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Performance enhancement of IEEE 802.15.4 by employing RTS/CTS and frame concatenation

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Abstract: IEEE 802.15.4 has been widely accepted as the de facto standard for wireless sensor networks (WSNs). However, as in their current solutions for medium access control (MAC) sub-layer protocols, channel efficiency has a margin for improvement, in this study, the authors evaluate the IEEE 802.15.4 MAC sub-layer performance by proposing to use the request-/clear-to-send (RTS/CTS) combined with frame concatenation and block acknowledgement (BACK) mechanism to optimise the channel use. The proposed solutions are studied in a distributed scenario with single-destination and single-rate frame aggregation. The throughput and delay performance is mathematically derived under channel environments without/with transmission errors for both the chirp spread spectrum and direct sequence spread spectrum physical layers for the 2.4 GHz Industrial, Scientific and Medical band. Simulation results successfully verify the authors' proposed analytical model. For more than seven TX (aggregated frames) all the MAC sub-layer protocols employing RTS/CTS with frame concatenation (including sensor BACK MAC) allow for optimising channel use in WSNs, corresponding to 18–74% improvement in the maximum average throughput and minimum average delay, together with 3.3–14.1% decrease in energy consumption.

1 Introduction

In the last decade, the growth of a wide range of wireless sensor network (WSN) deployments and applications [1–3] has been witnessed. In the WSN research domain, there is a vast amount of proposals for energy-efficient medium access control (MAC) protocols [4]. Resulting from the standardisation efforts, IEEE 802.15.4 [5] has been widely accepted as the de facto standard for the physical (PHY) and MAC layers of WSNs enabling to provide ultra-low complexity, cost and power consumption for low-data rate wireless connectivity between wireless sensors. Due to its reduced power consumption, IEEE 802.15.4 has been used as a basis for ZigBee®, WirelessHart® and MiWi™ applications. Moreover, it represents a significant breakthrough from the 'faster' standards that the IEEE 802 Working Group continues to develop and improve. Instead of higher data rates and more functionality, this family of standards addresses the low-data universe, applied to control and sensor networks, which had existed without global standardisation through a series of proprietary methods and protocols. Actually, in 2014, annual shipments of IEEE 802.15.4 and ZigBee wireless chipsets doubled in comparison with 2013, and are forecast to reach a cumulative 2.5 billion chipset sales in 2020, as described in [6]. Since WSNs and Internet-of-Things (IoT) are increasingly taking part in people's lives, there are gradually more and more applications where these smart systems are used. Moreover, the deployment of WSNs applied to a wide range of applications will change the way people interact, live or even work within their surrounding environment [7]. Allied to this fact, IEEE 802.15.4 is the common denominator that is enabling this ubiquitous networking to become a reality. Although the authors from [8] proposed a model that accurately captures IEEE 802.15.4 MAC behaviour with periodic traffic, the evolution towards the creation of the next-generation of WSNs motivates the need for research on new MAC mechanisms, since one of the fundamental reasons for the IEEE 802.15.4 standard MAC inefficiency is overhead.

In this work, we investigate MAC sub-layer enhancements for IEEE 802.15.4 (non-beacon mode) by considering the use of request-to-send/clear-to-send (RTS/CTS) combined with frame concatenation in a similar manner that has been carried out for IEEE 802.11 protocols in [9, 10]. The authors from [11] propose an adaptive mechanism based on RTS/CTS in order to combat the hidden terminal problem in an IEEE 802.15.4 non-beacon enabled the multi-hop network. By employing the RTS/CTS handshake mechanism, we avoid the repetition of the backoff procedure for each data frame that is sent within each RTS/CTS set, unlike the basic access mode of 802.15.4. As such, channel utilisation is maximised by decreasing the deferral time period before transmitting a data frame [12]. RTS/CTS is considered because there are applications that require larger bandwidth and bit rate than other ones, e.g. high and medium data streams (HDS/MDS), events, habitat [13] or user monitoring [14], as defined in [7]. We also propose the use of frame concatenation and piggyback block acknowledgement (BACK) mechanisms aiming at reducing overhead in IEEE 802.15.4. The characteristics of the BACK mechanism enable to improve channel efficiency by aggregating several acknowledgement (ACK) responses into one single backward frame. This aggregation aims at reducing the overhead by transmitting less ACK control frames whilst decreasing the time periods that the transceivers should spend in order to switch between different states. Hence, by providing a feedback mechanism to enable the receiver to inform the sender about how many transmitted (TX) frames were successfully received (RX), throughput is increased whilst decreasing end-to-end delay and enhancing bandwidth efficiency.

This work extends the contributions given by the authors in [15, 16]. Barroca *et al.* [15] address the proposal of RTS/CTS combined with packet concatenation applied to the non-beacon enabled mode of IEEE 802.15.4. The analytical formulation for the minimum delay and maximum throughput the existence of retransmissions in channels with packet errors is also considered in [15]. However, in [15], the performance evaluation is only determined as a function of the number of transmitted packets, whereas in this paper, the comparison is also performed as a function of the payload size, for a fixed number of transmitted packets ($n = 10$), while payload varies from 1 to >115 bytes. The difference in the behaviour for payload sizes of less/more than 18 packets is discussed. Furthermore, this work compares the performance between RTS/CTS and the one from the two versions of the BACK MAC protocol proposed here. The employment of a BACK mechanism to achieve channel efficiency in IEEE 802.15.4 non-beacon

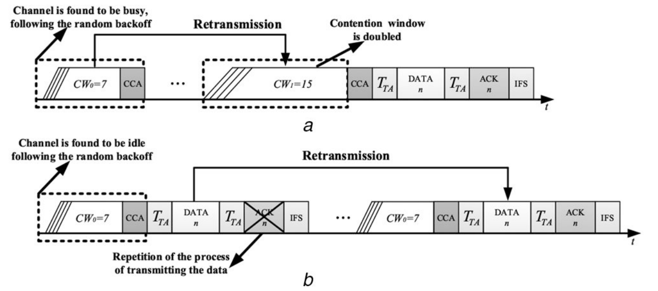

Fig. 1 *IEEE 802.15.4 basic access mode with retransmissions*
(a) Channel is found to be busy and, ***(b)*** Channel is found to be idle

Table 1 Backoff stages for IEEE 802.15.4 in the presence/absence of RTS/CTS with frame concatenation, $NB_{max} = 4, BE_{max} = 5$

NB	BO_s	BE_i	$CW_{NB} = [2^{BE_i} - 1]$	$\overline{CW}_{NB}$
0	0	3	$CW_0 = 7$	3.5
1	1	4	$CW_1 = 15$	7.5
2	2	5	$CW_2 = 31$	15.5
3	3	5	$CW_3 = CW_2 = 31$	15.5
4	4	5	$CW_4 = CW_2 = 31$	15.5

enabled networks was proposed in [16] for the chirp spread spectrum (CSS) and direct sequence spread spectrum (DSSS) physical (PHY) layers of the 2.4 GHz industrial, scientific and medical (ISM) band. However, in this work, we go further and consider the case of the erroneous channel, where retransmissions are needed, and are essential for keeping the performance of the proposed protocol. The advantages of using both the BACK request or not considering it (‘piggyback mechanism’) are analysed for channels either without any errors or in the presence of errors. Although different payload sizes are considered (short or long packets, $L_{DATA} = 3$ or 20 bytes, respectively), the results in this work are essentially analysed as a function of a number of transmitted packets (whereas in [16] the results have been presented as a function of the payload size). Differently from [15, 16], in this work, the energy consumption trade-off is discussed. In [17], these MAC sub-layer protocols are compared with multi-channel scheduled channel polling MAC protocol by considering the DSSS PHY.

The remainder of the paper is organised as follows. Section 2 presents an overview of the MAC sub-layer timing constraints of the IEEE 802.15.4 standard, and discusses our proposal to employ the RTS/CTS scheme combined with frame concatenation. An analytical model to derive the limits for the theoretical throughput and end-to-end delay is proposed. Retransmissions are considered. Section 3 describes the use of BACK mechanisms and discusses the benefits and limitations of using the frame concatenation and piggyback mechanisms. Section 4 addresses the numerical and simulation results that are utilised to verify our proposals for both the best-case scenario and the case of an erroneous channel. The analysis of the sensor BACK MAC (SBACK-MAC) protocol considers both the DSSS and CSS PHY layers. Apart from throughput and delay performance, energy efficiency is also addressed. Finally, in Section 5, conclusions are drawn and suggestions for future ongoing work are discussed.

2 IEEE 802.15.4 in the presence and absence of RTS/CTS for the non-beacon mode

IEEE 802.15.4 includes beacon- and non-beacon enabled MAC sub-layer mechanisms. The latter uses unslotted carrier-sense multiple access with collision avoidance (CSMA/CA). Each time a device needs to access the radio channel, it waits for a random backoff period, and then senses the channel to perceive its status. If the channel is found to be idle, then the device transmits its pending data; otherwise, it waits for another random period before trying to access again the channel, as described in [18].

In the current research work, we only consider the non-beacon enabled mode, since otherwise, in the beacon-enabled mode [19], beacon collisions could occur with other beacons, data or control frames, making difficult to build and maintain a multi-hop beacon-enabled based network [20]. The non-beacon enabled mode seems to conveniently fit the scalability requirement (influenced by network size, node density and topology). In particular, nodes may die over time, other ones may be added later and some may move to a different location. All nodes are independent from the personal area network (PAN) coordinator and the communication is completely decentralised. Moreover, for beacon-enabled networks [21], there is an additional timing requirement for sending two consecutive frames, so that the ACK frame transmission should be started between the TX/RX–RX/TX switching time and backoff time period. Hence, there is time remaining in the contention access period (CAP) for the data frame, appropriate interframe spacing (IFS) and ACK.

