Comparison of CSMA/CA Protocols Applied in Wireless Body Area Network Standards

Dimitra S. Kaitalidou, Alexandros – Apostolos A. Boulogeorgos, and Fotini – Niovi Pavlidou
Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
e-mail: {dkaitali; ampoulog; niovi} @auth.gr

***Abstract*—This paper deals with the performance assessment of the wireless body area network (WBAN) standards proposed by the institute of electrical and electronics engineers (IEEE), namely IEEE 802.15.4 and IEEE 802.15.6, emphasizing on the different carrier sensing multiple access/collision avoidance (CSMA/CA) mechanisms. By comparing the different proposals, we provide an engineering insight, which elaborates the reasons of the performance differences and reveals important trade-offs in terms of successful packet transmission and energy consumption. These trade-offs should be seriously taken into consideration when designing a WBAN.**

I. Introduction

Advances in wearable and implantable body sensors, wireless communication technologies, inspired by the scientific progress on embedded computing, enable the development and the deployment of low-cost, small-scale, lightweight wireless body area networks (WBANs) [1]. Motivated by their unique capabilities and promising applications, many proposals of medium access control (MAC) protocols for WBANs have been published [2]–[4]. An often encountered MAC protocol for WBANs in the open technical literature is the IEEE 802.15.4 standard [5]. Although this standard protocol was not specifically developed for WBANs, it demonstrates low-power consumption and low-cost wireless networking, which are key requirements for the deployment of a WBAN. On the contrary, to achieve the special requirements of the WBANs, the IEEE 802.15.6 standard was developed by the institute of electrical and electronics engineers (IEEE) task group 6 [6].

Both IEEE 802.15.4 and IEEE 802.15.6 employ carrier sensing multiple access/collision avoidance (CSMA/CA) mechanisms for contention, but the different implementations lead to significant differences in their performance. Even though IEEE 802.15.4 and IEEE 802.15.6 are commonly used in WBANs, the performances of their CSMA/CA mechanisms have been investigated separately. Most of these studies are based on theoretical models to derive analytical expressions of quality metrics (see for example [7]–[9] and references therein). Additionally, the authors in [10]–[12] compared the performances of IEEE 802.15.4 and IEEE 802.15.6 using simulation evaluations. However, these works are not focused on the contention access mechanism of the protocols and they do not elaborate on the reasons hidden behind the derived results.

In this paper, we analyze and compare the different CSMA/CA protocols utilized in IEEE 802.15.4 and IEEE 802.15.6, in terms of successful/failed packet transmission and reception, and energy consumption, through reliable simulation results. Furthermore, providing a technical insight, we reveal the reasons of the performance differences and illustrate trade-offs that should be taken into consideration when designing a WBAN. As far as the authors know, this is the first work, where the performances of these mechanisms are compared, considering a realistic environment.

II. Overview of CSMA/CA mechanisms

In this section, a brief overview of the CSMA/CA mechanisms employed in IEEE 802.15.4 and IEEE 802.15.6 is presented, based on which we will elaborate the reasons behind the different performances.

A. *IEEE* 802.15.4

In the IEEE 802.15.4 standard, a slotted or unslotted CSMA/CA mechanism is used in the contention access period (CAP), depending on whether the operation mode is beacon or non-beacon enabled, respectively. In this work, we only refer to the slotted version.

The algorithm is implemented using units of time called backoff periods (BOP). The CSMA mechanism is based on three fundamental variables, named number of back-offs (NB), contention window (CW) and back-off exponent (BE). NB stands for the number of times the node has to back off while attempting to access the medium, whereas CW is the number of BOPs that the channel must be idle before starting transmission. Moreover, BE specifies how many BOPs a device shall wait before attempting to sense the channel. The CSMA/CA mechanism can be summarized in three steps, as illustrated in Fig. 1.

