Block Acknowledgment Mechanisms for the optimization of channel use in Wireless Sensor Networks

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***Abstract*—One of the fundamental reasons for the IEEE 802.15.4 standard Medium Access Control (MAC) inefficiency is overhead. The current paper proposes and analyses the Sensor Block Acknowledgment MAC (SBACK-MAC) protocol, a new innovative protocol that allows the aggregation of several acknowledgment responses in one special *BACK Response* packet. Two different solutions are addressed. The first one considers the SBACK-MAC protocol in the presence of BACK Request (concatenation) while the second one considers the SBACK-MAC in the absence of BACK Request (piggyback). The proposed solutions address a distributed scenario with single-destination and single-rate frame aggregation. The throughput and delay performance is mathematically derived under ideal conditions (a channel environment with no transmission errors). The proposed schemes are compared against the basic access mode of IEEE 802.15.4 through extensive simulations by employing the OMNET++ simulator. We demonstrate that the network performance is significantly improved in terms of throughput and end-to-end delay.**

I. Introduction

IEEE 802.15.4 has become the *de facto* standard for Wireless Sensor Networks (WSNs) being used in a wide range of scenarios and applications [1], [2]. This MAC protocol is responsible for triggering the current transmission allowing for multiple sensor nodes to share the same communication medium as well as to determine and change the operation mode of the radio transceivers whilst saving energy.

In [3] the authors have shown that one fundamental reason for IEEE 802.15.4/4a MAC inefficiency is overhead, where the use of ACK control packets can decrease the bandwidth efficiency about 10%.

In this work, we propose and analyse two innovative mechanisms to reduce overhead in IEEE 802.15.4 [4]: 1) concatenation and 2) piggyback. The main idea is to improve channel efficiency by aggregating several acknowledgment (ACK) responses into one single transmission (i.e., one single packet) like in the IEEE 802.11e standard [5]. This aggregation of ACKs aims at reducing the overhead by transmitting less ACK control packets and by decreasing the time periods the transceivers should switch between different states. We aim at increasing the throughput as well as decreasing the end-to-end delay, whilst providing a feedback mechanism for the receiver to inform the sender about how many transmitted (TX) packets were successfully received (RX). Our proposal also considers the use of the Request-To-Send/Clear-To-Send (RTS/CTS) mechanism, in order to avoid the hidden terminal problem [6]. For every RTS/CTS we aggregate at least 4 data packets (i.e., by using aggregation), allowing for improving the network performance in terms of throughput and end-to-end delay. This is explained by the fact that after the RTS/CTS exchange there is no backof phase before determining the channel state (i.e., busy or idle) during CCA for each DATA/ACK exchange.

The remainder of this 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 and by the hardware constraints of typical radio transceivers. The theoretical throughput and end-to-end delay limits are also derived. Section III describes the SBACK-MAC protocol with and with no *BACK Request*. The benefits from using BACK are discussed. An accurate analytical model for the throughput and end-to-end delay is also proposed for the best-case scenario. Section IV addresses the numerical and simulation results to verify the validity of our model. Section V discusses the retransmissions strategies under an erroneous channel. Finally, Section VI presents the conclusions.

II. IEEE 802.15.4 Channel Access Timing

In the IEEE 802.15.4 basic access mode, nodes use a nonbeacon-enabled Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) algorithm for accessing the channel and transmit their packets. 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 [4]. 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,

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2^{BE}-1]. Therefore, it is worthwhile to mention that even there is only one transmitter and one receiver, the transmitter will always choose a random backoff time period within [0, 2^{BE}-1]. 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. Table I summarizes the key parameters from the IEEE 802.15.4 standard.

The maximum backoff contention window, CW_{max}, is given as follows:

$$CW_{max} = \left(2^{BE} - 1\right) \times T_{BO} \tag{1}$$

The time delay, due to CCA, is given by:

$$ccaTime = rxSetupTime + T_{CCA} \tag{2}$$

The *rxSetupTime* is the time to switch the radio between the different states and must be extracted from the datasheet from the radio transceiver [7], [8], [9]. During CCA, which lasts, T_{CCA}, the radio transceiver must determine the channel state within the duration of 8 symbols (1 symbol period is equal to 16μs). Figure 1 presents the frame sequence for the IEEE 802.15.4 basic access mode with DATA/ACK.

