IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 31, 2019, accepted April 29, 2019, date of publication May 10, 2019, date of current version May 28, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916159

Throughput and Channel Aware MAC Scheduling for SmartBAN Standard

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This work supported in part by the European Union's Horizon 2020 Research and Innovation Program under Grant 668995, in part by the European Union Regional Development Fund through the framework of the Tallinn University of Technology Development Program 2016–2022, in part by the Estonian Research Council under Grant PUT-PRG424, and in part by the Academy of Finland 6Genesis Flagship under Grant 318927.

ABSTRACT In this paper, a throughput- and channel-aware (TCA) medium access control (MAC) scheduling scheme is presented and evaluated for smart body area network (SmartBAN) standard, developed by the European Telecommunication Standard Institute (ETSI). The presented algorithm utilizes the radio link signal-to-noise ratio (SNR) to select the candidate nodes for a given time slot in the first phase, while, in the second phase, the slot is assigned to one of the chosen nodes based on their priority level and data packet availability. The algorithm uses an m-periodic scheduling technique, in which the nodes are considered for slot assignment according to their data packet generation rates during the second phase. Subsequently, a comprehensive explanation of the TCA algorithm execution through the slot reassignment method in SmartBAN is provided. For performance comparison, we use four key performance indicators (KPIs), which include packet reception rate (PRR), latency, energy consumption per successful transmission, and throughput. The simulation results indicate a significant performance gain of the SmartBAN-complaint TCA algorithm in terms of PRR and energy efficiency over the reference SmartBAN MAC scheduling with and without repetition. The average improvement in the PRR results is approximately 40%, whereas a maximum enhancement of 66% is observed in terms of energy efficiency while satisfying the throughput and latency requirements of the use case considered during simulations. Furthermore, we introduce some enhancements in the primary TCA to decrease the frequency of TCA execution via slot re-assignment frames transmission for reducing energy consumption, which results in a slight improvement of energy efficiency.

INDEX TERMS Energy consumption, enhanced TCA, latency, MAC, PRR, SmartBAN, TCA, throughput, WBAN.

I. INTRODUCTION

With the growing trends in ubiquitous networking and contemporary evolution in ultra-low-power wireless technologies, there have been significant research efforts dedicated to the utilization of wireless networks around human bodies. Wireless body area networks (WBANs) are the wearable monitoring systems, consisting of interconnected low-power and energy efficient tiny nodes such as sensors, actuators and coordinators for WBAN management, to realize numerous applications in the domain of healthcare, athletic monitoring and training, public safety networks, and consumer electronics [1]–[3]. To deal with the requirements set forth by WBAN applications, IEEE standards association came up with the first officially recognized operational guidelines, termed as IEEE 802.15.6 [4], for WBAN functioning. A low-complexity and flexible WBAN standard, known as SmartBAN, was introduced by European Telecommunication Standards Institute (ETSI). SmartBAN defines more efficient system specifications to facilitate faster initial set up times, hub-to-hub communication, better co-existence management and many additional features over IEEE 802.15.6 standard [5], [6].

The significant changes in the pathloss measurements of space-time varying WBAN channels result in a considerable degradation of error performance at low transmission power levels [7]. Due to human body shadowing, the packet reception rate (PRR) performance is shown to severely decrease for

The associate editor coordinating the review of this manuscript and approving it for publication was Tawfik Al-Hadhrami.

transmission power levels below -5 dBm and increased packet sizes [8]. At the physical (PHY) layer, SmartBAN provides the options for Bose-Chadhuri Hocquenghem (BCH) error correction codes and frame repetitions for enhanced error performance [9], [10]. In [11], authors highlight the importance of this repetition to get the acceptable 1% frame error rate under high interference scenario. But at very low transmission power and realistic WBAN channels, even the repetition was not able to achieve above 90% PRR.

A. RELATED WORK AND MOTIVATION

For mitigating the packet losses due to poor radio link quality, several channel variations-based dynamic medium access control (MAC) schemes have been proposed in the literature. Authors in [12] propose a scheduling algorithm which contemplates the success or failure status of packet transmissions using the two-state Gilbert's model of wireless links to improve the packet loss rate. Considering the context-specific temporal correlation properties of WBAN channels, authors in [13] determine the WBAN channel state during the upcoming transmission trials and suggest the variations in transmission power levels accordingly, resulting in improved energy consumption outcomes. BANMAC protocol in [14] first detects that whether the WBAN node is mobile or stationary. For nodes on the mobile limbs, the transmissions are made when the received signal strength (RSS) is likely to be higher whereas the remaining available time is used in transmissions from stationary nodes. In [15], a channel-aware polling-based MAC protocol for WBANs is presented in which the sensors are triggered for polling and packet transmission when the channel conditions become favorable. Since WBAN channel quality is also affected by the co-channel interference, therefore, authors in [16] suggest an interference avoidance algorithm which employs carrier sense multiple access with collision avoidance (CSMA/CA) between sources and relays and a flexible time division multiple access between relays and coordinator. The scheme allows low interfering nodes to send their messages using primary channel and the high interfering nodes double their contention windows coupled with the possible usage of a switched orthogonal channel. Using the correlation properties of the on-body links, a prediction-based dynamic relay transmission method is suggested in [17] in which WBAN relay transmissions are made depending upon the recently obtained channel states.

To sum up, the above mentioned research efforts primarily consider the channel characteristics of the WBAN links for dynamic MAC scheduling while either minimizing the energy consumption at higher PRR or providing better channel estimation to improve PRR performance. The emerging wearable applications have diverse data rate requirements for various sensor nodes [18] which constitute another important metric in dynamic MAC scheduling techniques. Addressing the data rate, energy efficiency and PRR performance requirements of WBAN applications, a joint throughput and channel aware dynamic scheduling algorithm is suggested in [7]. The IEEE 802.15.6 complaint algorithm is shown to boost the PRR performance while maintaining the energy consumption levels substantially low. Motivated by these factors, this article thoroughly explores the implementation of SmartBAN-complaint joint throughput and channel aware (TCA) dynamic MAC scheduling algorithm. In TCA, first the channel conditions are examined for each scheduled access slot and later the data rate considerations of the selected nodes (with favorable radio link quality) are taken into account for slot assignments to a given node.

B. SUMMARY OF CONTRIBUTIONS

The fully-complaint execution of TCA with SmartBAN is based on the slot re-assignment operation defined in SmartBAN MAC [19] at alternate inter-beacon intervals (IBIs), followed by the acknowledgement of the updated slot assignments. In slot reassignment, the hub re-allocates the unused scheduled access slots to sensor nodes for efficiently utilizing the MAC resources [19]. Executing TCA this way comes with its own set of limitations in terms of PRR and throughput performance. For some on-body links under a certain mobility scenario (walking, sit-stand, running), the channel state may change from the moment slot re-assignment packet is sent until the updated assignments are actually executed which leads to a decrease in performance. In other words, the channel SNR conditions for few links under a given mobility change significantly fast and as a result the assigned slots to the nodes do not give good performance. Whereas for some WBAN links and mobility cases, the slot re-assignment for TCA execution is not required to be performed at the alternate IBIs due to relatively stable channel conditions. Based on this discussion, the key contributions for this article include:

- Implementation of TCA MAC algorithm in full compliance with the SmartBAN standard. TCA improves the error performance of reference SmartBAN MAC by scheduling and re-allocating time slots to certain nodes when their channel conditions are favorable. But performing slot reassignment at alternate IBIs leads to an increase in overall energy consumption. However the energy used up this way is utilized in successful data packet receptions, thus enhancing the overall energy efficiency.
- Presentation of results for the SmartBAN complaint TCA algorithm in terms of four key performance indicators (KPIs), i.e., PRR, Latency, Throughput and energy consumption evaluation against reference SmartBAN MAC with and without repetitions. Moreover, both the reference SmartBAN MAC and SmartBAN complaint TCA are compared in terms of all these KPIs with respect to varying transmission power levels. A comprehensive analysis of the PRR, energy consumption, latency and throughput results generated this way, is given in Table 3.
- Since the baseline TCA execution may increase the overall energy consumption by performing slot reassignments at alternate IBIs, therefore the third contribution

includes the proposal of an enhanced TCA MAC algorithm. Enhancing the TCA execution only when the channel SNR severely degrades or when the packet status at the sensor nodes changes, improves the energy consumption profile by lowering the frequency of slot reassignments. A performance comparison of the generic and enhanced TCA is also given, taking PRR and energy consumption as the evaluation metrics.

