SmartBAN Performance Evaluation for Diverse Applications

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Abstract. Wireless Body Area Networks (WBANs) envision the realization of several applications which involve the physiological monitoring and/or feedback generations according to the monitored vital signs. These applications range from telehealth or telemedicine to sports and entertainment. SmartBAN provides the physical (PHY) and medium access control (MAC) layer specifications for a simplified and efficient execution of these applications. This paper provides an overview of the existing WBAN use-cases and categorizes them according to their data rate requirements. The SmartBAN performance is thoroughly investigated for the implementation of these diverse applications. For performance evaluation, packet reception rate (PRR), aggregated throughput and latency are taken as the primary quality of service (QoS) criteria. We assume two different channel models, namely static CM3B (S-CM3B) and realistic CM3B (R-CM3B), and different options for the slot durations to further comprehend the results. The simulation results indicate that smaller slot duration performs better in terms of PRR and latency while longer slot durations are more effective to support high data rate application throughput requirements.

Keywords: Wireless body area network (WBAN) · SmartBAN · Data rate · Packet reception rate (PRR) · Throughput · Latency

1 Introduction

Telemedicine and telehealth monitoring systems require the collection of vital information, and in some cases transmission of appropriate feedback, from/to remote patients or subjects through a central hub. Wireless body area network (WBAN) is a set of sensor nodes placed on/inside the subject body for collecting

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physiological information, actuators for receiving the feedback information and a central hub for managing WBAN functioning and communicating with the gateway [1]. Initially, some generic mesh-topology based low power and reduced data rate standards, like IEEE 802.15.4 [2,3], were considered as potential candidates for WBAN applications. But the first attempt to standardize the WBAN physical (PHY) and medium access control (MAC) layer operations was made by IEEE, resulting in the release of IEEE 802.15.6 WBAN standard [4]. European Telecommunication Standard Institute (ETSI) later introduced another WBAN specific standard, called SmartBAN, with rather simplified and energy efficient network structure [5]. Other important features exclusively provided by SmartBAN include faster channel acquisitions, interoperability with other network nodes, hub-to-hub communication or inter-hub relay and coexistence management by coordinator [5].

WBAN can expedite several medical and non-medical applications such as stress monitoring, cardiac monitoring, sports and entertainment [1]. The application requirements vary according to the types of sensor nodes employed, number of nodes, urgency of data delivery, information sampling rate and bit resolution. Some use-cases require only few kilo bits per second (kbps) of data rate while some use-cases demand a throughput as high as hundreds of kbps. A SmartBAN is designed to handle these high variations in data transmission rates while satisfying the other quality of service (QoS) parameters like packet reception rate (PRR) and latency.

In the view of the above discussion, we aim to make the following contributions in this paper:

- We categorize the WBAN use-cases into three categories according to their respective throughput requirements, as low, medium and high data rate applications.
- We evaluate each of these use-cases in terms of PRR, attainable throughput and latency as key performance indicators.
- For a better analysis of associated results, we take static IEEE CM3B (S-CM3B) [6] as well as realistic IEEE CM3B (R-CM3B) [7] channel models. Moreover, different options for slot durations in SmartBAN are also considered for performance evaluation.

The remaining paper is organized in the following way: Sect. 2 describes the SmartBAN PHY and MAC layer specifications and Sect. 3 explains the inherent system model. In Sect. 4, numerical results are investigated and Sect. 5 concludes the paper along with the future work.

2 SmartBAN PHY and MAC Layer Specifications

This section elaborates the ultra low power PHY layer and simplified scheduled access MAC layer structures in SmartBAN.

2.1 Ultra Low Power PHY Layer

SmartBAN operates on 2.4 GHz unlicensed spectrum with 2 MHz bandwidth for each individual channel. The employed modulation scheme is Gaussian Frequency Shift Keying (GSFK) with a bandwidth-bit period product $BT = 0.5$, and modulation index $h = 0.5$. An optional systematic Bose-Chaudhuri Hocquenghem (BCH) code is also provided for the error correction control of MAC-layer protocol data unit (MPDU). SmartBAN proposes the utilization of one, two and four physical-layer protocol data unit (PPDU) repetitions for improving the PRR performance [8].

