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SYSTEMS-LEVEL QUALITY IMPROVEMENT

Strategies for Optimal MAC Parameters Tuning in IEEE 802.15.6 Wearable Wireless Sensor Networks

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Abstract Wireless body area networks (WBAN) has penetrated immensely in revolutionizing the classical heathcare system. Recently, number of WBAN applications has emerged which introduce potential limits to existing solutions. In particular, IEEE 802.15.6 standard has provided great flexibility, provisions and capabilities to deal emerging applications. In this paper, we investigate the application-specific throughput analysis by fine-tuning the physical (PHY) and medium access control (MAC) parameters of the IEEE 802.15.6 standard. Based on PHY characterizations in narrow band, at the MAC layer, carrier sense multiple access collision avoidance (*CSMA/CA*) and *scheduled access* protocols are extensively analyzed. It is concluded that, IEEE 802.15.6 standard can satisfy most of the WBANs applications throughput requirements by maximum achieving 680 Kbps. However, those emerging applications which require high quality audio or video transmissions, standard is not able to meet their constraints. Moreover, delay, energy efficiency and successful packet reception are considered as key performance metrics for comparing the MAC protocols. *CSMA/CA* protocol provides the best results to meet the delay constraints of medical and non-medical WBAN applications. Whereas, the *scheduled access* approach, performs very well both in energy efficiency and packet reception ratio.

Keywords Wireless body area networks (WBAN) · MAC protocols · Performance evaluation · IEEE 802.15.6 · WBAN application-specific MAC · Realistic channel and mobility models · Latency · Energy efficiency · Packet reception ratio · Performance metrics

Introduction

Human assistive and wearable technologies such as Wireless Body Area Networks (WBANs) are emerging as an important part of the daily life. These information and communication technologies (ICT) has not only helped to provide innovative heath care solutions but also able to significantly reduce health care spending around the world. For instance, recently it was reported that the UKs National Health Service (NHS) could save up to seven billions pounds per year by using innovative technologies to deliver quality health care to the chronically ill with fewer hospital visits and admissions [1].

Typical WBANs envisioned applications range from the medical field (e.g., vital sign monitoring, ECG, EEG signals monitoring, automated drug delivery etc.) [2–5], to entertainment, lifestyle, gaming and ambient intelligence [6, 7]. However, with regards to applications such as disaster, rescue and critical missions, workers safety in harsh environments (e.g., oil and gas fields, refineries, petro chemical and mining industries) as well as roadside and building workers, wearable WBAN technology can also play a vital role to not only save human lives but also to protect critical and valuable assets [8, 9].

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With regards to number of emerging applications, WBAN communication has to extend beyond on-body communication to deal with body-to-body and off-body communications illustrated in Fig. 1. In our on going research work [10], recently we have studies the impact of interference and coexistence strategies in body-to-body networks (BBN) [11]. In this paper, we will emphasize on effective and reliable on-body communication using IEEE 802.15.6 standard.

The medium access control (MAC) layer plays a vital role in controlling the communication and optimizing the energy consumption of low power WBAN devices. IEEE 802.15.6 MAC can be implemented through *CSMA/CA*, *TDMA*, *slotted aloha*, *scheduled access* as well as *polling* and *posting* mechanisms. Concerning the evaluation of these protocols, the current studies [12–17], lack significantly in accuracy. Number of unrealistic assumptions are considered such as ideal channel models (i.e., without body shadowing, space and time variations), limited mobility scenarios and ideal radio-link conditions. Further, hardly any impact from physical (PHY) layer such as varying transmission (TX) power, varying data rates and operating frequencies are analyzed. Therefore, to overcome the existing limitations, in this paper we present an extensive and comprehensive evaluation of the IEEE 802.15.6 MAC protocols.

The contribution of this paper are as follows; **First**, we proposed a system model which is based on realistic mobility scenarios including sitting, standing, walking and running patterns to cater diverse applications context. Accurate radio link and enhanced channel models are utilized for accurately taking into account the spatial and temporal dependencies in the WBAN channel. **Second**, application specific throughput analysis is carried out to understand the upper bound of IEEE 802.15.6 standard. *Scheduled access* scheme is extensively analyzed by taking into account all the required PHY and MAC parameters. Optimal slot duration's are evaluated under varying PHY and MAC configurations and consequently maximum achievable throughput is presented under various applications constraints. **Third**, a comprehensive comparison is presented between *scheduled access* and *CSMA/CA* MAC protocols under different frequency bands, varying data rates, transmission powers and data payload sizes in narrow band transmission. The results of key performance metrics including Energy efficiency, delay and packet delivery ratio are presented.

State of the art

In classical health-care WBAN systems, *time division multiple access* (TDMA) based medium access control is most often considered. Every sensor node has a dedicated slot to transfer its data to the other sensors or coordinator. Moreover, works such as [18, 19] can further help to optimize the slot scheduling based on the traffic load. Historically, limited attention has been given to *CSMA/CA*, however, very-low duty cycle *CSMA/CA* based protocols such as [20, 21] seems very attractive for ultra low power applications. The IEEE 802.15.6 standard [22], provided a great flexibility to adapt the medium access according to the specific users requirements. The MAC layer includes *Aloha, Slotted Aloha, CSMA/CA, scheduled* and *unscheduled access* as well as *polling* and *posting* channel access mechanisms.

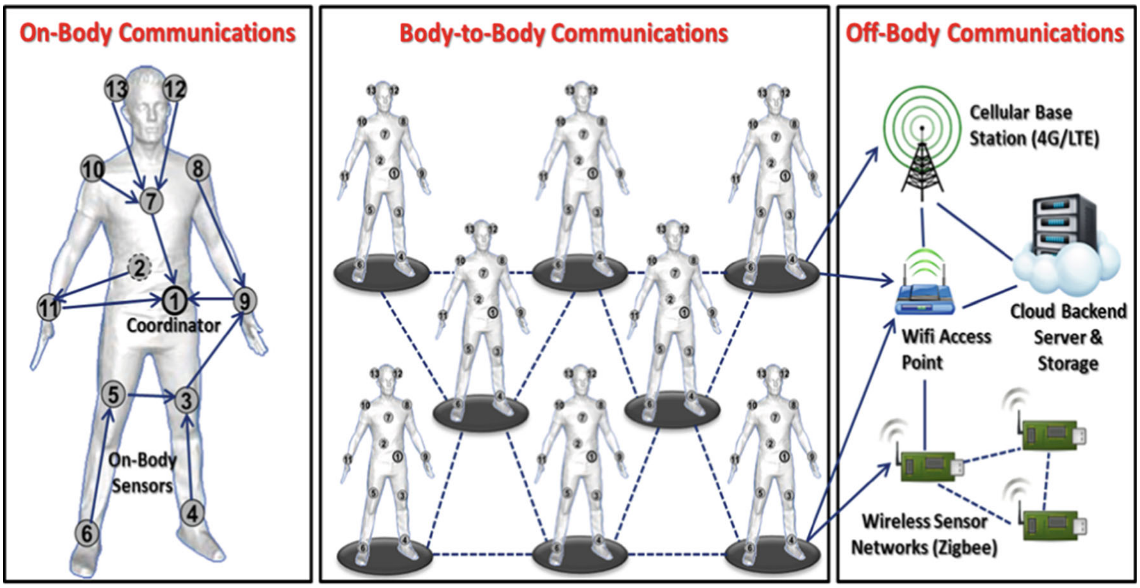

Fig. 1 On-Body, Body-to-Body and Off-Body Wearable Networks

Research on WBANs, especially targeting the performance evaluation of the MAC protocols of the IEEE 802.15.6 standard has attracted increased interest in recent years [12–17]. For instance, the authors in [12, 13] developed analytical models for estimating the IEEE 802.15.6 device lifetime in *scheduled access* mode under ideal channel model, and observed that the overall lifetime could be improved by fine-tuning the MAC superframe (SF) duration, adopting the block acknowledgment policy and increasing the proportion of inactive SFs [13]. Also, discrete-time Markov chain based models were proposed in [14] to evaluate the performance of IEEE 802.15.6 *CSMA/CA* based networks. Whereas in [15], the throughput and delay limits of IEEE 802.15.6 were evaluated analytically under ideal channel model for different frequency bands and data rates.

