Article

Impact of Using CSS PHY and RTS/CTS Combined with Frame Concatenation in the IEEE 802.15.4 Non-Beacon Enabled Mode Performance

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Abstract: This paper studies the performance improvement of the IEEE 802.15.4 nonbeacon-enabled mode originated by the inclusion of the Request-To-Send/Clear-To-Send (RTS/CTS) handshake mechanism resulting in frame concatenation. Under IEEE 802.15.4 employing RTS/CTS, the backoff procedure is not repeated for each data frame sent but only for each RTS/CTS set. The maximum throughput and minimum delay performance are mathematically derived for both the Chirp Spread Spectrum and Direct Sequence Spread Spectrum Physical layers for the 2.4 GHz band. Results show that the utilization of RTS/CTS significantly enhances the performance of IEEE 802.15.4 applied to healthcare in terms of bandwidth efficiency.

Keywords: Wireless Sensor Networks; MAC sub-layer; RTS/CTS/ non-beacon mode; packet concatenation; channel use; IEEE 802.15.4

1. Introduction

IEEE 802.15.4 is the de-facto communication standard [1], [2] that provides low-power and low-data-rate communication for Wireless Personal Area Networks (WPANs) and defines both Physical (PHY) and Medium Access Control (MAC) layers. Various Working Groups within IEEE 802.15.4 have been putting great efforts on developing new spectrum resource usage mechanisms or include the best of the best already existing ones for WPANs at Industrial, Scientific and Medical (ISM) and unlicensed bands [2]. The idea has been to respond to the demands of the evolution of WSN applications, offering higher data rates when needed.

The Request-To-Send/Clear-To-Send (RTS/CTS) scheme has not been considered in any of the existing IEEE 802.15 standards but facilitates to shorten the duration of frame collisions, as shown in [3]. The proposed scheme involves the exchange of short RTS and CTS control frames prior to the exchange of the actual data frames. The fields of application from WSNs where the use of RTS/CTS assumes particular importance includes manufactory, healthcare and augmented reality, for which there is a need of sharing bursts of information with low collision probability. Although the proposal of employing RTS/CTS is not new and has already been standardized and implemented in legacy Wi-Fi (since it shortens packet collision duration, as shown in [3]), this reservation scheme has not been considered in any of the existing IEEE 802.15.4 standards.

The research developed in the context of this work shows that inclusion of the RTS/CTS mechanism significantly improves network performance, clearly demonstrating that its omission is not beneficial for the IEEE 802.15.4 standards. The nonbeacon-enabled mode of the IEEE 802.15.4 MAC sub-layer enhancement by employing the RTS/CTS handshake scheme combined with frame aggregation concatenation is evaluated. Unlike the Direct Sequence Spread Spectrum (DSSS) physical (PHY) layer for the 2.4 GHz frequency band, which only supports data rates up to 250 kb/s, the Chirp Spread Spectrum

(CSS) PHY enables speeds up to 1 Mb/s and, apart from supporting off-body Wireless Personal Area Network (WPAN) communications, it can provide on-body networking similarly to IEEE 802.15.6, as in [4], not supporting however in-body communications [5] for healthcare. Inspired in [6], we considered RTS/CTS combined with packet concatenation in our initial work published in [7], while authors from [4] have considered our approach to introduce RTS/CTS in the beacon-enabled MAC protocol of IEEE 802.15.6 supporting unobtrusive medical services to individuals with chronic health conditions.

One assumes that wireless nodes use equal backoff procedure from the IEEE 802.15.4 basic access mode. Nonetheless, this procedure is only repeated for each RTS/CTS set and not for each individual data frame. As such, channel utilization is optimized by decreasing the deferral time before transmitting each data frame. Differently from [7] and [8], in this work, the performance enhancement of applying RTS/CTS is studied both for the CSS and DSSS PHY that operate in the 2.4 GHz Industrial, Scientific and Medical (ISM) band.

The remaining of this paper is organized as follows. Section 2 explores the formulations for time delay after addressing aspects of the MAC sub-layer and control messages flowchart for the nonbeacon-enabled mode of IEEE 802.15.4. Section 3 presents the MAC sub-layer system model for the minimum delay and maximum throughput. Section 4 presents results delay, throughput and bandwidth efficiency, and extracts lessons from the comparison between the application of CSS and DSSS PHY for healthcare services support. Finally, conclusions are drawn in Section 5.