2.2 Scheduled Access MAC Layer

SmartBAN mainly supports star topology for communication between sensors and central hub. Separate control and data channels are used to enable faster channel acquisitions and simplify the MAC layer operation. Once a sensor node joins SmartBAN, all the communication between the hub and node takes place on data channel. Each inter-beacon interval (IBI) on data channel starts with the D-Beacon, followed by the scheduled access, control and management (C/M) and inactive durations. Scheduled access period involves the data transmission by sensor nodes and the reception of corresponding acknowledgements from hub. C/M period is used for other WBAN operations such as connection establishment, connection modification and connection termination. Inactive period is provided to enable the sleep mode and power saving in SmartBAN [9].

Each scheduled access or C/M slot consists of PPDU transmissions and PPDU acknowledgements separated by inter-frame spacing (IFS). The actual data or control information payload is present in MAC frame body, that is appended with MAC header and frame parity to generate an MPDU. For uncoded transmission, an MPDU becomes physical-layer service data unit (PSDU). PSDU, along with physical-layer convergence protocol (PLCP) header and preamble, constitutes a complete PPDU. In scheduled access mode with two and four repetitions, the transmitted PPDU is repeated twice and four times, respectively, within the assigned time slot duration for each node, resulting in a decrease of the maximum allowed payload size for each slot transmission. Figures 1 and 2 respectively illustrate the IBI formats for no repetition and 2-repetition transmission scenarios [9].

The slot duration T_{slot} for each slot in the IBI on data channel is determined by the parameter L_{slot} as $T_{slot} = L_{slot} \times T_{min}$, where $L_{slot} = \{1, 2, 4, 8, 16, 32\}$ and T_{min} is the minimum slot duration. The slot duration is broadcast in control channel beacon and all the connected sensors transmit their data at this pre-defined slot length in each IBI, after connection establishment with their corresponding central hub. A longer slot length can accommodate more payload, with lesser PHY-MAC layer overheads and acknowledgement transmissions, and facilitates higher throughput whereas a shorter slot duration is sufficient to support low data rate applications. Further details about the SmartBAN PHY and MAC layer specifications are given in [8] and [9].

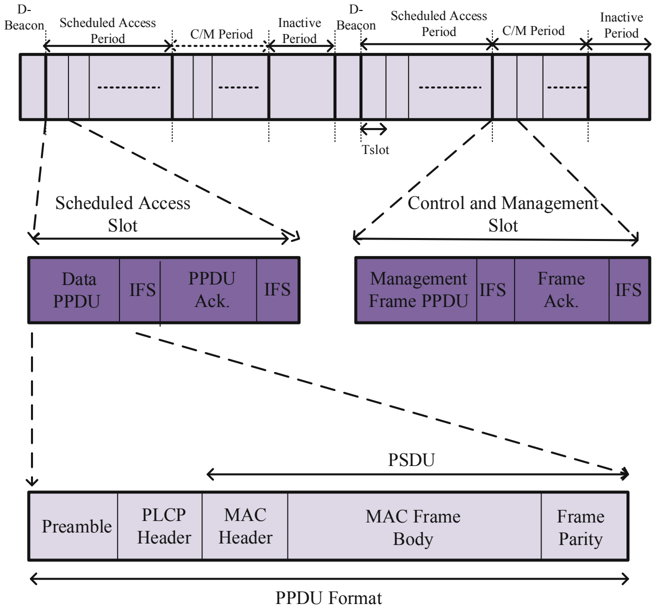

Fig. 1. IBI format with no PPDU repetitions in scheduled access and C/M durations.

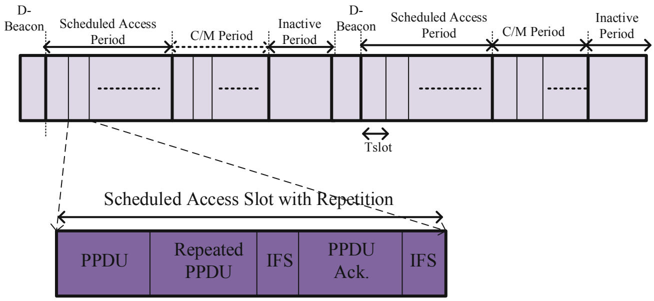

Fig. 2. IBI format with two PPDU repetitions in scheduled access duration.

3 System Model

This section explains the related physical channel and application-specific details of the system model, utilized for carrying out the simulations. Additionally, the simulation setup details are also provided.