1) Initialization of the algorithm variables. During this step, NB and CW are set to 0 and CW_0, respectively. Notice that CW is initialized before each transmission attempt and reset to CW_0 each time the channel is assessed to be busy. When the battery life extension (BLE) field is set to zero, BE is initialized to $\mathrm{BE}_{\min}$. Conversely, when the BLE field is set to one, BE is initialized to $\min(2, \mathrm{BE}_{\min})$.
2) After locating a BOP boundary, the algorithm waits for a random number of BOPs before attempting to access the medium.
3) If the clear channel assessment (CCA) returns a busy channel, NB is incremented by 1 and the algorithm goes to step 2. This iteration only happens while NB

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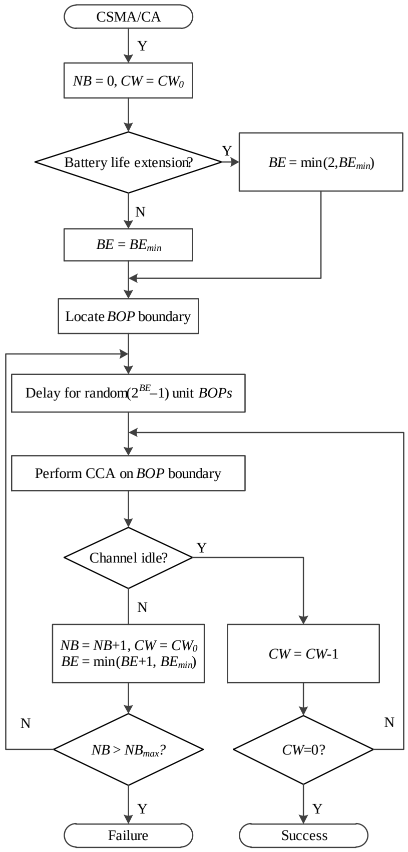

Fig. 1. IEEE 802.15.4 CSMA/CA mechanism. In this figure "Y" and "N" stands for "Yes" and "No", respectively.

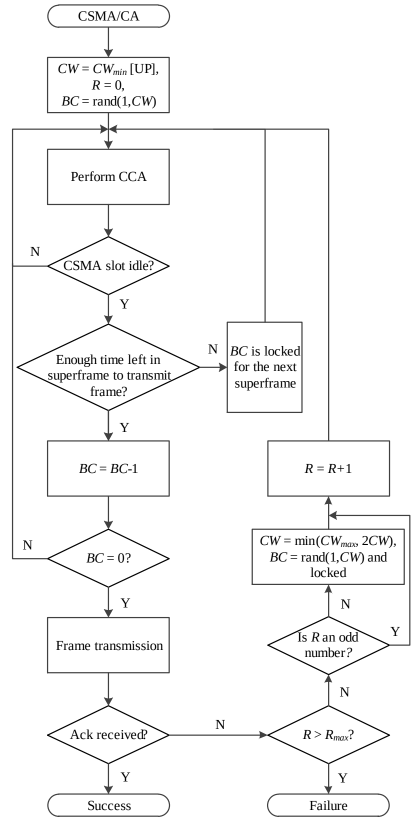

Fig. 2. IEEE 802.15.6 CSMA/CA mechanism. In this figure "Y", "N" and UP stands for "Yes", "No" and user priority, respectively.

is less than the maximum number of backoffs $\mathrm{NB}_{\max}$. If the CCA returns an idle channel, CW is decremented by 1 and when it reaches 0, the frame is transmitted, otherwise the algorithm goes to step 3. In this work, if the number of failures exceeds an upper limit, equal to the maximum frame retries ($\mathrm{R}_{\max}$), the transmission has failed and the frame is dropped.

B. IEEE 802.15.6

As described in the flow chart presented in Fig. 2, in the IEEE 802.15.6 standard, the node initiates its back-off counter (BC) to a random integer that is uniformly distributed over the interval $[1, \mathrm{CW}]$, where CW stands for the contention window. The value of CW is determined by the user priorities described in the standard; however, for simplicity and without loss of generality, they are not taken into consideration in this work. The node decrements BC by one for each idle CSMA slot with length equal to L_{CSMA}. Note that the node considers a CSMA slot to be idle, if it determines that the channel has been idle for less than T_{CCA} after the start of the CSMA slot. When the T_{CCA} expires, the node decreases the BC. If there is not enough remaining time for a transmission in the CAP, the counter locks until the next CAP. Moreover, if the node senses a busy channel due to another frame transmission, the counter locks until the channel is idle. The BC unlocks when the channel has been idle for a short interframe space period (p_{SIFS}) within the CAP and the time duration from the current time plus a CSMA slot to the end of the CAP is long enough for completing a frame transmission. Once the BC reaches zero, the node transmits the frame at the end of the CSMA slot. If the node does not receive an acknowledgment (ACK) for this transmission, a failure happened. The CW is doubled for an even number of failures (R) and the procedure is repeated. If the new CW exceeds a maximum value ($\mathrm{CW}_{\max}$), the node shall set the CW to $\mathrm{CW}_{\max}$. It is important to mention that if the number of failures exceeds an upper limit of retries, which is equal to $\mathrm{R}_{\max}$, the transmission has failed and the frame is dropped.

