A Flexible Enhanced Throughput and Reduced Overhead (FETRO) MAC Protocol for ETSI SmartBAN

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Abstract—Smart body area networks (SmartBAN) is an emerging wireless body area networks (WBAN) standard proposed by the European Telecommunications Standards Institute (ETSI). This paper first examines the potential of SmartBAN medium access control (MAC) layer with scheduled access to support a myriad of WBAN applications, having diverse data rate requirements. Extra scheduled access slots can be allocated to high date rate sensor nodes for managing their data rate requirements. High data rate sensor nodes can also be re-assigned to use the available time slots of low data rate sensor nodes in Inter-Beacon Interval (IBI) by the central hub. But these two schemes incorporate different physical (PHY) and MAC layer overheads related to frame transmission, frame acknowledgement and slot re-assignment. This redundant overhead transmission results in high overhead energy consumption and reduced effective throughput. Therefore, an innovative and flexible enhanced throughput and reduced overhead (FETRO) MAC protocol for scheduled access is proposed in this article. In the proposed scheme, the sensor node data rate requirements are considered while assigning the scheduled access slot duration by allowing minimal changes in the base-line standard implementation. This infers the provision of scheduled access slots with variable slot durations within an IBI. We also evaluate the existing techniques of extra slot allocation and slot re-assignment in SmartBAN as well as the proposed FETRO MAC protocol with variable slot length. The proposed FETRO MAC scheme results in optimizing both the overall throughput and normalized overhead energy consumption per kilo bits per second (Kbps). Additionally, the impact of various WBAN channel models over these throughput management approaches is also investigated. The proposed FETRO MAC protocol with variable slot duration gives an average reduction of 65.5 and 59.16 percent, respectively, in the hub and nodes normalized overhead energy consumption per Kbps outcomes, as compared to the de-facto SmartBAN MAC scheduling strategies.

Index Terms—Energy consumption, FETRO, MAC, overheads, scheduled access, SmartBAN, throughput

1 Introduction

Wireless body area networks (WBANs) have gained significant popularity among research and innovation communities in both academia and industry because of their potential in realizing many different applications. Smart body area network (SmartBAN) is among several standards which define WBAN operation at the physical (PHY) and medium access control (MAC) layers. It is distinguished for its low complexity, energy efficient network structure, faster channel acquisitions, interoperability and data semantic models, hub-to-hub communication or inter-hub transmission and coexistence management by the central hub [1]. WBAN applications involve diverse fields such as health care, military, rescue and emergency management, sports and entertainment [2]. These applications may include the monitoring of vital signs such as electrocardiogram (ECG) and electromyograph (EMG) signals which require very high throughput as well as body temperature and blood oxygen level signals which are characterized by their low data rates. WBAN MAC should be designed to manage these massive variations in data transmission rates while maintaining a reduced energy consumption especially on overheads transmission as well as better quality of service (QoS).

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Manuscript received 11 Dec. 2019; revised 9 Nov. 2020; accepted 10 Dec. 2020. Date of publication 25 Dec. 2020; date of current version 1 July 2022.
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Digital Object Identifier no. 10.1109/TMC.2020.3047596

1.1 Related Work and Motivation

In order to efficiently accommodate WBAN throughput requirements within the energy constraints, several dynamic MAC strategies have been proposed in the existing literature. One such study was conducted in [3] in which authors presented a traffic aware dynamic MAC (TAD-MAC) protocol. The TAD-MAC algorithm is heuristically modeled to comprehend its convergence patterns, resulting in the network nodes wake-up intervals with minimal energy consumption at the receiving end. Authors in [4] suggest a traffic priority aware MAC (TraPy-MAC) protocol which is based on the classification of WBAN traffic into emergency and non-emergency categories. Emergency data are allocated slots without contention while non-emergency data are again categorized for contention depending upon their priority levels. In [5], dynamic adjustments in the sensor nodes transmission order and transmission duration (number of scheduled access slots) are considered in the baseline time division multiple access (TDMA) protocol. The channel status (using Markov model) and application context are taken as scheduling criteria to yield minimum energy consumption by sensor nodes. A context aware MAC (CA-MAC) is proposed in [6] which defines a new hybrid contention/TDMA superframe structure, consisting of four parts: beacon, contention access slots, TDMA scheduled-based slots and TDMA polling-based slots. The superframe and the beacon durations remain unchanged while the duration allocated to contention or TDMA part can be modified depending upon the application requirements. Also, the polling-based TDMA slots are used to manage time-critical contexts. Complying with the channel conditions and data traffic requirements, authors in [7] propose a context aware and channel-based WBAN resource allocation scheme. The WBAN data are separated into non-medical, constant bit rate medical and emergency medical types and the intervals of consecutive transmission are adaptively changed depending upon the channel conditions. Similar approach is adopted in [8] in which the TDMA based technique is improved to provide reliability and energy efficiency while synchronizing the sensor nodes for packet transmission based on their predicted link status. A priority-based adaptive MAC (PA-MAC) protocol for WBANs is suggested in [9] in which different channels are allocated for beacon frame and data frames. The algorithm incorporates traffic prioritization, simultaneous usage of parallel data transmission channels and the presence of both the contention access and contention free periods to accommodate various data traffic categories with minimum energy resources. In order to exclusively manage the WBAN emergency traffic, a MEB MAC protocol is provided in [10] which dynamically inserts listening windows in the contention free period of beacon-enabled IEEE 802.15.6 superframe.