2.1 IEEE 802.15.4 in the absence of RTS/CTS

As stated above, in the basic access mode, IEEE 802.15.4 non-beacon enabled networks are ruled by a backoff phase before accessing the channel. To the best of our knowledge, within the different releases of the standard, there is no proposal to include the RTS/CTS mechanism for IEEE 802.15.4 in order to resolve the hidden-node problem. As illustrated in Fig. 1, nodes with a frame to transmit monitor the channel only during the clear channel assessment (CCA) phase, which starts immediately after the expiration of the random backoff delay. The backoff phase (N.B.: this time period is not generally called contention window in IEEE 802.15.4) algorithm is implemented by considering basic units of time, called backoff periods. The backoff period duration is equal to $T_{BO} = 20 \times T_{symbol}$ (i.e. 0.32 ms), where $T_{symbol} = 16\,\mu s$ is the symbol time [5]. Before performing CCA, a device shall wait for a random number of backoff periods, determined by the backoff exponent (*BE*). Consequently, the transmitter randomly selects a uniformly distributed backoff time period, in the range $[0, 2^{BE} - 1]$. It is worthwhile to mention that, even if there is only one transmitter and one receiver, the transmitter will always choose a random backoff period within $[0, 2^{BE} - 1]$, which causes delay, as defined in [22]. Before starting a new transmission, each device sets initially the *BE* equal to *macMinBE*. On the other hand, after every failed attempt to access the channel, the device increments the value of BE.

By considering the same assumptions from the model presented in [18], one can model the backoff procedure by a bi-dimensional process $Q(t) = \{BO_c(t), BO_s(t)\}$, where t is an integer that represents the time slot. More precisely, the jth slot, lasting from $j \cdot T_{BO}$ to $(j+1) \cdot T_{BO}$, is denoted by $t = j$. The variables $BO_c(t)$ and $BO_s(t)$ represent the backoff time counter and the backoff stage at slot t, respectively. Since the $BO_c(t)$ is not a memoryless process, the dimensional process given by the $BO_c(t)$ and $BO_s(t)$ cannot be derived by considering a Markovian chain [18]. Moreover, the *BE* is dependent of the $BO_s(t)$. By analysing the possible combinations between the pair (NB, BE) one concludes that there are $NB_{max} + 1$ different backoff stages, where NB_{max} represents the maximum number of backoffs allowed by the CSMA-CA algorithm. Table 1 presents the different values for the backoff stage and the corresponding CW_{NB} by assuming the combination pair ($NB_{max} = 4, BE_{max} = 5$).

As mentioned before, one of the fundamental reasons associated to the IEEE 802.15.4 standard MAC inefficiency is overhead. The sources of overhead are the following ones:

- *Interframe spacing (IFS)* – For every IEEE 802.15.4 transmission, there is an idle period before accessing the medium (called interframe spacing, IFS). In the basic access mode, short IFS (SIFS) is used when the MAC protocol data unit (MPDU), i.e. $F_{H\_MAC} + L_{DATA}$, is less or equal than 18 bytes; otherwise, long IFS (LIFS) is considered. The purpose of IFS is to regulate the data exchange flow and provide priority for certain types of transmissions.

- *Backoff period* – When IEEE 802.15.4 nodes contend to access the wireless medium, they use a backoff algorithm. This process ultimately reduces collisions and allows for realising quality-of-service (QoS). The random backoff time represents a number of 'slots' (i.e. periods of time) when the wireless medium must be idle.
- *PHY and MAC headers* – In the basic access mode, the PHY protocol data unit (PPDU) must contain the synchronisation header (SHR) and the PHY header (PHR) fields in order to achieve reliable reception of frames. The MAC header contains information about how to coordinate nodes, and provide a fair mechanism to share the medium access among nodes. It is responsible for how and when the nodes should use PHY functions for accessing the shared physical medium. Although headers are needed, they introduce overhead and are responsible for decreasing the throughput.
- *Acknowledgements* – The lossy and inherently unreliable wireless medium imposes the use of ACK frames in order to confirm that frames have successfully reached the destination. However, ACK frames are overhead as they do not contain any useful information.
- *Interference* – In a very generic sense, all sources of interference create overhead, since nodes must perform a CCA procedure to determine whether the wireless medium is busy or idle (as it is described in the IEEE 802.15.4 standard [5]) to determine if the wireless medium is busy or idle.
- *Retransmissions* – When a transmitted frame is not received by the intended node, i.e. there is no ACK response, retransmissions (RTXs) are required. Transmitting a frame more than once creates additional overhead, e.g. repetition of the backoff phase and IFS. Hence, although RTXs are an important source of overhead, the issue can be mitigated by using efficient RTX mechanisms.

In [22], we have proposed a mathematical model that derives the throughput and end-to-end delay limits under ideal conditions (a channel environment with no transmission errors). In the scope of this research, we address both the best-case scenario, where no transmission errors exist, and the more realistic case that considers transmission errors, which originates frame RTXs. For both cases, we study the impact on the performance of employing RTS/CTS with frame concatenation, for both the CSS and DSSS PHY layers at 2.4 GHz, and compare their performance against the basic access mode.

Table 2 presents the key parameters, and defines symbols and values for the DSSS PHY, previously utilised in [12], that will be considered throughout this work. Detailed definitions are given in [22]. Table 3 [12] presents a comparison between the DSSS and CSS PHY layers. Our previous work in [12, 22] considered the impact on the performance of RTS/CTS with frame concatenation for the CSS PHY only. By analysing Table 3, we observe that the CSS PHY proposal by IEEE 802.15 working group (WG) for wireless PANs (WPANs) implies several MAC enhancements that clearly improve IEEE 802.15.4 [23] performance.

One important improvement is overhead mitigation by decreasing the IFS and backoff times, hence by reducing the impact of the PHY layer header. However, to the best of our knowledge, there is no proposal in the literature on the inclusion of RTS/CTS in order to avoid the hidden terminal problem, and associated degradation [20].

In the remaining of this section, we propose an analytical model to evaluate the theoretical throughput and end-to-end delay limits for the IEEE 802.15.4 non-beacon-enabled mode (a similar manner as it was carried out in [25]) and we further analyse the impact of frame RTXs by considering an erroneous channel.

In the basic access mode of IEEE 802.15.4, the minimum delay due to CCA, $D_{\text{min\_CCA}}$, is as follows:

$$D_{\text{min\_CCA}} = \sum_{i=1}^{n} \sum_{k=0}^{k \le \text{NB}} \left(\overline{\text{CW}_k} + ccaTime\right) \tag{1}$$

Table 2 Parameters, symbols and values for IEEE 802.15.4 employing or not employing RTS/CTS with frame concatenation

Description	Symbol	Value
backoff period duration	T_{BO}	320 μs
CCA detection time ($8 \cdot T_{\text{symbol}}$)	T_{CCA}	128 μs
setup radio to RX or TX states [24]	*rxSetupTime*	1720 μs
time delay due to CCA	*ccaTime*	1920 μs
TX/RX or RX/TX switching time	T_{TA}	192 μs
ACK wait duration time	T_{AW}	560 μs
PHY length overhead	$L_{\text{H\_PHY}}$	6 bytes
MAC overhead	$L_{\text{H\_MAC}}$	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 μs
ACK transmission time	T_{ACK}	352 μs
short interframe spacing (SIFS) time	T_{SIFS}	192 μs
long interframe spacing (LIFS) time	T_{LIFS}	640 μs
RTS ADDBA transmission time	$T_{\text{RTS\_ADDBA}}$	352 μs
CTS ADDBA transmission time	$T_{\text{CTS\_ADDBA}}$	352 μs
BACK request transmission time	T_{BRequest}	352 μs
BACK response transmission time	$T_{\text{BResponse}}$	352 μs
number of TX frames	n	1–112
data rate	R	250 kb/s

Table 3 Parameters, symbols and values for IEEE 802.15.4 by considering the DSSS and CSS PHY layers

Symbol	DSSS PHY	CSS PHY
$L_{\text{H\_PHY}}$	6 bytes	7 bytes
$L_{\text{H\_MAC}}$	9 bytes	9 bytes
T_{TA}	192 μs	72 μs
T_{SIFS}	192 μs	72 μs
T_{LIFS}	640 μs	240 μs
T_{BO}	320 μs	120 μs
R	250 kb/s	1 Mb/s

where the number of backoff periods is given by $\text{NB} \in [0, \text{NB}_{\text{max}}]$, as shown in [18]. The time delay due to CCA is given by $ccaTime = rxSetupTime + T_{\text{CCA}}$, where *rxSetupTime* is the time to switch the radio between the different states and must be extracted from the radio transceiver data sheet [24]. Equation (1) also accounts for each transmitted frame ranging from 1 to the total number of transmitted frames, for each active period, n.

The following equation gives the minimum delay due to frame RTXs, $D_{\text{min\_DataRet}}$, when the channel is found to be idle during CCA, there is the data transmission and an ACK is not received within the ACK wait duration period (defined by T_{AW}, and represents the longest time needed to receive an ACK control frame)

$$\begin{aligned} D_{\text{min\_DataRet}} &= \sum_{i=1}^{n} k_i \\ k_i &= \begin{cases} H_1 & j = 0 \\ H_2 + (j-1) \times H_4 + H_3 & j \in [1, MaxRet] \end{cases} \end{aligned} \tag{2}$$

where j is the number of frame RTXs, whose range is between 0 and the maximum number of RTXs, like in [5].