III. System Model and Simulation Setup Details

We consider a 6 node WBAN, in which the nodes are located at static and standing positions of the human body, as illustrated in Fig. 3, and they are connected employing one-hop star topology using node 0 as coordinator[1]. This setup emulates the fundamental processes involved in the communication procedure of the WBAN, according to the 802.15.4 and 802.15.6 specifications.

The carrier frequency is set to 2.45 GHz, since this frequency band belongs to the industrial, scientific and medical

[1]Notice that the position of node 0 is a common position for a mobile phone that can be used as a coordinator.

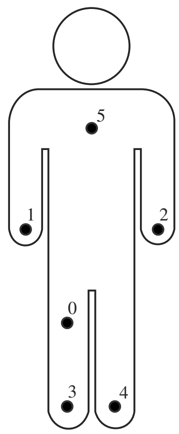

Fig. 3. The positions of the nodes on the body.

band (ISM), is unlicensed, globally available, requires an antenna with small dimensions, and is supported by both IEEE 802.15.4 and IEEE 802.15.6. To agree with the majority of datasheets for commercial WBAN sensors, we assumed that the receiver (RX) sensitivity is -87dBm. Furthermore, the transmission power is in the range of $[-20\text{dBm}, -10\text{dBm}]$, where the maximum transmit power (-10 dBm) agrees with the IEEE 802.15.6 standard. Note that this limitation applies to keep the interference with other devices at low levels and make sure that the operation of the nodes is safe for the human body. The data rate is set to 1024 Kbps, while the packet rate is considered to be variable in the range of 2 to 70 packets per second (pkts/sec) or fixed to 15 pkts/s. Notice that this range contains the saturation point, i.e., the point in which the buffer of a node starts to overflow, for both IEEE standards. Moreover, since the nodes are considered to be devices with low computational capabilities, we assume that differential quadrature phase shift keying (DQPSK) modulation is used.

Because of the complexity of the human body tissues it is not easy to derive a realistic channel model for the wireless communication link between the node $i \in \{1, \cdots, 5\}$ and the coordinator. Depending on the frequency of operation, the human body can lead to high losses caused by power absorption, central frequency shift, and radiation pattern destruction. In literature, many studies focus on channel characterization for such systems [13], [14]. Unlike traditional wireless communications, the path loss for a body area network system (on body applications), exhibits both distance and frequency dependence. In this work the pathloss and shadowing effects are calculated from the channel model 3 A (CM3A) that cover frequencies of $2.4 - 2.5$GHz [15]. The path loss is modelled as a lognormal shadowing process which is described by

$$\text{PL}(\text{d}_\text{i})[\text{dB}] = \text{a} \log_{10}(\text{d}_\text{i}) + \text{b} + \text{N}, \quad (1)$$

where a and b are evaluated through experimental measures and are equal to 6.6 and 36.1, respectively, d_i represents the distance between the node i and the node 0, and N is a zero mean Gaussian process with variance σ_N^2 equal to 3.8, which models the shadowing effects. Furthermore, since the actual path loss may differ significantly from the average path loss during the time, a probability density function (PDF) is produced to deal with this problem. The PDF is defined from the last observed value and from the time it has passed since then. The PDF cannot be produced dynamically from actual model, but it has to come from experimental measurements [16].

TABLE I
SUPERFRAME COMPARISON.