The SmartBAN standard defines low complexity PHY and MAC layers for managing both the periodic and emergency WBAN traffic. SmartBAN PHY layer specifies separate channels for control signals and data packet transmissions. The data channel is partitioned into Inter-Beacon Intervals (IBIs). All IBIs are divided into distinct time slots that constitute data beacon (D-Beacon) period, scheduled access duration, control and management (CM) duration and inactive duration. D-Beacons mark the boundaries of IBI and are broadcast by hub for communicating specific information about SmartBAN. Scheduled access duration is reserved for data transmission by sensor nodes and CM period is used for control information exchange between hub and sensor nodes. Finally inactive duration is provided for employing duty cycling in SmartBAN for energy preservation [11]. Authors in [12] suggest a time-optimized MAC framework in which the IBI, scheduled access period, CM period and inactive duration are optimized for minimizing both delay and energy consumption. Authors in [13] propose a resource allocation scheme for SmartBAN in which IBI duration and single slot durations are optimized depending upon the delay requirements of periodic uplink transmissions. The proposed optimization also allows sensor nodes to remain in the longest possible sleep mode to minimize the energy consumption while maintaining the delay constraints. In [14], variations in both the channel and data traffic are taken into account to adapt the time slot allocation in reference SmartBAN standard. The algorithm, termed as joint throughput and channel aware (TCA) scheduling, adopts m-periodic scheduling approach. The sensor nodes are assigned slots depending upon the wireless channel conditions as well as data packet availability using slot reassignment procedure at alternate IBIs. Another MAC scheduling scheme for improving channel utilization and better throughput management is provided in [15] which suggests the usage of managed access phase (MAP) and random access phase (RAP) for pre-allocated and un-allocated time slots respectively. In MAP, the emergency data is sent by high priority sensor nodes immediately without the prior channel sensing. If no transmissions are detected for emergency traffic upon channel sensing, slot owner nodes make their transmissions. If none of these node types send data, the remaining sensor nodes in BAN contend for transmission. In RAP with unassigned time slots, this procedure takes place only between high priority sensor nodes and other transmission entities. However this method of channel sensing and contention at subsequent slots may lead to higher energy consumption, leading to the notion that scheduled access methods yield better outcomes in terms of energy efficiency.

SmartBAN defines a parameter L_{Slot} to imply the single slot duration within every IBI. L_{Slot} is broadcast in the control channel beacon (C-Beacon) by hub and it remains essentially the same in each IBI. The connected sensor nodes transmit their data at this pre-defined slot duration, irrespective of their particular data rate requirements. Slot duration is changed only when the coordinator node broadcasts a different L_{Slot} value in its C-Beacon and the connection is re-established with all the sensor nodes [11]. A longer slot length can accommodate more payload, with the same PHY-MAC and acknowledgement overheads, and facilitates higher throughput while shorter slot duration is sufficient to support low data rate sensor nodes. The allocation of fixed longer slot durations in the presence of low data rate sensor nodes leads to the wastage of scheduled access resources. Whereas the throughput requirements of high data rate sensors cannot be met with fixed smaller slot durations. For better throughput management in existing SmartBAN standard with scheduled access, extra slots can be allocated to high data rate sensor nodes. Another option for handling data traffic with scheduled access method is slot re-assignment in which the unused slots of low data rate sensor nodes are reassigned to high data rate sensor nodes within an IBI. Both of these throughput management techniques in scheduled access MAC are the proposed as part of the ETSI SmartBAN MAC layer specifications [11]. While these options with fixed slot durations may accommodate the throughput requirements of a WBAN system, their related PHY-MAC overheads, acknowledgement transmissions and re-assignment procedures lead to high overhead energy consumption in overheads and relatively decreased throughput. In order to encounter these shortcomings, the assignment of slot durations in scheduled access MAC should be flexible enough to adapt according to the throughput requirements of the individual sensor nodes, at minimized overhead energy consumption.