In order to improve the accuracy of performance evaluation studies, IEEE 802.15.6 proposed channel models (i.e., CM3-A and CM3-B [23]), were considered in [16]. The performance evaluation of the *CSMA/CA* MAC protocols of both IEEE 802.15.6 and IEEE 802.15.4 at 2.4 GHz operating frequency is presented. The obtained results (packet loss rate, delay and throughput) suggest that depending on the application requirements, IEEE 802.15.4 could be more suitable in some cases than IEEE 802.15.6. In [17], the authors investigated the performance of the IEEE 802.15.6 *CSMA/CA* MAC over a Rician-faded channel, and considered accurate radio-link modeling approach by properly computing *Signal-to-Noise-Ratio* (SNR) and *Bit-Error-Rate* (BER) values. The obtained results indicate that the size of the data frames and the channel quality between a node and the coordinator are the most effective parameters for the PHY/MAC performance of a WBAN.

Table 1 summarize the limitations of the existing work concerning the performance evaluation of the IEEE 802.15.6. Pros and cons are presented based on the number of different parameters. At the MAC layer, the evaluations are mainly based on either *TDMA scheduled access* or *CSMA/CA* which are proposed in the standard. In WBAN, specific radio-link and their space and time variations are extremely important. However, most of the existing works presented in Table 1, do not take these parameters into account. Only [16] and [17] have considered channel models, whereas rest of all the performance evaluation is without considering any WBAN specific channel model. Authors in [25] claim that their model implement complete

Table 1 Pros and cons of the existing state-of-the-art work related to the performance evaluation of the MAC layer of the IEEE 802.15.6 standard

MAC schemes	Ref.	Channel models	PHY configurations	Mobility pattern	WBAN networks	Performance metrics	Evaluation method
CSMA/CA							
	[14]	×	HR, (420-450) MHz	×	On-body	Throughput, Energy	Numerical + Mathlab simulations
	[15]	×	LR/HR, (420-450, 863-870, 902-928, 2360-2400) MHz	×	On-body	Throughput, Delay, Bandwidth efficiency	Numerical
	[16]	IEEE 802.15.6 (CM3-B)	LR/HR, (2360-2400, 2400-2483.5) MHz	×	On-body	Packet loss rate, Average delay, Average throughput	Numerical
	[17]	Rician fading	HR, (2400-2483.5) MHz	×	On-body	Average SNR, Delay,	Numerical + Opnet simulator
	[24]	×	HR, (2400-2483.5) MHz	×	On-body	Throughput, Delay	Numerical + Opnet simulator
	[25]	×	HR, (2400-2483.5) MHz	×	On-body	Packet reception rate, Delay	Numerical + simulator Opnet simulator
Schedled access							
	[12]	×	LR, (2360-2400 2400-2483.5) MHz	×	On-body	Energy and lifetime (fixed payload)	Numerical
	[13]	×	LR, (2360-2400, 2400-2483.5) MHz	×	On-body	Energy and lifetime (Varying payloads)	Numerical

Ref.: References
HR: High rate
LR: Low rate

functionality of the IEEE 802.5.6 standard, however, the work is limited only to *CSMA/CA* evaluation without considering IEEE 802.15.6 channel model, accurate mobility and radio link models. Work such as [17, 24, 25] have developed analytic models using Markov chain for *CSMA/CA* protocol. However, the main limitation of these studies is that the considered channel models are quite static and do not take into account the spatial and temporal dependencies of the WBAN channel. More importantly, the performance is evaluated without considering mobility, body shadowing or postures impacts. Further, very limited PHY layer parameters, variations and configurations are taken into account.

Finally, Concerning the IEEE 802.15.6 channel models for narrow band (CM3 A and CM3 B [23]), one of the important limitations is that the measurements are conducted under restricted mobility conditions (i.e., only straight walking from one point to another) is considered and without taking into account the space and time variations. Such type of models may be suitable only for a very specific case whereas, they are not realistic for many other emerging WBANs applications where scenarios such as sitting, laying, standing up, jogging, swimming and running etc., are required. Further, they consider static distances among the different sensors connected on the body and therefore, are not realistic in mobile WBANs context. In addition to that, the IEEE 802.15.6 proposed channel models even though claim to be valid for both line-of-sight (LOS) and non-line-of-sight (NLOS) links, but in reality the pathloss formulas are exactly the same and there is no proper distinction made between the two link types. For example, [26] presents a clear difference between LOS and NLOS links and conclude that on average there is an increase of about 13 % pathloss for NLOS links.

Consequently, in this paper, we take into account all the limitations mentioned above and presented a comprehensive study of *scheduled access* and *CSMA/CA* MAC protocols under realistic environment.

Proposed system models

The accurate mobility, path-loss and radio link modeling is a key requirement in order to get more insight into the performance of wireless communication stacks under real deployment and operating assumptions [27–29]. This is especially true in the context of BANs whose radio channels might undergo harsh multi-path fast fading and time-varying slow fading due to human body shadowing effects [30]. To that end, we consider in this work the Intra-BAN biomechanical mobility and radio link models.

Intra/Inter-BANs biomechanical mobility modeling

Modeling the mobility and posture behaviors of real human bodies is a complex task. One solution consists in exploiting real-time motion capture data and to couple them with geometrical transformation and analysis techniques to properly investigate the performance of BANs and BBNs under different mobility scenarios (e.g. walking, running, exercising, etc). As shown in Fig. 2, our proposed Intra and Inter-BANs mobility modeling works based on six main steps: ***Step 1***:

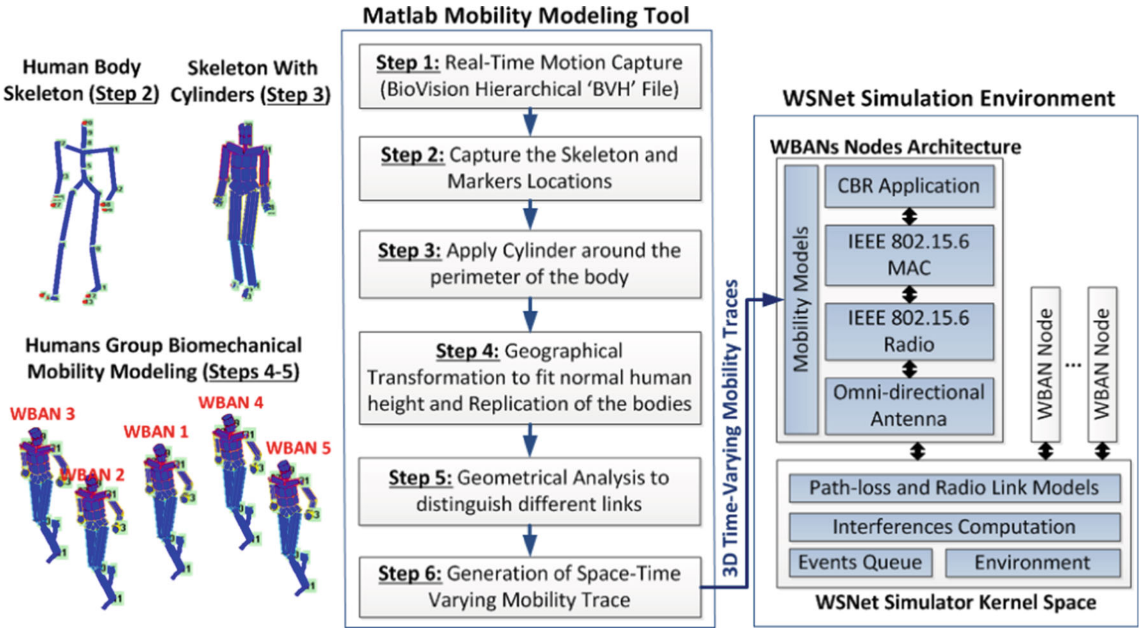

Fig. 2 Joint Biomechanical, Group Mobility and Radio Link Modeling for BANs and BBNs