	IEEE 802.15.4	IEEE 802.15.6
Contention access	Slotted/unslotted CSMA/CA or ALOHA	CSMA/CA or slotted ALOHA
Scheduled access	Guaranteed time slots (GTSs)	Type I/II
Improvised access	–	Polling, posting
User priorities	–	8 user priorities
Inactive period	Inactive period at the end of superframe	One or more inactive superframes following an active one

Both in IEEE 802.15.4 and IEEE 802.15.6 standards, the operation in beacon mode with superframes is proposed, although there are important differences in their structure, which are summarized in Table I. Despite these differences, to guarantee a fair comparison between the different CSMA/CA mechanisms, the active and inactive portion of the superframe, the length of each access mechanism, and the user priorities scheme must be the same. Furthermore, since this work is focused on the CSMA/CA, the contention access mechanism (slotted CSMA/CA for IEEE 802.15.4 and CSMA/CA for IEEE 802.15.4) is used, and both the scheduled and the improvised accesses are ignored.

In IEEE 802.15.4 the structure of the superframe is described by the values of the MAC beacon order (MBO) and the MAC superframe order (MSO), where MBO describes the interval at which the coordinator shall transmit its beacon frames, whereas the MSO corresponds to the length of the active portion of the superframe, which includes the beacon frame. MBO and MSO are related with the beacon interval (BI) and the active superframe duration (SD) through

$$\text{BI} = 2^{\text{MBO}}\text{BSD}, \text{ for } 0 \leq \text{MBO} \leq 14 \quad (2)$$

and

$$\text{SD} = 2^{\text{MSO}}\text{BSD}, \text{ for } 0 \leq \text{MSO} \leq \text{MBO} \leq 14 \quad (3)$$

where BSD stands for the base superframe duration and represents the duration (in symbols) of the superframe when $\text{MSO} = 0$. Note that as MBO increases, the superframe length increases, therefore beacons are transmitted at lower frequency, which might cause synchronization problems, while as MBO decreases, the superframe length decreases, consequently beacons are transmitted at higher frequency, which might increase the latency of many frames. More particularly, the case where the remaining CAP is not enough for the completion of a frame transmission and any ACK will become more frequent, forcing the frame transmission to be deferred

TABLE II
SIMULATION PARAMETERS.

Parameters	Value
Number of nodes	6
Carrier frequency	2.4 GHz
Receiver sensitivity	−87 dBm
Noise floor	−104 dBm
Modulation	DQPSK
Topology	One-hop star
Pathloss model	CM3 A
Temporal model	From experimental measurements
Maximum number of retries	3

until the next superframe. Hence, we choose a medium value for MBO, i.e., 6, which leads to a superframe duration for IEEE 802.15.4 equal to 120 ms. For fairness, the same value is chosen for the duration of the superframe of IEEE 802.15.6.

If only active portions exist in the superframe, i.e., $\text{MSO} = \text{MBO}$, the coordinator and the rest of the nodes will never enter power saving mode. The larger the inactive portion, the greater the energy conservation and the latency for the frames created during the inactive portion of the superframe. It is obvious that there is a trade-off between energy efficiency and latency. Since in a WBAN low energy consumption is a key requirement, we choose to insert an inactive portion in the superframes. Since MSO and MBO are powers of two, the minimum inactive portion that can be set is the half of the superframe (active portion equals inactive portion). For instance, by setting $\text{MSO} = 5$ and $\text{MBO} = 6$, Eqs. (2) and (3) yield $\text{SD}/\text{BI} = 0.5$. Again to reassure a fair comparison, the inactive portion in IEEE 802.15.6 is chosen to be equal to the active portion.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we put together the elements from the system model, and analyze and compare the performance of each of the IEEE 802.15.4 and IEEE 802.15.6 CSMA/CA mechanisms, in terms of packet loss and consumed energy. This will give us an engineering insight and understanding of the performance and the trade-offs of these mechanisms. To guarantee that the results are valid, realistic and practical, we use the Castalia Simulator, which is a widely accepted simulator for WBANs. The simulation parameters considered are summarized in Table II.