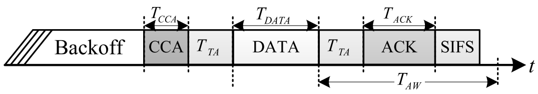

Figure 1. IEEE 802.15.4 basic access frame sequence.

There is a random deferral period of time before transmitting every data packet, given by:

$$D_T = InitialbackoffPeriod + ccaTime + T_{TA} \tag{3}$$

In this research work, we only consider the nonbeacon-enabled mode (not the beacon-enabled one, since collisions can occur between beacons or between beacons and data or control frames, making a multi-hop beacon-based network difficult to be built and maintained [10]).

Another important attribute is scalability, due to changes in terms of network size, node density and topology. Nodes may die over time. Others may be added later and some may move to different locations. Therefore, for such kind of networks, the nonbeacon-enabled mode seems to be more adapted 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 [4], there is 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 periods (and there is time remaining in the Contention Access Period, CAP, for the message, appropriate interframe space, IFS and ACK). Figure 2 present the timing requirements for transmitting a packet and receive an ACK for the beacon and nonbeacon-enabled modes, respectively.

TABLE I
PARAMETERS, SYMBOLS AND VALUES FOR THE IEEE 802.15.4 STANDARD AND SBACK-MAC PROTOCOL.

Description	Symbol	Value
Backoff period duration	T_{BO}	320 μs
CCA detection time	T_{CCA}	128 μs
Setup radio to RX or TX states [8]	$rxSetupTime$	1720 μs
Time delay due to CCA	$ccaTime$	1920 μs
TX/RX or RX/TX switching time	T_{TA}	192 μs
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
Short Interframe spacing (SIFS) time	T_{SIFS}	192 μs
Long Interframe spacing (LIFS) time	T_{LIFS}	640 μs
RTS ADDBA transmission time	T_{RTS_ADDBA}	352 μs
CTS ADDBA transmission time	T_{CTS_ADDBA}	352 μs
BACK Request transmission time	$T_{BRequest}$	352 μs
BACK Response transmission time	$T_{BResponse}$	352 μs
Number of TX frames	n	1 to 112
Data Rate	R	250 kb/s

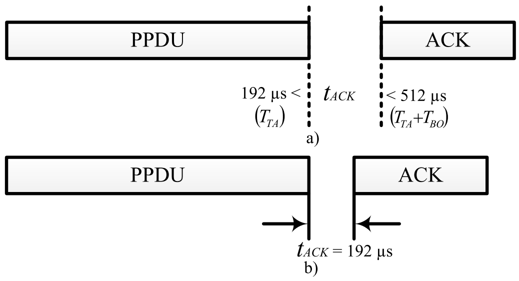

Figure 2. IEEE 802.15.4 acknowledgment frame timing: a) beacon and b) nonbeacon-enabled modes.

By analysing Figs. 1 and 2 we conclude that overhead is one of the fundamental problems of MAC inefficiency. It includes the physical (PHY) and MAC headers, backoff duration, IFS (i.e., Short Interframe Spacing - SIFS, and Long Interframe Spacing - LIFS) and ACKs. Moreover, IEEE 802.15.4 radio compliant transceivers also have restricted hardware constraints. The inefficient switching delay time periods between the radio states (i.e., *rxSetupTime*) cannot be neglected, since nodes are continually switching between them, resulting in significant energy spent [11]. The IEEE 802.15.4 standard supports a maximum over-the-air data rate of 250 kb/s for the 2.4 GHz band. However, in practice, the effective data rate is lower due to the protocol/hardware timing specifications. This is explained by the various mechanisms that are employed to ensure robust data transmission, including channel access algorithms, data verification and frame acknowledgement.

In this work, we analyse the maximum throughput, S_{max}, and the minimum delay, D_{min}, for the IEEE 802.15.4 standard. 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, on average. D_{min} is the time needed to transmit a packet and the successfully reception of the ACK, on average. Although we are considering the 2.4 GHz band, the proposed formulation is also valid for other frequency bands. As explained before, initially, the *BE* is set to *macMinBE*. 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:

$$\overline{CW} = (CW_{max}/2) \times T_{BO} \quad (4)$$

S_{max} and D_{min} can be determined for the best-case scenario (i.e., an ideal channel with no transmission errors). During one transmission cycle, there is only one active node that has always a frame to be sent 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}.