real motion capture measurements, which contain the actual human mobility traces according to different mobility scenarios (e.g. walking, running, etc.), are extracted into our Matlab mobility modeling tool [27]; ***Step 2***: the complete human body skeleton is captured from the input motion capture measurements and which consists in a set of markers (i.e. the joints between the different parts of the body) and segments (i.e. the body parts). These markers provide the dynamic distances among all the locations over time. An example of human body skeleton is shown in Fig. 2; ***Step 3***: In order to properly model the human body parts (e.g. arms, torso, head, legs, etc.), cylinders are applied around the different segments of the human body skeleton. This is an important step to take into account for the body shadowing effects on the performance of radio links; which can either be in direct *line-of-sight* (LOS) or *non-line-of-sight* (NLOS) condition; ***Step 4***: geographical transformations are then applied in order to scale the dimensions into a normal human height and width. Moreover, the determined human body is replicated into a configurable numbers of other human bodies in order to enable the simulation of complex and highly dynamic inter-BANs scenarios; ***Step 5***: geometrical analysis is thus applied in order to determine the types of all the available links (e.g. LOS or NLOS, Intra or Inter BANs) and during the whole trace duration. Exact link types during mobility are evaluated by checking the intersection of the cylinders between all the links. If a link intersects with a cylinder, then the link is declared as NLOS, otherwise it is in LOS state; ***Step 6***: finally, space-time varying links and mobility traces are generated and stored in an external file, which ultimately can be fed into the **WSNet** packet-oriented simulation environment [28] to enable the realistic performance evaluation of high level communication protocols.

Intra-BAN and Inter-BANs channel models

Once the space-time varying links and mobility traces are properly generated for a given mobility scenario, channel models can be applied in order to assess the performance of radio-links. The IEEE 802.15.6 standard has already proposed various channel models, including the *CM3* (*body surface to body surface*) and *CM4* (*body surface to external*) models. However, it was shown that these models provide only basic distance-based path-loss without any time varying effects and correlations features [27]. To that end, consider two on-body nodes i (transmitter) and j (receiver) located on the same BAN, the corresponding time-varying path-loss variation, $PL(d_{ij})$, is computed based on the enhanced IEEE 802.15.6 path-loss models as proposed in [27]. For example, considering the CM3-B model, the path-loss is computed as: $PL(d_{ij})[dB] = a \cdot log_{10}(d_{ij}) + b + N$; where d_{ij} refers to the distance between the nodes i and j, a and b are the coefficients of the linear fitting, and N is the normally distributed random variable with standard deviation which have different values based on the frequency bands and the environment [27]. However, in case of a radio link of type inter-BAN, i.e. the two nodes i and j are located on different BANs, the corresponding path-loss is computed as [31]: $PL(d_{ij}) = G(d_0) + 10 \cdot n \cdot log_{10}(d_{ij}/d_0) + F$; where $G(d_0)$ is the channel gain at the reference distance, d_0 is the reference distance which is equal to $1m$, n is the path-loss exponent factor, and F is the fading. Typical values (validated experimentally) for these components are provided in [31].

Radio link modeling

Finally, in order to determine if a given transmission was successful (despite of interference), it is important to evaluate the corresponding *packet-error-rate* (PER), as: $PER_{ij} = 1 - (1 - BER_{ij}^t)^n$; where n is the packet length in bits, and BER_{ij}^t is the corresponding *bit-error-rate* which is computed based on the current SINR level at time t (i.e. $SINR_{ij}^t$), and the considered physical layer characteristics (e.g. data rates and modulation schema), as follows :

$$BER_{ij}^t = \begin{cases} 0.5 \times e^{-Eb/No} & \text{DBPSK} \\ Q(\sqrt{4 \times Eb/No} \times sin(\frac{\pi}{4 \times \sqrt{2}})) & \text{DQPSK} \end{cases} \quad (1)$$

Where, Eb/No is the energy per bit to noise power spectral density ratio in dBm which is computed based on the current SINR level, as: $Eb/No[dB] = SINR_{ij}^t[dB] + 10 \times log_{10}(BW/R)$; where BW is the bandwidth in Hz, and R is the data rate in bps.

Theoretical analysis-based on the PHY and MAC layers of the IEEE 802.15.6 standard

scheduled access MAC protocol is one of the widely used approach in WBAN as it provides higher reliability of successful transmission. It is utilized in managed access phase (MAP) of the IEEE 802.15.6 MAC superframe. In this section, we present a numerical analysis based on the *scheduled access* MAC protocol proposed in the IEEE 802.15.6 standard. Beacon enabled mode and superframe boundary as it is best suited for on-body applications [12, 13]. However, for an extensive and thorough evaluation, later in "Extensive performance evaluation", both *scheduled access* and *CSMA/CA* based MAC protocols are compared.

It is necessary to analyze all the numerical parameters of the PHY and MAC layers that contribute towards the evaluation of the exact MAC layer slot duration. First, the optimal values and numerical formulas are presented for all the relevant parameters and then a numerical analysis is carried out to understand the throughput (in terms of theoretical upper bound of IEEE 802.15.6 standard) under the application-specific requirements and constraints.

Overview of IEEE 802.15.6 PHY/MAC frame formats

The Physical-Layer Protocol Data Unit (PPDU) represents the information that is transmitted through the propagation medium to the receiver. It is composed of the physical layer convergence protocol (PLCP) preamble, physical layer convergence protocol (PLCP) header, and physical layer service data unit (PSDU), as illustrated in Fig. 3. The purpose of the preamble is to aid the receiver in packet detection, timing synchronization and carrier-offset recovery. Whereas, PLCP header is added to convey information about the PHY and MAC parameters that are needed at the receiver side in order to decode the PSDU. The PSDU is formed by concatenating the MAC header with the MAC frame body and Frame Check Sequence (FCS). The PSDU is then scrambled and optionally encoded by a BCH code. The MAC frame format is also shown in Fig. 3. It consists of a fixed-length MAC header (seven octets), a variable-length MAC frame body (upto 256 bytes) and a fixed-length Frame Check Sequence (FCS). The Low-Order Security Sequence Number and Message Integrity Code (MIC) fields are only present in unsecured frames.

Numerical analysis of IEEE 802.15.6 scheduled access MAC/PHY parameters

Typical sensor types and corresponding data rates of medical and non-medical applications are presented in Table 2. The actual packet transmission time and maximum allowable data rates under narrow band transmission is observed. However, the Human Body Communication (HBC) and Ultra Wide Band (UWB) parameters evaluation is also possible through similar approach. Further, as an example, coded transmission is considered which can be easily adapted for un-coded as can be found in our previous work [32]. The total duration of a packet transmission (in time), which comprises of the symbols of the PLCP preamble ($N_{preamble}$), PLCP header (N_{header}), and PSDU, can be expressed as,

$$T_{packet} = T_S \times [(N_{preamble} + N_{header} \times S_{header}) + (N_{total}/(\log_2(M)) \times S_{PSDU}] \tag{2}$$

where, T_S is the symbol duration, $N_{preamble}$ and N_{header} is the length of the PHY layer preamble PLCP header (in bits), S_{header} is the spreading factor of the PLCP. The symbol M is the modulation constellation size and S_{PSDU} is the spreading factor of PSDU. Table 3 shows the values of the PHY layers parameters for Narrow band spectrum of two frequencies of the IEEE 802.15.6 standard, $t_{Turnaround}$ and $Clock$ are the transceiver's turn around time between transmit and receive states and the clock resolution which is 40 parts per million (PPM) respectively. N_{total} is the number of interleaved bits, which can be expressed as:

$$N_{total} = N_{PSDU} + N_{CW} \times (n - k) + N_{pad} \tag{3}$$

Where, N_{PSDU} is the actual payload and can be calculated as $N_{PSDU} = N_{MACheader} + N_{MACFrameBody} + N_{FCS}$. The MAC header i.e., $N_{MACheader}$ consists of 7 octets (as can be seen from Fig. 3), $N_{MACFrameBody}$ is the actual payload (which can be maximum upto 256 bytes) and N_{FCS} is the

Fig. 3 IEEE 802.15.6 Standard Physical and MAC Frame Formats [22]