3.1 Channel, Mobility and Radio Link Modeling

We take two different channel models for computing the pathloss values which include static IEEE CM3B (S-CM3B) channel with additive white Gaussian noise (AWGN) [6] and realistic IEEE CM3B (R-CM3B) channel with AWGN

[7]. The distances related to each on-body link between the sensor node and hub remain the same in static CM3B model and pathloss is calculated for those constant distances. In the realistic channel model with AWGN, dynamic distances and link types are generated for different on-body links using a biomechanical mobility trace file. Dynamic distances and link types, as defined by a specific mobility scenario like walking, running or sit-stand, are taken as inputs for pathloss calculations. The space-time varying link types identify a particular on-body link as either line of sight (LOS) or non-line of sight (NLOS). An additional NLOS factor of 13% is added to the resultant pathloss value with time-varying distances, for NLOS link status, otherwise the pathloss remains unchanged [7].

After computing the static as well as realistic pathloss values, radio link modeling is performed which includes signal-to-noise ratio (SNR), bit error ratio (BER) and packet error ratio (PER) computations. The theoretical expression for the GFSK BER calculation at SmartBAN PHY layer is given in [10] for a single PPDU transmission scenario. Whereas, for finding BER with two and four PPDU repetitions, SNR calculations are performed according to the diversity technique used for integrating the repetition gain. We assume the maximal ratio combining (MRC) diversity scheme with statistically independent channels for repetition scenarios, therefore, the resulting SNR is the summation of instantaneous link SNRs during each round of the identical PPDU transmission [11]. Subsequently, BER for the repeated PPDU transmissions is computed using the similar BER expression, as mentioned in [7]. Further details about the inherent radio link modeling and the packet reception rate (PRR) analysis are provided in [7].

3.2 WBAN Application-Specific Requirements

A number of medical and consumer electronics use-cases can be identified as potential scenarios for SmartBAN PHY and MAC layer implementation. Each use-case has its own data rate and latency requirements that are peculiar to the number of nodes, sampling rate and quantization, urgency of the data delivery and types of the nodes present in the given use-case. Generally SmartBAN supports a nominal data rate of 100 kbps and a maximum transmission rate of up to 1 Mbps at the PHY layer. The maximum node capacity is 16 nodes per WBAN but typically up to 8 nodes are present in a SmartBAN. For real time high priority traffic, 10 ms latency can be facilitated while for regular traffic 125 ms latency is required [5].

We take three different use-cases classified according to their throughput requirements as low, medium and high data rate applications. A safety and fall monitoring medical use-case is assumed as a low rate application in which patch-type sensors are attached on an elderly adult body. An alert signal is transmitted to the data server when the elder feels physically sick or falls during the regular everyday activities. A rescue and emergency management use-case is considered as medium data rate WBAN application in which sensor data is used to monitor the physical conditions, surrounding environment and location of the rescue workers. A precise athlete monitoring use-case is taken as a high rate application to measure the electrical activity of the muscles and for checking the pitching form in an athlete. All the relevant information about these use-cases is summarized in Table 1.

Table 1. Low, medium and high data rate example use-cases [5,12,13].

Safety and fall monitoring (low-data rate)				
Sensor type	Sampling rate/ Quantization	Data rate	Number of sensors	Real time/ Non-real time
Pulse Wave/ ECG	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	1	Real time
Accelerometer/ Gyroscopic sensor	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	3	Real time
Rescue and emergency management (medium-data rate)				
Pulse Wave	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	1	Real time
Accelerometer/ Gyroscopic sensor	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	2	Real time
Voice Command	-	50 kbps–100 kbps	1	Real time
Ambient sensor	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	1	Real time
GPS node	-	96 bps	1	Real time
Precise athlete monitoring (high-data rate)				
EMG	6–12 bit, 10 kHz–50 kHz	60 kbps–600 kbps	1	Real time
Accelerometer/ Gyroscopic sensor	10–16 bit, 64 Hz–1 kHz	640 bps–16 kbps	4	Real time

According to Table 1, all example applications require a maximum 10 ms latency whereas the aggregated throughput requirements range from 2.56 kbps–64 kbps, 52.656 kbps–164.096 kbps and 62.56 kbps–664 kbps for low, medium and high data rate applications respectively. The PRR should be above 90% for all the given use-cases.