To appropriately establish (2), H_1, H_2, H_3 and H_4 need to be defined. After CCA, if nodes determine that the channel is found to be idle and an ACK is correctly received, following the

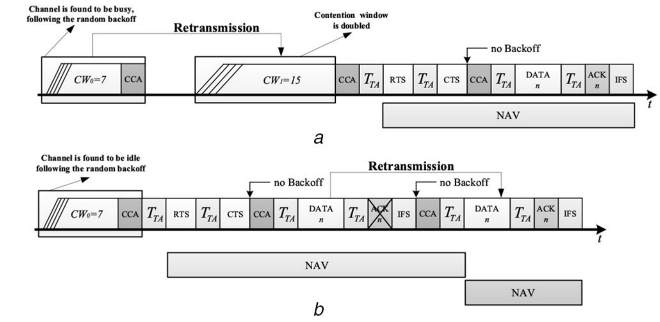

Fig. 2 *Frames for IEEE 802.15.4 with RTS/CTS and retransmissions*
(a) Channel is found to be busy, ***(b)*** Channel is found to be idle

transmission of a data frame, the minimum delay, $D_{\text{min\_DataRet}}$, is given by H_1, as follows:

$$H_1 = T_{\text{TA}} + T_{\text{DATA}} + T_{\text{TA}} + T_{\text{ACK}} + T_{\text{IFS}} \quad (3)$$

The number of RTX frames for this case is given by $j = 0$. Since a successful transmission occurs, there is no need to consider the ACK wait duration period, T_{AW}, in (3).

After CCA, if nodes determine that the channel is found to be idle, and an ACK is not correctly received following the transmission from a data frame, if an RTX has only been tried once by the node ($j = 1$), the minimum delay due to frame RTX, $D_{\text{min\_DataRet}}$, is given by $H_2 + H_3$, where

$$H_2 = T_{\text{TA}} + T_{\text{DATA}} + T_{\text{AW}} \quad (4)$$

$$H_3 = \overline{\text{CW}_0} + ccaTime + H_1 \quad (5)$$

H_2 indicates that in the first transmission attempt no ACK has been received within T_{AW}. The term H_3 indicates that the node has only received an ACK control frame once after retransmitting the data frame once more. Frames are retransmitted by considering the first contention window, CW_0, defined by the CSMA-CA algorithm [5].

If the number of RTX attempts is more than one, where a node has failed to previously transmit a frame, and will retry to transmit it again until the number of maximum RTXs, *MaxRet*, will be reached, the minimum delay due to frame RTXs, $D_{\text{min\_DataRet}}$, is given by

$$H_4 = H_2 + (j - 1) \times H_5 + H_3 \quad (6)$$

where $H_5 = \overline{\text{CW}_0} + ccaTime + H_2$. The term $(j-1) \times H_5$ indicates that the frame will be retransmitted by considering the first contention window in the range $j \in [2, MaxRet]$, and an ACK control frame will be correctly received in the last RTX attempt, given by H_3.

The minimum average delay, $D_{\min}$, due to the channel state (i.e. busy or idle) and frame RTXs can be determined by combining (1) and (2), as follows:

$$D_{\min} = \frac{(D_{\text{min\_CCA}} + D_{\text{min\_DataRet}})}{n} \quad (7)$$

In the basic access mode of the IEEE 802.15.4 with frame RTXs, if an erroneous channel is considered, the maximum average throughput, $S_{\max}$, in bits per second, is given by

$$S_{\max} = \frac{8L_{\text{DATA}}}{D_{\min}} \quad (8)$$

2.2 IEEE 802.15.4 in the presence of RTS/CTS

Although the RTS/CTS reservation scheme is not new and has already been standardised and implemented in IEEE 802.11 (since it shortens frame collision duration, as shown in [26]), it has not been considered in any of the existing versions of IEEE 802.15.4 that utilise the non-beacon-enabled mode. This handshaking mechanism involves the transmission of short RTS and CTS control frames prior to the transmission of data frames. In this work, we analyse the benefits from the inclusion of RTS/CTS combined with frame concatenation in the IEEE 802.15.4 MAC sub-layer. In our proposal, we assume that RTS/CTS frames have the structure of an ACK frame, with a limited size of 11 bytes, as shown in Table 2.

Fig. 2 presents the structure of MAC frames for IEEE 802.15.4 employing RTS/CTS with frame concatenation. It is composed by the backoff phase, CCA mechanism, the time needed for switching from receiving to transmitting, RTS transmission time, the time needed for switching from transmitter to receiver, and CTS reception time. Furthermore, nodes will use the same backoff procedure as in the basic access mode, as shown in Fig. 2. However, this process is not repeated for each data frame sent but only for each RTS/CTS set. As a consequence, the channel utilisation is maximised by decreasing the deferral time period before transmitting a data frame, as shown in Fig. 1, and the maximum throughput, minimum delay and bandwidth efficiency are improved.

The following analytical model stands for the RTX delay and a maximum number of backoff stages. The minimum delay due to CCA, $D_{\text{min\_CCA\_RTS}}$, that corresponds to determining if the channel is found to be busy or idle, after the backoff phase, and before each RTS/CTS set, is given by

$$D_{\text{min\_CCA\_RTS}} = \sum_{i=1}^{n/N_{\text{agg}}} \sum_{k=0}^{k \le \text{NB}} \left(\overline{\text{CW}_k} + ccaTime\right) \quad (9)$$

According to (9), as nodes only determine the channel state once per RTS/CTS pair, if a node has, for example, $n = 100$ data frames to send, and the number of aggregated frames is equal to $N_{\text{agg}} = 10$, it only determines the channel state $n/N_{\text{agg}} = 10$ times plus the time needed for frame transmission (until the maximum retry limit, $NB_{\max} = 4$, is reached). By utilising the RTS/CTS scheme, if the channel is found to be idle during CCA and, after sending a data frame, and an ACK is not received within a duration of T_{AW}, the RTX process will not include the backoff phase between two consecutive data frames. The lack of contention results in a significant decrease of the total overhead, as shown in Fig. 2*b*. Since any other stations can receive RTS, CTS, DATA or ACK frames in the first transmission attempt, they will set a so-called network allocation vector (NAV), which is responsible for defining the time period each node will defer the channel access, in order to avoid collisions.

In our proposed IEEE 802.15.4 MAC protocol with RTS/CTS and frame concatenation, the minimum delay due to frame RTXs, $D_{\text{minDataRetRTS}}$, when the channel is found to be idle during CCA (after the backoff phase), there is data transmission, and an ACK is not received within a duration of T_{AW}, is obtained as follows:

$$D_{\text{minDataRetRTS}} = \begin{cases} H_6 & \text{for } j = 0 \\ H_7 & \text{for } j \in [1, MaxRet] \end{cases} \quad (10)$$

where j is the number of frame RTXs and varies between 1 and *MaxRet*, as defined in [5]. The following lessons can be learned from the analysis of (10):

- If, after CCA, a node determines that the channel is idle and an ACK is correctly received for each frame sent, the minimum delay, $D_{\text{minDataRetRTS}}$, is determined by

$$H_6 = T_{\text{TA}} + T_{\text{RTS}} + T_{\text{TA}} + T_{\text{CTS}} + \cdots + \sum_{i=1}^{N_{\text{agg}}} (ccaTime + H_1) \quad (11)$$

These ACKs are received if there are no transmission errors (the number of RTXs is $j = 0$).

- If, after CCA, a node founds the channel to be idle and an ACK has not been received within T_{AW}, for one or more aggregated frames, the minimum delay due to frame RTXs, $D_{\mathrm{minDataRetRTS}}$, is determined by

$$\begin{aligned} H_7 = & T_{\mathrm{TA}} + T_{\mathrm{RTS}} + T_{\mathrm{TA}} + T_{\mathrm{CTS}} \\ & + \cdots + \sum_{i=1}^{N_{\mathrm{agg}} - m} (ccaTime + H_1) \\ & + \cdots + \sum_{i=1}^{m} (j_i) \times (ccaTime + H_2) \\ & + \cdots + \sum_{i=1}^{m} (ccaTime + H_1) \end{aligned} \qquad (12)$$

The term $\sum_{i=1}^{N_{\mathrm{agg}} - m} (ccaTime + H_1)$ represents the time duration of $N_{\mathrm{agg}} - m$ transmitted aggregated frames that have successfully received an ACK response, where m denotes the number of transmitted frames that needs an RTX. Since each individual frame can be retransmitted more than once due to the lack of an ACK reception within a T_{AW} duration, the term j_i represents the number of times a frame has experienced RTXs until *MaxRet* has been reached. We then assume that the ACK frame is received, which is represented by the last sum, given by $\sum_{i=1}^{m} (ccaTime + H_1)$.

By combining (9) and (10), the minimum average delay, $D_{\mathrm{min\_RTS\_CTS}}$, that corresponds to the channel state (busy or idle) and frame RTXs is computed as follows:

$$D_{\mathrm{min\_RTS\_CTS}} = \frac{D_{\mathrm{min\_CCA\_RTS}} + D_{\mathrm{minDataRetRTS}}}{n} \qquad (13)$$

The maximum average throughput, $S_{\mathrm{max\_RTS\_CTS}}$, is obtained by replacing D_{min} by $D_{\mathrm{min\_RTS\_CTS}}$ in (8).