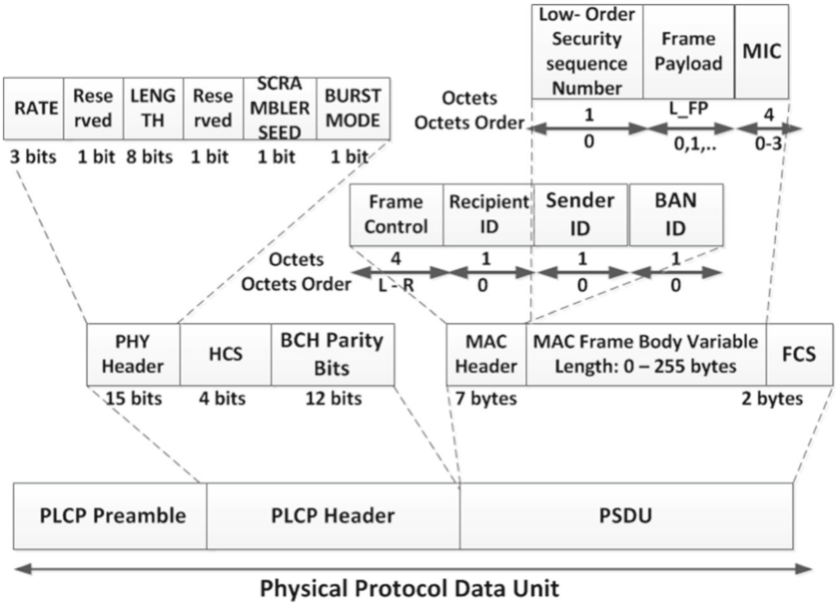

Table 2 Typical sensor types and data rates [9]

WBAN applications	Signals	Data range	Frequency (Hz)	Accuracy (bits)	Data rate
Medical/Health					
	Sweating	-	4	12	48 bps
	Stress	-	50	12	600 bps
	Respiratory rate	2-50 breaths/min	20	12	240 bps
	Pulse rate	0-150 BPM	4	12	48 bps
	Blood pressure	10-400 mm Hg	100	12	1.2 Kbps
	Blood pH	6.8-7.8 pH units	4	12	48 bps
	Body temperature	24-44°C	0.2	12	2.4 bps
Non-Medical					
	High quality audio	-	-	-	1.4 Mbps
	Voice	-	-	-	100 Kbps
	Video	-	-	-	1-2 Mbps
	GPS positions	-	1	32	96 bps
	Motion sensor	-	100	16	4.8 Kbps

number of frame check sequence composed of two octets (i.e., bytes). N_{CW} is a BCH code word which is equal to N_{PSDU}/k, where k is the message bits for the selected BCH code. N_{CW} is set to zero for the case of un-coded transmission. The term $(n-k)$ is the number of parity bits, where $n = 63$ and $k = 51$ [22]. Finally, N_{pad} is the pad bits which can be evaluated as,

$$N_{pad} = \log_2(M) \times \frac{(N_{PSDU} + N_{CW} \times (n-k))}{\log_2(M)} - (N_{PSDU} + N_{CW} \times (n-k)) \tag{4}$$

For un-coded transmission, N_{pad} will be always equal to 0. Therefore, with above parameters settings the total number of bits (i.e.,N_{total}) with actual payload (e.g, 256 Bytes), including all the headers (i.e., PPDU Length) for the coded and un-coded transmission is 2668 bits and 2120 bits respectively. Further, each preamble is constructed by concatenating a 63 m-sequence with a 0101010101011011011011011101 extension sequence. The length of the PLCP preamble, ($N_{preamble}$), is therefore consists of 90 bits, whereas, the PLCP header N_{header} consists of 31 bits.

After knowing all the parameters of the Eq. (2), now we can calculate the real packet duration which includes all the preambles, overheads etc., from MAC and PHY layers. To complete this analysis, as an example, let us focus on the most widely used frequency bands of narrow band spectrum (i.e., *900 MHz and 2450 MHz*). The detailed physical layers parameters are utilized to evaluate the MAC parameters as illustrated in Table 4. It includes, operating frequencies, data rates, modulations-types, bandwidths, spreading factors, encoding rates, symbol rates, effective packet lengths, clock drifts, synchronizations intervals, guard duration, transceivers turn around time, interframe spacing etc. Further by using the MAC layer parameters such as, varying packet size (MAC payloads), MAC headers, and frame check sequence (FCS). Moreover, beacon and acknowledgment (ACK) packets duration are also calculated based on their specific lengths. In the case of beacon packet, 21 bytes are used as suggested in the standard, whereas we have considered 5 bytes of ACK packet which includes source id, destination id, BAN coordinator id and packet sequence numbers with 1, 1, 1 and 2 bytes respectively.

Table 3 PHY Layer Parameters

Frequency	T_s	M	S_{Header}	S_{PSDU}	$t_{Turnaround}$
900MHz	$4\mu s$	2/4	2	2/1	$80\mu s$
2450MHz	$1.6\mu s$	2/4	4	4/1	$80\mu s$

The accurate MAP-slot duration's with and without ACK are evaluated based on all the parameters as explained above and are presented in Table 4. In general, as expected with an increase in payload the slot duration also increase. Whereas comparing the impact of data rates, while moving from lower payload to higher, the increment in slot duration is slightly more than 3 and 4 times at high data rates for 2450 MHz and 900 MHz operating frequencies respectively, and almost 7 times for the lowest rate at both frequencies. Further, it is evident that with the highest data rates best possible throughput can be achieved.

After having detailed parametric analysis of the physical and MAC layers, it is important to realize whether the data rate requirements of different WBANs applications (discussed in "Introduction") can be satisfied by the *IEEE 802.15.6* standard or not?. To answer this important

Table 4 Optimal IEEE 802.15.6 PHY/MAC layer parameters and duration under different configurations for beacon enabled mode with SF boundary

IEEE 802.15.6 PHY configurations				IEEE 802.15.6 MAC layer parameters					
Frequency (MHz)	Data rates (Kbps)	Data payload (bytes)	PPDU length$*$ (bytes)	PPDU (ms)	Guard (us)	ACK packet‡ (ms)	MAP slot without ACK (ms)	MAP slot with ACK (ms)	Beacon packet∓ (ms)
900	101.2 (Lowest)								
		16	45.125	3.0	0.14		3.28	5.08	
		128	157.125	11.8	0.14	1.8	12.08	13.88	3.4
		256	285.125	22.0	0.14		22.28	24.08	
	404.8 (Highest)								
		16	45.125	1.2	0.14		1.48	2.38	
		128	157.125	3.4	0.14	0.9	3.68	4.58	1.3
		256	285.125	5.9	0.14		6.18	7.08	
2450	121.4 (Lowest)								
		16	45.125	2.3	0.14		2.58	3.98	
		128	157.125	9.7	0.14	1.4	9.98	11.38	2.7
		256	285.125	18.1	0.14		18.38	19.78	
	971.4 (Highest)								
		16	45.125	0.6	0.14		0.88	1.38	
		128	157.125	1.5	0.14	0.5	1.78	2.28	0.6
		256	285.125	2.6	0.14		2.88	3.38	

*Including headers, preambles, etc. ‡ 5 bytes. ∓ 21 bytes

question, in next section, an application specific throughput analysis is carried out.

Applications-specific throughput analysis: PHY/MAC exploitation Vs applications requirements

First of all, specific data rate requirements of different applications are presented. For example, in sports and fitness typically monitoring of sweating, respiratory rate, body temperature, pulse rate and motion sensors could be required with data rates upto 10 Kbps. Whereas, for heathcare applications, such as vital signs monitoring as well as ECG, EMG and EEG signals monitoring, the data rates requirements can start from few bps up to 500 Kbps [33, 34]. With reference to rescue and critical application, along with vital signs monitoring, voice, GPS positions, motions sensors could be required with data rates upto 200 Kbps. Finally considering the newly emerging entertainment and augmented reality applications with audio and video signal requirements the data rates reached beyond 1 Mbps.

The maximum achievable throughput possible in IEEE 802.15.6 standard under narrow band can be expressed as,

$$T = \frac{1000(ms)}{(t_{Slot}(ms) \times N + t_B(ms)) \times M} \times \frac{P}{1024} \tag{5}$$

where, T is the effective throughput in Kbps, t_{Slot}, t_B and P is the MAP slot duration (in ms), Beacon duration (in ms) and Payloads P (in bytes, which has to be converted into bits). All these parameters can be extracted from Table 4 based on the different PHY/MAC configurations. Further, N is the number of nodes corresponding to specific application and M is the order of periodicity (called m-periodicity) [22], which means for example, if certain nodes only want to transmit once every two superframes then M will be equal to 2. Here the term '$\frac{1000(ms)}{(t_{Slot}(ms)*N+t_B(ms))\times M}$' provides number of superframes in 1 second. Finally, the payload is converted into bits and normalized with 1024 to have effective throughput in Kbps.