3.3 Simulation Setup

Table 2 mentions all the SmartBAN PHY and MAC layer parameters assumed during the simulation. We allocate a single scheduled access slot per sensor node while there are two slots in both the C/M period and inactive durations for all the given use-cases. Therefore, safety and fall monitoring application has four scheduled access slots in its IBI, rescue and emergency management application employs six scheduled access slots and precise athlete monitoring application requires five scheduled access slots. The trace file that provides space-time varying distances and link types for the R-CM3B channel model assessment of the safety and fall monitoring use-case is about 59 s long and contains walking, sitting and hand motions mobility patterns. For the rescue and emergency management and precise athlete monitoring use-cases, the mobility trace file is 63 s long and includes walking, sit-stand and running mobility scenarios. The pathloss values for the S-CM3B channel models are repeated for the similar durations to ensure the performance evaluation at a similar time span. The simulations with the given trace files are repeated 100 times to give performance outcomes with more certainty. All the simulations are carried out in the MATLAB run-time environment.

Table 2. Simulation setup parameters [8,9].

RF parameters	
Transmitted Power (dBm)	−10, −7.5, −5, −2.5, 0
Receiver Sensitivity (dBm)	−92.5
Bandwidth per channel (MHz)	2
Information Rate (kbps)	1000
Modulation	GFSK ($BT = 0.5$, $h = 0.5$)
PHY/MAC parameters	
Minimum slot length (T_{min})	625 µs
Slot duration (T_{slot})	0.625 ms, 1.25 ms, 2.5 ms
Interframe spacing (IFS)	150 µs
Symbol Rate (R_{Sym})	10^6 symbols/sec
MAC header (N_{MAC})	7 octets
Frame Parity (N_{par})	2 octets
PLCP header(N_{PLCP})	5 octets
PLCP Preamble ($N_{preamble}$)	2 octets
PPDU repetition	1, 2 and 4

4 Performance Evaluation

This section analyzes the simulation results to comprehend the QoS obtained using SmartBAN system specifications, for various use-cases.

4.1 Packet Reception Rate (PRR)

The average PRR results for low, medium and high data rate applications are illustrated in Figs. 3, 4 and 5. For low data rate use-case, the smallest slot duration of 0.625 ms, represented by $L_{slot} = 1$ in Fig. 3, can achieve a PRR above 90% under all transmission power levels, single PPDU transmission and both the channel models. PPDU repetitions with smallest slot duration are not possible because the amount of related PHY-MAC overheads to constitute a complete PPDU cannot be transmitted more than once. For 1.25 ms and 2.5 ms slot durations, respectively indicated by $L_{slot} = 2$ and $L_{slot} = 4$ in Fig. 3, the transmission power should be -7.5 dBm or above to obtain the required PRR for single transmission while with PPDU repetitions, all transmission power levels result in the target PRR. In Figs. 4 and 5 for medium and high data rate applications respectively, the PRR values are not significantly affected by the PPDU repetition scheme or transmission power levels for S-CM3B channel. However the transmission power levels above −2.5 dBm are generally required to achieve the target PRR for all slot durations and repetition schemes. Furthermore, larger slot durations, despite carrying more payload with less PHY-MAC overheads, can have decreased PRR because of the increase in overall packet size [10]. The reason for lower PRR values, with realistic CM3B (R-CM3B) channel model in Figs. 3, 4 and 5, is that the R-CM3B model integrates the NLOS or human body shadowing losses as well in radio link modeling, while computing the pathloss, SNR, BER and PER values. The channel losses due to human body shadowing or NLOS conditions are not considered in static CM3B (S-CM3B) channel model and pathloss calculations are performed only for the fixed hub-node link distances. Consequently, the impact of human mobility on PRR performance is not evident with the S-CM3B channel model.