2. MAC Sub-Layer

In the IEEE 802.15.4 basic access mode [8], nodes use a nonbeacon-enabled CSMA-CA algorithm for accessing the channel and transmit their packets. The unslotted Carrier Sensing Multiple Access – Collision Avoidance (CSMA-CA) in the nonbeacon-enabled mode will facilitate a better flexibility for large-scale IEEE 802.15.4-compliant peer-to-peer networks [9]. Before, each transmission the MAC sub-layer exchange messages with the PHY layer for packet transmission (TX)/reception (RX). Figure 1 presents the algorithms flowchart showing the interaction between the different packet types (e.g., DATA and ACK) and the control messages involved in packet transmission/reception.

The PHY and MAC layers exchange control messages every time an event occurs as follows:

PHY -> MAC

- RX_START: Start of message indicator;
- RX_FAIL: Failed to receive message after RX_START. The message can fail because Cyclic Redundancy Check (CRC) or collision;
- TX_END: Message being transmitted has completed;
- TX_FAIL: End of transmission (like TX_END) but the message transmission has failed. For most radio transceivers this should never happen (but there are valid cases for packet-based radios, e.g., CC2420).

After starting carrier sense, one of the following messages must be sent to the MAC layer:

- CHANNEL_IDLE: If the specified "packet length" has been processed, and the carrier sense returns channel not "busy";
- CHANNEL_BUSY: If the carrier sense returns channel "busy".

MAC -> PHY

- SET_TRANSMIT: Switch the PHY layer to the transmit mode;
- SET_LISTEN: Switch the PHY layer to the listen mode;
- SET_SLEEP: Switch the PHY layer to the sleep mode;
- START_CARRIER_SENSE: Start carrier sense.

If slotted CSMA-CA is used each operation (channel access, backoff counter and clear channel assessment, CCA) can only occur at the boundary of a backoff period (BP). Additionally, the BP boundaries must be aligned with the slot boundaries of the superframe time [10].

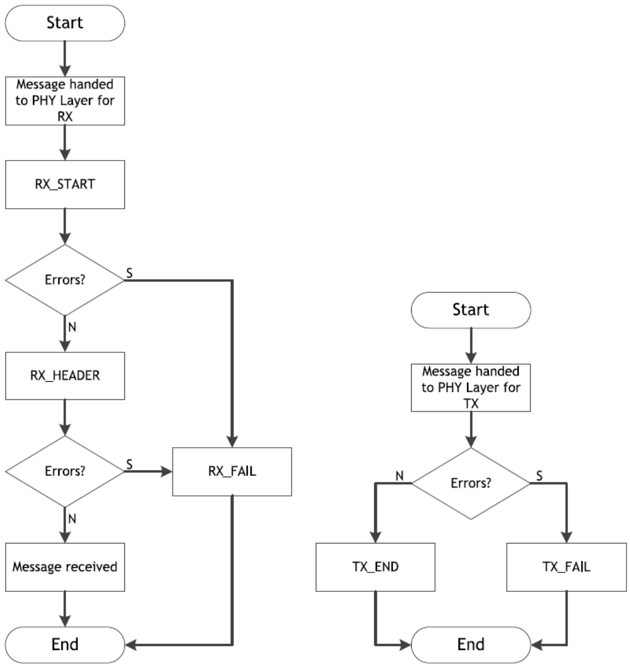

Figure 1. Control messages flowchart for the nonbeacon-enabled mode of IEEE 802.15.4.

In non-slotted CSMA-CA the backoff periods of one node are completely independent of the backoff periods of any other node in a PAN/Body Area Network (BAN). The backoff phase (generally called contention window in 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 $T_{symbol} = 16$ µs is the symbol time [4]. Before performing CCA, a device shall wait for a random number of backoff periods, determined by the backoff exponent (BE). Then, the transmitter randomly selects a backoff time period uniformly distributed in the range $[0, 2^{BE} - 1]$. Therefore, it is worthwhile to mention that even if 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* is not incremented since we are assuming ideal conditions.

Table 2 from [11] summarizes the key parameters for IEEE 802.15.4 both employing and not employing RTS/CTS with frame concatenation in the 2.4 GHz band, by considering the DSSS PHY layer with the O-QPSK modulation (250 kb/s).

