

Block Acknowledgment in IEEE 802.15.4 by Employing DSSS and CSS PHY Layers

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Abstract—The IEEE 802.15.4 standard has been widely accepted as the *de facto* standard for Wireless Sensor Networks (WSNs), since it provides ultra-low complexity, cost and energy consumption for low-data rate wireless connectivity. However, one of the fundamental reasons for the IEEE 802.15.4 Medium Access Control (MAC) inefficiency is overhead. In the context of our research, we demonstrate that WSNs may benefit from packet concatenation. In this paper we introduce and study the employment of a block acknowledgment mechanisms in order to achieve enhanced channel efficiency in IEEE 802.15.4 nonbeacon-enabled networks for both the Chirp Spread Spectrum (CSS) and Direct Sequence Spread Spectrum (DSSS) Physical (PHY) layers for the 2.4 Industrial, Scientific and Medical (ISM) frequency band. The proposal of the two new innovative MAC sub-layer mechanisms can also be considered as a future possible contribution to the standard itself. The throughput and delay performance is mathematically derived under ideal conditions, (i.e., a channel environment without transmission errors). The performance of the proposed schemes is compared against the IEEE 802.15.4 standard through extensive simulations by employing the OMNeT++ simulator. We demonstrate that, for both PHY layers, the network performance is significantly improved in terms of throughput, end-to-end delay and bandwidth efficiency.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) is one of the most exciting and important technological innovations in the field of ad-hoc wireless communications of our time. They are responsible for interconnecting several wireless sensor nodes by providing global ad-hoc communication and computational capabilities. This type of networks are capable of linking the PHY layer with the digital world by sensing, processing, and transmitting the real-world phenomena, and by converting these into a form that can be processed, stored and acted upon.

In the last decade, we have witnessed the growth of the wide range of WSN scenarios and applications [1], [2], [3], [4]. In the WSNs domain there is a huge amount of proposals for energy-efficient Medium Access Control (MAC) protocols [5]. However, these MAC protocols have not been capable of having enough success to be set as a real commercial application due to the lack of standardization.

In contrast, IEEE 802.15.4 has been widely accepted as the *de facto* standard for WSNs, enabling to provide ultra-low complexity, cost and power for low-data rate wireless connectivity for wireless sensors.

One of the fundamental causes for the IEEE 802.15.4 MAC inefficiency is overhead. In this work, two different enhancements are introduced in order to reduce overhead for the IEEE 802.15.4 protocol. In particular, both our proposals employ a Block Acknowledgment (BACK) mechanism, where the first approach implements a BACK Request (concatenation mechanism), while the second one does not consider the presence of BACK Request (the so-called piggyback mechanism).

The main idea is to improve channel efficiency by aggregating several acknowledgment responses into one single transmission (i.e., one single packet). This aggregation of ACKs aims at reducing the overhead by transmitting less ACK control packets and by decreasing the time periods that the transceivers need to switch between different states. We actually aim at increasing throughput as well as decreasing end-to-end delay, whilst providing a feedback mechanism to the receiver informing the sender about how many transmitted (TX) packets were successfully received (RX).

The remainder of our paper is organized as follows. Section II presents a technical overview of the IEEE 802.15.4 standard, taking into account the timing constraints imposed by the standard itself as well as by the various radio transceivers. The theoretical throughput and end-to-end delay limits for the IEEE 802.15.4 standard are also derived. In Section III we provide an accurate analytical model for the throughput and end-to-end delay limits by considering our proposed BACK mechanism for both the cases of implementing or not BACK Request. Section IV provides both numerical and simulation results and extends our earlier work in [6] by evaluating the performance for both the Chirp Spread Spectrum (CSS) and Direct Sequence Spread Spectrum (DSSS) Physical (PHY) layers for the 2.4 GHz Industrial, Scientific and Medical (ISM) frequency band. Finally, Section V presents conclusions as well as future extension of our work.

II. IEEE 802.15.4 CHANNEL ACCESS TIMING

In our previous work in [6], we have shown that one of the fundamental reasons for the IEEE 802.15.4 standard MAC inefficiency is overhead, and we have proposed a mathematical model that derives the throughput and end-to-end delay limits under ideal conditions (a channel environment without transmission errors). In the scope of our current research, we

study the impact on the performance of the CSS and DSSS PHY layers and we also carry out a comparison against the IEEE 802.15.4 standard.