Figure 4 shows the maximum achievable application level throughput against varying number of nodes, with and without ACK, for 8 (most interesting) different configurations (as mentioned earlier in Table 4). Application thresholds are highlighted and it can be seen that majority of the configurations can only be able to achieve upto 100 kbps or fewer, only high rate configurations are able to generate data rates higher than 200 kbps (after including all the overheads). Though all the vital signs-based application, m-heath as well as rescue and critical applications requirements were able to satisfy. Whereas, gaming and entertainment or any such applications which require high quality audio or video, IEEE 802.15.6 standard is not able to

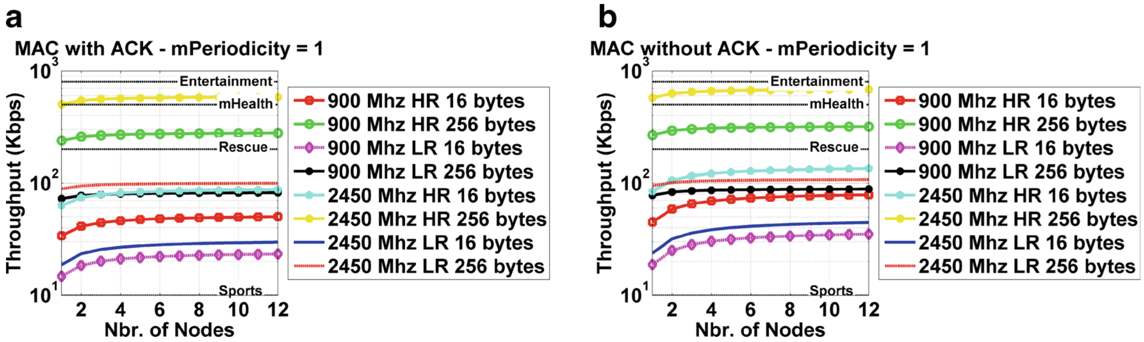

Fig. 4 Maximum achievable application throughput in IEEE 802.15.6 standard. (**a**) Throughput including ACK duration, (**b**) Throughput without including ACK duration

meet that requirements even by considering the maximum data rates and highest packet size and therefore some other radio technologies can be added to support that features such as Bluetooth or Wi-Fi [35].

Following important observations are also concluded:

- With the increase in number of nodes, the maximum achievable throughput also increases. This is mainly because the contribution of the MAC and PHY overheads reduces in one second, as the number of overall superframes reduces with an increase in number of nodes. [1]
- Although, using an ACK can help to improve the performance of the MAC protocols (as shown later in Section 1), however with reference to throughput, it takes an extra time in the slot duration without actually being able to transmit real data so it does not help to increase the throughput. The impact of ACK is reflected in Fig. 4a, where for example, maximum achievable throughput (with 2450 MHz, high rate and 256 bytes) is almost 90 Kbps lower in comparison to without ACK as can be seen in Fig. 4b.
- Finally, m-periodicity with $m = 1$ is only considered in above analysis which means in every superframe there will be one slot allocated to every node. As shown in Fig. 4, the maximum throughput possible at the application layer is only 680 Kbps (without ACK + m-periodicity=1). This is definitely not an optimized solution since multiple sensors have different data rate requirements and there is a huge variations among the data rates of different sensors being used in these applications. Therefore, there are number of physiological signals that does not need to be transmitted in every superframe and hence m-periodic *scheduled access* should be used to fully optimize for the better throughput.

Extensive performance evaluation

In this section detailed results of the PHY/MAC layers performance evaluation are presented. There are number of challenges and limitation for accurate performance evaluation of IEEE 802.15.6 standard. Recently [36–38], claimed to be the IEEE 802.15.6 compliant radio transceivers however, they are limited due to several reasons. First, the utilization of low frequency bands does not often satisfy most of the applications data rates requirements. Second, only transmitter is available without fully IEEE 802.15.6 standard compliant. Therefore, to best of our knowledge, IEEE 802.15.6 compliant radio transceivers are still to come. Another possible solution is to realize mathematical proofs and develop analytical models, however, WBAN and BBN networks are very complex mainly due to large set of parameters and variables and their dynamic behavior. For example, at the physical (PHY) and medium access control (MAC) layers there are number of possible combinations and along with constantly varying radio-link and channel, accurate mobility model for different applications, the analytical analysis becomes highly complex. Therefore, very specific and small scale analysis are feasible which are not complete and extensive. So, the simulations can be a viable alternate provided an extensive set of parameters and all the important components (as explained in "Propose system model") being taken into account.

Simulation setup

A packet-oriented network simulator called **WSNet** [28], is used as highlighted in Fig. 2. It contains various models for wireless sensor networks, wireless local area network and adhoc networks. However, previously it does not contain WBAN specific modules. Therefore, we have enhanced the simulator (with focus on IEEE 802.15.6 standard compliance) to accurately model body area networks using enhanced channel models, accurate radio-link and mobility models (as explained earlier in "Proposed system models").

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[1] Please note that in the presented application level throughput all the overheads and preambles are taken into account inside the slot duration t_{Slot} which is calculated through PPDU length.

Table 5 List of simulations parameters and corresponding values

Protocol stack	Configurations and parameters		
	Frequency (MHz)	2450	900
PHY. Layer(Narrow band)	Data Rates (Kbps)	121.4 - 971.4	101.2 - 404.8
	TX. Power (dBm)	0, -10, -20, -25	0, -10, -20, -25
	TX. Current consumption (mA)	17.4, 11, 9.2, 8	15, 9, 7.2, 6
	RX. Current consumption (mA)	19.7	23.5
	Sleep. Current consumption (mA)	0.9	0.0005
	Sensitivity (dBm)	-92 to -83	-94 to -87
	Channel models ([27])	CM3-B-enhanced	CM3-B-enhanced
	Channel bandwidth (KHz)	1000	400
	Protocols	Scheduled access(MAP)	CSMA/CA
MAC layer	ACK policies	Immediate, BLOCK, None	Immediate, BLOCK, None
	ACK packet size (Bytes)	5	5
	Beacon packet size (Bytes)	21	0
	Re-transmission limit	0	4
	Priority-level	0	2
APP. layer	Payloads (Bytes)	2, 16, 64, 128, 256	2, 16, 64, 128, 256
	Packet interval	100 ms	100 ms
	Number of nodes	12 (Sensors), 1 (Coordinator)	12 (Sensors), 1 (Coordinator)

At the application layer, 12 sensor nodes and 1 coordinating node is considered, where every node generates a packet at 100ms interval. From the application layer, every packet is parsed into the MAC layer. Two protocols are developed at the MAC level. First, *CSMA/CA* with priorities using a state machine is implemented. The 'back-off' mechanism is followed exactly as proposed in IEEE 802.15.6 standard (i.e., for every odd 'backoff' the contention window size is doubled), where, maximum 'backoff' and 're-transmissions' are set as 5 and 4 respectively. Further, three acknowledgment policies are developed. Second, *scheduled access* (i.e., *Beacon MAP*) scheme is implemented with a superframe architecture which includes a beacon period, each node has one guaranteed time slot (which is optimized based on the actual payload and all the overheads of the MAC and PHY layers). Specific timings details of the MAC configurations in the *scheduled access* scheme can be found in Table 4.

The simulation setup is based on version 3.0, which is an up-to-date version of **WSNet**. By using all the above explained models, extensive parameters and configuration, the WSNet's XML configuration files (i.e., **xml**) are generated for simulations. The simulations are repeated for 50 iterations and 95 % confidence interval is considered. The simulations are executed for number of scenarios including walking, sitting/standing and running for dynamic mobility patterns for a duration of 63 sec. The detailed simulations parameters and corresponding values are presented in Table 5.