IEEE 802.15.4 [8] nodes support a maximum over-the-air data rate of 250 kb/s. However, in practice, the effective data rate is lower due to the protocol timing specifications, [8]. This is also 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, unicast data transmissions with ACKs are addressed, and the channel access time is a dominant factor in the overall performance of the network. The nonbeacon-enabled mode is considered. The regular procedure of the IEEE 802.15.4 nonbeacon-enabled mode is presented in Figure 2. When a device wishes to transfer data, it simply transmits its data frame, using unslotted CSMA-CA, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an ACK control packet.

The beacon-enabled mode is not considered because 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 [12]. Another important attribute is scalability, an intrinsic characteristic of multi-hop WSNs. Changes in terms of network size, node density and topology may occur. Nodes may die over time. Other nodes may be added later, and some may move to different locations. Consequently, for such kind of networks, the nonbeacon-enabled mode better adapts to the scalability requirement than the beacon-enabled mode. In the former case, all nodes are independent from the PAN coordinator and the communication is completely decentralized.

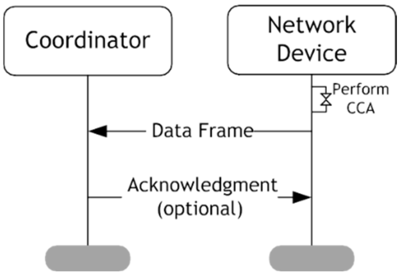

Figure 2. IEEE 802.15.4 - Communication to a coordinator in a nonbeacon-enabled PAN.

Moreover, for beacon-enabled networks [8], there is an additional timing requirement for sending two consecutive frames, so that the ACK frame transmission should be started between the TX/RX or RX/TX switching time, 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, Interframe Space (IFS) and ACK). Figure 3 presents the timing requirements for transmitting a packet and receiving an ACK for the beacon and nonbeacon-enabled modes.

In IEEE 802.15.4 [8], [10], the CSMA-CA algorithm is significantly different from the one used in IEEE 802.11e [13]. The main differences are related to the backoff algorithm. In IEEE 802.11e [13], the value of the Contention Window (CW) depends on the number of failed retransmissions for the packet, whereas, in the basic access mode for IEEE 802.15.4, this value (denoted as backoff phase) depends on the backoff exponent (BE), and number of backoffs (NB). Moreover, in IEEE 802.11e, the backoff time counter (BO_c) is decreased as long as the channel is sensed idle and is frozen when a transmission occurs. In the IEEE 802.15.4 basic access mode, nodes do not continuously monitor the channel during the backoff phase and the sensing phase (i.e., CCA) only occurs at the end of the backoff phase.

According to the IEEE 802.15.4 standard [10], a sensor node that sends a data or a MAC command frame with its ACK Request subfield set to one shall wait for at most an ACK wait duration period, TAW , for the corresponding ACK frame to be received. The T_{AW} already includes the time for the ACK frame itself. The transmission of an ACK frame in a nonbeacon-enabled PAN or in the Contention Free Period (CFP) shall start *aTurnaroundTime* symbols (i.e., 192 µs) after the reception of the last symbol of the DATA or MAC command frame ([10], Section 7.5.6.4.2).

The ACK wait duration period, T_{AW}, is given by:

$$T_{AW} = T_{Symbol} + T_{TA} + T_{SHR} + [6 \times T_{Symbol} \times phySymbolsPerOctect] (1)$$

Assuming the DSSS PHY layer for the 2.4 GHz band, the maximum ACK wait duration period, T_{AW}, is given by:

$$T_{AW} = 16\ \mu s + 192\ \mu s + 160\ \mu s + 192\ \mu s = 560\ \mu s\ (2)$$

Figure 4 presents the ACK timing required for the IEEE 802.15.4 standard, by considering the DSSS PHY layer for the 2.4 GHz band at 250 kb/s. The receivers start transmitting the ACK, 192 μs (i.e., TTA) after the reception of the DATA frame.

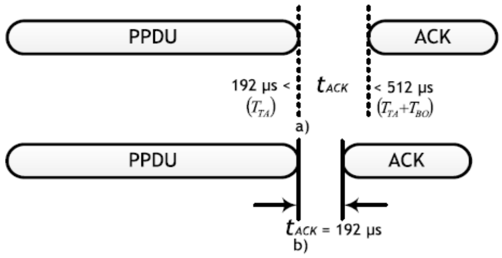

Figure 3. IEEE 802.15.4 acknowledgment frame timing: a) beacon and b) nonbeacon-enabled modes.