1.2 Summary of Contributions

In the view of the above discussion, we aim to make the following contributions.

- First, we numerically evaluate the conventional SmartBAN MAC performance in the presence of constant bit rate sensor nodes with distinct data rate requirements. The two primary methods of throughput management proposed in ETSI SmartBAN MAC layer specifications [11] for scheduled access, i.e., extra slot allocation and slot reassignment, are considered to satisfy the high data rate requirements of some particular sensor nodes.
- Second, an innovative and "flexible" enhanced throughput and reduced overhead (FETRO) scheduled access MAC protocol with variable slot length is introduced. In the proposed algorithm, slot duration is assigned based on the individual traffic demands of each sensor node. So in every IBI, the slot durations are distinctive to the data rate requirements of the individual sensors. The FETRO MAC with variable slot length can be executed by making few changes in the connection request and the connection assignment information modules of the existing SmartBAN standard, as further discussed in Section 4. A flexible L_{Slot} will help satisfy the throughput demands of high data rate sensor nodes in the presence of nominal data traffic nodes. It will also prevent the under-utilization of SmartBAN resources when low throughput sensor nodes are allocated larger slot durations due to the presence of high data rate sensor nodes. To the best of our knowledge, this is the first dynamic MAC protocol proposed to enhance the performance of ETSI SmartBAN MAC in which individual slot duration is varied within IBI to manage the data rate requirements of each sensor node at the same time reducing the associated overheads with each slot allocation.
- Both of these MAC strategies with fixed and variable slot durations are assessed taking effective throughput and normalized energy consumption per kilo bits per second (Kbps) as the key performance indicators. The proposed FETRO MAC protocol with variable slot duration retains the base structure of SmartBAN MAC and is shown to outperform the conventional methods. Four different WBAN channel models which are widely considered in WBAN performance evaluations, are also integrated in the simulation setup for better understanding of the results associated with both methods. These channel models include the standard IEEE CM3B model [16], CM3B model with Rician fading [16], dynamic IEEE CM3B (deterministic) channel model [17] and deterministic channel model with fading.

The remainder of the paper is organized as follows: SmartBAN PHY-MAC layer specifications and functional details are provided in Section 2. The throughput and energy consumption analysis with SmartBAN specifications is elaborated in Section 3 and the proposed FETRO MAC scheduling algorithm with variable slot length is explained in Section 4. Section 5 comprehensively discusses the simulation setup and simulation results whereas Section 6 concludes the paper. For ease of reference, the symbols and notations used in this paper are summarized in Table 1.

2 SmartBAN MAC Specifications and Functioning

SmartBAN standard defines a relatively low complexity and efficient MAC structure. This section elaborates the key characteristics and functioning of SmartBAN MAC layer.

2.1 Channel Structure and MAC Frame Format

A SmartBAN coordinator uses a separate control channel to transmit C-Beacons for channel acquisition and connection initialization by sensor nodes that intend to join the network. C-Beacon mainly defines the data channel parameters such as slot duration T_{Slot} indicated by L_{Slot} in C-Beacon, number of slots in IBI N_{Slot}, hub address and data channel number. The minimum allowed slot duration in SmartBAN is T_{Min} which equals 0.625ms and T_{Slot} equals $L_{\text{Slot}} \times T_{\text{Min}}$. L_{Slot} increases as an exponent of two, therefore the possible slot durations (T_{Slot} values) in SmartBAN become 0.625 ms, 1.25 ms, 2.5 ms, 5 ms, 10 ms and 20 ms. After the initialization of connection establishment, data channel is used for transmitting both control as well as data frames. Both the control channel and data channel structures along with the general MAC frame format are depicted in Figs. 1a and 1b respectively.

The beginning of IBI at the data channel is marked by D-Beacon, followed by scheduled access period, CM period and inactive period at the end. Each of these access periods is divided into the individual slots of duration T_{Slot}, broadcast in C-Beacon. D-Beacon communicates the number of slots in IBI N_{Slot}, slot numbers at which CM and Inactive periods start and other fields to indicate the MAC functioning within the current IBI. A scheduled access period is mainly used for data transmission by sensor nodes to the hub. Each slot of duration T_{Slot} within the scheduled access period contains a data frame transmission duration, a subsequent inter-frame spacing (IFS), acknowledgement transmission by the receiver node and another IFS. A CM period involves the transmission of control frames for initiating and regulating the SmartBAN MAC functioning. A CM period generally has a similar slot structure as the scheduled access period.