The remainder of the paper is arranged as given. Section II presents the detailed description of the reference SmartBAN MAC characteristics while Section III explains the TCA algorithm basics, TCA execution in SmartBAN and the enhancements in the TCA algorithm. Section IV describes the systems model and parameters used in simulation setup. The section also discusses the simulation results for the given KPIs under different mobilities. Finally, concluding remarks are provided in Section V.

II. SMARTBAN MAC SPECIFICATIONS

This section provides a detailed explanation about the reference SmartBAN MAC superframe format MAC details with and without repetition in scheduled access mode. Additionally the slot-reassignment method in SmartBAN MAC is also given.

A. REFERENCE SMARTBAN MAC WITHOUT REPETITION

The data channel used for packet transmission between the coordinator and sensor nodes is partitioned into IBIs. A data channel beacon (D-Beacon) marks the IBI beginning, followed by scheduled access period for data transmissions by sensor nodes and the corresponding data packet acknowledgements. Management and control signaling by hub and/or sensor nodes is communicated in control and management (C/M) period and the entire IBI duration ends with an inactive period [19], [20]. Every scheduled access slot consists of physical-layer protocol data unit (PPDU) transmissions and PPDU acknowledgements with inter-frame spacing (IFS) in between. MAC frame body contains the actual payload, that along with MAC header and frame parity creates a MAC protocol data unit (MPDU). For uncoded transmissions, the resultant MPDU becomes physical-layer service data unit (PSDU). PSDU, after the addition of physical-layer convergence protocol (PLCP) header and preamble, constitutes a complete PPDU [19], [20]. The entire IBI duration is made of beacon duration, time slot duration and the number of time slots in scheduled access period, time slot duration and the number of time slots in control and management period and the duration of inactive period, as depicted in Fig. 1. The duration of each time slot in the entire IBI is found according to a pre-defined parameter L_{Slot} [19], as follows

$$T_{Slot} = T_{min} \times L_{Slot}, \tag{1}$$

where T_{min} is the minimum slot duration defined in SmartBAN MAC specifications [19]. Beacon period, scheduled access period, control and management period and inactive period are made of the identical slot duration T_{Slot} throughout the IBI.

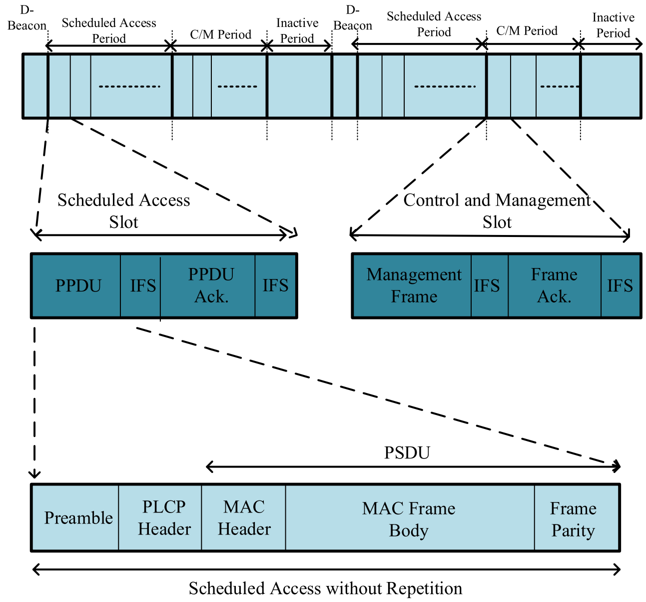

FIGURE 1. Reference smartBAN MAC without repetition.

During the scheduled access period of each time slot, there is acknowledgement and IFS duration as well [19]. IFS duration is fixed and the duration for acknowledgement is computed as

$$T_{Ack} = \frac{N_{preamble} + N_{PLCP} + N_{par} + N_{MAC}}{R_{Sym}}, \tag{2}$$

where $N_{preamble}$, N_{PLCP}, N_{par} and N_{MAC} are the number of bits in physical-layer preamble, PLCP header, MAC frame parity and MAC frame header respectively. After the calculation of T_{Ack}, the effective duration for PPDU transmission becomes

$$T_{Tx} = T_{Slot} - T_{Ack} - 2 \times T_{IFS}. \tag{3}$$

After finding T_{TX}, the maximum allowed MAC frame body size for uncoded MPDU can be found as

$$Payload = T_{Tx} \times R_{Sym} - N_{preamble} - N_{PLCP} - N_{par} - N_{MAC}. \tag{4}$$

In scheduled access duration, all the sensor nodes are assumed to have their respective time slots pre-assigned by hub and the mandatory C/M period is also present within IBI. For applications with diverse data rate requirements, it becomes inefficient for sensor nodes to wake up at every IBI for data transmission, therefore, the low rate nodes are assumed to employ m-periodicity in which they only wake up for transmission when data is available, and remain in the sleep mode otherwise.

B. REFERENCE SMARTBAN MAC WITH REPETITION

In scheduled access mode with repetition, the sensor node repeats the PPDU transmission within the assigned time slot. This alters the effective PPDU transmission time as under

$$T_{Tx} = \frac{T_{Slot} - T_{Ack} - 2 \times T_{IFS}}{REP}, \tag{5}$$

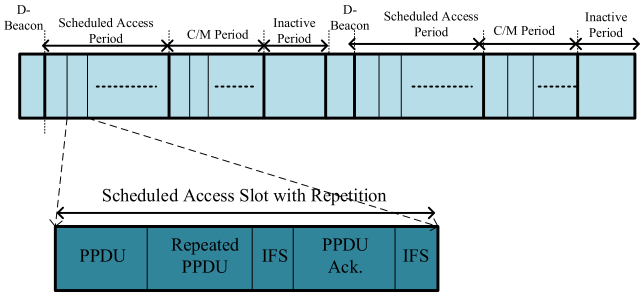

FIGURE 2. Reference smartBAN MAC with repetition.

where *REP* is the number of times a PPDU is repeated. The effective payload size is also reduced, as per (4), which results in more frequent transmissions by sensor nodes to send the same amount of data. SmartBAN proposes two and four repetitions for improving the error performance [9] but it leads to the reduced amount of transmitted payload in a given duration, lowering the effective throughput. The rest of the IBI operation in scheduled access MAC with repetition is similar to the reference SmartBAN MAC without repetition and is illustrated in Fig. 2.

C. SLOT REASSIGNMENT

Slot reassignment operation in SmartBAN is performed to inform sensor nodes of their newly allocated slots in scheduled access duration. In order to perform slot reassignment, the hub indicates in D-Beacon about the execution of slot reassignment during the C/M period and the list of nodes for which slot re-assignment would be performed. The hub then sends slot reassignment frame in the C/M period with the highest level user priority employing the slotted ALOHA channel access mechanism. The procedure is repeated again in the next IBI if the transmission of slot reassignment frame fails in the current IBI. The slot reassignment frame contains the timing information specifying the starting and ending time slot allocated to the node. The nodes, upon successful reception of slot re-assignment frame during the C/M period, acknowledge hub in the MAC header of the data frame during the following IBI. The complete procedure of slot reassignment in SmartBAN is depicted in Fig. 3. The new slot allocation comes into practice for data transmission by nodes in the next IBI, making the slot reassignment procedure take at least two IBIs to be completed.

III. THROUGHPUT AND CHANNEL AWARE MAC

This section elaborates TCA basics, details of the TCA execution in SmartBAN and enhancements within the existing TCA algorithm.