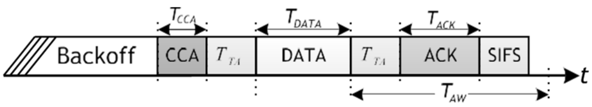

Figure 4. Acknowledgement process timing.

By assuming a DATA and an ACK frame with 18 and 11 bytes, respectively (including the PHY and MAC overhead), the transmission time is 576 μs and 352 μs, respectively. Besides, Figure 4 also includes the ACK wait duration period, T_{AW}. For every DATA packet transmitted, there is a random deferral time period, D_T, before transmitting, given by:

$$D_T = InitialbackoffPeriod + ccaTime + T_{TA} \quad (3)$$

The initial backoff period, *Initialbackoff* Period, is given as follows:

$$InitialbackoffPeriod = CW_{NB} = (2^{BE} - 1) \times T_{BO} \quad (4)$$

whereas the time delay, due to CCA, is given by:

$$ccaTime = rxSetupTime + T_{CCA} \quad (5)$$

The *rxSetupTime* is the time to setup the radio from a previous state to the transmission or reception states, and it mainly depends on the radio transceiver used. During the T_{CCA}, the radio transceiver must determine the channel state within 8 symbol duration (i.e., 128 μs, which corresponds to one symbol duration of 16 μs). In a normal transmission, for every DATA packet sent an ACK must be received, as shown in Figure 5. Details on the analytical model for the maximum throughput and minimum delay are given in [11].

3. Brief Overview of the MAC Sub-Layer System Model

The main reasons why IEEE 802.15.4 basic access mode does not consider the adoption of the RTS/CTS handshake mechanism are the following ones:

a) The introduction of RTS/CTS packets adds protocol overhead and, in a situation with low traffic load, short packet sizes could have the same order of magnitude of a RTS/CTS packet;

b) The absence of a RTS/CTS handshake mechanism allows to reduce the system complexity. Although these assumptions are true for some particular cases, we argue that in the presence of link layer errors the additional protocol overhead due to the use of RTS/CTS packets is mitigated by the resulting concatenation mechanism.

In our proposal, we assume that both the RTS and CTS packets have the structure of an ACK packet, which is assumed to have a limited size of 11 bytes, as shown in Table 2 from [9]. The maximum data payload for IEEE 802.15.4 depends on the application (maximum payload could range between 102 and 118 bytes).

Figure 5. Acknowledgement process timing within the IEEE 802.15.4 basic access mode.

Consequently, the length of the data packets could be approximately ten times larger than the control packets length. In reality, IEEE 802.15.4 employing RTS/CTS with packet concatenation is composed by the following time periods: backoff phase, CCA mechanism, time needed for switching from receiving to transmitting, RTS transmission time, time needed for switching from transmitting to receiving and CTS reception time.

Both the IEEE 802.15.4 basic access and the proposed RTS/CTS schemes consider acknowledgment (ACK) frames to confirm successful frame reception. Aiming at overhead reduction, the use of RTS/CTS frames enables channel reservation and avoids the replication of the backoff phase for every consecutive transmitted frame and implies zero backoff exponential. Moreover, by considering RTS/CTS, nodes avoid frame collisions, which often take place due to the hidden terminal problem. Hence, IEEE 802.15.4 performance is considerably enhanced, since the number of retransmitted frames is significantly decreased. Differently from [11], block acknowledgement is not considered, and such frame concatenation mechanism is not applied.

In reality, authors from [7] have demonstrated that one fundamental reason for IEEE 802.15.4 MAC inefficiency is overhead, originated, e.g., by inter-frame spaces from the protocol, backoff period, transmission of PHY/MAC headers and ACKs, interference and retransmissions (due to unsuccessful reception of data frames). The un-slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm and the backoff phase are characterized by using the formulation presented in [14]. N.B.: we designate the backoff phase by Contention Window (CW).