These formulations are essential to understand the improvement in the IEEE 802.15.4 MAC sub-layer performance arising from the introduction of the RTS/CTS mechanism.

3 IEEE 802.15.4 with BACK

Aiming at reducing delay and increase the throughput of IEEE 802.15.4 non-beacon-enabled networks, in this section, we propose the employment of BACK mechanisms. In our proposal, the IEEE 802.15.4 standard allows the aggregation of several ACK responses into one special frame. The *BACK response* primitive is responsible to confirm the set of data frames successfully delivered to the destination by using a M bit bitmap. A bit equal to 1/0 means that a data frame has succeeded/failed to reach the destination. Hence, when the transmitter node receives a *BACK response*, it compares the send/received M bit bitmap and, if needed, it retransmits the frames that have not reached the destination.

By decreasing the number of ACK control frames exchanged in the wireless shared medium, it is possible to decrease not only the number of collisions but also the number of backoff phase time intervals (the time that a node must wait before attempting to transmit/retransmit the frame) at each node. Since nodes are battery operated, the transmission of such frames leads to the energy decrease whilst reducing the number of data frames that are transmitted containing useful information (i.e. the ones considered to compute goodput).

3.1 BACK mechanism with BACK request

The proposed adaptation of the IEEE 802.15.4 that employs *BACK request* considers the exchange of two special frames, *RTS ADDBA* and *CTS ADDBA*, where *ADDBA* stands for 'Add Block Acknowledgement'. After this successful exchange, data frames are transmitted to the receiver (e.g. the ten aggregated frames we have previously considered). By making use of the *BACK request* primitive, the transmitter inquires the receiver about the total number of data frames that successfully reached the destination. In response, the receiver sends a special data frame, called *BACK response* identifying frames that require RTX, and the BACK mechanism is concluded. The occurrence of RTS/CTS handshake at the beginning of the BACK mechanism enables to avoid the hidden- and exposed-terminal problems that are very common in IEEE 802.11 networks [26]. In our analysis, for every *RTS ADDBA/CTS ADDBA* exchange, we assume saturation conditions, i.e. there are always frames available for aggregation.

We propose several efficient MAC enhancements that adopt frame concatenation, as presented in Fig. 3. The idea to reduce overhead is to transmit multiple frames [i.e. MAC protocol data units (MPDUs)] by using the BACK mechanism.

A distributed scenario is studied, with single-destination and single-rate frame aggregation. Moreover, we also assume that the payload from MAC frames cannot be changed. In IEEE 802.15.4 with the *BACK request*, every time a node has an *RTS ADDBA* to send, the transmission will follow the same backoff procedure like the one presented for IEEE 802.15.4 with RTS/CTS. The minimum delay due to CCA, $D_{\mathrm{min\_CCA\_BACK}}$, in seconds, to determine if the channel state is found to be busy or idle, after the backoff phase, and before each *RTS ADDBA/CTS ADDBA*, is given as follows:

$$D_{\mathrm{min\_CCA\_BACK}} = \sum_{i=1}^{n/N_{\mathrm{agg}}} \sum_{k=0}^{k \le \mathrm{NB}} \left(\overline{\mathrm{CW}_k} + ccaTime \right) \qquad (14)$$

Nodes only determine the channel state once per *RTS ADDBA/CTS ADDBA*, like in (9). After sending a set of frames, the receiver confirms the total amount of frames correctly received by using the *BACK response* primitive. All proposed signalling frames (*RTS ADDBA*, *CTS ADDBA*, DATA, *BACK request* and *BACK response*) have a NAV duration field that enables to reserve the channel while avoiding to repeat the backoff phase for every consecutive frame, targeting to reduce overhead. The neighbouring nodes are required to set their NAV field accordingly. This procedure avoids the occurrence of frame transmissions until the NAV has expired.

It is worthwhile to mention that the NAV duration shall include the time period needed for retransmitting the frames plus the *ccaTime* and T_{TA} time periods, enabling to avoid frame collisions between neighbouring nodes. In fact, when neighbouring nodes wake-up, they will try to access the channel by using the backoff phase, defined by the first contention window. The backoff timer

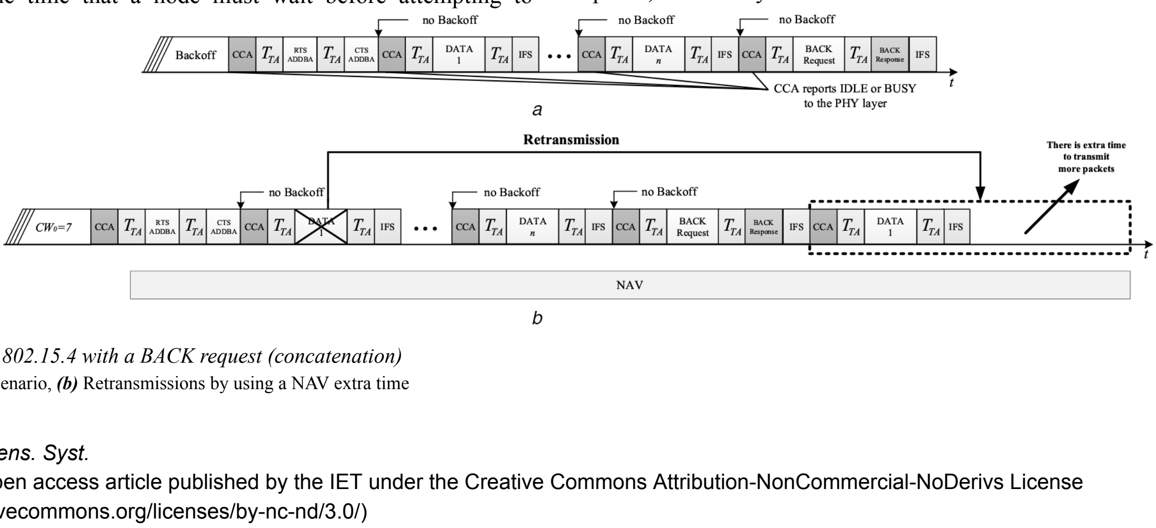

Fig. 3 *IEEE 802.15.4 with a BACK request (concatenation)*
(a) Best-case scenario, ***(b)*** Retransmissions by using a NAV extra time

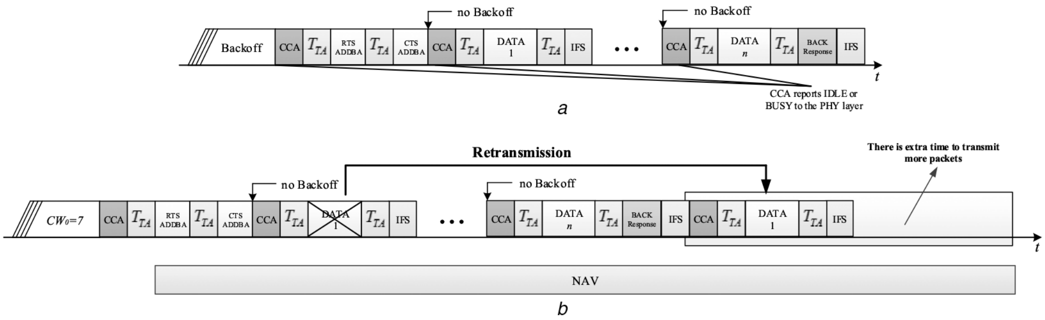

Fig. 4 *IEEE 802.15.4 with no BACK request (piggyback)*
(a) Best-case scenario, ***(b)*** Retransmissions by using a NAV extra time

counter plus the *ccaTime* and T_{TA} time periods will avoid possible collisions with the ongoing RTX process. In SBACK-MAC with the *BACK request*, by using a NAV extra time, we account the RTX of *k* lost frames, as shown in Fig. 3*b*. In our proposed mechanism, the value of *k* will be 20% of the TX aggregated frames. In this case there is no ACK to confirm that a given frame has successfully reached the destination, and nodes only try to retransmit a frame once, based on the *BACK response*.

In SBACK-MAC with the *BACK request*, the minimum delay, $D_{\mathrm{minDataRet\_BACK}}$, when the channel is found to be idle during CCA and there is data transmission, is given as follows:

$$D_{\mathrm{minDataRet\_BACK}} = \begin{cases} H_8 & \text{for } j = 0 \\ H_9 & \text{for } j = 1 \end{cases} \qquad (15)$$

where *j* is the number of frame RTXs, as defined in [5]. The RTX process is ruled by a NAV extra time.