Performance evaluation of Intra-BAN communication

In this section, a comprehensive study on the performance of the *CSMA/CA* and *scheduled access* MAC protocols is carried out under the simulating environment explained in previous section. Energy efficiency, latency and packet reception ratio (PRR) are considered as performance metric throughout this section.

Concerning the energy consumption of the on-body communication between 12 different nodes, Fig. 5 shows an average energy consumption under varying transmit power, payloads and ACK policies for four different PHY configurations. The energy consumption for each transmitted packet is calculated as follows,

$$E_{packet} = T_{packet} \times 3_{Volts} \times I_{mA} \quad (6)$$

where, T_{packet} is the PPDU duration in ms which is based on the effective packet length and is obtained from real propagation time in the simulator, 3_{Volts} is the considered battery voltage and I_{mA} is the current consumption which is used from the widely used radio transceiver chip i.e., Texas Instrument's *cc2420* for 2450 MHz, whereas, for 900 MHz, AMI Semiconductor's transceiver chip *amis52100*

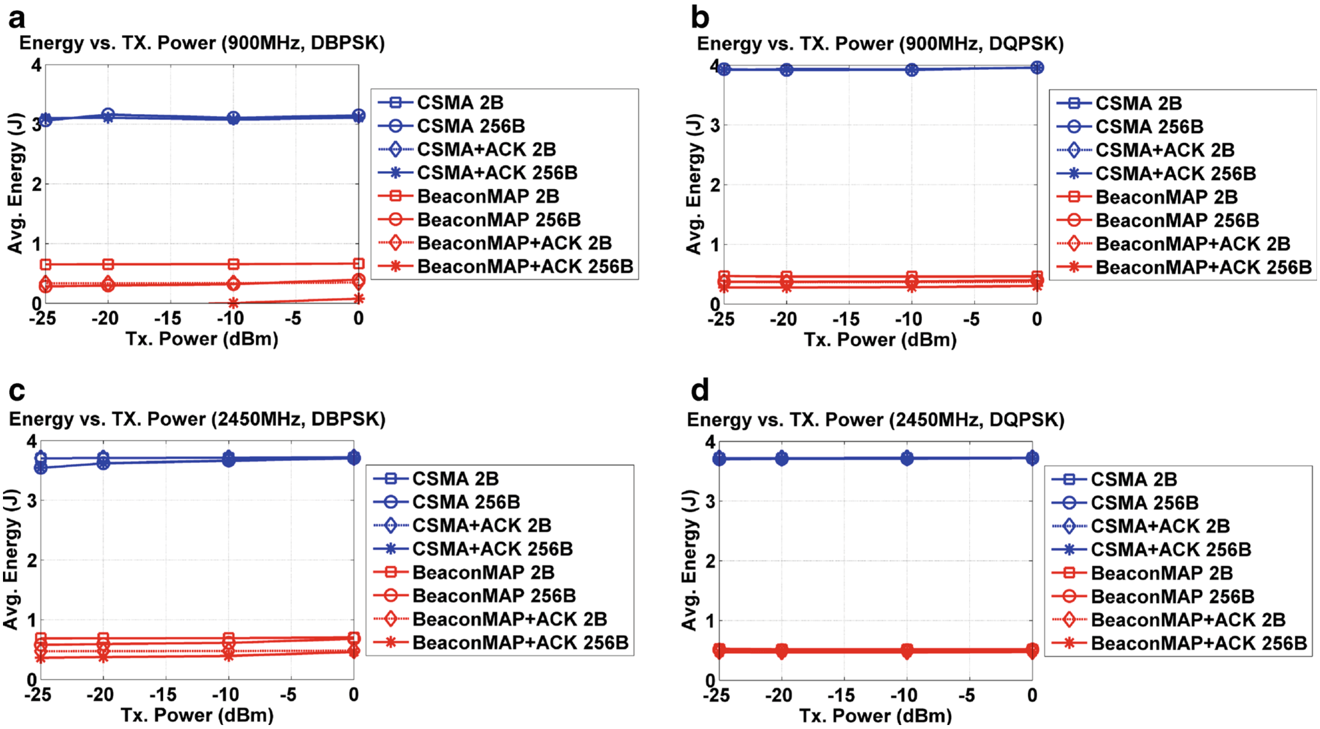

Fig. 5 Average Energy consumption of the *CSMA/CA* and Beacon Enabled MAP protocols at varying transmit power with and without ACK under lowest and highest payloads, (**a**) Freq = 900 MHz, Modulation = DBPSK(**b**)Freq = 900 MHz, Modulation = DQPSK (**c**)Freq = 2450 MHz, Modulation = DBPSK and (**d**): Freq = 2450 MHz, Modulation = DQPSK

[39] is used. All the details regarding current consumption is provided in Table 5.

In general, it can be seen from Fig. 5, that *CSMA/CA* consumes three to four times more energy in comparison to *scheduled access* beacon MAP. This is mainly because in *CSMA/CA* all the nodes are considered to be in active state all the time to achieve best performance in terms of packet transmission and reception. Whereas, in *scheduled access* (i.e., Beacon enabled MAP), all the nodes have their own slots to transmit (which they obtain from the beacon packet in every superframe) and accordingly they schedule their active and sleep duration which help to minimize their energy consumption.

Figure 5a and b shows the results of 900 MHz with DBPSK (i.e., low data rate) and DQPSK (i.e., high data rate). The energy consumption is higher for high rates especially for the *CSMA/CA* protocol. While comparing the 900 and 2450 MHz configurations, both *CSMA/CA* and Beacon MAP consume more in 2450 MHz mainly because of the difference in current consumption levels at two operating frequencies.

In specific, the variation in energy consumption due to ACK and extreme payloads in *CSMA/CA* is almost in the order of 10 mJ. This is not clearly visible in Fig. 5, though Table 6 shows the difference starting from second and third decimal place. Whereas, the variations in *scheduled access* protocols are slightly more almost in the order of 100 mJ. It can be noticed that, lower payload configurations consumes relatively more energy than higher ones. This is mainly due to more transmission of superframes which contains extra communication overheads.

Finally, the impact of different transmission power is also in the order of 10^{-3} Joules for both protocols, which can be seen in Table 6. For the highest data rate with 2450 MHz configuration (i.e., C1), the difference due lowest and highest transmission power is 2 to 3 times (at mJ level). Whereas, for the rest of the other configurations the order is between 6 to 7 times.

The results of average packet reception ratio (PRR) are presented in Fig. 6, in general *scheduled access* Beacon MAP achieves between 99-to-100 % PRR under all the variations. On the other hand *CSMA/CA* has much more variations mainly impacted by the transmission power and at best it is able to achieve about 94 % PRR at the highest transmit power and frequency of 2450 Mhz. Focusing on to the Beacon MAP, under low rate we observe that the average PRR is more than 99 %, however, at transmit power -25 dBm, the performance reduces to about 97 % for 900 MHz in both configurations. Whereas in worse case, it reaches upto 90 % for the 2450 MHz and high rate as can be seen in Table 6. So for the *scheduled access* Beacon MAP, the minimum transmit power should not be lower than -20 dBm to

Table 6 Detailed results of *scheduled access* (Beacon MAP) and *CSMA/CA* Protocols