4.2 Throughput

The effective throughput under the given static and realistic CM3B channel conditions can be computed as $Th_{pr} = \frac{N_{Rx}}{T_{trace}}$, where N_{Rx} is the total number of received bits for each node in the given time span and the T_{trace} is complete duration of the pathloss file, as mentioned in Subsect. 3.3. We assume that the maximum allowed payload size, as determined by the slot duration (L_{slot}) is transmitted for each use-case or application. The aggregated throughput results of all the sensor nodes for all the considered use-cases are shown in Figs. 6, 7 and 8. We evaluate the throughput results for −2.5 dBm transmitter power since it ensures the PRR above 90% in almost all of the scenarios, as discussed in Subsect. 4.1. Considering the safety and fall monitoring application, the smallest slot duration 0.625 ms would be enough to satisfy the throughput QoS requirements, as given in Subsect. 3.2. However for medium data rate application, which requires 52.656 kbps–164.096 kbps data rate, 1.25 ms and 2.5 ms slot durations are more suitable with single PPDU transmission and two PPDU repetitions. Finally, for high data rate application throughput requirements, 2.5 ms slot duration with single PPDU transmission and two PPDU repetitions serves as the best

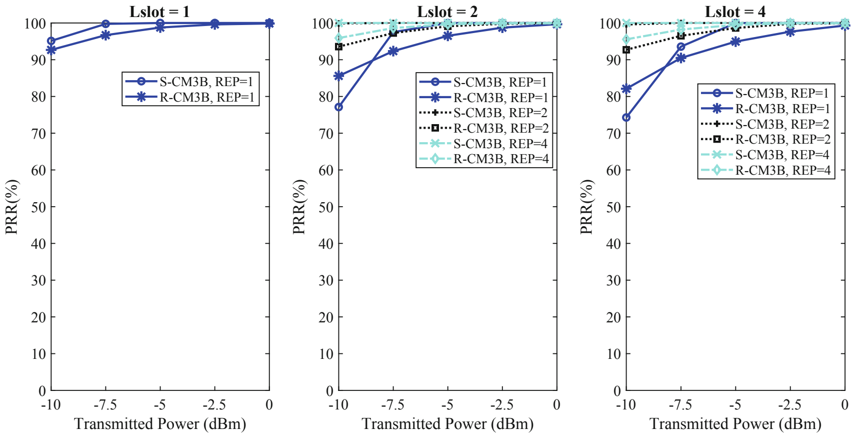

Fig. 3. Packet reception rate (PRR) (%) w.r.t transmission power (dBm) for safety and fall monitoring application (low-data rate), at (a) $L_{slot} = 1, 2, 4$ or $T_{slot} = 0.625$ ms, 1.25 ms, 2.5 ms (b) $REP = 1, 2, 4$ (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B).

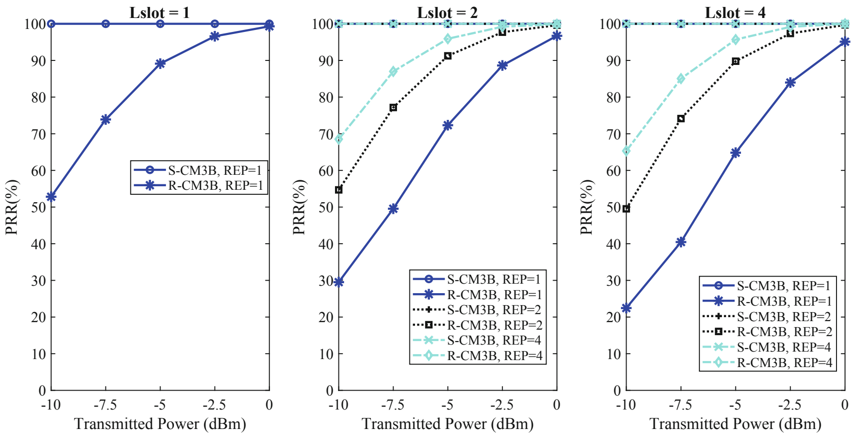

Fig. 4. Packet reception rate (PRR) (%) w.r.t transmission power (dBm) for rescue and emergency management application (medium-data rate), at (a) $L_{slot} = 1, 2, 4$ or $T_{slot} = 0.625$ ms, 1.25 ms, 2.5 ms (b) $REP = 1, 2, 4$ (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B).

option since it enables the transmission of more payload at once. The increase in throughput with the increase in slot duration (L_{slot}) can be explained by the phenomenon that larger L_{slot} values allow the transmission of more payload with the same PHY-MAC overheads, as compared to the smaller L_{slot} values, in a single transmission.