- If, after CCA, a node determines that the channel is found to be idle, the aggregated frames are sent and a *BACK response* is correctly received, confirming that all the transmitted frames have successfully reached the destination, then there are no transmission errors (i.e. the number of RTXs is given by $j = 0$), and the minimum delay due to frame RTXs, $D_{\mathrm{minDataRet\_BACK}}$, is given by

$$\begin{aligned} H_8 = {} & T_{\mathrm{TA}} + T_{\mathrm{RTS\_ADDBA}} + T_{\mathrm{TA}} + T_{\mathrm{CTS\_ADDBA}} \\ & + \sum_{i=1}^{N_{\mathrm{agg}}} (ccaTime + T_{\mathrm{TA}} + T_{\mathrm{DATA}} + T_{\mathrm{TA}} + T_{\mathrm{IFS}}) \\ & + \cdots + ccaTime + T_{\mathrm{TA}} + T_{\mathrm{BRequest}} + T_{\mathrm{TA}} \\ & + \cdots + T_{\mathrm{BResponse}} + T_{\mathrm{IFS}} \end{aligned} \qquad (16)$$

- If, after CCA, a node determines that the channel is found to be idle, the aggregated frames are sent and a *BACK response* is correctly received, indicating that some frames need RTX, then the minimum delay due to frame RTXs, $D_{\mathrm{minDataRet\_BACK}}$, is given by

$$\begin{aligned} H_9 = {} & H_8 \\ & + \cdots + \sum_{i=1}^{k} (ccaTime + T_{\mathrm{TA}} + T_{\mathrm{DATA}} + T_{\mathrm{TA}} + T_{\mathrm{IFS}}) \end{aligned} \qquad (17)$$

where *k* represents the number of aggregated frames that are allowed to be retransmitted like in [5]. This value must be carefully selected. Depending on the channel conditions, nodes may only need to retransmit few data frames or, in an extreme case, there is the need to retransmit all the aggregated frames.

By combining (14) and (15), the minimum average delay, D_{minBACK}, due to the channel state (i.e. busy or idle) and frame RTXs, is given by

$$D_{\mathrm{minBACK}} = \frac{D_{\mathrm{min\_CCA\_BACK}} + D_{\mathrm{minDataRet\_BACK}}}{n} \qquad (18)$$

The maximum average throughput, $S_{\mathrm{max\_BACK}}$, is obtained by replacing D_{min} by D_{minBACK} in (8).

3.2 Block ACK mechanism without BACK request

The version of the SBACK-MAC protocol without *BACK request* (i.e. ‘piggyback mechanism’) also considers the exchange of the *RTS ADDBA* and *CTS ADDBA* frames at the beginning of the communication. However, if the last aggregated frame (DATA frame *n*) is lost, the destination does not know that a *BACK response* needs to be sent back.

The retransmission scheme from SBACK-MAC without *BACK request* is the same as in SBACK-MAC with *BACK request* version, as shown in Figs. 4*a* and *b*. As a consequence, the minimum delay, $D_{\mathrm{min\_CCA\_Piggy}}$ to determine if the channel state is found to be busy or idle during CCA, following the backoff phase, in seconds, is given as follows:

$$D_{\mathrm{min\_CCA\_Piggy}} = \sum_{i=1}^{n/N_{\mathrm{agg}}} \sum_{k=0}^{k \le \mathrm{NB}} \left(\overline{\mathrm{CW}_k} + ccaTime\right) \qquad (19)$$

In SBACK-MAC without *BACK request*, the information is piggybacked by using the last data frame transmitted within a burst, which includes a *M* bit bitmap responsible for indicated the frames that successfully reach the destination. Then, if frame RTXs are needed, nodes consider a fixed extra time for frame retransmission, like in [5], as shown in Fig. 4*b*. If the last data frame is lost and the *BACK response* is not received within the *BACK response* wait duration period, $T_{\mathrm{BRW}} = T_{\mathrm{AW}}$, nodes will retry to retransmit the last data frame again once, as shown in Fig. 4*b*.

Moreover, when a group of data frames is transmitted with only one *RTS ADDBA*/*CTS ADDBA* set between the transmitter and receiver, the receiver confirms the total amount of frames is correctly received by using the *BACK response* primitive. As before, all such frames (*RTS ADDBA*, *CTS ADDBA*, DATA and *BACK response*) have a duration field, and neighbouring nodes are required to set its NAV field accordingly. If frame RTXs are needed, nodes consider a longer NAV period, accounting the retransmission of *k* lost frames. In our proposed mechanism, the value of *k* will be 20% of the TX aggregated frames. In this case, there is confirmation that a given frame has successfully reached the destination, and nodes only try to retransmit a frame once, based on the *BACK response*. The RTX process does not consider the use of the backoff phase between two consecutive data frames, which allows for decreasing the total overhead, as shown in Fig. 4. As such, a ‘sort’ of priority is being created for frame RTXs.

The extra NAV duration due to retransmissions includes the time period needed for frame RTX plus the *ccaTime* and T_{TA} time periods, enabling to avoid frame collisions between neighbouring nodes. In fact, when neighbouring nodes wake-up, they will try to access the channel by using the backoff phase, defined by the first contention window.

In SBACK-MAC without *BACK request*, the minimum delay, $D_{\mathrm{minDataRet\_Piggy}}$, when the channel is found to be idle during CCA, there is a data transmission (by considering aggregation) and the

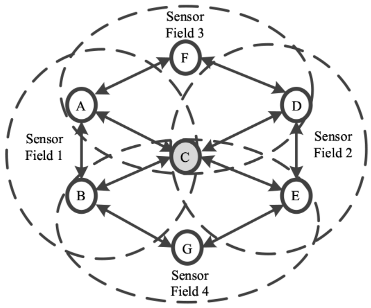

Fig. 5 *Multi-hop star topology simulation scenario with two interferers*

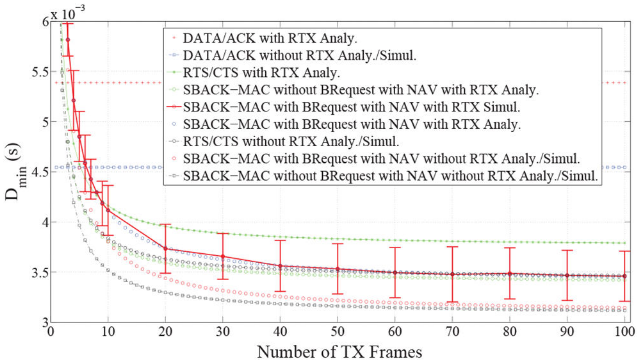

Fig. 6 *Minimum average delay as a function of the number of TX frames for a fixed payload size of 3 bytes for IEEE 802.15.4 with and without RTS/CTS and SBACK-MAC, with and without BACK request (DSSS PHY layer)*

retransmission process is ruled by a NAV extra time, is given as follows:

$$D_{\text{minDataRet\_Piggy}} = \begin{cases} H_{10} & \text{for } j = 0 \\ H_{11} & \text{for } j = 1 \end{cases} \tag{20}$$

where j is the number of frame RTXs and ranges between 1 and the maximum number of RTXs, *MaxRet*, as defined in [5].

- If, after CCA, a node determines that the channel is found to be idle, the aggregated frames are sent and a *BACK response* is correctly received, confirming that all the transmitted frames have successfully reached the destination, then there are no transmission errors (i.e. $j = 0$), and $D_{\text{minDataRet\_Piggy}}$ is given by

$$\begin{aligned} H_{10} &= T_{\text{TA}} + T_{\text{RTS\_ADDBA}} + T_{\text{TA}} + T_{\text{CTS\_ADDBA}} \\ &+ \sum_{i=1}^{N_{\text{agg}}-1} (ccaTime + T_{\text{TA}} + T_{\text{DATA}} + T_{\text{TA}} + T_{\text{IFS}}) \\ &+ \cdots + ccaTime + T_{\text{TA}} + T_{\text{DATA}} + T_{\text{TA}} \\ &+ \cdots + T_{\text{BResponse}} + T_{\text{IFS}} \end{aligned} \tag{21}$$

- If after CCA, a node determines that the channel is found to be idle, the aggregated frames are sent and a *BACK response* is correctly received, indicating that some frames need RTX, $D_{\text{minDataRet\_Piggy}}$, is given by

$$\begin{aligned} H_{11} &= H_{10} \\ &+ \cdots + \sum_{i=1}^{k} (ccaTime + T_{\text{TA}} + T_{\text{DATA}} + T_{\text{TA}} + T_{\text{IFS}} \end{aligned} \tag{22}$$

  where k represents the number of aggregated frames that are allowed to be retransmitted, like in [5]. This means that this value must be carefully selected depending on the application, since nodes may need to retransmit only a few data frames. However, in an extreme case, there is a need to retransmit all the aggregated frames.

By combining (19) and (20), the minimum average delay, $D_{\text{min\_Piggy}}$, due to the channel state (i.e. busy or idle) and frame RTXs can be determined by:

$$D_{\text{min\_Piggy}} = \frac{D_{\text{min\_CCA\_Piggy}} + D_{\text{minDataRet\_Piggy}}}{n} \tag{23}$$

The maximum average throughput, $S_{\text{max\_Piggy}}$, is obtained by replacing D_{min} by $D_{\text{min\_Piggy}}$ in (8).

4 Performance evaluation

In this section, we evaluate IEEE 802.15.4 performance by comparing the cases of the presence and absence of RTS/CTS and/or *BACK request*. The MiXiM simulation framework [27] from the OMNeT++ simulator is considered. The performance of IEEE 802.15.4, with and without *BACK request*, as well as with and without RTS/CTS, is studied in terms of throughput, end-to-end delay, bandwidth efficiency and energy consumption. Five different random simulations with different seeds are considered, and a 95% confidence interval is assumed. Tables 2 and 3 present all the parameters for the DSSS and CSS PHY layers utilised in our simulations. Fig. 5 shows the considered multi-hop star topology whose frames flow from source node A, through node C, to sink node D while frames originated by source node B flow, through node C, to sink node E. The interfering nodes F and G are responsible for sending broadcast frames that will collide with the frames being sent by both the sources and the central node (in case of interference). The level of interference of nodes F and G imposes the RTX, on average of 20% of the total number of frames being exchanged within the network.