PHY/MAC parameters			PRR (%)				Energy consumption (J)				Latency (ms)			
MAC protocols	PHY configuration	TX. power	W-ACK		WO-ACK		W-ACK		WO-ACK		W-ACK		WO-ACK	
			P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
CSMA/CA														
	C1													
		0	99.5	91.5	99.8	92.9	3.720	3.722	3.722	3.720	0.22	1.90	0.22	1.90
		-10	99.4	92.6	98.8	93.1	3.712	3.721	3.721	3.712	0.22	1.90	0.22	1.90
		-20	96.9	82.5	97.8	85.0	3.708	3.721	3.721	3.708	0.22	2.00	0.22	2.00
		-25	88.1	68.8	88.1	66.4	3.702	3.721	3.721	3.702	0.26	2.30	0.26	2.30
	C2													
		0	92.9	62.5	92.5	60.2	3.720	3.707	3.720	3.707	1.7	15.2	1.70	15.2
		-10	94.2	59.0	93.8	61.9	3.712	3.664	3.712	3.667	1.7	15.3	1.70	15.3
		-20	92.2	51.8	90.0	51.0	3.709	3.621	3.709	3.621	1.8	18.8	1.70	18.5
		-25	87.4	35.2	87.6	37.8	3.706	3.543	3.706	3.545	1.9	22.3	1.90	22.6
	C3													
		0	98.31	83.55	97.94	82.85	4.371	3.959	4.371	3.964	0.52	4.60	0.52	4.60
		-10	98.89	85.36	98.17	86.70	4.368	3.932	4.368	3.924	0.52	4.60	0.52	4.60
		-20	97.35	83.27	96.11	85.49	4.368	3.934	4.369	3.921	0.53	4.60	0.53	4.60
		-25	95.30	78.26	93.33	76.87	4.367	3.925	4.368	3.933	0.56	5.0	0.56	5.0
	C4													
		0	92.20	57.61	91.69	56.05	4.177	3.112	4.179	3.149	2.0	18.30	2.0	18.30
		-10	92.09	57.21	91.08	55.91	4.169	3.078	4.171	3.107	2.0	18.30	2.0	18.30
		-20	90.57	54.64	92.77	52.40	4.169	3.108	4.163	3.162	2.0	18.50	2.0	18.50
		-25	92.42	50.59	91.95	51.86	4.160	3.103	4.162	3.064	2.0	19.70	2.0	19.70
Scheduled access														
	C1													
		0	100.0	100.0	100.0	100.0	0.479	0.476	0.518	0.515	18.70	20.40	18.70	20.40
		-10	100.0	100.0	100.0	100.0	0.478	0.468	0.517	0.506	18.70	20.40	18.70	20.40
		-20	99.6	99.6	99.6	99.6	0.479	0.465	0.517	0.504	18.80	20.50	19.10	20.80
		-25	93.2	93.5	92.2	92.3	0.483	0.469	0.527	0.512	21.50	23.0	29.30	30.90
	C2													
		0	100.0	100.0	100.0	100.0	0.484	0.462	0.704	0.682	105.1	118.7	105.1	118.6
		-10	100.0	100.0	100.0	100.0	0.476	0.394	0.695	0.613	105.1	118.6	105.1	118.6
		-20	100.0	100.0	100.0	100.0	0.473	0.375	0.692	0.594	105.1	118.6	105.1	118.6
		-25	99.9	99.9	99.8	99.9	0.472	0.362	0.691	0.581	105.1	119.2	106.5	119.8
	C3													
		0	99.98	99.98	99.99	99.99	0.369	0.301	0.465	0.397	37.5	41.6	37.5	41.5
		-10	99.98	99.98	99.98	99.99	0.366	0.282	0.462	0.378	37.5	41.5	37.5	41.5
		-20	99.74	99.74	99.70	99.98	0.366	0.277	0.462	0.372	37.7	41.8	38.1	42.1
		-25	97.41	97.68	97.34	97.15	0.368	0.276	0.468	0.371	39.4	43.4	44.4	48.4
	C4													
		0	99.96	99.96	99.96	99.96	0.347	0.077	0.666	0.397	123.4	139.7	123.3	139.6
		-10	99.96	99.96	99.96	99.96	0.338	0.001	0.656	0.319	123.4	139.7	123.5	139.6
		-20	99.96	99.96	99.96	99.96	0.336	0.021	0.653	0.296	123.3	139.7	125.7	140.2
		-25	99.87	99.89	99.87	99.87	0.334	0.036	0.652	0.280	131.8	143.0	139.4	161.4

C1=2450 MHz+DQPSK, *C2*=2450 MHz+DBPSK, *C3*=900 MHz+DQPSK, *C4*=900 MHz+DBPSK . *P1* = 2 Bytes, *P2* = 256 Bytes, *W-ACK* = With Acknowledgment, *WO-ACK* = Without Acknowledgment

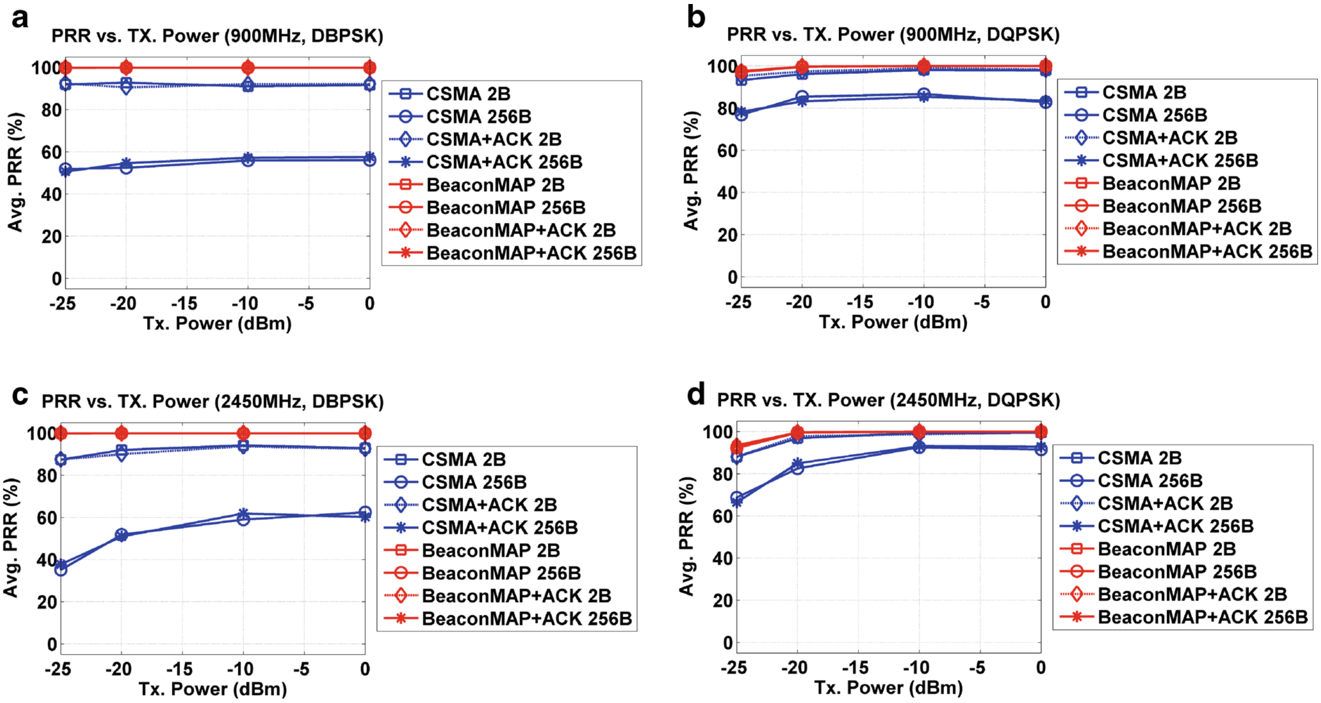

Fig. 6 Average successful packet reception ratio of the *CSMA/CA* and Beacon Enabled MAP protocols at varying transmit power with and without ACK under lowest and highest payloads, (**a**) Freq = 900 MHz, Modulation = DBPSK (**b**)Freq = 900 MHz, Modulation = DQPSK (**c**)Freq = 2450 MHz, Modulation = DBPSK and (**d**): Freq = 2450 MHz, Modulation = DQPSK

satisfy the 95 % performance constraints of packet reception ratio [22]. Further, it is also interesting to note that the impact of even highest payload on the PRR is negligible because proper time is allocated based on the payload size (as illustrated in Table 4), and under no interference best performance can be achieved as shown in all the results of *scheduled access* in Fig. 6.

With regards to *CSMA/CA*, most of the configurations do not satisfy 95 % requirements. However, with lowest payloads the achievable PRR is upto 90 %, especially in configurations with higher transmit power and high data rate with both 900 and 2450 MHz. The most interesting results for *CSMA/CA* under highest payload are presented in Fig. 6d. In this configurations, *CSMA/CA* becomes comparable with Beacon MAP at lowest payloads and the performance with highest payloads reaches more than 90 % PRR at -10 dBm or higher Table 6. Also very similar pattern can be seen in Fig. 6b. So, it is better to use *CSMA/CA* with higher data rates and transmit power more than -10 dBm.