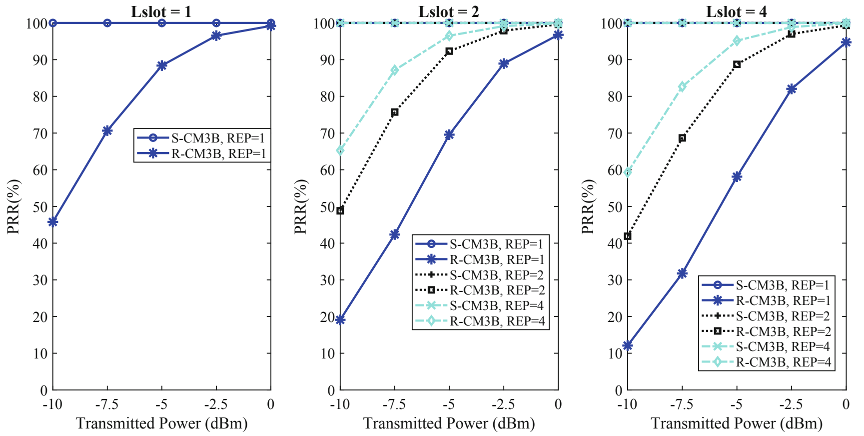

Fig. 5. Packet reception rate (PRR) (%) w.r.t transmission power (dBm) for precise athlete monitoring application (high-data rate), at (a) L_{slot} = 1, 2, 4 or T_{slot} = 0.625 ms, 1.25 ms, 2.5 ms (b) REP = 1, 2, 4 (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B).

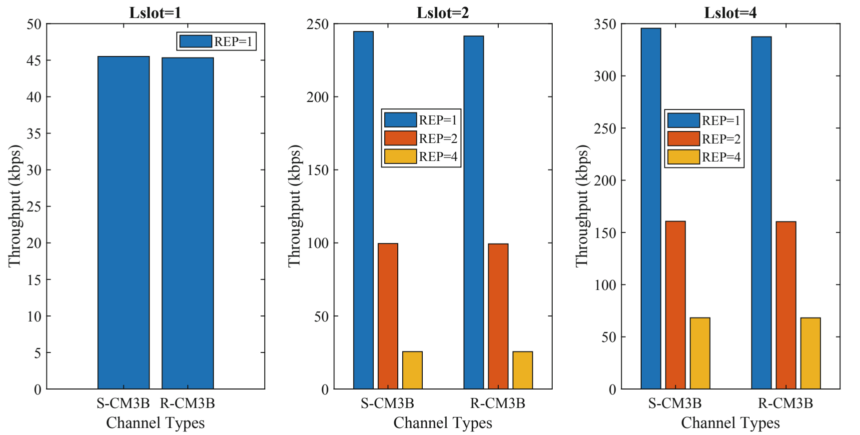

Fig. 6. Throughput (kbps) for safety and fall monitoring application (low-data rate), at (a) L_{slot} = 1, 2, 4 or T_{slot} = 0.625 ms, 1.25 ms, 2.5 ms (b) REP = 1, 2, 4 (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B) (d) −2.5 dBm transmission power.

4.3 Latency

The packet latency is calculated as the time difference between the data packet generation and its successful reception. Table 3 enlists the latency values for all the given use-cases with different slot durations. It should be noted that the repetition scheme or the channel types do not affect the obtained latency values since the latency is computed only for the successfully received packets. The latency values increase with the increase in slot durations because larger slot

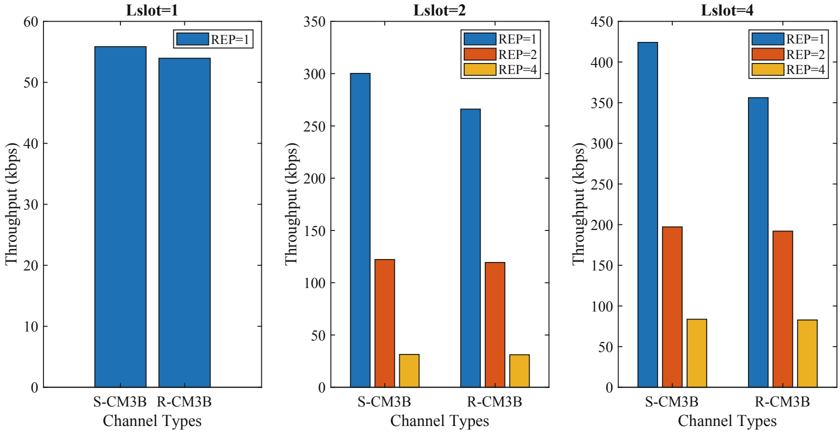

Fig. 7. Throughput (kbps) for rescue and emergency management application (medium-data rate), at (a) $L_{slot} = 1, 2, 4$ or $T_{slot} = 0.625$ ms, 1.25 ms, 2.5 ms (b) $REP = 1, 2, 4$ (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B) (d) -2.5 dBm transmission power.