To determine the maximum average throughput, S_{max}, for the basic access mode, the minimum average delay, D_{min} is first derived. Figure 6 presents the frame structure for the IEEE 802.15.4 basic access mode in the absence of RTS/CTS while considering retransmissions [14]. As mentioned above, under IEEE 802.15.4 employing RTS/CTS and frame concatenation, nodes use the same backoff procedure as in 802.15.4 but only for each RTS/CTS set. Hence, the channel utilization is enhanced by decreasing the deferral time before transmitting each data frame, as shown in Figure 7.

The minimum delay due to Clear Channel Assessment (CCA), $D_{min\_CCA\_RTS}$, (enabled to estimate if the channel state is busy or idle after the backoff phase), and prior to each RTS/CTS set, is given by:

$$D_{min\_CCA\_RTS} = \sum_{i=1}^{n/N_{agg}} \sum_{k=0}^{k\leq NB} \left(\overline{CW_k} + ccaTime\right) \quad (6)$$

As in [15], the number of backoff periods is given by $NB \in [0, NB_{max}]$. The time delay due to CCA is given by (5).

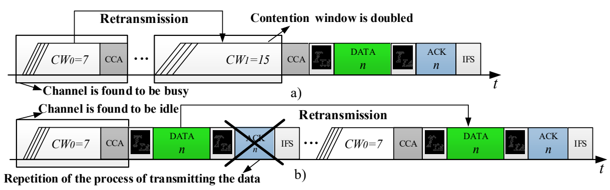

Figure 6. IEEE 802.15.4 basic access mode with retransmissions when channel is assessed as a) busy and b) idle.

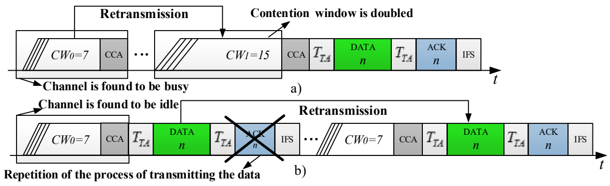

Figure 7. IEEE 802.15.4 with RTS/CTS and retransmissions.

Equation (6) considers that nodes only determine the channel state once per RTS/CTS exchange, i.e., if the total number of transmitted data frames is, for example, n=100 and the number of aggregated frames is N_{agg}=10, nodes only determine the channel state n/N_{agg}=10 times, i.e., once per exchange of RTS/CTS, plus the time needed for transmitting the frames (until the maximum limit for the number of retries, NB_{max}=4, is reached).

If the estimation of the channel is idle during CCA and, if after sending a data frame an ACK is not received within a duration equal to T_{AW}, the retransmission process does not consider a backoff phase between two consecutive data frames. This simplification decreases the total overhead, as shown in Figure 7. Since any other station will receive all RTS/CTS/DATA/ACK frames, in the first transmission attempt, it will set the Network Allocation Vector (NAV). The NAV is responsible for defining the time duration for channel access deferring in order to avoid collisions.

With erroneous channels under IEEE 802.15.4 employing RTS/CTS, if the channel estimation is idle during CCA, there is data transmission and an ACK is not received within a duration of T_{AW}, the delay due to frame retransmissions RTXs), is given by:

$$D_{minDataRetRTS} = \begin{cases} H_1, & \text{for } j = 0 \\ H_2, & for\ j \in [1, MaxRet\,] \end{cases} \quad (7)$$

where j is the number of RTXs, which varies up to $MaxRet$ [1].

From the analysis of equation (1) one can conclude the following:

a) after CCA, if a node determines that the channel is found to be idle and an ACK is correctly received for each sent frame, the minimum delay, $D_{minDataRetRTS}$, is determined by:

$$H_1 = T_{TA} + T_{RTS} + T_{TA} + T_{CTS} + \cdots + $$

$$+ \sum_{i=1}^{N_{agg}} (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS}) \ (8)$$

where T_{TA} is the TX/RX or RX/TX switching time. T_{DATA}, T_{ACK}, and T_{IFS} are the durations of the data frame, ACK frame and inter-frame spacing (IFS), respectively. Since transmission errors do not exist, the number of retransmissions is j=0. As such, in equation (8), there is no need to consider the ACK wait duration period, T_{AW}, which represents the longest time needed to receive an ACK control frame.