Finally the results of latency for both *Beacon MAP* and *CSMA/CA* are presented under various configurations in Fig. 7. Generally *CSMA/CA* has much lower delay (nearly 100 times) in comparison to the Beacon MAP. With reference to the impact of transmission power, it can be seen that below -20 dBm all the configurations and both protocols tend to have higher transmission delay because while considering the realistic mobility and enhanced channel models it is not possible to consider very low power such as -25 dBm. Moreover, this is very much inline with the results of PRR where at -25 dBm, PRR decreases sharply.

The variations of the payload as well as ACK has minimal impact on the latency of Beacon MAP. However, for the *CSMA/CA* the highest payload has 10 times more delay in comparison to the lowest payload. Though the results of using an ACK or without ACK are very similar. Finally by considering the delay requirements of IEEE 802.15.6 standard (i.e., 125 ms for medical signals), both protocols at high data rates satisfy this requirement, whereas at low rate Beacon MAP is almost touching the limit of 125 ms. It is important to note that these results are presented with 12 nodes and each node has only one slot allocated during the superframe, which is not an optimized solution for all the applications discussed earlier. Here we considered a case of rescue and critical application and the results are according to our considered context which can be seen for more details in [40].

To conclude the On-body communication results of the MAC layer, it is evident that both *CSMA/CA* can be used based on the specific applications requirements. On one hand, if energy consumption is the most important concern then, Beacon MAP should be considered, however, definitely an optimized low duty cycling based approaches can improve the energy efficiency of the *CSMA/CA* approach and can be considered as a future work. On the other

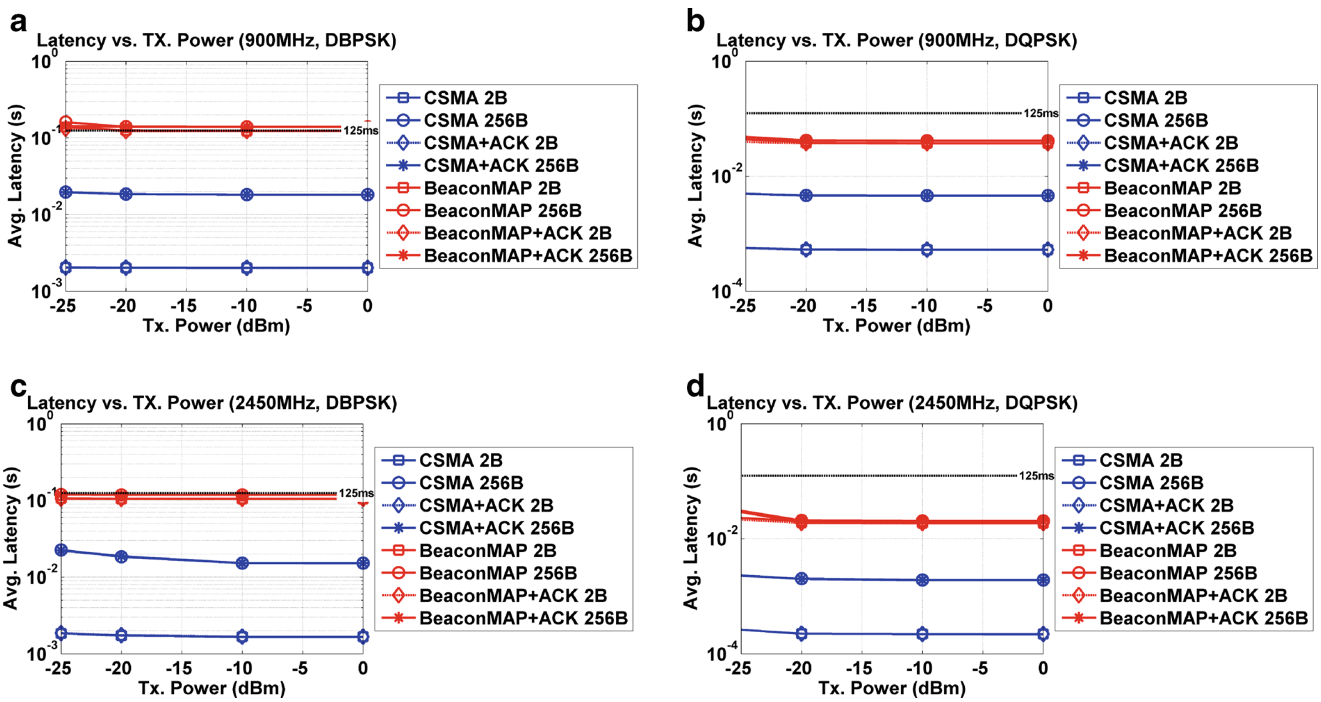

Fig. 7 Average delay of the *CSMA/CA* and Beacon Enabled MAP protocols at varying transmit power with and without ACK under lowest and highest payloads, (**a**) Freq = 900 MHz, Modulation = DBPSK(**b**)Freq = 900 MHz, Modulation = DQPSK (**c**)Freq = 2450 MHz, Modulation = DBPSK and (**d**): Freq = 2450 MHz, Modulation = DQPSK

hand if delay is the most important design parameter, then *CSMA/CA* should be considered. Finally, if packet reception is the major constraint, definitely Beacon MAP is much better, whereas, *CSMA/CA* under few configurations can provide comparable packet reception ratio results as well.

Conclusions

IEEE 802.15.6 standard provides great flexibility at the MAC layer to adapt the access scheme based on the applications requirements. Previously, *CSMA/CA* and *scheduled access* protocols proposed in the standard were evaluated, however, there are number of shortcoming to their evaluation. Closed-form MAC layer evaluation are available without taking into account the impact of realistic channel models (i.e., no space and time variations). In addition, limited mobility scenarios with consistently static channel and radio-links are considered (without considering LOS and NLOS impact into account). This paper provides a significant addition to the accuracy of the current state of the art performance evaluation especially with regards to emerging applications by taking into account all the above mentioned limitations. An extensive MAC protocols evaluation is realized at the narrow band, 900 MHz and 2450 MHz operating frequencies with lowest and highest data rates and corresponding detailed parameters are considered. Application specific throughput analysis is carried out which is based on the evaluation of optimal slot duration under various PHY configurations in *scheduled access* MAC protocol. It is found that IEEE 802.15.6 standard can maximum achieve 680 Kbps while taking all the PHY and MAC overheads into account. Sports and fitness applications can be realized very easily in both 900 MHz and 2450 MHz operating frequencies using lowest data rate and only 16 bytes of payload. Whereas, rescue and critical applications can be satisfied by only high data rates and highest payloads (i.e., 256 bytes) at both frequencies. Further, health-care application requiring ECG, EEG signals monitoring can be only possible using 2450 MHz frequency with highest payload and highest data rate to satisfy its throughput requirements.

While comparing *CSMA/CA* and *scheduled access* MAC protocols, in general, there is a trade off and it is concluded that, *CSMA/CA* protocol provides the best results to meet the delay constraints of medical and non-medical WBAN applications. However, its performance for energy efficiency and packet reception ratio needs significant enhancements to meet the constraints of IEEE 802.15.6 standard. On the other hand, *scheduled access* approach, performs very well both in energy efficiency and packet reception ratio, whereas, it does not able to meet the delay constraints of WBAN applications.

In specific, with reference to varying transmission power and payloads, following conclusions are drawn: as far as

PRR is concerned, it seems that *scheduled access* can operate successfully upto -20 dBm under all PHY configurations even with highest payloads. Whereas, *CSMA/CA* has to operate higher than -10 dBm for achieving packet delivery higher than 90 %. Moreover, in certain cases only by lowering the payload from 256 bytes can help to achieve better PRR.

With regards to the impact on the energy consumption, the PHY configuration with highest rate at 2450 MHz (which satisfy most of the applications), it is found that in CSMA/CA protocol, the minimum transmit power able to reduce the energy consumption by 2-to-3 times whereas, 6-to-7 times in all other configurations.

Finally, in *CSMA/CA*, the lowest transmission power has highest delay in all the configurations, further, lowest rate has much higher delay especially at 900 MHz, and there is about 8-to-9 times more delay with highest payload in comparison to the lowest payload. Whereas, in *scheduled access* the payload influence on the delay is almost negligible.

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