Figs. 4 and 5 illustrate the received packet breakdown as function of the transmission power. The breakdown shows the probability that the packets will be received successfully and unsuccessfully, as well as the circumstances under which the success/failure occurred. An unsuccessful reception may be due to interference, caused by the transmissions of the other nodes, an outage event, or if the coordinator is not in the expected RX state. For the latter failure reason, the most common scenario is when a simple node sends data packets to the hub, but the hub is busy sending an ACK to another node. In these figures, we observe that regardless of

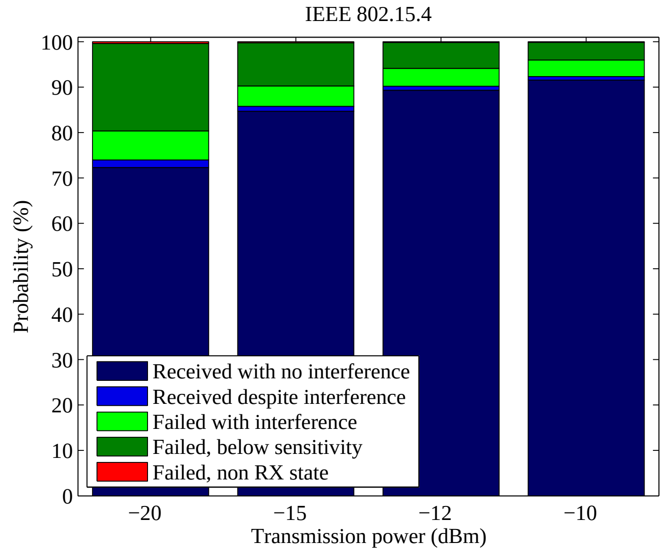

Fig. 4. Received packets breakdown for IEEE 802.15.4 against the transmission power, when the packet rate is considered to be equal to 15 pkts/s

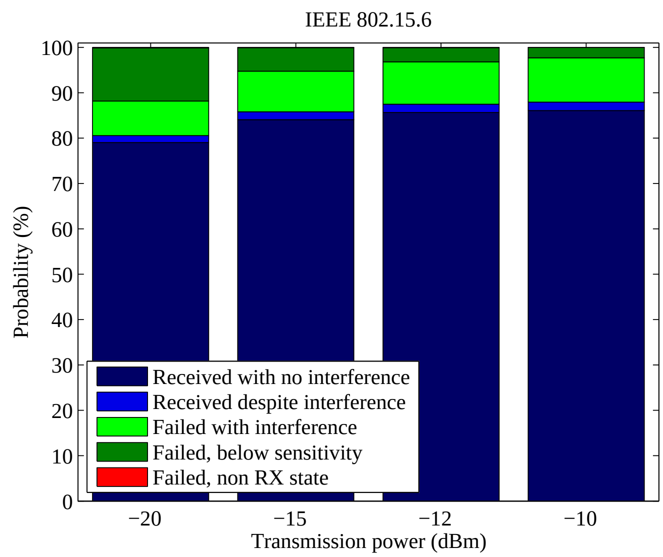

Fig. 5. Received packets breakdown for IEEE 802.15.6 against the transmission power, when the packet rate is considered to be equal to 15 pkts/s

whether IEEE 802.15.4 or IEEE 802.15.6 is used, when the transmission power increases, the signal strength rises, which subsequently increases the overall probability of success, while at the same time the outage probability, i.e., the probability that the received signal power is below the sensitivity of the receiver, decreases. However, as the transmission power increases, the percentage of failure because of interference increases in IEEE 802.15.6, whereas the opposite occurs in IEEE 802.15.4. In both protocols, the nodes perform the CCA via received signal strength indicator (RSSI) readings. When the transmission power is low, the CCA might not be able to sense the busy channel and some nodes might wrongly attempt a transmission. On the other hand, when the transmission power is high the channel sensing is more accurate. In IEEE 802.15.4, the low transmission power increases the possibility of the channel wrongly being sensed idle, which consequently increases the packet transmissions and decreases the BOPs, which would be more utilized otherwise. The use of BOPs after every busy channel sensing is an interference limitation mechanism, since BOPs keep the node idle for some time, during which it will not impose any threat to the transmissions of other nodes. When BOPs are decreased, the interference problem becomes more significant. On the other hand, in IEEE 802.15.6, as the transmission power increases, the power of interference also increases, which makes it difficult for the hub to derive the content of the packets. As a result, as the transmission power increases, the packet transmissions decrease. This problem is constrained for IEEE 802.15.4, because of the BOPs utilization. Consequently, IEEE 802.15.6 is more vulnerable to interference than IEEE 802.15.4.