4.1 Minimum average delay in the presence and absence of RTS/CTS and BACK request for the DSSS PHY layer

The performance analysis of the proposed schemes is conducted not only for the best-case scenario, but also in the presence of RTXs. In the former case, we are assuming an ideal channel with no transmission errors. During the active period, there is only one node that always has a frame ready to be sent. The other stations can only accept frames and provide acknowledgements. The analysis of the minimum average delay considers (7) for the basic access mode (DATA/ACK), while the equations for the RTS/CTS, SBACK-MAC and BACK-MAC with BACK request schemes are (13), (18) and (23), respectively.

Results from Fig. 6 show that, by considering the DSSS PHY layer for IEEE 802.15.4 with SBACK-MAC, with and without *BACK request*, for the shortest payload sizes ($L_{\text{DATA}} = 3$), it is possible to improve network performance by using SBACK-MAC with and without *BACK request* by using a NAV extra time. For example, when the number of TX frames is longer than 7, SBACK-MAC with/without *BACK request*, with/without RTXs, achieves shorter delay in comparison to the basic access mode.

The performance results for D_{min} as a function of the number of TX frames show that, when compared with the basic access mode with RTXs, by using RTS/CTS or SBACK-MAC, with and without *BACK request*, with retransmissions, the behaviour is the following ($L_{\text{DATA}} = 3$):

- For 7 aggregated (transmitted) frames, D_{min} decreases 21, 19 and 27%, respectively.
- For 10 aggregated frames, D_{min} decreases 22, 23 and 32%, respectively, (D_{min} for SBACK-MAC with *BACK request* becomes shorter than D_{min} for the adoption of RTS/CTS for 9 TX frames).
- For 28 aggregated frames, D_{min} decreases 29, 33 and 35%, respectively.

By analysing Fig. 6, we also conclude that results for IEEE 802.15.4 employing RTS/CTS, without RTXs, when the number of TX frames is >40, are similar to the ones from SBACK-MAC, with and without *BACK request*, when RTXs are considered.

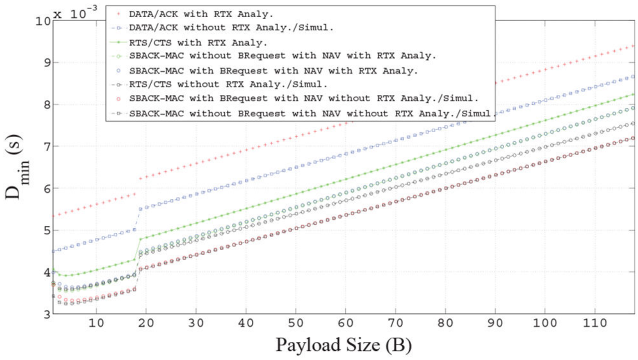

Fig. 7 *Minimum average delay as a function of the payload size for a number of TX frames equal to 10, with and without RTS/CTS and SBACK-MAC, with and without BACK request (DSSS PHY layer)*

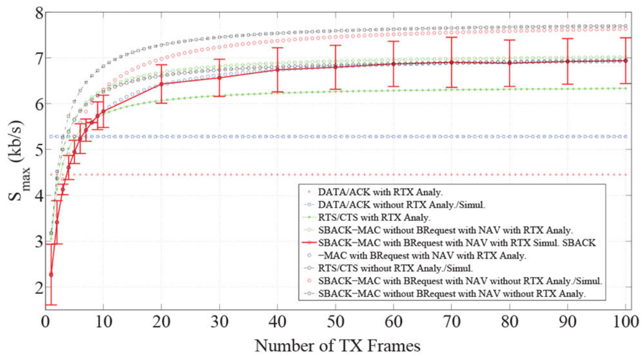

Fig. 8 *Maximum average throughput as a function of the number of TX frames for a fixed payload size of 3 bytes, in the presence and absence of RTS/CTS, and SBACK-MAC, with and without BACK request (DSSS PHY layer)*

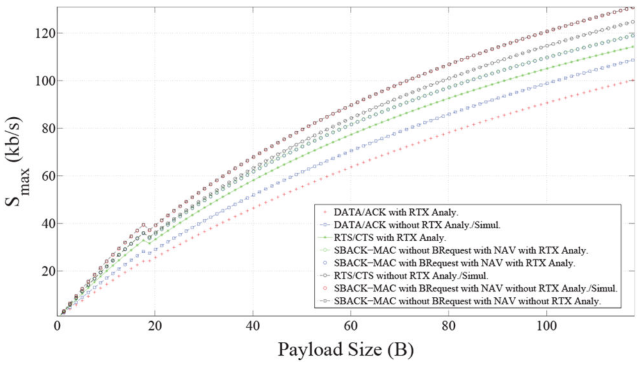

Fig. 9 *Maximum average throughput as a function of the payload size for a number of TX frames equal to 10, with and without RTS/CTS and SBACK-MAC, with and without BACK request (DSSS PHY layer)*

As saturation conditions are considered, in the basic access mode, the delay is constant, as for given channel conditions each data frame is transmitted at the maximum rate by considering the same sequence of control/data frames. However, in our proposed schemes, there is the benefit from aggregation of a given number of frames in the reduction of the delay, as less control of frames is needed to transmit a set of (at least two to seven) frames (depending on the adopted solution). The enhancement in the minimum delay becomes slower while the number of TX frames increases, as the advantage of having less control frames vanishes when the number of frames augments, and there is a horizontal asymptote for the minimum delay. This asymptote somehow represents the limit for system capacity, as it will be seen in the analysis of the maximum throughput.

Fig. 7 presents the analytical results for the minimum average delay, $D_{\min}$, as a function of the payload size by considering the four different scenarios presented in Figs. 1–4. In this case, the number of transmitted (aggregated) frames is equal to 10. There is a discontinuity around 18 bytes occurs because MPDUs less or equal than 18 bytes are followed by a SIFS, while MPDUs longer than 18 bytes are followed by a LIFS.

Results show that, IEEE 802.15.4 basic access mode globally presents the worst performance in terms of minimum average delay, $D_{\min}$, for both cases, with and without RTXs. By considering SBACK-MAC with and without *BACK request*, and with RTXs, for $n = 10$ and short frames sizes (i.e. data payload <18 bytes), $D_{\min}$ is reduced by 51 and 50%, respectively, when compared to IEEE 802.15.4 basic access mode with RTXs. For longer frame sizes, $D_{\min}$ only decreases between 18 and 40%, and is approximately equal for both cases.

We have also concluded that the analytical and simulation results are similar. This verifies the accuracy of our proposed model for frame concatenation with RTXs.

4.2 Maximum average throughput in the presence and absence of a BACK request for the DSSS PHY layer

Fig. 8 considers RTS/CTS and the maximum average throughput and shows that, by using a NAV extra time, for the shortest payload sizes (i.e. $L_{\text{DATA}} = 3$), it is possible to improve network performance by using the SBACK-MAC, with and without *BACK request*. Equation (8) is considered while replacing $D_{\min}$ by (18) and (23). When the number of TX frames is longer than 7, SBACK-MAC, with and without *BACK request*, with and without RTXs, achieves shorter delay compared to the basic access mode.

Results for $S_{\max}$ as a function of the number of TX frames show that, when compared with the 802.15.4 basic access mode with RTXs, the observed throughput in SBACK-MAC, with and without *BACK request*, and with RTXs, increases in percentage terms exactly in the same way as the respective decrease of the minimum average delay. Besides, as the relative advantage of having less control frames in these frame aggregation solutions vanishes when the number of frames augments, there is a horizontal asymptote for the maximum throughput that represents an upper bound for system capacity. By analysing Fig. 8 while replacing (13) into (8), we also conclude that the performance of IEEE 802.15.4 with RTS/CTS, and without RTXs, when the number of TX frames is higher than 40, is similar to the one from SBACK-MAC, with and without *BACK request*, with retransmissions, the latter two obtained by replacing (18) or (23) into (8).

Fig. 9 presents the analytical results for the maximum average throughput, $S_{\max}$, as a function of the payload size, by considering the four different cases (for the frames) from Figs. 1–4 and ten TX frames. Results show that the basic access mode without RTS/CTS globally presents the worst performance in terms of maximum average throughput, $S_{\max}$, for both the cases, with and without RTXs. The performance enhancement from SBACK-MAC, with and without *BACK request*, relatively to the basic access mode, both with RTXs, is the following:

- For short frame sizes (i.e. data payload <18 bytes), $S_{\max}$, improves by 50 and 51%, respectively;
- For longer frame sizes, $S_{\max}$, increases between 18 and 40%, and is approximately equal for both cases.

As mentioned above, these improvements are similar to the ones from the minimum delay.

4.3 Bandwidth efficiency in the presence and absence of a BACK request for the DSSS PHY layer

The bandwidth efficiency, η, suggested by the authors from [28], is obtained by the following equation:

$$\eta = S_{\max}/R \qquad (24)$$

where R represents the maximum data rate.