A. TCA DESCRIPTION

TCA algorithm is based on the principle of m-periodic scheduling recommended by IEEE 802.15.6 standard. In m-periodic allocation, time slots within the scheduled access duration are assigned based on the data generation rates of individual sensor nodes. Therefore, high rate or emergency nodes can be defined as the priority nodes which are assigned time slots at consecutive IBIs while low data rate nodes are assigned scheduled access slots m-periodically only when they have data packets to send [7]. This concept of m-periodic allocation is exploited in TCA mechanism, along with the information about the channel conditions between coordinator and sensor nodes. TCA algorithm comprises of two main steps; slot allocation based on the WBAN link SNR conditions and a final slot assignment based on m-periodicity.

The input of the algorithm consists of the estimated pathloss values, transmission power and noise power. In this paper, the deterministic pathloss values are used which are obtained from the experimental traces of the motion capture system and biomechanical modeling [21] as one of the inputs. The obtained pathloss is used for the computation of signal-to-noise ratio (SNR) threshold for the first step. For defining the SNR threshold during the first phase, a packet error rate (PER) value of 0.1 is considered to acquire the PRR above 90% and reverse radio link computations are made to obtain the corresponding SNR threshold [21]. For the required PER value of 0.1, the resultant bit error rate (BER) value is computed using the relation $PER = 1 - \left(1 - P_e\left(\frac{E_b}{N_0}\right)\right)^N$, where N is the packet size in bits, which subsequently provides $\frac{E_b}{N_0}$ after being evaluated in

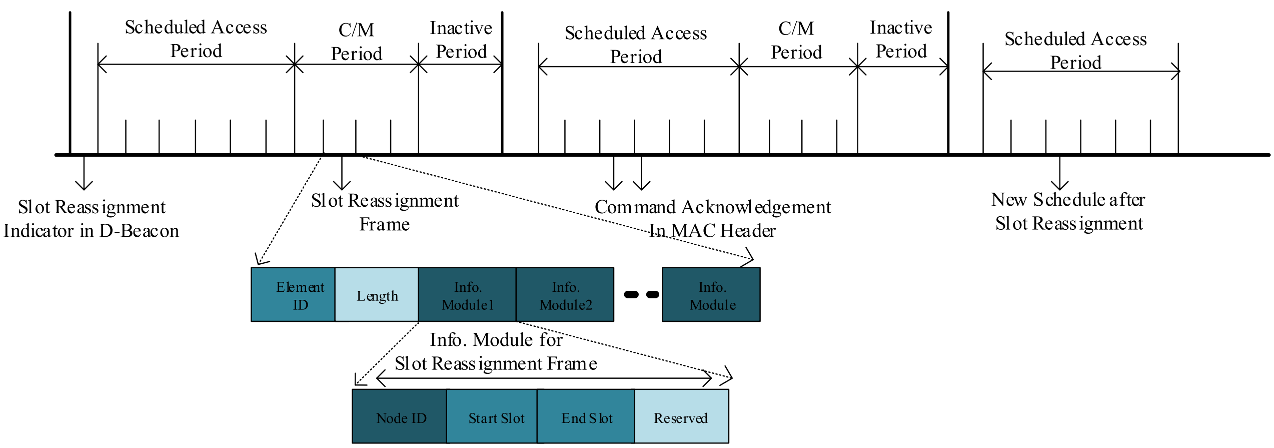

FIGURE 3. Slot reassignment operation in smartBAN.

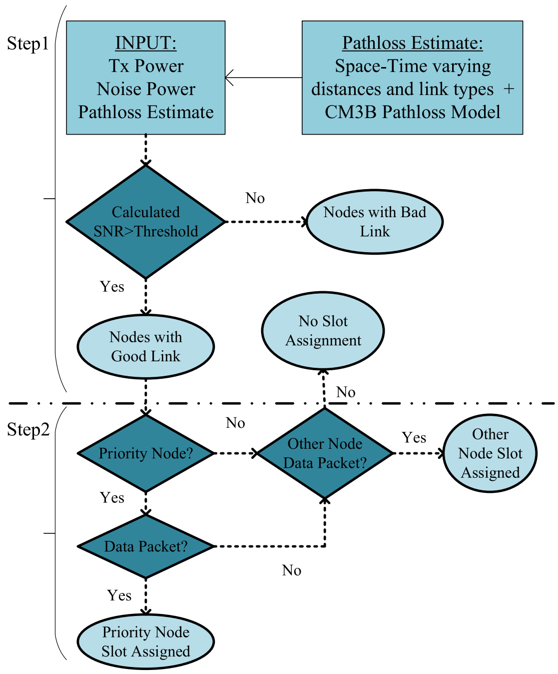

FIGURE 4. Throughput and channel aware MAC algorithm.

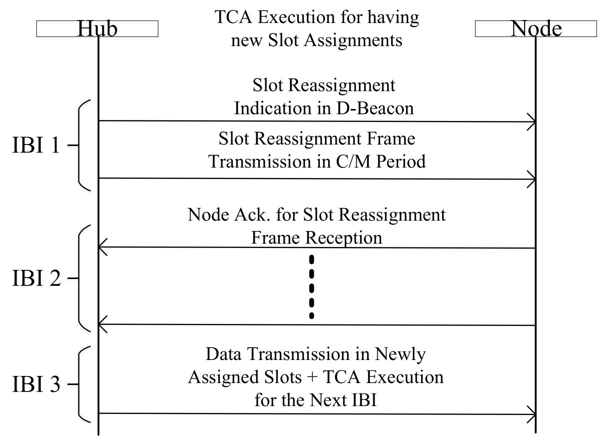

FIGURE 5. TCA execution in smartBAN.

the BER expression. SmartBAN defines Gaussian frequency shift keying (GFSK) modulation at the physical layer [9], therefore the corresponding BER expression will be used for $\frac{E_b}{N_0}$ computations. The required SNR can be obtained using the equation $\frac{E_b}{N_0}[dB] = SNR[dB] + 10 \times log_{10}\left(\frac{BW}{R}\right)$, where BW is 2MHz channel bandwidth and R is 1MSymbols/s information rate, specified for SmartBAN [9]. The pertinent SNR threshold found for TCA execution in SmartBAN using this method is 7dB or higher for a packet length of 86 bytes in order to obtain a PRR above 90%.

During the first step, the SNR conditions of each time slot are checked for every node-hub link and if the link SNR is greater than the pre-defined threshold value, the node is considered as a candidate node for slot assignment in the next step. The resulting set of sensor nodes, in the second step, is checked for priority node and if priority node is among the candidate sensor nodes with data packet available, it is allocated the given time slot. If priority node does not have good SNR conditions at the radio link or is already allocated the slot, other low priority nodes are assigned the given slot based on their data packet status. The flow chart representation of TCA algorithm is shown in Fig. 4.

B. TCA EXECUTION IN SMARTBAN

A reasonable way of executing TCA in SmartBAN is the implementation of slot reassignment operation at the alternate IBIs. Initially, the hub checks the SNR conditions between itself and the sensor nodes for the given time slot in the scheduled access period and finds the most suitable candidate nodes for packet transmission, with their link-SNR values greater than the per-defined threshold. Depending upon the channel state and data packet availability of the candidate nodes, the given slot is allocated to one of the sensor nodes. Based on TCA algorithm, a list of the assigned slots is created for all the nodes present in WBAN. At the beginning of each IBI in D-Beacon, hub sends the information about the possible slot reassignment operation during the C/M period. Later in the C/M period, hub sends slot reassignment frames to all the nodes that are meant to perform packet transmission. If the hub fails to send slot reassignment frame within the current IBI, it attempts to perform the slot reassignment for TCA scheduling in the successive IBI. All the sensor nodes which receive slot reassignment frame perform mandatory command acknowledgement via MAC header in the scheduled access period of the following IBI. The new slot assignment, as suggested by coordinator, comes into operation in the next IBI while the coordinator simultaneously analyzes the current WBAN link SNR conditions to perform the TCA scheduling via slot reassignment method again. Fig. 5 summarizes the details of the TCA execution and the related frame exchange in SmartBAN. This way TCA algorithm can be carried out by sending the slot reassignment frames at the most in the alternate IBIs.