The transmission packet breakdown against the packet rate, taking into consideration the packets sent by all nodes with transmission power equal to -15 dBm, is presented in Figs. 6 and 7, when IEEE 802.15.4 and IEEE 802.15.6 are used. The transmitted packet breakdown shows the probability that the packets are sent successfully and unsuccessfully, as well as the circumstances under which the success/failure occurs. Specifically, as demonstrated in these figures, a transmission failure might happen if the channel is busy, the transmitting node has not received an ACK in the required time interval, or a buffer overflow occurs[2]. In IEEE 802.15.4, the channel is considered to be busy, when the maximum number of BOPs is reached at contention and a packet transmission is abandoned when no ACK is received for $\mathrm{R_{max}}$ times. On the other hand, in IEEE 802.15.6, a carrier-sensing failure counter (CSFails) is increased every time that the remaining time in current CAP is not enough for transmission. When CSFails reaches the maximum number of deferments, i.e., $\mathrm{CSFails} = \mathrm{R_{max}}$, the channel is considered to be busy. This approach is made, because, as shown in Fig. 2, there is no upper limit on how many times the channel is sensed busy. When the node keeps sensing the busy channel with no boundaries and the CAP is coming to an end, a deferment will happen. Furthermore, in case that the transmitting node has not received the required ACK in a fixed time interval, a counter named pktTXs increases, while the packet transmission is considered unsuccessful and is repeated. If the maximum retry number is reached ($\mathrm{pktTXs} + \mathrm{CSFails} = \mathrm{R_{max}}$), the packet fails and the transmission effort is abandoned. Moreover, regardless of whether IEEE 802.15.4 or IEEE 802.15.6 is employed, if the packets arrive at the buffer faster than they can be transmitted, the packet with the higher FIFO priority for transmission is dropped, because of the buffer overflow.

It becomes evident from Fig. 7 that in IEEE 802.15.6 many packets are lost because the channel is found busy. This happens since there is no upper limit on how many times the channel is sensed busy and when the channel is assessed idle, multiple transmission attempts with increasing duration

[2]It is important to note that the buffers employ first in first out (FIFO) priority scheme.

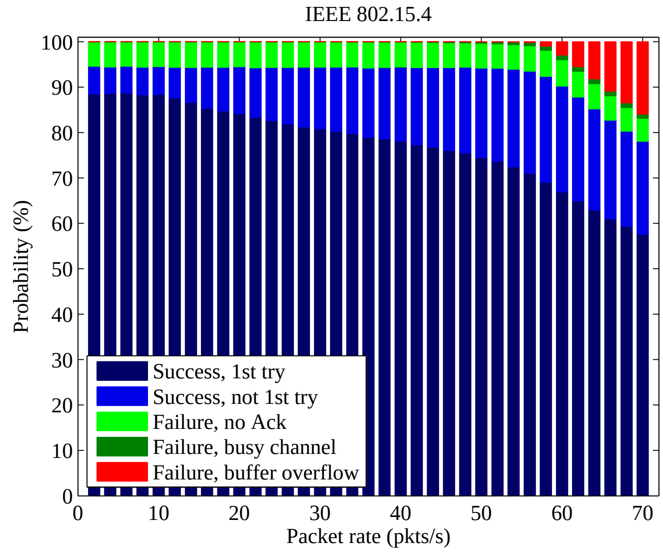

Fig. 6. Transmitted packets breakdown for IEEE 802.15.4 against the packet rate, when the transmission power is set to -15 dBm.

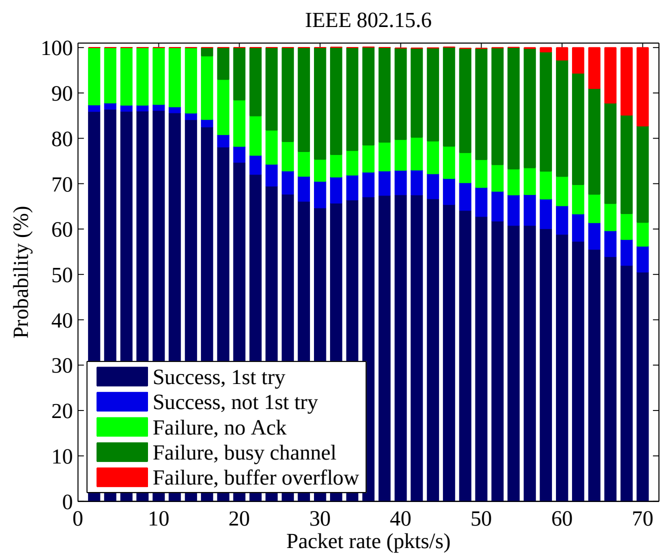

Fig. 7. Transmitted packets breakdown for IEEE 802.15.6 against the packet rate, when the transmission power is set to -15 dBm.