Table I presents the key parameters, symbols and values that we will consider throughout our work. Hence, there is no need to redefine any parameter after every equation.

In this research work, we only consider the nonbeacon-enabled mode (not the beacon-enabled one, since beacon collisions can occur with other beacons, data or control frames, making a multi-hop beacon-based network difficult to be built and maintained [7]).

Another important attribute is scalability, due to changes in terms of network size, node density and topology. Nodes may leave the network over time, whereas others may be added later or some may move to different locations [8]. Therefore, for such kind of networks, the nonbeacon-enabled mode seems to be more suitable to the scalability requirement than the beacon-enabled mode. In the former case, all nodes are independent from the Personal Area Network (PAN) coordinator and the communication is completely decentralised. Moreover, for beacon-enabled networks [9] have an additional timing requirement for sending two consecutive frames, so that the ACK frame transmission should be started between the T_{TA} and $T_{TA} + T_{BO}$ time instants (and there is time remaining in the Contention Access Period, CAP, for the data payload, appropriate Interframe Space, IFS and ACK).

The IEEE 802.15.4 DSSS and CSS PHY layers operate at the 2.4 GHz frequency band and support a maximum over-the-air data rate of 250 kb/s and 1 Mb/s, respectively [11]. However, in practice, the effective data rate is much lower due to the various protocol/hardware timing restrictions and limitations. This is explained by the various mechanisms that are employed to ensure robust data transmission, including channel access algorithms, data verification and frame acknowledgement.

Table II presents a comparison between the two considered PHY layers in terms of channel access timing.

Like in [6], we analyse the maximum throughput, S_{max} , and the minimum delay, D_{min} , for the IEEE 802.15.4 DSSS and CSS PHY layers. S_{max} is defined as the number of data bits generated from the MAC layer that can be transmitted per second to its destination including the ACK reception. D_{min} is the time needed to transmit a packet and the successfully reception of the ACK. Although we are considering the 2.4 GHz band, the proposed formulation is also valid and can be applied to other frequency bands.

Before performing Clear Channel Assessment (CCA), a device shall wait for a random number of backoff periods, determined by the Backoff Exponent (BE). Then, the transmitter randomly selects a backoff time period uniformly distributed in the range $[0, 2^{BE} - 1]$. Hence, it is important to mention that even if there is only one transmitter and one receiver, the transmitter will always choose a random backoff time period within the interval $[0, 2^{BE} - 1]$ (this actually leads to communication delay and, thus, lower performance). Initially, each device sets the BE equal to $macMinBE$, before starting

a new transmission, and increments it after every failure to access the channel. In this work we assume that the BE will not be incremented since we are assuming ideal conditions. By considering the default value $BE=3$ for $macMinBE$, and assuming the channel is free, the worst-case channel access time that corresponds to the maximum backoff window is given by equation (1).

The average backoff window is given by:

$$\overline{CW} = (CW_{max}/2) \times T_{BO} \quad (1)$$

S_{max} and D_{min} can be determined for the best-case scenario (i.e., the channel is ideal and there are no transmission errors). During one transmission cycle, there is only one active node that has always a frame to be sent (i.e., saturation conditions) whereas the other neighbouring nodes can only accept frames and provide ACKs. We then propose an analytical model to evaluate S_{max} and D_{min} .

The transmission times, in seconds, for the DATA and ACK frames are given as follows:

$$T_{DATA} = 8 \times \frac{L_{H_PHY} + L_{H_MAC} + L_{H_DATA}}{R} \quad (2)$$

$$T_{ACK} = 8 \times \frac{L_{H_PHY} + L_{H_ACK}}{R} \quad (3)$$

D_{min} , in seconds, is given by:

$$D_{min} = H_1 \quad (4)$$

where $H_1 = \overline{CW} + ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS}$.

S_{max} , in bits, is given by:

$$S_{max} = 8L_{DATA}/D_{min} \quad (5)$$

TABLE I
PARAMETERS, SYMBOLS AND VALUES FOR THE IEEE 802.15.4
STANDARD (BASED ON [6]).