C. ENHANCED TCA FOR SMARTBAN

The conventional TCA scheme mentioned in sub-section III-B proposes the slot reassignment performed at every alternate IBI after creating the list of assigned slots using TCA algorithm. The recurrence of slot reassignment at alternate IBIs can be decreased by executing TCA only when required, depending upon the channel conditions and the packet availability of the previous slot assignments. Therefore, the enhanced TCA algorithm consists of the following main steps before carrying out the slot reassignment at alternate IBIs

- At first, hub checks that whether TCA was executed and a slot reassignment frame was sent in the preceding IBI or not since TCA execution through slot reassignment is not possible at the consecutive IBIs. If TCA execution was carried out in the last IBI, the algorithm stops and repeats the same procedure during the next IBI, else the algorithm proceeds to the next step.

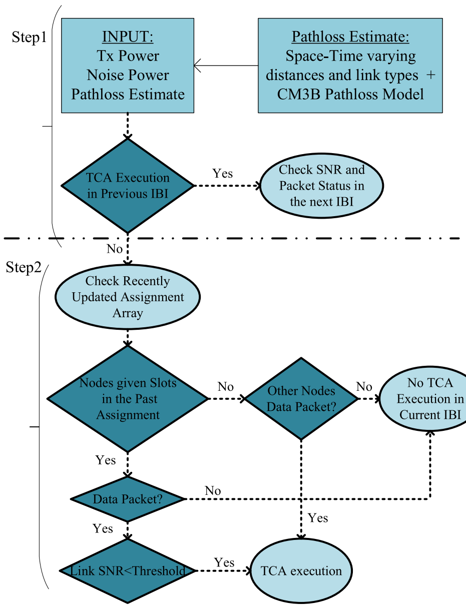

FIGURE 6. Enhanced TCA modifications.

- The hub checks the past assignment array having the details of the assigned slots to sensor nodes. The hub executes the generic TCA and implements slot reassignment if i) SNR values of all the nodes in the previous assignment array, having data packet to send, go below the pre-defined threshold for the current IBI. OR ii) some other sensor node, not included in the past assignment array, has data packet to send. Otherwise the next IBI is checked for possible changes in the channel conditions of the hub-node links or packet status of the sensor nodes.

Fig. 6 summarizes the modifications done in TCA algorithm for performance enhancements.

IV. PERFORMANCE EVALUATION

This section, at first, describes the inherent system model and the simulation parameters utilized in performance evaluation of various WBAN applications. Then a comprehensive analysis of the acquired simulation results, in terms of PRR, energy consumption per successful transmission and latency, is presented.

A. SYSTEM MODEL

The system model to provide PHY-MAC performance analysis consists of mobility modeling for dynamic links generation, channel models for finding realistic pathloss values, and radio link modeling. Bio-mechanical mobility modeling, as suggested in [21], provides space-time varying distances and link types, classified as line of sight (LOS) or non-line of sight (NLOS), between sensor nodes and the central hub. Both the dynamic distances and link types serve as inputs to generate pathlosses for dynamic mobility scenarios.

In order to compute pathloss values for space-time varying distances and link types, IEEE 802.15.6 proposed CM3-B channel model [22] is used. An additional NLOS term of 13% is added to the calculated pathloss value for the NLOS categorized links. Radio link modeling involves the successive computations of SNR, bit energy-to-noise ratio, BER and PER from the obtained realistic pathlosses [21].

GFSK modulation, with the bandwidth-bit period product BT and modulation index h of 0.5, is used at the physical layer described by SmartBAN [9]. Frequency shift keying modulation becomes minimum shift keying modulation for $h = 0.5$ [23] and therefore, the corresponding BER expression becomes

$$P_e\left(\frac{E_b}{N_0}\right) = Q\left(\sqrt{2\epsilon\frac{E_b}{N_0}}\right), \tag{6}$$

where $\frac{E_b}{N_0}$ is signal-to-noise ratio for a bit, ϵ is a constant and for BT of 0.5, equals 0.79 [24]. Further details about the radio link modeling performed in this paper are given in [21]. For obtaining BER with repetition, SNR is found according to the diversity technique employed at the receiver. We assume maximal ratio combining (MRC) diversity scheme for assessing the maximum achievable gain that SmartBAN can provide with repetition. In MRC, the instantaneous SNRs of individual transmissions are directly added if statistically independent transmission channels are assumed [23].

TABLE 1. Simulation setup parameters. [9], [19], [25].

RF Parameters	
Transmitter Power (dBm)	-10.9, -6.9, -2.5
Receiver Sensitivity (dBm)	-92.5
Current Consumption Tx (mA)	15, 15.9, 17.6
Current Consumption Rx (mA)	16
Bandwidth per channel (MHz)	2
Receiver Sensitivity (dBm)	-92.5
Information Rate (kbps)	1000
PHY/MAC Parameters	
Minimum slot length (T_{min})	625μs
Slot duration (T_{SLOT})	1.25ms
Interframe spacing (IFS)	150μs
Symbol Rate (R_{Sym})	10^6
MAC header (N_{MAC})	7 octets
Frame Parity (N_{par})	2 octets
PLCP header(N_{PLCP})	5 octets
PLCP Preamble ($N_{preamble}$)	2 octets

B. SIMULATION SETUP

The parameters considered in the simulation setup are summarized in Table 1. We evaluate the performance at three different transmission power levels of -10.9dBm, -6.9dBm and -2.5dBm, defined for RN4020 Bluetooth low energy (BLE) devices [25]. For three distinct mobility patterns, which include walking, sit-stand and running, $L_{SLOT} = 2$ is assumed to give T_{Slot} in all the simulations. From the calculations performed according to (1), T_{SLOT} equals 1.25ms.

For the performance assessment of the reference SmartBAN as well as TCA scheduled access mechanisms, we consider precise athlete monitoring application scenario, as given in Table 2, along with the sensor node data rate requirements. In precise athlete monitoring application scenario, hub is located on the right shoulder, ECG and respiratory nodes

TABLE 2. Use case scenario for performance evaluation. [5], [26]–[28].

Precise Athlete Monitoring	
Sensor Type	**Required Data Rates (kbps)**
ECG (1 node)	6-48
IMU (4 nodes)	4.8-35
Respiratory Rate (1 node)	0.24-0.8
Sensor Placement	
Sensor Type	**Location**
ECG	Chest
IMU1	Left elbow
IMU2	Right elbow
IMU3	Left knee
IMU4	Right knee
Respiratory Rate	Upper chest

are respectively placed on the lower and upper chest and four IMU sensors are positioned on left and right, knees and elbows. In the reference SmartBAN MAC, ECG node sends packets at every IBI due to its potentially high data rate requirement while IMU and respiratory node may transmit data after a few IBIs and remain in sleep mode for energy preservation because of their relatively low data rate specifications. However, for reference SmartBAN MAC with repetition, these low rate nodes make transmissions more often to accommodate their throughput requirements. TCA MAC performs slot assignments depending upon the channel conditions as well as the sensor nodes packet generation rates and transmissions are made only when both scheduling factors are in agreement. For all scheduling scenarios, we assume mandatory scheduled access and C/M periods with an IBI duration on 11.25ms, resulting in the transmission of 88 IBIs per second.

C. SIMULATION RESULTS

We define the KPIs for performance evaluation, mentioned in sub-section IB, as under

- PRR, for each sensor node, is the ratio of successfully decoded packets and the total number of packets transmitted by each node throughout the trace duration.
- Latency is the amount of time elapsed between the data packet generation at a particular node and its successful reception at coordinator.
- We define the total energy consumed as the summation of energy utilized during transmission and reception at the circuitry as well as the amplifier, according to the energy consumption model given in [29]. For sensor nodes, energy consumption per successful transmission becomes $\frac{E_i}{n_i}$, where E_i is the total energy consumed at node i and n_i is the number of successful transmissions made by the particular node. In case of hub, the energy consumption equals $\frac{E_h}{n_{total}}$, where E_h is the total energy utilized by hub and n_{total} is the total number of successful transmissions made by all sensor nodes.
- The attained throughput is defined as the number of bits successfully transmitted by a node per second, and can be written as $\frac{n_i \times N}{T_{IBI} \times n_{IBI}}$, where T_{IBI} is complete IBI duration in seconds and n_{IBI} is the number of IBIs elapsed throughout the trace file.