Table I presents the key parameters, symbols and values. Hence, there is no need to redefine every parameter after every equation again. The transmission times, in seconds, for the DATA and ACK frames are given as follows:

$$T_{DATA} = [8 \times (L_{H\_PHY} + L_{H\_MAC} + L_{H\_DATA})]/R \quad (5)$$

$$T_{ACK} = [8 \times (L_{H\_PHY} + L_{H\_ACK})]/R \quad (6)$$

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

$$S_{max} = 8L_{DATA}/H_1 \quad (7)$$

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

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

$$D_{min} = H_1 \quad (8)$$

For IFS, SIFS is considered when 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 considered.

By analysing equations (5) to (8), we conclude that, if a short frame is transmitted the data transmission time is relatively short when compared to the associated overhead time, resulting to 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. Moreover, we also conclude that the effective data rate of IEEE 802.15.4 in the basic access mode is lower than the maximum over-the-air data rate of 250 kb/s for the 2.4 GHz band. As stated in [12] this lower effective data rate is explained by the fact that IEEE 802.15.4 was built into the frame structure, and various mechanisms where employed to ensure robust data transmission, including the channel access algorithms, data verification and frame acknowledgement.

III. Performance Analysis of the SBACK-MAC Protocol for the Best-Case Scenario

In IEEE 802.15.4 the protocol overhead impacts on end-to-end delay and throughput. In order to reduce end-to-end delay and increase throughput, we propose a new innovative MAC protocol that solves the above problems, along with the elimination of the backoff period repetitions, the Sensor Block Acknowledgment (SBACK)-MAC protocol.

The main difference compared to IEEE 802.15.4 is related to the way that SBACK-MAC treats the ACK control packets. The SBACK-MAC allows the aggregation of several ACK responses into one special packet. The *BACK Response* will be responsible to confirm a set of data packets successfully delivered to the destination. This packet has the same length as an ACK packet in IEEE 802.15.4. Hence, an ACK control packet will not be received in response to every data packet sent/received.

By decreasing the number of control packets exchanged in a 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 the packet) on each node. Moreover, in WSNs the length of control packets can be of the order of magnitude of the data packets. Since nodes are battery operated, the transmission of such packets leads to energy decrease, whilst reducing the number of data packets that will be transmitted containing useful information (i.e., goodput).

The SBACK-MAC also considers the $ccaTime$. This way, during CCA nodes are able to determine the channel state (i.e., busy or idle), which allows for providing statistical information for the MAC sub-layer and upper layers. Moreover, since the CCA result is based on the obtained Received Signal Strength Indicator (RSSI), transmission power control techniques could be used to to estimate the minimum transmission power for sending each packet to a neighbouring node.

A. Block Acknowledgment Mechanism with BACK Request

The version of the SBACK-MAC protocol with *BACK Request* considers the exchange of two special packets: *RTS ADDBA* and *CTS ADDBA*, where ADDBA stands for "Add Block Acknowledgement". The structure of these packets is presented in Fig. 3.a).

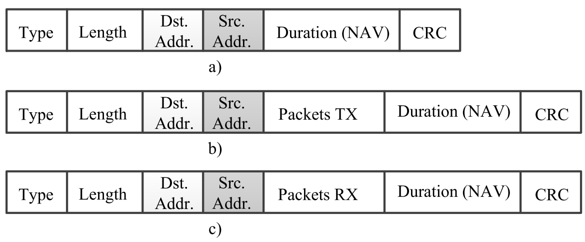

Figure 3. a) *RTS ADDBA* and *CTS ADDBA*, b) *BACK Request* and c) *BACK Response* packets format.