By analysing the variation of the bandwidth efficiency as a function of the number of TX frames, for payload size of 3 bytes (one of the shortest frame sizes), Fig. 10 shows that for IEEE

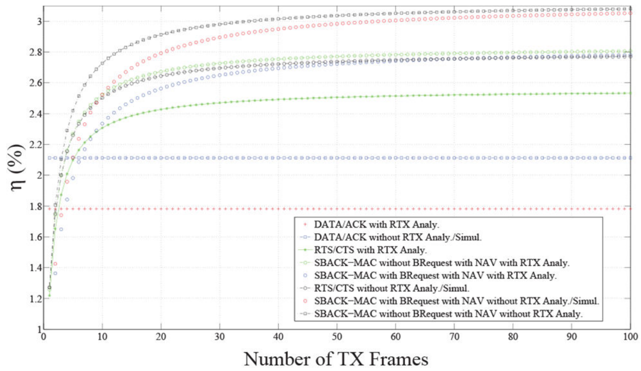

Fig. 10 *Bandwidth efficiency as a function of the number of TX frames for a fixed payload size of 3 bytes, with and without RTS/CTS and SBACK-MAC, with and without BACK request (DSSS PHY layer, $R = 250\,kb/s$)*

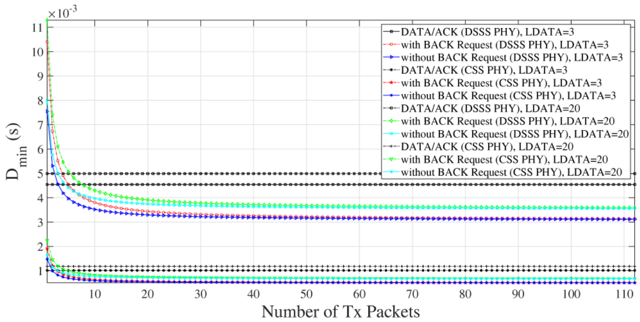

Fig. 11 *Minimum average delay as a function of the number of TX frames*

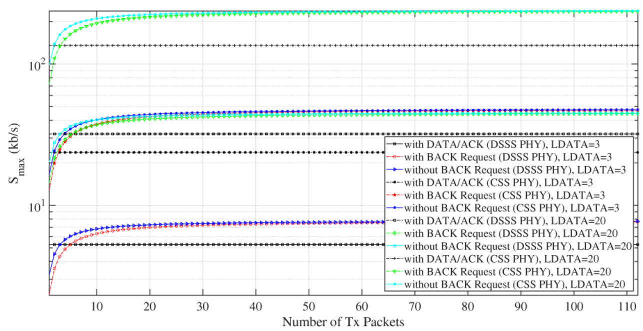

Fig. 12 *Maximum average throughput as a function of the number of TX frames*

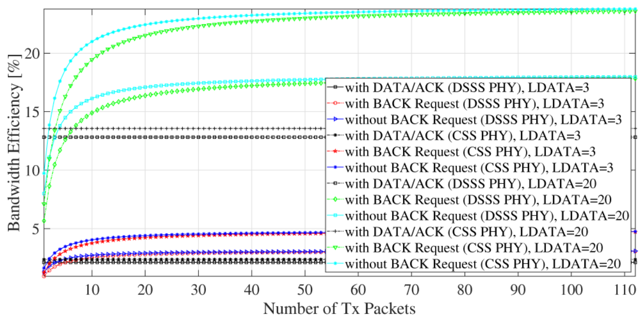

Fig. 13 *Bandwidth efficiency as a function of the number of TX frames*

802.15.4 in the absence of RTS/CTS, with and without RTXs, bandwidth efficiency is ∼1.8 and 2.1%, respectively.

It is also observed that, by varying the number of TX frames, channel efficiency remains constant but at low levels. Analytical results consider (24). Without retransmissions, the obtained results are very similar to the ones obtained in [28, 29], which again verify the proposed formulation.

For IEEE 802.15.4 with RTS/CTS, with and without retransmissions, the bandwidth efficiency depends on the number of TX frames (since we consider aggregation). Results show that, without retransmissions, by aggregating more than five frames, IEEE 802.15.4 that employs RTS/CTS outperforms the one without RTS/CTS in terms of bandwidth efficiency, η, where the maximum achievable value is ∼2.8% for a payload size $L_{DATA} = 3$ bytes. This asymptote reflects an upper bound for system capacity. With retransmissions, the better behaviour of IEEE 802.15.4 that employs RTS/CTS (compared with the basic access mode) starts to occur for more than two aggregated frames. When compared with the basic access mode with retransmissions, SBACK-MAC, with and without *BACK request*, with RTXs, obtains the following behaviour:

- For 7 aggregated frames, η increases by circa 22 and 35%, respectively.
- For 28 aggregated frames, η increases by 48 and 53%, respectively.

These performance results (and underlying horizontal asymptotes) are in line with the improvement in the minimum average delay/maximum average throughput.

4.4 Impact of considering CSS PHY layer into the performance results for SBACK-MAC with and without BACK request

This section studies the impact of considering CSS PHY in the performance of the new proposed protocols for the 2.4 GHz frequency band. Fig. 11 presents the minimum average delay, D_{min}, as a function of the number of transmitted frames, by considering the three different scenarios introduced in Figs. 3 and 4. The number of frames transmitted in a burst, n, varies from 1 to 112.

Payload sizes of 3 and 20 bytes are considered in this analysis. For a given PHY layer, the shorter the frame sizes are the shorter the minimum delay is (a decrease of the minimum average delay horizontal asymptotes for SBACK-MAC with and without *BACK request* from circa 3.6 s to circa 3.1 s in DSSS PHY, and from circa 0.66 to 0.50 s in CSS PHY). DSSS PHY clearly corresponds to values of the minimum delay longer than for the CSS PHY. Although the minimum delay for SBACK-MAC without *BACK request* is clearly shorter than the minimum delay for SBACK-MAC with a *BACK request* for few transmitted frames, asymptotically it is only slightly shorter.

Fig. 12 presents the S_{max} as a function of the number of transmitted frames. By considering the DSSS or CSS PHY layers, with and without *BACK request*, the observed average throughput increase in percentage terms is exactly the same as the corresponding decrease in the minimum average delay. In this figure, the y-axis is in logarithmic scale.

By comparing the basic access mode (labelled DATA/ACK in the figure) without retransmissions against the results presented in [29], we conclude that the difference in the results for the minimum average delay, D_{min}, is because authors in [29] have not considered the time needed to switch the radio between the different states (*rxSetupTime*), as it has been done in [24].

Fig. 13 presents the bandwidth efficiency as a function of the number of TX frames for $L_{DATA} = 3$ and 20 bytes.

While in the basic access mode the average throughput is constant for a given payload size (as saturation is assumed and the packet rate transmission is constant), by considering block acknowledgement, for few packets, aggregating them is not advantageous. However, after a few packets, as the throughput is almost linearly increasing, the performance clearly overcomes the one from the basic access mode. The employment of the CSS PHY layers (in comparison to DSSS PHY) is clearly advantageous not only in terms of the maximum average throughput but also in terms of bandwidth efficiency. The use of longer packets (20 bytes payload) corresponds to the higher bandwidth efficiency compared to payload sizes of only 3 bytes.

Furthermore, the horizontal asymptote that represents an upper bound for system capacity occurs for slightly higher values of the throughput for IEEE 802.15.4 without *BACK request* (compared to IEEE 802.15.4 employing *BACK request*).

Table 4 Specifications from the CC2420 radio transceiver

Parameter	CC2420
frequency, GHz	2.4
modulation	O-QPSK
P_{Sleep}, μW	0.06
$P_{Receive}$, mW	56.4
$P_{Transmit}$, mW	52.2
data rate, kb/s	250

Table 5 Notations for energy estimation

Notation	Parameter
t_{tx}	time on TX state
P_T	power consumption in the transmitting state
t_{rx}	time on RX state
P_R	power consumption in the receiving state
t_{sleep}	time on SLEEP state
P_S	power consumption in the sleep state
t_{idle}	time on IDLE state
P_I	power consumption in the idle state

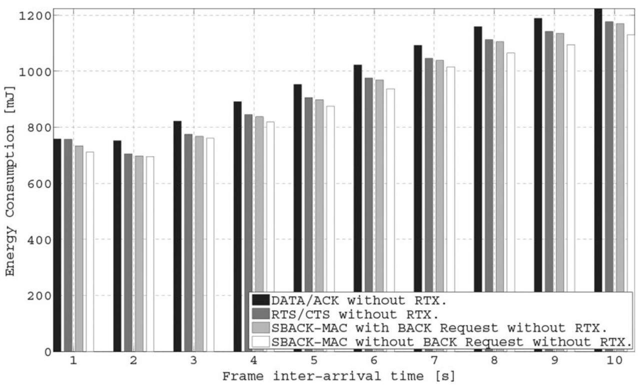

Fig. 14 *Energy consumption for the (i) IEEE 802.15.4 basic access, (ii) IEEE 802.15.4 with RTS/CTS, (iii) SBACK-MAC with BACK Request (concatenation) and (iv) SBACK-MAC without BACK request (piggyback)*

Table 6 Key parameters for energy consumption

Parameter	Value
channel bitrate	250 kb/s
operating frequency	2.4 GHz
bandwidth	2 MHz
modulation	O-QPSK
transmitter power	0 dBm (1 mW)
channel model	free-space path loss
path loss exponent	2.5
data payload	3 bytes
data frame size	18 bytes
control frame sizes (ACK/RTS/CTS/*BACK request*/*BACK response*)	11 bytes
duty cycle	12%
number of runs	5
maximum simulation time	100 s
frame inter-arrival time	from 1 to 10 s

4.5 Energy consumption for IEEE 802.15.4 in the presence and absence of RTS/CTS and SBACK-MAC with/without BACK request

In order to evaluate how much energy is spent by the proposed MAC protocols in each state, an analytical model has been conceived. A two-hop network, with two sources, one relay and two sinks (and interferers) has been considered. Fig. 5 shows the OMNeT++ [30] multi-hop star topology simulation setup. Frames flow from source node A, through node C, to sink node D, while frames originated by source node B flow, through node C, to reach sink node E.