b) After CCA, if a node estimates that channel is idle and an ACK has not been received within the duration T_{AW}, for one or more transmitted frames (since we consider frame concatenation), the minimum delay due to frame RTXs, $D_{minDataRetRTS}$, is determined by:

$$H_2 = T_{TA} + T_{RTS} + T_{TA} + T_{CTS} + \ldots + \sum_{i=1}^{N_{agg}-m} (ccaTime + T_{TA} + T_{DATA} + +T_{TA} + T_{ACK} + T_{IFS})$$

$$+ \sum_{i=1}^{m} (j_i \cdot (ccaTime + T_{TA} + T_{DATA} + T_{AW})\,)$$

$$+ + \sum_{i=1}^{m} (ccaTime + T_{TA} + T_{DATA} + T_{TA} + T_{ACK} + T_{IFS}) \ (9)$$

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The term $\sum_{i=1}^{N_{agg}-m}(ccaTime+T_{TA}+T_{DATA}+T_{TA}+T_{ACK}+T_{IFS})$ represents the duration of the $N_{agg}-m$ transmitted frames whose ACK response was successful, where m denotes the number of transmitted (TX) frames that need retransmission. Due to lack of ACK frame reception, each individual frame can be retransmitted more than once.

The term j_i represents the number of RTXs until *MaxRet* has been reached. The last term corresponds to successful reception of the ACK.

The minimum average delay, D_{min_RTS}, accounting for channel state and frame RTXs is obtained by combining equations (6)-(9):

$$D_{min\_RTS} = \frac{D_{min\_CCA\_RTS} + D_{minDataRetRTS}}{n} \quad (10)$$

The maximum average throughput, by considering frame RTXs, S_{max_RTS}, in bits per second, is then given by:

$$S_{max\_RTS} = 8 \cdot L_{DATA}/D_{min\_RTS} \quad (11)$$

4. Analytical and Simulation Results

We have compared IEEE 802.15.4 employing and not employing RTS/CTS by using the MiXiM framework of the OMNeT++ simulator [15]. A two-hop network, with two sources nodes, one relay and two sink nodes has been considered. Two interferers are responsible for sending broadcast frames that collide with the frames sent by the sources and central node. The DSSS and CSS PHY layers performance analysis considers several runs with five different random seeds and a 95 % confidence interval. A perfect match between analytical and simulation results was obtained.

Table 1 compares channel access times and overhead for the DSSS and CSS PHY. Respective maximum data rates are 250 kb/s and 1 Mb/s [1]. Likewise, in [7], we analyse both S_{max} and D_{min}.

Although we consider the 2.4 GHz band, the proposed formulation can be also applied to other frequency bands. A fixed payload size L_{DATA}=3 bytes is considered. In [17], authors proved that, for short frame sizes, IEEE 802.15.4 achieves poor performance. Here, it is shown that the proposed mechanism can significantly improve channel efficiency even with retransmissions (RTX of 10 % of packets is assumed).

Table 1 Comparison of the values and time parameters between the DSSS and CSS PHY layers for IEEE 802.15.4 (2.4 GHz band).

Symbol	DSSS PHY	CSS PHY
L_{H_PHY} / L_{H_MAC}	6 bytes / 9 bytes	7 bytes / 9 bytes

Figures 8, 9 and 10 present D_{min}, S_{max} and the bandwidth efficiency, η, as a function of the number TX frames [16] for the DSSS and CSS PHYs:

$$\eta = S_{max}/R \quad (12)$$

where R represents the maximum data rate.

Results show the global inefficiency of the basic access mode of IEEE 802.15.4 compared to the use of RTS/CTS and frame concatenation, regardless of the use of frame RTXs, in terms of D_{min}, S_{max} and η.

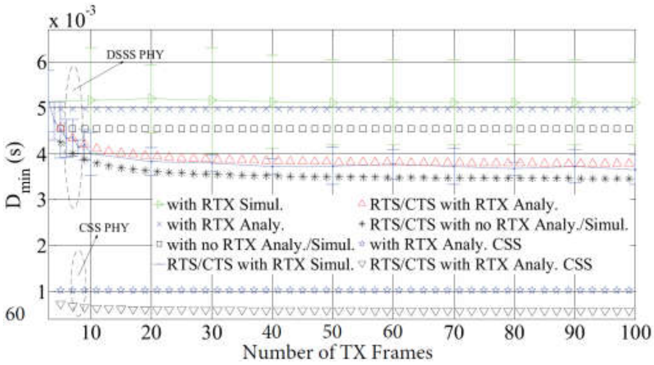

Figure 8. Minimum average delay versus the number of TX frames for the basic access and RTS/CTS modes.

