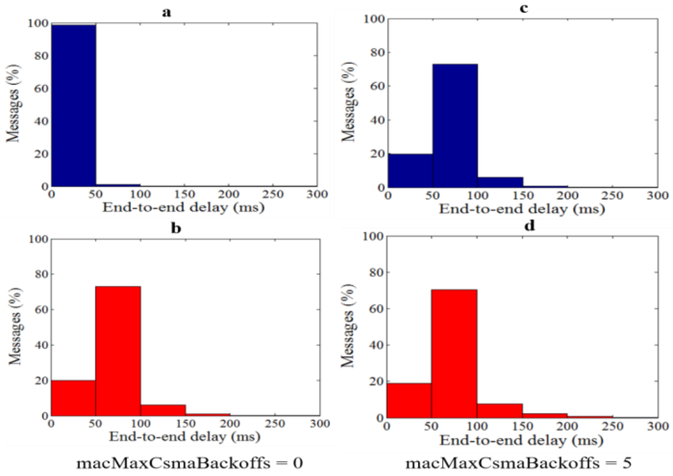

Fig. 4. E2E delay distribution varying the macMaxCsmaBackoffs parameter in case *b* - (4a,4c): using the plain CSMA/CA (regular messages); (4b,4d) using the CSMA/CA with PCA (critical messages).

The results in Fig. 4 show that the plain CSMA/CA performs slightly better than the CSMA/CA with PCA as far as the end-to-end delay is concerned. When the *maxMacCSMABackoffs* is set to 5, the end-to-end delay distributions of the protocols are similar (Fig. 4c-d). In particular, the nodes that send regular messages can experience a higher number of backoff intervals, consequently, on average, the end-to-end delay of non-critical messages grows. The E2E delay of all the messages is lower than 200ms in most cases, while in a few cases the E2E delay is between 200ms and 1s. For the sake of readability, Fig. 4 does not show the very low percentage of messages (both regular and critical) that experience E2E delays higher than 300ms, as they represent less than 0.1% of the total number of messages. Summarizing, in the considered scenario the priority channel access (PCA) does not provide critical messages with lower latencies than the plain CSMA/CA, but offers similar performance. However, the PCA significantly reduces the PLR of critical messages.

Next, we simulated the configuration mode *b* (i.e., the one with the PCA enabled for the transmission of the critical messages) using the propagation parameters of a realistic indoor environment. In particular, we adopted the log-normal shadowing propagation model, with α set to 2.92 and σ set to 10.27 as in [18]. In this condition, we evaluated the effect on the PLR of the *macMaxFrameRetries* parameter, which sets the maximum number of retries allowed after a transmission failure. Figs. 5-6 show the PLR of the critical and regular messages, respectively, when the *macMaxFrameRetries* is set to 3 (the default value) and 7 (the maximum value), so as to assess the influence of this parameter on the PLR.

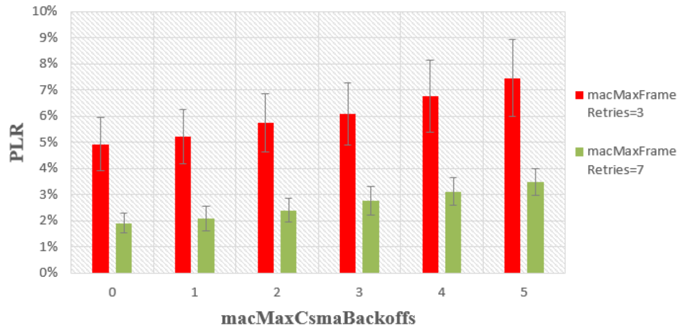

Fig. 5. PLR of critical messages in the configuration b using the log-normal shadowing propagation model.

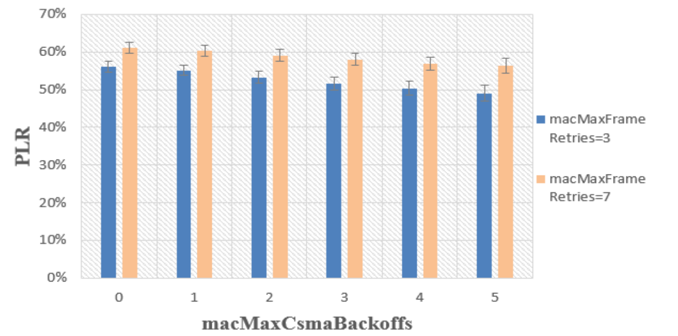

Fig. 6. PLR of regular messages in the configuration b using the log-normal shadowing propagation model.