1) SIMULATION RESULTS FOR SMARTBAN COMPLAINT TCA

Fig. 7 sums up the PRR results for each link between different sensor nodes and the hub, under walking, sit-stand and running mobility scenarios at −10.9dBm transmission power. Link1, link2, link3, link4, link5 and link6 respectively correspond to the nodes placed on chest, left knee, right knee, left elbow, right elbow and upper chest. Under walking scenario, TCA scheduling in SmartBAN outperforms the reference SmartBAN MAC schemes with and without repetition due to link SNR-based appropriate slot assignment for all the WBAN links. Despite using packet repetitions with MRC combining, a considerable improvement in performance is not observed because of repeated data transmission under poor channel conditions. The similar remarks can be made about the PRR performance under running scenario. The related mobility and body shadowing due to posture changes under walking and running scenarios severely

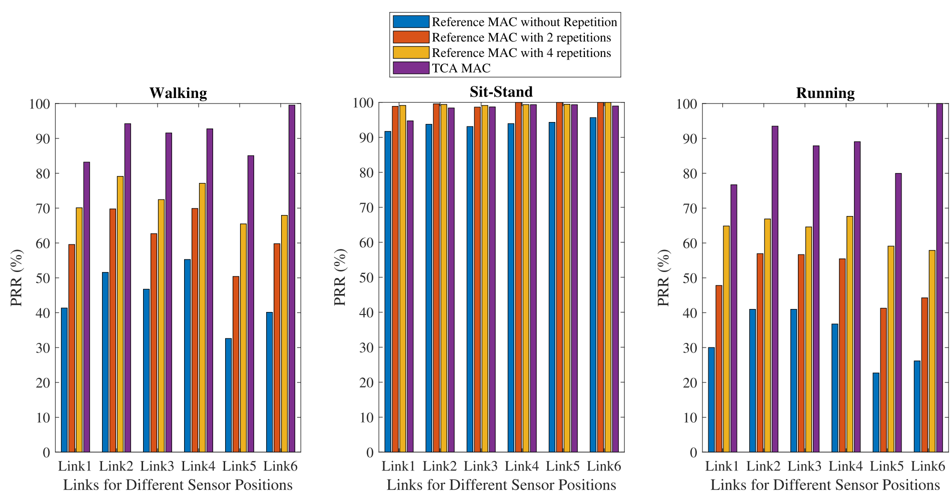

FIGURE 7. Packet reception rate (PRR) (%) under: Walking, sit-stand, and running mobility profiles.

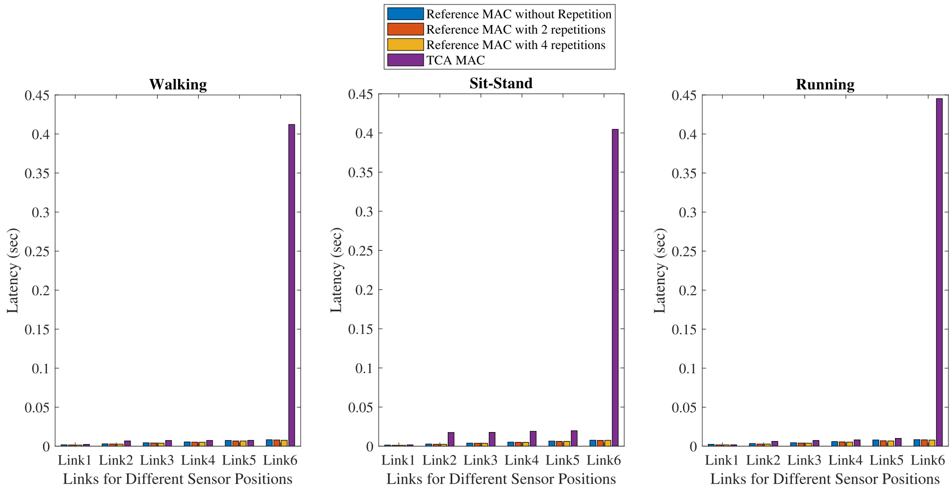

FIGURE 8. Latency (sec) under: Walking, sit-stand, and running mobility profiles.

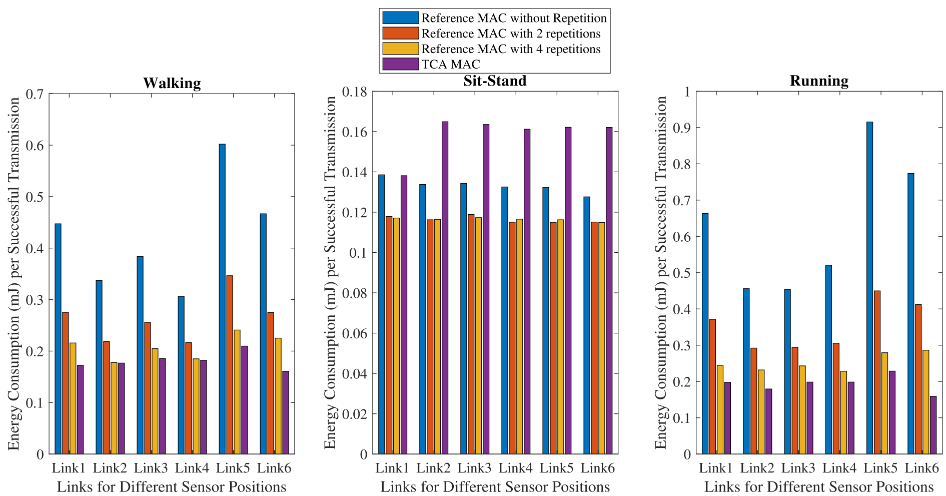

FIGURE 9. Energy consumption per successful transmission (mJ) under: Walking, sit-stand, and running mobility profiles.

degrades the PRR performance. However, SmartBAN reference MAC scheduling gives good performance under sit-stand posture for all the links due to reduced mobility. On average under walking conditions, SmartBAN complaint TCA gives a respective PRR performance gain of about 40%, 25% and 12% over the reference SmartBAN without repetition, SmartBAN MAC with 2-repetitions and 4-repetitions. The similar trends in performance enhancement can be seen under running mobility scenario.

Fig. 8 summarizes the latency results for each link under the given mobility conditions at −10.9dBm transmission power. TCA, being based on the concept of m-periodicity and sensor node packet generation rates, compromises the latency metric while still not exceeding the maximum allowable latency limits of 125ms, mentioned under SmartBAN standard [5]. This is evident from the results provided in Fig. 8. The latency outcomes for links 1-5 do not increase more than the latency limits of few tens of milliseconds under all mobility conditions. But for link6, which corresponds to the respiratory rate node with a single packet generated per second, the latency is increased but is still under the given latency requirements of the respiratory rate application. However, TCA MAC does not meet the 125ms latency constraints of SmartBAN standard for respiratory rate application. Additionally, link1 has the lowest latency for all the scheduled techniques in all mobility profiles since it is associated with the priority node which makes transmissions in consecutive IBIs.