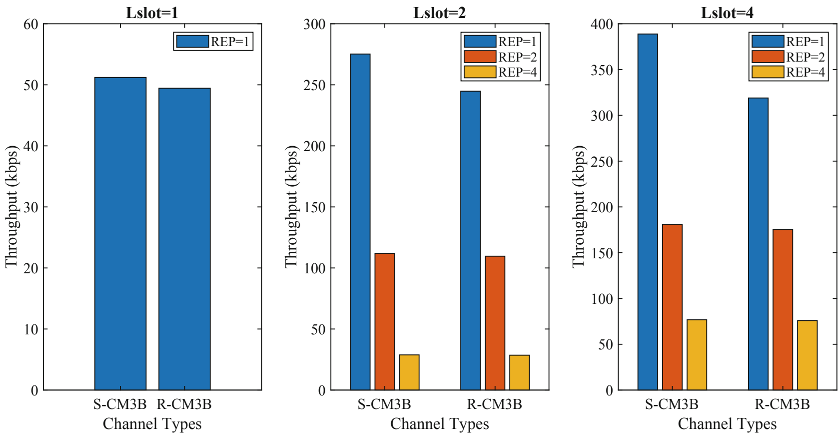

Fig. 8. Throughput (kbps) for precise athlete monitoring application (high-data rate), at (a) $L_{slot} = 1, 2, 4$ or $T_{slot} = 0.625$ ms, 1.25 ms, 2.5 ms (b) $REP = 1, 2, 4$ (c) static CM3B (S-CM3B) and realistic CM3B (R-CM3B) (d) -2.5 dBm transmission power.

durations have longer IBIs. Also the latency values are the highest for the rescue and emergency management application since it has the largest number of sensor nodes and the assigned scheduled access slots. For safety and fall monitoring application, the PRR and throughput requirements are met with the 0.625 ms slot duration, so using this slot duration can guarantee the minimum possible latency for this real time application. The minimum latency can be ensured for rescue and emergency management application with 1.25 ms slot size while satisfying the PRR and throughput demands. Finally, for precise athlete monitoring application, a slight compromise in latency is observed since only 2.5 ms slot can support the required throughput.

Table 3. Latency (ms) for low, medium and high data rate use-cases.

Safety and fall monitoring (low-data rate)		
$L_{slot} = \mathbf{1}/T_{slot} = \mathbf{0.625\ ms}$	$L_{slot} = \mathbf{2}/T_{slot} = \mathbf{1.25\ ms}$	$L_{slot} = \mathbf{4}/T_{slot} = \mathbf{2.5\ ms}$
2.5	5	10
Rescue and emergency management (medium-data rate)		
$L_{slot} = \mathbf{1}/T_{slot} = \mathbf{0.625\ ms}$	$L_{slot} = \mathbf{2}/T_{slot} = \mathbf{1.25\ ms}$	$L_{slot} = \mathbf{4}/T_{slot} = \mathbf{2.5\ ms}$
3.8	7.5	15
Precise athlete monitoring (high-data rate)		
$L_{slot} = \mathbf{1}/T_{slot} = \mathbf{0.625\ ms}$	$L_{slot} = \mathbf{2}/T_{slot} = \mathbf{1.25\ ms}$	$L_{slot} = \mathbf{4}/T_{slot} = \mathbf{2.5\ ms}$
3.1	6.3	12.5

5 Conclusion and Future Work

The paper evaluates the SmartBAN PHY and MAC layer performance to support the low, medium and high data rate applications in terms of PRR, aggregated throughput and latency. Smaller slot durations are more suitable for low data rate real-time applications as they provide improved PRR, reduced latency while satisfying the throughput requirements. While for high data rate applications, longer slot durations should be considered since they help achieving better throughput results with a slight trade-off in latency constraints. As a future work, we aim to perform these evaluations with multi-use channel access mode and coded transmissions in SmartBAN.

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