Description	Symbol	Value
Backoff period duration	T_{BO}	320 μ s
CCA detection time	T_{CCA}	128 μ s
Setup radio to RX or TX states [10]	$rxSetupTime$	1720 μ s
Time delay due to CCA	$ccaTime$	1920 μ s
TX/RX or RX/TX switching time	T_{TA}	192 μ s
ACK wait duration time	T_{AW}	560 μ s
PHY length overhead	L_{H_PHY}	6 bytes
MAC overhead	L_{H_MAC}	9 bytes
DATA payload	L_{DATA}	3 bytes
DATA frame length	L_{FL}	18 bytes
ACK frame length	L_{ACK}	11 bytes
DATA transmission time	T_{DATA}	576 μ s
ACK transmission time	T_{ACK}	352 μ s
Short Interframe spacing (SIFS) time	T_{SIFS}	192 μ s
Long Interframe spacing (LIFS) time	T_{LIFS}	640 μ s
RTS ADDBA transmission time	T_{RTS_ADDBA}	352 μ s
CTS ADDBA transmission time	T_{CTS_ADDBA}	352 μ s
BACK Request transmission time	$T_{BRequest}$	352 μ s
BACK Response transmission time	$T_{BResponse}$	352 μ s
Number of TX frames	n	1 to 112
Data Rate	R	250 kb/s

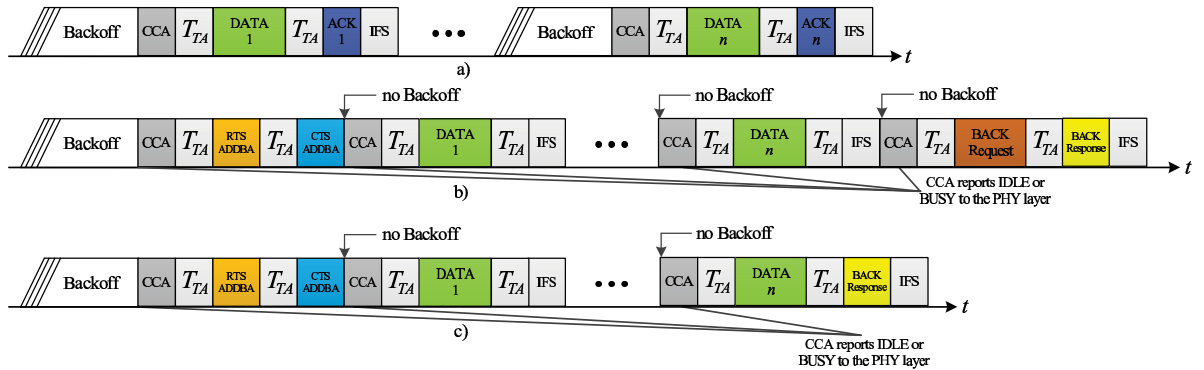


Figure 1. IEEE 802.15.4 frame sequence: a) basic access, b) with *BACK Request* (concatenation) and c) with no *BACK Request* (piggyback).

TABLE II
PARAMETERS, SYMBOLS AND VALUES FOR THE IEEE 802.15.4
STANDARD BY CONSIDERING THE DSSS AND CSS PHY LAYERS.

Symbol	DSSS PHY	CSS PHY
L_{H_PHY}	6 bytes	7 bytes
L_{H_MAC}	9 bytes	9 bytes
T_{TA}	192 μ s	72 μ s
T_{SIFS}	192 μ s	72 μ s
T_{LIFS}	640 μ s	240 μ s
T_{BO}	320 μ s	120 μ s
R	250 kb/s	1 Mb/s

For IFS, SIFS is used when a MAC Protocol Data Unit (MPDU) (i.e., $L_{H_PHY} + L_{H_MAC} + L_{DATA}$) is less or equal than 18 bytes; otherwise LIFS is utilized.

By analysing equations (2) to (5), we conclude that, if a short frame is transmitted the data transmission time is relatively short when compared to the associated overhead time, resulting in relatively low throughput. When a long frame is transmitted (by increasing the payload), data transmission time increases. This way, IEEE 802.15.4 is capable of achieving a much higher throughput.