Fig. 9 and Fig. 10 depict the energy consumption profile for various links and the hub respectively, under the given mobility scenarios at −10.9dBm transmission power. Energy consumption during **transmission**, for **sensor** node mainly includes, i) data packet transmission energy and ii) slot reassignment acknowledgement transmission energy in case of TCA MAC. For **hub**, the transmission energy consists of i) D-Beacon ii) data packet acknowledgement and

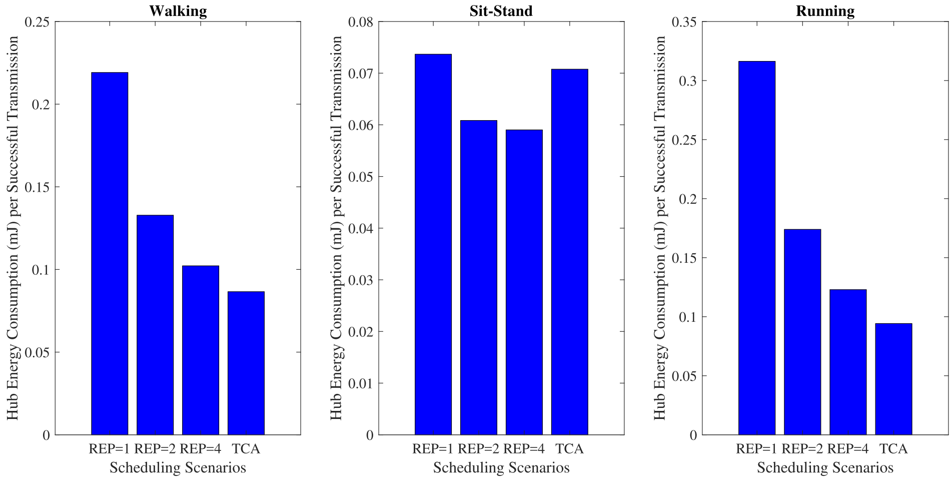

FIGURE 10. Hub energy consumption per successful transmission (mJ) under: Walking, sit-stand, and running mobility profiles.

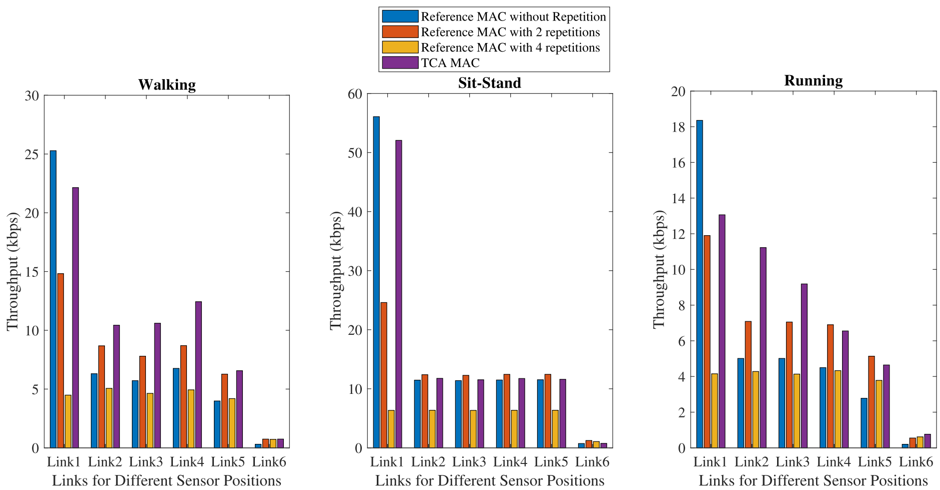

FIGURE 11. Throughput (kbps) under: Walking, sit-stand, and running mobility profiles.

iii) slot reassignment frame transmission energy in case of TCA MAC. During the **reception**, the corresponding energy consumption for **sensor** and **hub** respectively becomes i) D-Beacon ii) data packet acknowledgement iii) slot reassignment frame reception energy in case of TCA MAC and i) data packet reception energy and ii) slot reassignment acknowledgement reception energy in case of TCA MAC. This could increase the overall energy consumption for TCA MAC in SmartBAN but the energy is actually utilized in the successful transmissions of data packets. TCA scheduling in SmartBAN has overall higher energy consumption but due to the higher rate of successful packet reception, the energy consumption per successful transmission is significantly reduced under walking and running scenarios. Under sit-stand mobility, a good PRR performance was observed even with the reference SmartBAN MAC, and therefore this metric increases for TCA due to the unnecessary transmission of slot reassignment frames by the coordinator and their reception by the sensor nodes. TCA MAC reduces the energy consumption by 50% and 60% on average as compared to the reference MAC with no repetitions under walking and running mobility scenarios respectively. For 4-repetitions, the increase in energy efficiency is not very evident because of the resulting higher PRR, as shown in Fig. 7, however, this could decrease the attained throughput at the sensor nodes, as will be investigated later. TCA also decreases the energy consumption at the hub by 60% and 66% in comparison with the reference MAC with no repetitions under walking and running conditions respectively.

Fig. 11 illustrates the attained throughput results for various sensor nodes under the given mobility conditions at −10.9dBm transmission power. TCA slightly decreases the throughput as compared to the reference SmartBAN with no repetitions for link1 (corresponding to the priority node) because of the selective transmissions under good channel conditions only. The obtained throughput for link1 is fairly

TABLE 3. Performance evaluation results with respect to transmission power levels.