Figs. 5-6 show that, as it can be expected, the PLR obtained using a realistic propagation model is higher than in the ideal case (shown in Table II – configuration mode b). Fig. 5 shows the PLR increase for the critical messages with the maximum number of CSMA/CA backoff attempts (macMaxCsmaBackoffs). The reason for this result is that this parameter, which only affects the plain CSMA/CA, decreases the PLR of regular messages (Fig. 6). The resulting increase in the number of regular messages transmitted also increases the network traffic, thus slightly worsening the PLR of the critical messages. Finally, Figs. 5-6 show that when the macMaxFrameRetries increases, the PLR of the critical messages decreases, while the PLR of regular messages increases. This is due to the features of PCA backoff algorithm, which is more reactive than the plain CSMA/CA when messages are lost. The fact that the critical messages always obtain lower PLR than the regular messages demonstrates that, for a given macMaxFrameRetries value, the regular messages require, on average, more retransmissions than the critical messages to be successfully delivered.

TABLE III. E2E delay – log-normal propagation model

macMax Csma Backoff	macMaxFrameRetries = 3		macMaxFrameRetries = 7	
	Critical	Regular	Critical	Regular
	Avg. E2E delay (ms)	Avg. E2E delay (ms)	Avg. E2E delay (ms)	Avg. E2E delay (ms)
0	119	74	156	86
5	131	81	191	92

Table III reports the end-to-end delay of regular and critical messages using the configuration mode *b* with a log-normal propagation model. In particular, we consider the extreme cases for the *macMaxCsmaBackoffs* value, i.e., 0 and 5, when the *macMaxFrameRetries* is set to 3 and 7, respectively. Table III reports the average end-to-end delay values.

As it was expected, the end-to-end delay using the realistic propagation parameters of an indoor environment is higher than the one obtained using the free space propagation model. Furthermore, Table III shows that, on average, the end-to-end delay obtained by critical messages, transmitted using the CSMA/CA with PCA, is slightly higher than the one obtained by the regular messages, transmitted with the plain CSMA/CA. However, the maximum delay experienced in the simulations is always lower than the transmission period for all the messages, both critical and regular.

6. Conclusions

This work presented a simulative assessment of the CSMA/CA with PCA for structural health monitoring applications. Simulation results show that adopting the PCA in the considered scenario significantly reduces the packet loss ratio of the critical messages, without significantly affecting the performance of regular messages. In particular, in the realistic scenario (i.e., in case b) although the end-to-end delays of the critical messages slightly increase using the PCA, such delays are always lower than the transmission period, so the timing constraints of the critical messages are still met. These results depend on the PCA backoff algorithm, which provides a lower packet loss ratio than the plain CSMA/CA at the expenses of the message delay. Instead, in the plain CSMA/CA the PLR is quite high, due to the high number of failed backoff attempts. In fact, most of the messages that would have experienced a high delay with the plain CSMA/CA are actually dropped, while the messages generated when the channel is idle are directly transmitted, thus obtaining lower average delays.

A way to reduce the end-to-end delay of critical message is setting the *macMaxBE* equal to *macMinBE* (a possible option, as specified in [3]) to not penalize the PCA backoff algorithm when the channel is idle at the first transmission attempt. The simulative assessment with realistic channel parameters also confirms the positive effect of PCA on the critical messages exchange, i.e., the significant PLR reduction. The PLR increase obtained, as it was expected, in the realistic channel model comparing with the ideal one, can be mitigated through a suitable setting of the PCA MAC parameters. For instance, setting the *macMaxFrameRetries* to the maximum value, the PLR of critical messages in scenario b is limited to 4% (in the worst case) with a confidence interval at the 95%.

Future work will investigate the applicability of the PCA to other application scenarios, also adopting suitable topology management protocols, such as the one proposed in [19], and a dynamic configuration mechanism for the MAC parameters to provide more flexibility and to improve the network performance.

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