III. DESIGN CONSIDERATION FROM IEEE 802.15.4 WITH BLOCK ACKNOWLEDGMENT

Packet concatenation facilitates the aggregation of several consecutive packets by means of channel reservation and different acknowledgement types and/or Network Allocation Vector (NAV) setting. In the current work, we follow a different approach comparing to [17], where the use of RTS/CTS was considered and [18] in which only DSSS layer was assumed. In particular, we propose the use of BACK in order to improve the channel use optimization in IEEE 802.15.4 nonbeacon-enabled networks. Our proposal considers the aggregation of several ACK responses into one special packet. The *BACK Response* primitive is responsible to confirm the set of data packets successfully delivered to the destination by using a M bit bitmap. A bit value equal to 1 means that a data packet has successfully reached the destination, while a bit value equal to 0 means that the corresponding data packet as failed to reach the destination. Therefore, when the transmitter node receives a *BACK Response*, it compares the send/received M

bit bitmap, and if needed it retransmits the frames that do not have reach the destination.

By decreasing the number of ACK control packets exchanged over the wireless medium, it is possible to decrease not only the number of collisions but also the number of backoff periods (the time a node must wait before attempting to transmit/retransmit packets) on each node. Since nodes are battery operated, it is very important that the transmission of aggregated packets leads to energy decrease, whilst increasing the number of data packets containing useful information that will be transmitted will result in higher goodput values.

A. Block Acknowledgment Mechanism with BACK Request

Our first BACK proposal implements *BACK Request* into IEEE 802.15.4 by considering the exchange of two special packets: *RTS ADDBA* and *CTS ADDBA*, where *ADDBA* stands for "Add Block Acknowledgement". After this successful exchange, the data packets are transmitted from the transmitter to the receiver (e.g., 10 frames are aggregated). Afterwards, by using the *BACK Request* primitive, the transmitter inquires the receiver about the total number of data packets that successfully reach the destination. The receiver replies by sending a special data packet called *BACK Response* identifying the packets that require retransmission. The exchange of two special control packets in the beginning of the BACK mechanism is employed in order to avoid the hidden-terminal and exposed-terminal problems like in the IEEE 802.11e standard [12] (i.e., by using a RTS/CTS handshake). In our proposed mechanism for every *RTS ADDBA/CTS ADDBA* exchange, we assume that there are always frames available for aggregation in the transmitter.

As presented in Figure 1, in order to decrease the overhead of the IEEE 802.15.4 MAC, we propose MAC enhancements that adopt frame concatenation. The idea is to transmit multiple frames (i.e., MPDU) by using the BACK mechanism. Our work addresses a distributed scenario, with single-destination and single-rate frame aggregation, as presented in Figure 2. Moreover, we also assume that the payload of the MAC frames cannot be changed.

The minimum average delay, D_{min_BACK} , and the maximum average throughput for IEEE 802.15.4 with *BACK*

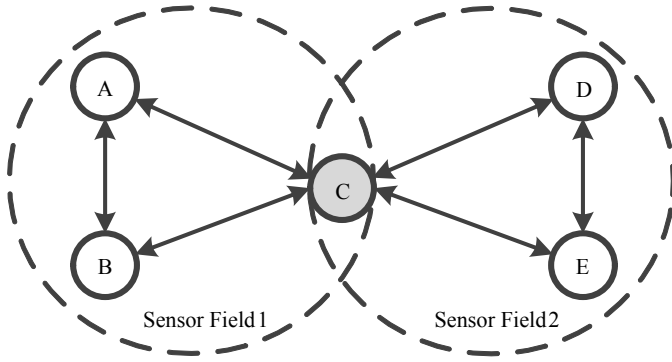


Figure 2. Multi-hop star topology simulation scenario without interferes.

Request are given as follows:

$$D_{min_BACK} = H_2/n \quad (6)$$

where $H_2 = \overline{CW} + ccaTime + T_{TA} + T_{RTS_ADDBA} + T_{TA} + \dots + T_{CTS_ADDBA} + n \times (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{IFS}) + ccaTime + T_{TA} + T_{BRequest} + T_{TA} + T_{BResponse} + T_{IFS}$.

$$S_{max_BACK} = 8L_{DATA}/D_{min_BACK} \quad (7)$$

The scheme with BACK presented in Figure 1.b) is more efficient than the one with DATA/ACK from Figure 1.a), since it does not consider the use of ACK packets and the backoff is equal to 0. However, error control becomes less robust than in the IEEE 802.15.4 basic access mode presented in Figure 1.a), because, by considering the BACK mechanism, there is no way for the source to know if one or more frames get corrupted until the *BACK Request/BACK Response* exchange mechanism is concluded. For the IEEE 802.15.4 basic access mode, when the ACK frame is lost the source only needs to retransmit the last frame.