Mobility	Tx Power (dBm)	Hub Energy (mJ)	Link	Node Energy (mJ)	PRR (%)	Latency (ms)	Throughput (kbps)
		R1 R2 R4 TCA		R1 R2 R4 TCA	R1 R2 R4 TCA	R1 R2 R4 TCA	R1 R2 R4 TCA
Walking	-2.5	**0.17, 0.14, 0.13, 0.17**	1	**0.61, 0.54, 0.52, 0.57**	**92.4, 97.8, 99.3, 95.8**	1.5, 1.3, 1.3, 1.7	56.5, 24.3, 6.36, 53.9
			2	**0.56, 0.52, 0.51, 0.64**	**96.9, 99.3, 99.9, 98.3**	2.7, 2.5, 2.5, 6.5	11.8, 12.3, 6.39, 21.8
			3	**0.57, 0.53, 0.52, 0.64**	**95.7, 99, 99.3, 98.6**	4.1, 3.8, 3.8, 6.7	11.7, 12.3, 6.35, 21.1
			4	**0.58, 0.53, 0.52, 0.65**	**94.3, 98.9, 99, 98**	5.2, 5, 5, 7.3	11.5, 12.3, 6.3, 21.8
			5	**0.61, 0.53, 0.52, 0.65**	**93.1, 98.7, 99.5, 98**	6.6, 6.3, 6.3, 8.1	11.3, 12.3, 6.3, 20.4
			6	**0.6, 0.53, 0.51, 0.62**	**93.5, 98.9, 99.9, 100**	7.8, 7.5, 7.5, 418.4	0.71, 1.2, 1.06, 0-.6
	-6.9	0.16, 0.1, 0.08, 0.11	1	0.44, 0.28, 0.25, 0.3	67, 88.2, 92.9, 86.2	1.9, 1.5, 1.3, 2.2	40.9, 21.9, 5.9, 34.5
			2	0.35, 0.25, 0.23, 0.32	77.7, 92.4, 96.3, 92.1	3, 2.7, 2.6, 6.6	9.5, 11.5, 6.1, 16.4
			3	0.4, 0.28, 0.24, 0.32	70.9, 88.3, 94.9, 91.9	4.3, 4, 3.9, 7.5	8.6, 10.9, 6.07, 16.8
			4	0.36, 0.27, 0.24, 0.32	75.7, 89.9, 95.2, 92.2	5.4, 5.2, 5.1, 7.3	9.3, 11.1, 6.09, 16.5
			5	0.49, 0.3, 0.25, 0.32	62.8, 85.1, 92.7, 92.5	7.2, 6.5, 6.4, 8.5	7.6, 10.6, 5.9, 12.6
			6	0.45, 0.29, 0.25, 0.28	65.3, 85.7, 92.8, 99.3	7.9, 7.8, 7.7, 0.42	0.5, 1.06, 0.99, 0.75
	-10.9	0.21, 0.13, 0.1, **0.086**	1	0.44, 0.27, 0.21, **0.17**	41.4, 59.3, 70.1, **83.2**	1.9, 1.6, 1.5, 2.4	25.3, 14.7, 4.48, 22.1
			2	0.33, 0.21, 0.17, **0.17**	51.8, 69.9, 79.2, **94.2**	3.1, 2.9, 2.7, 6.8	6.3, 8.7, 5.07, 10.4
			3	0.38, 0.25, 0.2, **0.18**	47.1, 62.8, 72.4, **91.4**	4.5, 4.2, 4, 7.4	5.7, 7.8, 4.63, 10.6
			4	0.3, 0.21, 0.18, **0.18**	54.9, 69.7, 77.1, **92.8**	5.5, 5.3, 5.2, 7.4	6.7, 8.6, 4.93, 12.4
			5	0.59, 0.35, 0.24, **0.21**	32.8, 50.2, 65.5, **84.8**	7.4, 6.8, 6.7, 7.6	4, 6.2, 4.19, 6.5
			6	0.46, 0.28, 0.22, **0.16**	40.4, 58.7, 67.7, **99.3**	8, 8, 7.7, 412.9	0.3, 0.73, 0.72, 0.74
Sit-Stand	-2.5	0.15 0.14 0.13 0.15	1	0.51, 0.51, 0.51, 0.52	100, 100, 100, 100	1.3, 1.3, 1.3, 1.3	61.1, 24.8, 6.4, 61.1
			2	0.51, 0.51, 0.51, 0.62	100, 100, 100, 100	2.5, 2.5, 2.5, 16.9	12.2, 12.4, 6.4, 12.2
			3	0.51, 0.51, 0.51, 0.62	100, 100, 100, 100	3.8, 3.8, 3.8, 18.1	12.2, 12.4, 6.4, 12.2
			4	0.51, 0.51, 0.51, 0.62	100, 100, 100, 100	5, 5, 5, 19.4	12.2, 12.4, 6.4, 12.2
			5	0.51, 0.51, 0.51, 0.62	100, 100, 100, 100	6.3, 6.3, 6.3, 20.6	12.2, 12.4, 6.4, 12.2
			6	0.51, 0.51, 0.51, 0.62	100, 100, 100, 100	7.5, 7.5, 7.5, 0.4	0.76, 1.2, 1.06, 0.76
	-6.9	0.08 0.08 0.076 0.089	1	0.22, 0.22, 0.22, 0.23	99.2, 100, 100, 99.3	1.3, 1.3, 1.3, 1.3	60.7, 24.8, 6.4, 60.7
			2	0.22, 0.22, 0.22, 0.28	99.3, 100, 100, 100	2.5, 2.5, 2.5, 16.8	12.1, 12.4, 6.4, 12
			3	0.22, 0.22, 0.22, 0.28	99.2, 100, 100, 100	3.8, 3.8, 3.8, 18	12.1, 12.4, 6.4, 12
			4	0.22, 0.22, 0.22, 0.28	99.3, 100, 100, 100	5, 5, 5, 19.2	12.1, 12.4, 6.4, 12.2
			5	0.22, 0.22, 0.22, 0.28	99.4, 100, 100, 100	6.3, 6.3, 6.3, 20.5	12.1, 12.4, 6.4, 12.2
			6	0.22, 0.22, 0.22, 0.28	98.9, 100, 100, 98.9	7.5, 7.5 ,7.5, 0.404	0.75, 1.2, 1.06, 0.756
	-10.9	0.07, 0.06, 0.06, 0.07	1	0.13, 0.11, 0.11, 0.13	91.6, 98.8, 99.1, 94.8	1.5, 1.3, 1.3, 1.8	56, 24.6, 6.34, 52.1
			2	0.13, 0.11, 0.11, 0.16	93.7, 99.6, 99.4, 98.4	2.9, 2.5, 2.5, 17.5	11.4, 12.4, 6.36, 11.7
			3	0.13, 0.11, 0.11, 0.16	92.7, 98.6, 99.1, 98.6	4, 3.8, 3.8, 17.7	11.3, 12.3, 6.34, 11.5
			4	0.13, 0.11, 0.11, 0.16	93.9, 99.9, 99.3, 99.3	5.3, 5, 5, 19.1	11.5, 12.4, 6.36, 11.7
			5	0.13, 0.11, 0.11, 0.16	93.8, 100, 99.4 99.3,	6.5, 6.3, 6.3, 19.9	11.4, 12.4, 6.36, 11.6
			6	0.12, 0.11, 0.11, 0.16	96, 100, 100, 98.9	7.7, 7.5, 7.6, 404.6	0.73, 1.2, 1.06, 0.756
Running	-2.5	0.17, 0.14, 0.13, 0.17	1	0.55, 0.51, 0.51, 0.54	97.6, 100, 100, 99.1	1.6, 1.3, 1.3, 1.7	59.7, 24.8, 6.4, 52.9
			2	0.56, 0.51, 0.51, 0.63	97.3, 100, 100, 99.2	2.9, 2.5, 2.5, 6.3	11.9, 12.4, 6.4, 21.9
			3	0.56, 0.52, 0.51, 0.63	96.8, 98.9, 99.9, 99.5	4, 3.8, 3.8, 7.1	11.8, 12.3, 6.4, 21.9
			4	0.6, 0.52, 0.51, 0.62	93.5, 99.1, 100, 99.9	5.3, 5.1, 5, 8.3	11.4, 12.3, 6.4, 22.4
			5	0.66, 0.53, 0.51, 0.64	88.6, 98.4, 100, 98.6	6.6, 6.4, 6.3, 8.2	10.8, 12.2, 6.4, 18.3
			6	0.64, 0.55, 0.53, 0.62	90.1, 97, 98.4, 100	7.8, 7.6, 7.5, 0.44	0.69, 1.2, 1.04, 0.764
	-6.9	0.18, 0.1, 0.086, 0.12	1	0.51, 0.27, 0.23, 0.32	61.5, 89.9, 96.7, 83.4	2.3, 1.6, 1.3, 3	37.6, 22.3, 6.18, 29.7
			2	0.44, 0.29, 0.24, 0.3	67.7, 86.4, 95.6, 95.6	3.2, 2.7, 2.7, 6.5	8.3, 10.7, 6.12, 16.6
			3	0.47, 0.27, 0.23, 0.35	64.3, 89.4, 96.6, 87.9	4.4, 4, 3.9, 7.2	7.8, 11.1, 6.18, 14.6
			4	0.46, 0.28, 0.24, 0.35	65.4, 87.1, 94, 87.9	5.8, 5.2, 5.1, 8.4	8, 10.8, 6.01, 14.6
			5	0.58, 0.31, 0.27, 0.35	55.9, 82.9, 88.8, 87.08	7.4, 6.8, 6.3, 9.7	6.8, 10.3, 5.68, 10.1
			6	0.58, 0.3, 0.26, 0.27	55.8, 84.2, 91.2, 100	8.3, 7.8, 7.6, 0.445	0.42, 1.04, 0.97, 0.764
	-10.9	0.31, 0.17, 0.12, 0.094	1	0.66, 0.37, 0.24, 0.19	30, 47.8, 64.8, 76.7	2.5, 1.8, 1.8, 1.9	18.4, 11.8, 4.14, 13.06
			2	0.46, 0.29, 0.23, 0.18	40.8, 56.7, 66.9, 93.6	3.5, 2.9, 2.8, 6.3	4.9, 7.06, 4.28, 11.2
			3	0.45, 0.29, 0.24, 0.19	41.1, 56.8, 64.6, 87.6	4.5, 4.1, 4, 7.4	5, 7.07, 4.13, 9.1
			4	0.52, 0.3, 0.22, 0.19	36.5, 55.4, 67.7, 88.7	6, 5.6, 5.4, 8.1	4.4, 6.9, 4.3, 6.5
			5	0.91, 0.45, 0.28, 0.22	22.8, 41.1, 58.9, 79.9	8.2, 7, 6.8, 10.1	2.8, 5.1, 3.77, 4.6
			6	0.78, 0.41, 0.28, 0.16	25.8, 43.7, 57.8, 100	8.4, 8.1, 7.9, 445.4	0.19, 0.54, 0.61, 0.76

decreased because of the repetitions in reference SmartBAN MAC under all the given mobility cases, giving a trade-off between the effective throughput results and the energy consumption per successful transmission. TCA outperforms the reference SmartBAN MAC in terms of throughput under the walking mobility while the performance of TCA and reference SmartBAN MAC is comparable under the sit-stand mobility for the remaining links. TCA gives the best throughput performance of all the scheduling strategies for link2, 3 and 6 whereas the reference SmartBAN MAC with 2-repetitions imparts the best throughput results for link4 and 5 under the running mobility. Overall, TCA seems to meet the individual throughput requirements of all the sensor nodes, as given in Table 2, while cutting down the energy consumption and enhancing the PRR.