After this successfully exchange, 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. In response, the receiver sends a special data packet called *BACK Response* identifying the packets that require retransmission, and the BACK mechanism finishes. The structure of these packets is shown in Figs. 3.b) and 3.c). Figure 4.b) presents the message sequence chart for the SBACK-MAC protocol with *BACK Request*. The exchange of two

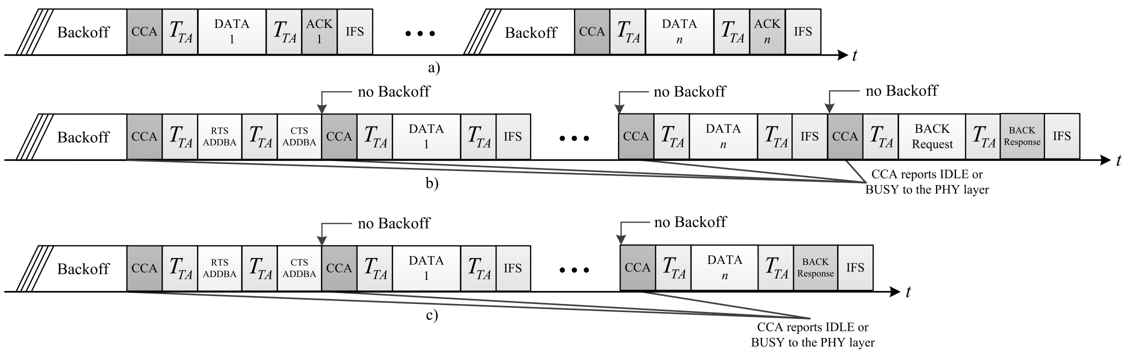

Figure 4. IEEE 802.15.4 frame sequence with no retransmissions: a) basic access, b) SBACK-MAC protocol with *BACK Request* (concatenation) and c) SBACK-MAC protocol with no *BACK Request* (piggyback).

special control packets used in the beginning of the BACK mechanism allows to avoid the hidden-terminal and exposed-terminal problems like in the IEEE 802.11e standard [5] (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.

As presented in Fig. 4.b), in order to overcome the overhead of the IEEE 802.15.4 MAC, we propose several efficient 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. Moreover, we also assume that the payload of the MAC frames cannot be changed.

The maximum throughput and the minimum delay for the SBACK-MAC protocol with *BACK Request* are given as follows:

$$S_{max\_BACK} = (8L_{DATA})/(H_2/n) \quad (9)$$

where H_2=$\overline{CW}$+$ccaTime$+T_{TA}+$T_{RTS_{ADDBA}}$+T_{TA}+$\cdots$+ $T_{CTS_{ADDBA}}$+$n\times(ccaTime+T_{TA}+T_{DATA}+T_{TA}+T_{IFS})+ccaTime + T_{TA} + T_{BRequest} + T_{TA} + T_{BResponse} + T_{IFS}$.

$$D_{min\_BACK} = H_2/n \quad (10)$$

The scheme with BACK presented in Fig. 4.b) can be more efficient than the one with DATA/ACK from Fig. 4.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 Fig. 4.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 phase 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 with no BACK Request

The version of the SBACK-MAC protocol with no *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 Fig. 4.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 can be less robust in comparison to the SBACK-MAC protocol 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 maximum throughput and the minimum delay for the SBACK-MAC protocol with no *BACK Request* are given as follows:

$$S_{max\_BACK} = (8L_{DATA})/(H_3/n) \quad (11)$$

where H_3=$\overline{CW}$+$ccaTime$+T_{TA}+$T_{RTS_{ADDBA}}$+T_{TA}+$\cdots$+ $T_{CTS_{ADDBA}}$+$(n-1)\times(ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{IFS})$+$ccaTime$+$T_{TA}$+$T_{DATA}$+$T_{TA}$+$T_{BResponse}$+$T_{IFS}$.

$$D_{min\_BACK} = H_3/n \quad (12)$$

IV. Simulation Evaluation

We have evaluated SBACK-MAC using the MiXiM simulation framework [13] from the OMNeT++ simulator. SBACK-MAC throughput and end-to-end delay with and with no *BACK Request* have been compared against IEEE 802.15.4, by considering a 95 % confidence interval, however, as it is too small, we decided not to plot it in the Figures. Table I presents the MAC parameters considered for the network in our simulations. The performance analysis of the proposed schemes is conducted for the best-case scenario. Therefore, we are assuming that the channel is an ideal channel, with no 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 5 presents the maximum throughput and the minimum delay versus the payload size, by considering the three different scenarios from Fig. 4. The discontinuity around 18 bytes is due to the use of SIFS and LIFS (i.e., MPDU less of equal than 18 bytes must be followed by a SIFS, whilst MPDU longer than 18 bytes must be followed by a LIFS).