B. Block Acknowledgment Mechanism without BACK Request

The version of the IEEE 802.15.4 without *BACK Request* ("piggyback mechanism") also considers the exchange of the *RTS ADDBA* and *CTS ADDBA* packets at the beginning of the communication. However, the *BACK Request* primitive is not transmitted, as shown in Figure 1.c), the last aggregated data frame, must include the information about the total number of packets previously TX. Therefore, by "piggybacking" the BACK information into the last data fragment, we reduce the overhead and the end-to-end delay whilst increasing the throughput. However, this scheme is less robust in comparison to the IEEE 802.15.4 with *BACK Request*. If the last aggregated frame (i.e., DATA frame n) is lost, the destination does not know that an ACK needs to be sent back.

The minimum average delay and the maximum average throughput for IEEE 802.15.4 without *BACK Request* are given as follows:

$$D_{min_Piggy} = H_3/n \quad (8)$$

where $H_3 = \overline{CW} + ccaTime + T_{TA} + T_{RTS_ADDBA} + T_{TA} + \dots + T_{CTS_ADDBA} + (n-1) \times (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{IFS}) + ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{BResponse} + T_{IFS}$.

$$S_{max_Piggy} = 8L_{DATA}/D_{min_Piggy} \quad (9)$$

IV. SIMULATION EVALUATION

We now evaluate the performance of IEEE 802.15.4 in the presence and absence of *BACK Request* by employing the MiXiM simulation framework [14] from the OMNeT++ simulator. Figure 3 presents the main components that are responsible for simulating the channel access within this WSN communication stack. In addition, a state transition diagram for the SBACK-MAC and IEEE 802.15.4 was also derived and proposed by the authors. The throughput and end-to-end delay performance with and with no *BACK Request* has been compared against IEEE 802.15.4 in the basic access mode, by considering a 95 % confidence interval. Table I and Table II provide all the parameters utilized in our simulations for the DSSS and CSS PHY layers. The performance analysis of the proposed schemes is conducted for the best-case scenario by assuming an ideal channel without transmission errors. During the active period, there is only one node that always has a frame to be sent. The other stations can only accept frames and provide acknowledgments.

Figure 4 presents the minimum average delay, D_{min} , as a function of the payload size, by considering the three different mechanisms presented in Figure 1. The number of transmitted frames, n , is 10 (i.e., for the IEEE 802.15.4 in the presence and absence of *BACK Request*, the frames are aggregated and transmitted in a burst). The discontinuity around 18 bytes is due to the use of SIFS and LIFS (i.e., MPDU less or equal than 18 bytes must be followed by a SIFS, whilst MPDU greater than 18 bytes must be followed by a LIFS).

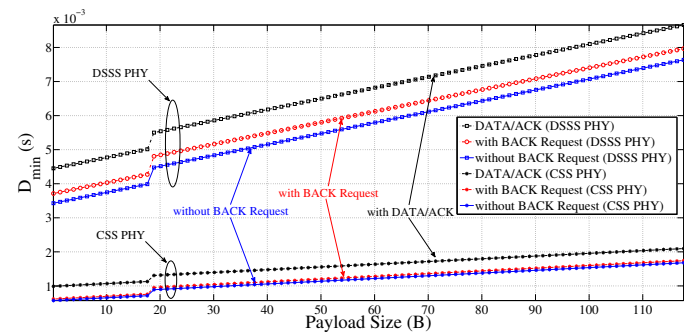


Figure 4. Minimum average delay as a function of the payload size.

Results show that, by using the DSSS PHY layer for IEEE 802.15.4 with and without *BACK Request* for shorter packets sizes (i.e., data payload less or equal to 18 bytes) D_{min} decreases by 17 % and 25 % respectively. For larger packet sizes, by considering IEEE 802.15.4 with and with no *BACK Request*, D_{min} decreases 8 % and 13 %, respectively.

For the CSS PHY layer with and without *BACK Request* for shorter packets sizes (i.e., data payload less or equal to 18 bytes) D_{min} , decreases by 50 % and 59 % respectively. For longer packet sizes, D_{min} , decreases by 20 % and 25 %, respectively.