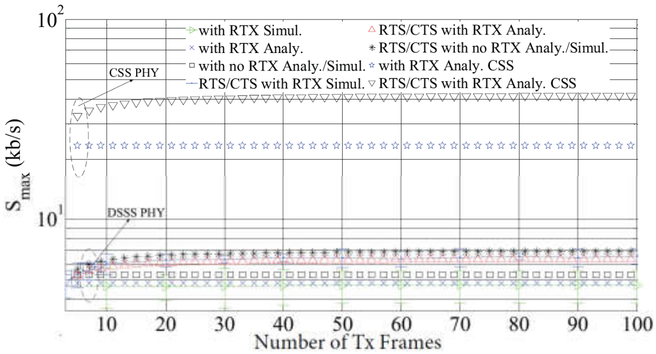

Figure 9. Maximum average throughput versus the number of TX frames for basic access and RTS/CTS modes.

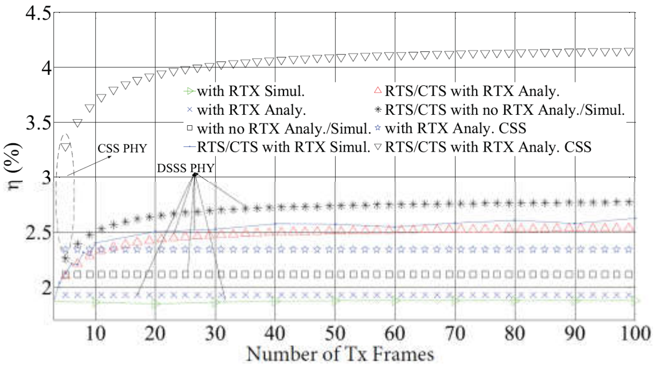

Figure 10. Bandwidth efficiency versus the number of TX frames for IEEE 802.15.4 basic access and RTS/CTS modes.

The performance of CSS is clearly better than the one of the DSSS PHY layer. Moreover, performance results for D_{min} as a function of the number of TX frames show that, for the DSSS PHY, when RTS/CTS with frame concatenation is considered, for 5 and 10 aggregated frames, D_{min} decreases (S_{max} increases) 8 % and 18 %, respectively. For more than 28 aggregated frames, D_{min} decreases (S_{max} increases) ~30 %, as shown in Figure 11. On the other hand, for the CSS PHY layer, by using RTS/CTS with frame concatenation, for 5 and 10 aggregated frames, D_{min} decreases (S_{max} increases) 33 % and 59 %, respectively. For more than 28 aggregated frames, D_{min} decreases (S_{max} increases) ~71 %.

5. Lessons Learned

The use of the RTS/CTS mechanism improves channel efficiency by decreasing the deferral time before transmitting a data frame. Although the RTXs are addressed here in a somehow rigid approach, the proposal shows that, even for the case with RTXs, if the number of aggregated frames is lower than five, IEEE 802.15.4 employing RTS/CTS combined with concatenation achieves higher values for the throughput in comparison to IEEE 802.15.4 without RTS/CTS. The advantage comes from not including the backoff phase into the RTX process like in the IEEE 802.15.4 basic access mode (i.e. BE = 0). Besides, the CSS PHY (1 Mb/s) efficiency gain is clearly more evident.

6. Conclusion

This paper proposes a retransmission model for the non-beacon-enabled mode of IEEE 802.15.4 that employs RTS/CTS and frame concatenation, where the backoff procedure is not repeated for each data frame sent, but only once for each RTS/CTS set. Performance results clearly show the substantial benefits of using RTS/CTS, in terms of bandwidth efficiency, in particular for the CSS PHY layer, as the proposed MAC sub-layer protocol shows a clear reduction in the minimum delay, enhancement in maximum average throughput, and improved bandwidth efficiency, from ~2.5 % to ~4.2 % when the CSS PHY is considered. This enhancement will be beneficial for WBAN off-body and on-body communications in the healthcare ecosystem. The study of the energy efficiency of the proposed MAC sub-layer enhancement is left for further study.