The number of transmitted frames, n, is 10 (i.e., for the SBACK-MAC, the frames are aggregated and transmitted in

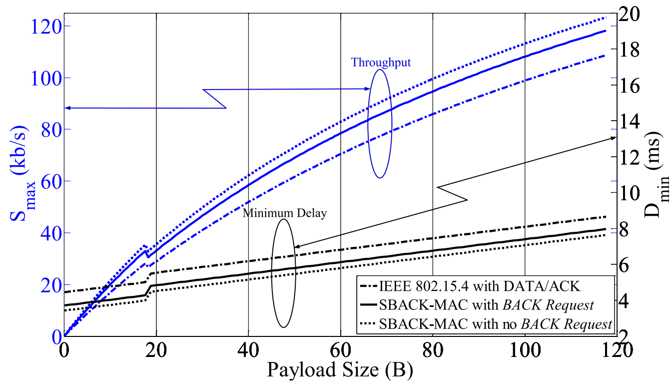

Figure 5. Maximum throughput and minimum delay versus payload size.

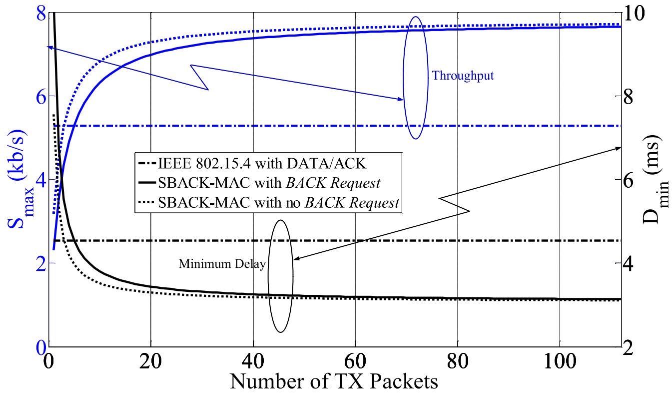

Figure 6. Maximum throughput and minimum delay versus number of TX packets.

a burst). It is observed that, by increasing the payload size, S_{max} also increases. This conclusion is valid for all the three presented mechanisms. For small packet sizes (i.e., data payload less or equal than 18 bytes) by comparing the IEEE 802.15.4 with the SBACK-MAC protocol, with and with no *BACK Request*, S_{max} increases 17 % and 25 %, respectively. Moreover, by using the IEEE 802.15.4 basic access mode with DATA/ACK, the maximum achievable throughput is approximately 108.7 kb/s whereas, by using the SBACK-MAC with and with no *BACK Request*, the maximum achievable throughput is 118.1 and 123.2 kb/s, respectively.

Results for D_{min} as a function of the payload size show that, by using SBACK-MAC with and with no *BACK Request* for small packets sizes (i.e., data payload less or equal to 18 bytes), D_{min} decreases 17 % and 25 %, respectively. For larger packet sizes, by considering SBACK-MAC with and with no *BACK Request*, D_{min} decreases 8 % and 13 %, respectively.

Figure 6 presents S_{max} and D_{min} as a function of the number of TX packets. A fixed payload size of 3 bytes (i.e., L_{DATA} =3 bytes) is considered, since is one of the values in the range from 1 to 18 bytes presented in Fig. 5, by consider the worst throughput performance, by taking into account the BACK mechanism. Even for the shortest payload sizes, it is possible to improve the network performance by using the proposed BACK mechanisms.

When the number of TX packets is less than 4, the IEEE 802.15.4 standard through the basic access mode, achieves higher throughput in comparison to SBACK-MAC (either with or with no *BACK Request*). Moreover, by considering the IEEE 802.15.4 standard in the basic access mode, S_{max} does not depend on the number of TX packets, and achieve the maximum value of 5.2 kb/s. In SBACK-MAC with and with no *BACK Request* (i.e., concatenation and piggyback), S_{max} increases by increasing the number of TX packets (i.e., the number of aggregated packets). For a number of TX packets equal to 18, by considering the SBACK-MAC with *BACK Request* (i.e., concatenation version) S_{max} is about 6.3 kb/s. This value corresponds to an increase of 21 % in the throughput in comparison to the MAC protocol from the IEEE 802.15.4 standard in the basic access mode, whereas by considering the SBACK-MAC with no *BACK Request* (i.e., piggyback version), the achievable throughput is 6.8 kb/s, an increase of 30 %. However, the difference on the throughput between the SBACK-MAC with and with no *BACK Request* tends to decrease by increasing the total number of TX packets (i.e., by aggregating more packets).