In Table 3, the performance comparison of all KPIs for the reference SmartBAN MAC and TCA MAC is given with respect to varying transmission power levels. TCA is meant to provide good error performance even at extremely low transmission power, therefore we compare the TCA performance results at -10.9dBm transmission power with the with reference SmartBAN MAC results at higher transmission power levels. Reference SmartBAN MAC gives good PRR performance at higher transmission power which in turn increases the energy consumption per successful transmission for both the hub and nodes under all the mobility scenarios.

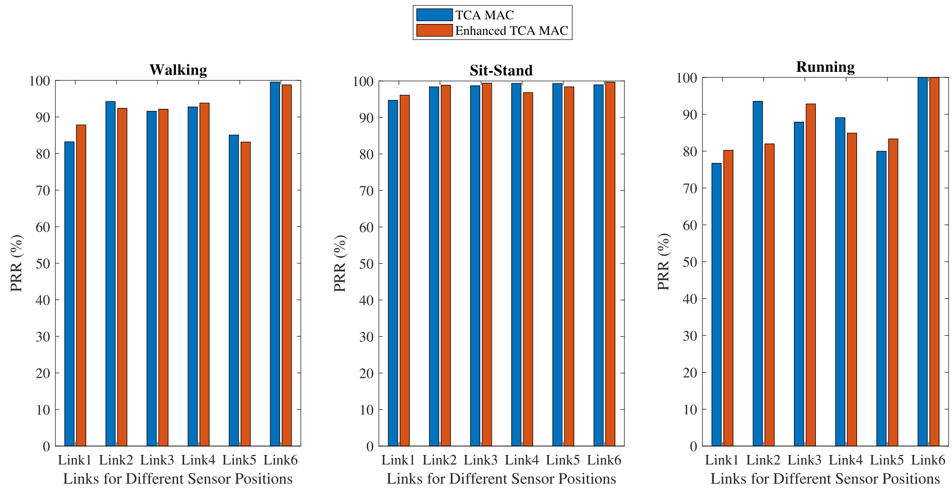

FIGURE 12. Packet reception rate (PRR) (%) under: Walking, sit-stand, and running mobility profiles (TCA and enhanced TCA).

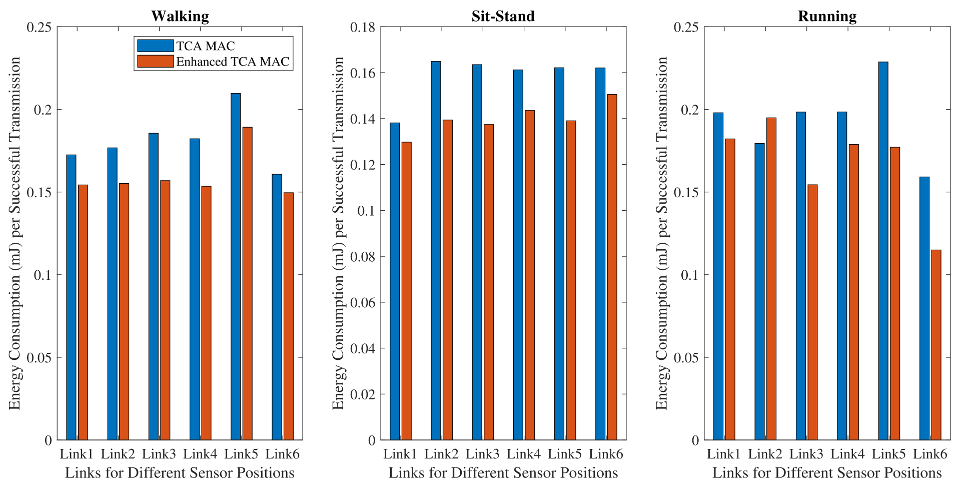

FIGURE 13. Energy consumption per successful transmission (mJ) under: Walking, sit-stand, and running mobility profiles (TCA and enhanced TCA).

For example, TCA MAC gives an average PRR of above 90% under the walking scenario at −10.9dBm as compared to the reference SmartBAN MAC which delivers an average PRR of around 93% at −2.5dBm transmission power, resulting in increased energy consumption with the reference MAC scheduling with and without repetition. In short, TCA provides the best trade-off between the PRR and energy consumption over the reference MAC, specially under walking and running mobility cases, while meeting the throughput and latency constraints of the individual sensor applications.

2) SIMULATION RESULTS FOR ENHANCED TCA

In order to make TCA more energy efficient for both hub and sensor nodes, we propose some enhancements in the existing TCA algorithm, as mentioned in sub-section IIIC. Fig. 12 provides a comparison of the basic and enhanced TCA in terms of PRR, under the given mobility scenario for all hub-node links. It can be observed that enhanced TCA gives a PRR performance comparable to the basic TCA for most of the links related to the different sensor positions under consideration. But from the energy consumption profile, illustrated in Fig. 13, an average decrease of 11.7% in energy consumption per successful transmission can be observed under the walking scenario. For sit-stand and running mobilities, enhanced TCA cuts down the energy consumption by 13% on average. This reduction in energy consumption is due to the selective execution of TCA via slot reassignment procedure only when the hub-node link SNR goes below the given threshold or sensors' packet availability status changes. The energy consumption variations for individual links are more prominent under the running and walking scenarios rather than sit-stand because of the expected rapid changes in the individual links channel conditions, which in turn alters the SNR as well. A similar trend can also be seen in the hub energy consumption profile, as depicted in Fig. 14. Under the walking and running scenario, enhanced TCA

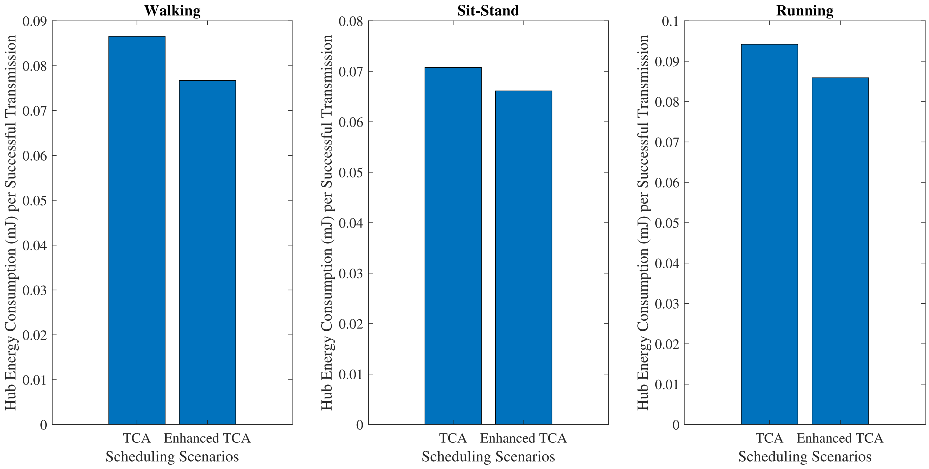

FIGURE 14. Hub energy consumption per successful transmission (mJ) under: Walking, sit-stand, and running mobility profiles (TCA and enhanced TCA).

again decreases the energy consumption per successful transmission by 11% while under sit-stand position, both the basic and enhanced TCA give almost identical energy consumption performance.

V. CONCLUSION

In this paper, we present the SmartBAN complaint Throughput and Channel Aware (TCA) and its execution through slot reassignment method. The algorithm performance is analyzed in terms of four KPIs, Packet Reception Rate (PRR), latency, energy consumption per successful transmission and throughput and compared with the reference SmartBAN MAC with and without repetitions. On the whole, SmartBAN complaint TCA improves the PRR and energy consumption over the reference SmartBAN MAC while satisfying the latency and throughput constraints of the application considered. Additionally, enhancements in the baseline TCA are performed which result in the reduction of energy consumption by the sensors and hub.

ACKNOWLEDGMENT

This material reflects only the authors view and the EC Research Executive Agency is not responsible for any use that may be made of the information it contains.

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