(for every even number of failures CW is doubled) might be required in order to receive an ACK. This procedure is time consuming causing the CAP to quickly run out and the packet transmissions to be deferred until the next superframe. On the contrary, in IEEE 802.15.4, to mitigate this phenomenon, an upper limit on the channel sensing rounds is set, which keeps the transmission effort for a packet short. As a result, it is observed in Fig. 6 that the failure probability due to the busy channel is less than 2%, where in Fig. 7 it reaches 25%. Additionally, regardless of whether IEEE 802.15.4 or IEEE 802.15.6 is used, when the packet rate increases, the size of each packet decreases. Hence, each packet holds smaller portions of information, which makes the system more resistant to corruptions over the wireless link. This observation is evident in both Fig. 6 and Fig. 7, where the probability of

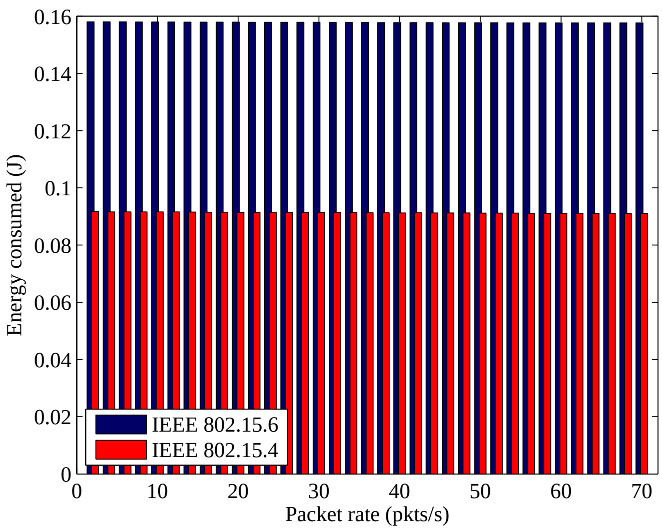

Fig. 8. Consumed energy.

success with 2 or more attempts is increasing with packet rate increase. Nonetheless, there is an upper limit on the packet rate. Since the size of the overhead attached to each packet is fixed, as the packet rate increases, the overhead increases, too. The buffer stores temporarily the packets with their overheads attached. Therefore, to avoid a buffer overflow the buffer should fill up slower than it empties.

In Fig. 8, the average energy consumption of all the nodes as a function of the packet rate is demonstrated. From this figure, it is observed that the energy consumption, in case of IEEE 802.15.4, is roughly 0.09 J, while, in case of IEEE 802.15.6, the energy consumption is about 0.16 J. It is clear that overall there is no significant change in energy consumption for variable packet rate. This happens because the packet rate increase makes the system more resistant to the corruptions of the wireless link and energy is saved from the re-transmissions. This energy is balanced by the energy consumed by the overhead production. Moreover, it is observed that WBANs that use the IEEE 802.15.4 protocol consume less energy than WBANs that employ IEEE 802.15.6, because of the less transmission efforts, which are power consuming, and the BOPs utilized, that can additionally be considered as an extra power saving countermeasure.

V. Conclusions

This paper dealt with the performance assessment of the CSMA/CA mechanisms, as specified in IEEE 802.15.4 and IEEE 802.15.6. It is shown that due to the different CSMA/CA mechanisms employed, IEEE 802.15.6 is more vulnerable to interference than IEEE 802.15.4 as the transmission power increases. However, in the low transmission power regime, IEEE 802.15.6 outperforms IEEE 802.15.4 in terms of successful reception probability. On the other hand, IEEE 802.15.4 outperforms IEEE 802.15.6 in terms of successful transmission probability and energy efficiency. Overall, our results indicate that there are important trade-offs that should be seriously taken into consideration, when designing a WBAN.

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