We also conclude that, for more than 4 TX packets, SBACK-MAC (with and with no *BACK Request*) delay is significantly shorter than for IEEE 802.15.4 in the basic access mode. The difference is mitigated by increasing the total number of TX packets (i.e., by aggregating more packets).

V. RETRANSMISSIONS STRATEGIES UNDER AN ERRONEOUS CHANNEL

Previously, we have presented the results for IEEE 802.15.4 basic access mode and SBACK-MAC with and with no *BACK Request* for the channel with no errors. However, data collisions between neighbouring nodes may occur if two or more nodes during the CSMA-CA algorithm perform CCA simultaneously, the channel is found to be idle and packet transmissions occur at the same time, as shown in Fig. 7. Both IEEE 802.15.4 basic access mode and SBACK-MAC with and with no *BACK Request* requires listening to the channel before transmitting in order to reduce the collision probability. Therefore, if the channel is found to be busy, they will double the backoff time counter during the backoff phase (i.e., the contention window is doubled), and the process is repeated until the maximum contention window is reached, as stated in [14]. However, in SBACK-MAC with and with no *BACK Request* this process is not repeated for each data packet sent, but only for each RTS/CTS set, allowing for decreasing the overall delay imposed by the initial backoff phase.

In the case the channel is found to be idle during CCA, two neighbouring nodes could start transmitting at the same time causing mutual interference. In IEEE 802.15.4 basic access mode, nodes will retransmit the packets by using the first contention window given by equation (1) defined by the CSMA-CA algorithm. Therefore, every time a transmitted packet collides or an ACK is not received within the ACK wait

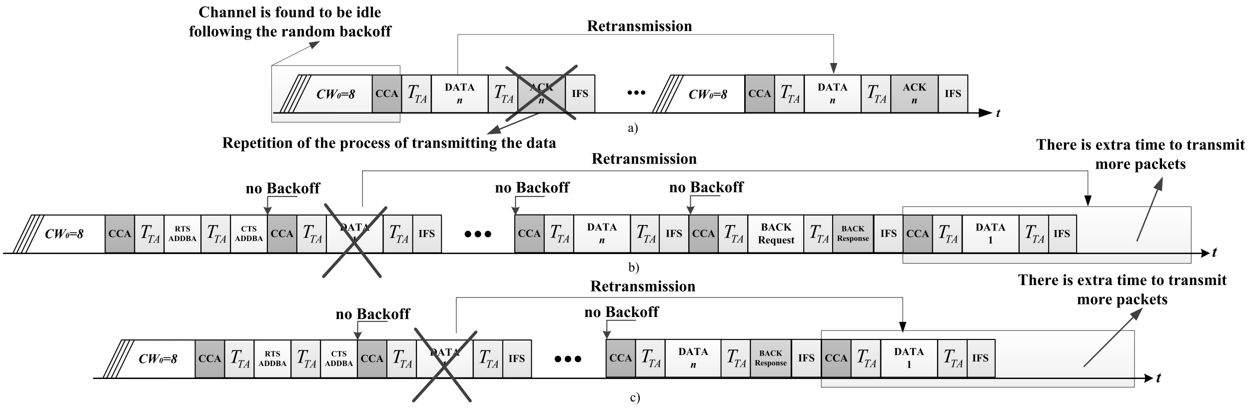

Figure 7. IEEE 802.15.4 frame sequence with retransmissions: a) basic access, b) SBACK-MAC protocol with *BACK Request* (concatenation) and c) SBACK-MAC protocol with no *BACK Request* (piggyback).

duration period, T_{AW}, the packet is retransmitted by using a new transmission procedure with *NB*, *CW* and *BE* reset to their initial values [15]. In turn the SBACK-MAC with and with no *BACK Request* will perform packet retransmission with no backoff avoiding adding extra time overhead due to the backoff period. The retransmission process is performed in a fixed extra time, like in [16].