The star network topology is challenging because there are abundant overhearing opportunities between neighbouring nodes. A node acting as coordinator may therefore take advantage of these opportunities to seek network optimisation. The star topology may also be viewed as a part of a larger network. Therefore, this type of network can be a building block for large-scale wireless networks. The performance metrics considered in the evaluation of the number of state transitions of SBACK-MAC are the following ones:

- *Energy to transmit* that denotes the amount of energy spent to transmit a frame.
- *Energy to receive/listen* that provides the amount of energy spent to receive a frame or listen to the medium.
- *Energy to sleep* that denotes the amount of energy spent by a node during the time of inactivity (sleep state).
- *Energy waste* provides the amount of energy spent by a node during the frame retransmission.
- *Total energy consumption* that incorporates all previous metrics together into a single one, providing a joint perspective for the total energy in a global way.

The analysis of the sensor nodes performance is obtained through simulation by considering the CC2420 radio transceiver from Chipcon, operating in the 2.4 GHz band. This transceiver is chosen because it is one of the most popular radio chips applied in the field of WSNs [31]. Table 4 shows its specifications. P indicates the power spent by each state for a supply voltage of 3 V.

The energy consumption of a given node over a period of time t is given as follows:

$$E(t) = (t_{tx} \times P_T) + (t_{rx} \times P_R) + (t_{sleep} \times P_S) + (t_{idle} \times P_I) \quad (25)$$

The meaning of each variable is presented in Table 5.

Fig. 14 presents the average energy consumption as a function of the frame inter-arrival time for the CC2420 radio transceiver. The multi-hop star topology from Fig. 5 is considered. Each source node (A and B) transmits 100 data frames, with a data payload size of 3 bytes (and data generation interval between 1 and 10 s) to the coordinator node (effective data rate is 250 kb/s). The coordinator forwards the frame to the destination (i.e. nodes D and E).

During one transmission cycle, there is only one active node that has always a frame ready to be sent, whereas the other neighbouring nodes can only accept frames and provide ACK or *BACK responses*. As such, in this section, we consider an ideal channel without transmission errors. Table 6 presents the network parameters considered in the simulations.

By analysing the results from Fig. 14 we conclude that, when the frame inter-arrival time increases, the energy consumption of the radio transceiver also increases. This is explained by the fact that the radio transceiver needs to stay active for longer periods of time in order to deliver the frames being generated from the source to sink nodes. Therefore, the results for energy consumption are lower for the shortest frame inter-arrival times, since the nodes are able to deliver frames faster and enter sooner into the sleep mode. In the case of frame inter-arrival time equal to 1 s, source nodes are able to deliver all data frames in the queue to the sink nodes in ∼10 s, whereas, for the case of frame inter-arrival time of 10 s, nodes need ∼100 s to deliver the same amount of data. Moreover, the power spent in the RX/TX states is higher than in the SLEEP state. Thus, every time a node wakes-up and there is no task to perform, energy waste is incurred.

This case is more frequent for longer frame inter-arrival times. Moreover, by using the SBACK-MAC protocol, with and without *BACK request*, we decrease the total energy consumption of the network for all the values of the inter-arrival time. In the case without retransmissions, SBACK-MAC, with and without *BACK request*, achieves better performance when compared with IEEE

802.15.4 in the presence and absence of RTS/CTS. If the RTS/CTS mechanism is considered, the decrease in energy consumption varies in between 6.3 and 6.9% for frame inter-arrival times between 2 and 10 s. Only for a frame inter-arrival time of 1 s the energy consumption does not decrease, and is maintained. If SBACK-MAC with or without BACK request is considered, energy consumption decreases between 3.3 and 8.2%, or 6.8 and 14.1%, respectively, for frame inter-arrival times between 1 and 10 s. The basic access mode presents the worst energy performance. The study of energy consumption for the cases with retransmissions is left for further study.

5 Discussion and conclusion

In this paper, we have first proposed to employ RTS/CTS combined with frame concatenation in order to enhance the performance of the IEEE 802.15.4 MAC sub-layer. The use of the RTS/CTS mechanism improves channel efficiency by decreasing the deferral time before transmitting a data frame. The maximum average throughput and minimum average delay have been analytically derived.

The proposed solution has shown that for the shortest payload sizes ($L_{\text{DATA}} = 3$), with RTXs, if the number of TX/aggregated frames is lower than 5, considering IEEE 802.15.4 with RTS/CTS and the application of frame concatenation reduces overhead whilst achieving higher throughput values in comparison to IEEE 802.15.4 without RTS/CTS, even for the shortest frame sizes. The advantage comes from reserving the channel while avoiding to repeat the backoff phase for every consecutive transmitted frame, differently of the IEEE 802.15.4 basic access mode (i.e. $BE = 0$). We verify that results arising from our proposed analytical model are very similar to the simulation ones. For the shortest payload sizes ($L_{\text{DATA}} = 3$), results have shown that, by considering IEEE 802.15.4 with RTS/CTS combined with frame concatenation, the minimum average delay, $D_{\min}$, decreases by 21, 22 and 29%, for 7, 10 and >28 aggregated frames, respectively.

This work also proposes the SBACK-MAC protocol whose novel BACK mechanism improves channel efficiency by aggregating several ACK into one special *BACK response* frame. The presence of *BACK request* (concatenation mechanism) and the absence of a *BACK request* (‘piggyback mechanism’) have been proposed. Results have shown that, for the shortest payload sizes ($L_{\text{DATA}} = 3$), it is possible to improve network performance by considering SBACK-MAC, with and without *BACK request*, by using a NAV extra time. When the number of TX frames is longer than 7, applying SBACK-MAC. with and without *BACK request*, with and without RTXs, facilitates to achieve shorter delay than in the basic access mode. Performance results for $D_{\min}$ as a function of the number of TX frames show that, for the DSSS physical layer and SBACK-MAC, with and without *BACK request*, with RTXs:

- For 7 aggregated frames, $D_{\min}$ decreases by 19 and 27%, respectively, when compared to the basic access mode.
- For 10 aggregated frames, $D_{\min}$ decreases by 23 and 32%, respectively, when compared to the basic access mode.
- For more than 28 aggregated frames, $D_{\min}$ decreases by 33 and 35%, respectively, when compared to the basic access mode.

We have observed that, in the basic access mode, the maximum average throughput, $S_{\max}$, does not depend on the number of TX frames, and achieves the value of 5.27 kb/s. For IEEE 802.15.4 with RTS/CTS combined with the frame concatenation feature, the horizontal asymptote for $S_{\max}$ is at circa 6.35 kb/s. This increase is due to the reduction of overhead. The numerical increase in the maximum average throughput, $S_{\max}$, for the DSSS PHY layer, is exactly the same as the decrease in $D_{\min}$. This behaviour occurs not only for the IEEE 802.15.4 employing RTS/CTS with frame concatenation but also for SBACK-MAC with RTXs. By analysing Fig. 8, we also conclude that, when the number of TX frames exceeds 40, results for IEEE 802.15.4 with RTS/CTS without RTXs are similar to the ones from SBACK-MAC with RTXs.

The use of DSSS (250 kb/s) and CSS (1 Mb/s) PHY layers have been analysed and the performance improvement of using BACK request has been studied. In comparison with the basic access mode, the behaviour is as follows for $n = 10$:

- For short frames sizes ($L_{\text{DATA}} = 3$), for the DSSS PHY layer, $S_{\max}$ is increased ($D_{\min}$ is decreased) by 23 and 32%, with and without *BACK request*, respectively. Similarly, for the CSS PHY layer, $S_{\max}$ is increased ($D_{\min}$ is decreased) by 65 and 74%, for $n = 10$, with and without *BACK request*, respectively.
- For longer frames sizes ($L_{\text{DATA}} = 20$) and DSSS PHY, $S_{\max}$ is increased ($D_{\min}$ is decreased) by 23 and 32%, with and without *BACK request*, respectively. Similarly, for CSS PHY, $S_{\max}$ is increased ($D_{\min}$ is decreased) by 41 and 52%, respectively.

By using the proposed BACK mechanism, we clearly improved channel use by decreasing the overhead when compared to the actual payload size. The analysis of the proposed mechanisms has shown that for more than ten TX frames the bandwidth efficiency, η, and energy consumption are improved by not considering the backoff phase between two consecutive data frames and by postponing ACKs, via the use of the *BACK response* control frame, enabling the aggregation of several ACK responses into one single frame.

This aggregation implies the reduction of the minimum average delay while the number of TX frames augments. However, as the advantage of having less control frames vanishes when the number of frames augments, there is a horizontal asymptote for the minimum average delay and maximum average throughput that represents an upper bound for system capacity. For frame inter-arrival times longer than 1 s, when each source transmits 100 data frames, the reduction in energy consumption is in the range of 3.3–14.1%, for SBACK-MAC, and 6.3–6.9%, for RTS/CTS with packet concatenation.

Our ongoing work consists of further investigating energy consumption and in particular, proposing innovative energy-saving mechanisms that will be combined with the presented MAC mechanisms and will allow further performance enhancement. Although our work considers the realistic case of RTXs (due to an imperfect channel), we also plan to extend the proposed mechanisms in order to study noisy environments that encounter bursty frame losses. Moreover, we also envision to evaluate the performance of our proposals supporting specific IoT applications.

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