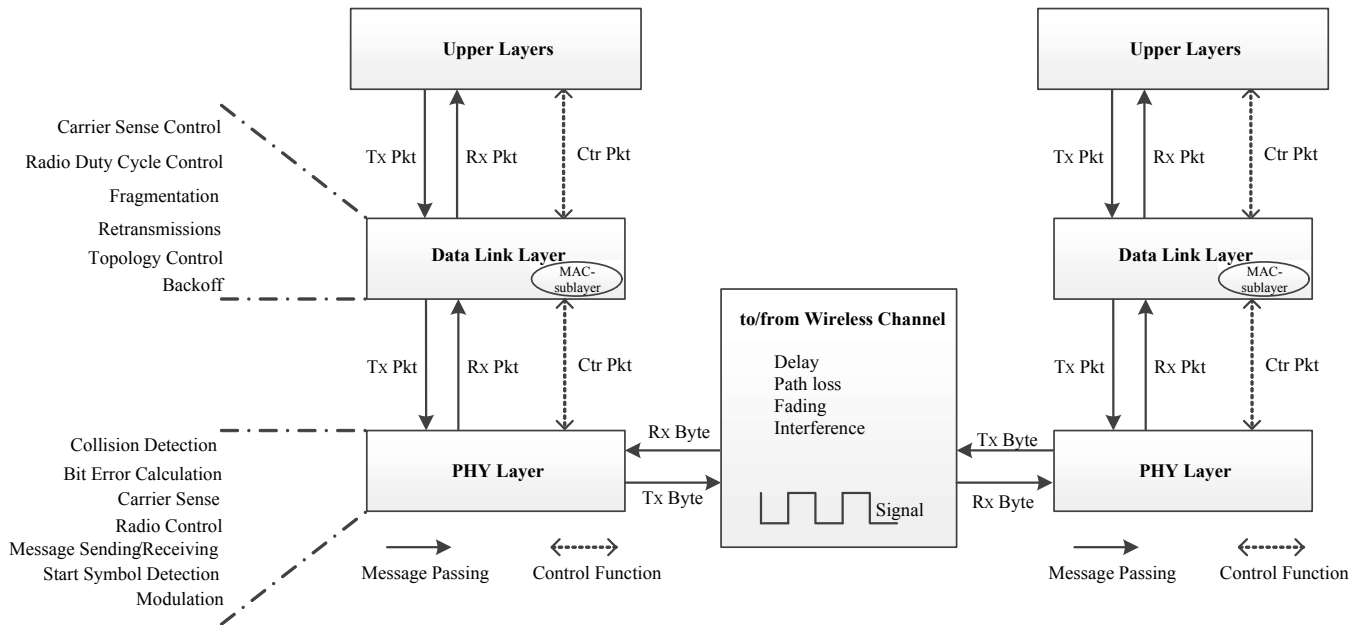


Figure 3. Layered model used by IEEE 802.15.4 and SBACK-MAC.

Figure 5 presents the maximum average throughput, S_{max} as a function of the payload size.

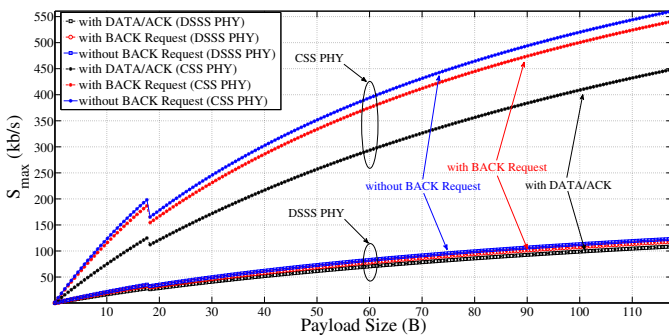


Figure 5. Maximum average throughput as a function of the payload size.

By considering the DSSS PHY layer for IEEE 802.15.4 with and without *BACK Request* for shorter packets sizes, S_{max} increases by 17 % and 25 % respectively. For longer packet sizes, by considering IEEE 802.15.4 with and without *BACK Request*, S_{max} , increases 8 % and 13 %, respectively.

For the CSS PHY layer in the presence and absence of *BACK Request* for shorter packets sizes (i.e., data payload less or equal to 18 bytes) S_{max} increases by 50 % and 59 % respectively. For longer packet sizes, S_{max} increases by 20 % and 25 %, respectively.