VI. Conclusion

In this paper, we have proposed SBACK-MAC a new contention-based MAC protocol for WSN. The use of a BACK mechanism improves channel efficiency by aggregating several ACK into one special packet, the *BACK Response*. Two innovative solutions were proposed to improve the IEEE 802.15.4 performance. The first one considers the SBACK-MAC protocol in the presence of *BACK Request* (concatenation mechanism), while the second considers the SBACK-MAC in the absence of *BACK Request* (piggyback mechanism). At the best-case scenario (i.e., with no errors), the throughput and end-to-end delay were analytically derived. By ranging the payload size between 1 and 118 bytes, for small packets sizes (i.e., data payload less or equal to 18 bytes) S_{max} is increased by 17 % and 25 % for the SBACK-MAC protocol with and with no *BACK Request*, respectively (in comparison with the IEEE 802.15.4 protocol in the basic access mode). Consecutively, D_{min} is decreased 17 % and 25 % for the SBACK-MAC protocol with and with no *BACK Request*, respectively. For more than 4 TX packets (the number of TX packets varies between 1 and 112), SBACK-MAC significantly outperforms the IEEE 802.15.4 standard in terms of throughput and end-to-end delay.

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References

[1] B. Nefzi and Y.-Q. Song "CoSenS: a Collecting and Sending Burst Scheme for Performance Improvement of IEEE 802.15.4," in *Proc. of The 35th Annual IEEE Conference on Local Computer Networks*, Denver, Colorado, USA. 2010.

[2] I. Demirkol, C. Ersoy and F. Alagz, "MAC protocols for wireless sensor networks: a survey," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 115121, Apr. 2006.

[3] M.S.Chowdhury, N. Ullah, Md. H. Kabir, P. Khan and K. S. Kwak, "Throughput, Delay and Bandwidth Efficiency of IEEE 802.15.4a Using CSS PHY," in *Proc. of The International Conference on Information and Communication Technology Convergence (ICTC)*, Jeju Island, Korea 2010.

[4] *Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks*, IEEE Std. 802.15.4, Sep. 2011.

[5] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, IEEE Std. 802.11e, Nov. 2005.

[6] P. Huang, L. Xiao, S. Soltani, M. W. Mutka and N. Xi, "The Evolution of MAC Protocols in Wireless Sensor Networks: A Survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 1, pp. 101-120, First Quarter 2013.

[7] "CC2420," http://www.ti.com/lit/ds/symlink/cc2420.pdf, Apr. 2012.

[8] J. Rousselot, M. Aoun and R. S. Oliver, "Accurate Timeliness Simulations for Real-TimeWireless Sensor Networks," in *Proc. of The Third UKSim European Symposium on Computer Modeling and Simulation*, Neuchatel, Switzerland, Nov. 2009.

[9] N. Barroca, P. T. Gouveia and F.J. Velez, "Impact of Switching Latency Times in Energy Consumption of IEEE 802.15.4 Radio Transceivers," in *Proc. of 9th Conference on Telecommunications - Conftele 2013*, Castelo Branco, Portugal, May 2013.

[10] M. Sun, K. Sun and Y. Zou, "Analysis and improvement for 802.15.4 multi-hop network," in *Proc. of International Conference on Communications and Mobile Computing*, Kunming, Yunnan, China, Nov. 2009.

[11] R. Jurdak, A. G. Ruzzelli and G. M.P. OHare, "Radio Sleep Mode Optimization in Wireless Sensor Networks," *IEEE Transactions on Mobile Computing*, vol. 9, no. 7, pp. 955968, Jul. 2010.

[12] "Calculating 802.15.4 Data Rates", http://www.jennic.com/files/support_files/JN-AN1035%20Calcula%2082-15-4%20Data%20Rates-1v0.pdf, Jun. 2013.

[13] "MiXiM framework," http://sourceforge.net/apps/trac/mixim/, Mar. 2013.

[14] C. Buratti and R. Verdone, "Performance Analysis of IEEE 802.15.4 Non Beacon -Enabled Mode," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, Sep. 2009.

[15] A. Faridi, M.R. Palattella, A. Lozano, M.Dohler, G. Boggia, L.A. Grieco, and P. Camarda, "Comprehensive Evaluation of the IEEE 802.15.4 MAC Layer Performance With Retransmissions," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 8, Oct. 2010.

[16] *Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks, IEEE Std. 802.15.4e (Amendment to IEEE Std 802.15.4-2011)*, Apr. 2012.