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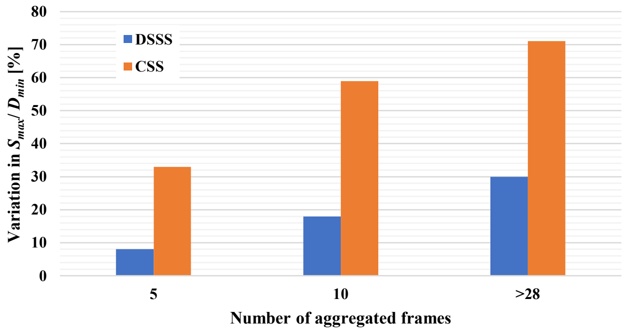

Figure 11. Increase of S_{max}/decrease of D_{min} as a function TX frames for IEEE 802.15.4 in the RTS/CTS mode.

References

[1] Wireless Medium Access Control and Physical Layer Specific. for Low-Rate Wireless Personal Area Networks, IEEE Std. 802.15.4, 2011.
[2] 'IEEE 802.15.4 Working Group for WPAN', http://www.ieee802.org/15, accessed June 2016.
[3] Chatzimisios, P., Boucouvalas, A.C., Vitsas, V.: Effectiveness of RTS/CTS handshake in IEEE 802.11a Wireless LANs. IEE Electronics Letters. 40(14), pp. 915-916 (2004). doi: 10.1049/el:20040510
[4] Ullah, S., Hassan, M.M., Hossain, M.S., and Alelaiwi, A.: Performance Evaluation of RTS/CTS Scheme in Beacon-Enabled IEEE 802.15.6 MAC Protocol for Wireless Body Area Networks. Sensors. 20(8), 2368 (2020). doi: 10.3390/s20082368
[5] Movassaghi, S., Abolhasan, M., Lipman, J., Smith, D. and Jamalipour, A.: Wireless Body Area Networks: A Survey. IEEE Communications Surveys & Tutorials. 16(3), pp. 1658-1686 (2014., doi: 10.1109/SURV.2013.121313.00064
[6] Mizuguchi, J., Murata, M. and Uemura, W.: A broadcasting method based on RTS/CTS for an ad-hoc network. In: *2011 IEEE 15th International Symposium on Consumer Electronics (ISCE)*, Singapore, pp. 104-106. (2011). doi: 10.1109/ISCE.2011.5973793
[7] Barroca, N., Borges L.M., Velez, F.J, Chatzimisios, C.: IEEE 802.15.4 MAC layer performance enhancement by employing RTS/CTS combined with packet concatenation. In: IEEE International Conference on Communications, Sydney, Australia, pp. 466-471 (2014), doi: 10.1109/ICC.2014.6883362
[8] Part 15.4: Low-Rate Wireless Personal Area Networks - Revision of IEEE Std 802.15.4-2006, IEEE Std. 802.15.4TM, Sep. 2011.
[9] Mahalik, N.P.: Sensor Networks and Configuration: Fundamentals, Standards, Platforms, and Applications. Springer, New York, USA (2007).
[10] Part 15.4: Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks, IEEE Std. 802.15.4TM, Sep. 2006.

[11] Barroca, N., Borges, L.M., Velez, F.J., and Chatzimisios, P.: Performance Enhancement of IEEE 802.15.4 by employing RTS/CTS with Packet Concatenation. IET Wireless Sensor Systems. 10(6) (2020). doi: 10.1049/iet-wss.2019.0003
[12] Sun, M., Sun, K., and Zou, Y.: Analysis and improvement for 802.15.4 multi-hop network. In: *International Conference on Communications and Mobile Computing*, Kunming, Yunnan, China, pp. 52-56 (2009).
[13] Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications, IEEE Std. 802.11eTM, Nov. 2005.
[14] Buratti, C., Verdone, R.: Performance Analysis of IEEE 802.15.4 Non Beacon-Enabled Mode. *IEEE Trans. Vehicular Technology*. 58(7), pp. 3480-3493 (2009). doi: 10.1109/TVT.2009.2014956
[15] 'MiXiM framework', http://sourceforge.net/apps/trac/mixim, accessed June 2016
[16] Chowdhury, M.S., Ullah, N., Kabir H., Khan, P., Kwak, K.S.: Throughput, delay and bandwidth efficiency of IEEE 802.15.4a using CSS PHY. In: Int. Conf. on Information and Commun. Technology Convergence, pp. 158-163 (2010). doi: 10.1109/ICTC.2010.5674258