By comparing IEEE 802.15.4 in the basic access mode (labeled DATA/ACK in the legend) for the case without retransmissions with the one presented in [15], we conclude that the differences in terms of minimum average delay, D_{min} , are justified by the fact that the authors in [15] have not considered the time needed to switch the radio between the different states (i.e., rxSetupTime) [10].

The bandwidth efficiency, η , for IEEE 802.15.4, suggested by the authors in [16], is provided by the following equation:

$$\eta = S_{max}/R \quad (10)$$

where R represents the maximum data rate of 250 kb/s and 1Mb/s for the DSSS and CSS PHY layers respectively.

Figure 6 presents the bandwidth efficiency as a function of the payload size.

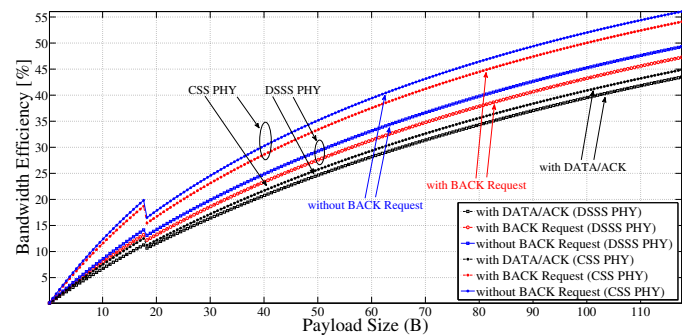


Figure 6. Bandwidth efficiency as a function of the payload size.

Table III presents the bandwidth efficiency results regarding shorter packets sizes (i.e., data payload less or equal to 18 bytes) and larger packets sizes (i.e., data payload equal to 118 bytes) for the different access modes shown in Figure 6.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed the use of Block Acknowledgment mechanisms by aggregating several ACKs into one special packet, the *BACK Response* in order to improve channel efficiency of IEEE 802.15.4 networks for both the DSSS and CSS PHY layers in the 2.4 GHz frequency band. Two

TABLE III

BANDWIDTH EFFICIENCY FOR PAYLOAD SIZES OF 18 AND 118 BYTES.

Payload	18 Bytes	118 Bytes
Access mode	Bandwidth efficiency	
DATA/ACK (DSSS PHY)	11 %	43 %
DATA/ACK (CSS PHY)	13 %	45 %
BACK REQUEST (DSSS PHY)	13 %	47 %
BACK REQUEST (CSS PHY)	18 %	54 %
no BACK REQUEST (DSSS PHY)	14 %	49 %
no BACK REQUEST (CSS PHY)	20 %	56 %

innovative solutions were proposed: The first one considers the presence of *BACK Request* (concatenation mechanism), while the second considers the absence of *BACK Request* (piggyback mechanism). At the best-case scenario (i.e., considering a channel environment without transmissions errors), the maximum average throughput and minimum average delay were analytically derived. For the DSSS PHY layer by ranging the payload size between 1 and 118 bytes, for shorter packets sizes, S_{max} , is increased by 17 % and 25 % for the IEEE 802.15.4 with and without *BACK Request*, respectively (in comparison with IEEE 802.15.4 in the basic access mode). Consecutively, D_{min} is decreased by 17 % and 25 %. For the CSS PHY layer for shorter packets sizes (i.e., data payload less or equal to 18 bytes) S_{max} is increased by 50 % and 59 % for the IEEE 802.15.4 with and without *BACK Request*, respectively (in comparison with IEEE 802.15.4 in the basic access mode). Consequently, D_{min} is decreased 50 % and 59 %. Furthermore, bandwidth efficiency results have shown that by using the proposed BACK mechanism we improved the channel use optimization by decreasing the overhead for all the cases.

Ongoing and future work consists of further exploring our proposed block acknowledgement mechanisms by employing additional performance metrics such as energy consumption as well as by studying the effect on performance of several factors such as the number of aggregated packets. Furthermore, in the scope of the current paper we have considered the best-case scenario (no transmission errors). However, very often this is not realistic since a transmitted frame is not received by the intended node and at least one retransmission is required. Thus, our future vision is to further explore both our concatenation and piggyback mechanisms for an erroneous channel, study the impact of retransmissions and propose additional performance enhancements.

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