Every data or a CM transmission time contains the actual payload appended with the MAC header and frame parity which jointly create a MAC protocol data unit (MPDU). The entire MPDU is optionally encoded to formulate a Physical-Layer Service Data unit (PSDU) which after the inclusion of PHY header and preamble, constitutes the Physical-Layer Protocol Data Unit (PPDU). The information about the local clock of hub device is broadcast in D-Beacon and then preamble further synchronizes the transmission between the sensor nodes and hub. PHY header provides information about the PPDU repetition and encoding [11], [18]. This PPDU is transmitted during the data or CM frame transmission times in either scheduled access or CM slot respectively.

TABLE 1
Summary of Symbols and Notations

Symbols	Notations	Symbols	Notations
3_{V}	3 volts supply voltage.	BT	Bandwidth-bit period product of GFSK.
h	Modulation index of GFSK.	E_{OHnode}	PHY-MAC overhead energy consumption at sensor node.
E_{OHhub}	PHY-MAC overhead energy consumption at hub.	E_{PLnode}	Data payload transmission energy consumption at sensor node.
E_{PLhub}	Data payload reception energy consumption at hub.	E_{SRaSnode}	Slot Reassignment energy consumption at sensor node.
E_{SRaShub}	Slot Reassignment energy consumption at hub.	$I_{\mathrm{mA}}^{\mathrm{Idle}}$	Current consumption in idle mode (mA).
$I_{\mathrm{mA}}^{\mathrm{Rx}}$	Current consumption at the receiving end (mA).	$I_{\mathrm{mA}}^{\mathrm{Tx}}$	Current consumption at the transmitting end (mA).
K_{Preamble}	Number of bits in preamble.	K_{PHY}	Number bits in of PHY header.
K_{Parity}	Number of bits in frame parity.	K_{MAC}	Number of bits in MAC header.
K_{Overhead}	Number of bits in complete PHY-MAC overhead.	K_{ID}	Number of bits in element ID field of information unit.
K_{L}	Number of bits in length field of information unit.	K_{SRas}	Number of bits in slot reassignment information module.
L_{IM}	Information module size in bits.	L_{Slot}	Parameter to indicate slot duration in C-Beacon.
N_{Min}	Number of minimum length units in IBI.	N_{Slot}	Number of slots in IBI.
N_{IBI}	IBIs transmitted in one second.	N_{SA}	Number of slots in scheduled access duration.
N_{CM}	Number of slots in CM duration.	N_{IA}	Number of slots in inactive duration.
N_{Rx}	Total number of received bits for the given sensor node.	N_{SRas}	Number of slot reassignment information modules.
PL	Data payload size in bits.	PL^{i}	Data payload size in bits with T_{Slot}^{i}.
REP	Number of PPDU repetitions.	R_{Sym}	Symbols per second.
T_{Slot}	Slot duration.	T_{Min}	Minimum possible slot duration.
T_{IBI}	IBI duration.	T_{Beacon}	Slot duration of D-Beacon in IBI.
T_{B}	D-Beacon transmission duration.	T_{SA}	Scheduled access duration in IBI.
T_{CM}	CM duration in IBI.	T_{IA}	Inactive duration in IBI.
T_{Tx}	PPDU transmission duration.	T_{Ack}	PPDU acknowledgement duration.
T_{IFS}	IFS duration.	T_{PL}	Data payload transmission duration.
T_{Trace}	Trace duration of the pathloss file.	T_{Slot}^{i}	Slot duration for the ith slot.
T_{Tx}^{i}	PPDU transmission duration with T_{Slot}^{i}.	TP_{Th}	Theoretical MAC throughput in Kbps.
TP_{Pr}	Effective MAC throughput under the given channel in Kbps.	$TP_{\mathrm{Th}}^{\mathrm{FETRO}}$	FETRO MAC theoretical throughput in Kbps.

Further information about the SmartBAN MAC and PHY layer structure and functioning is correspondingly provided in [11] and [18].

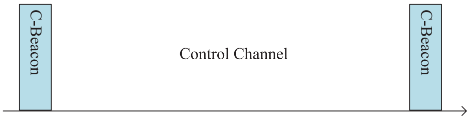
2.2 Connection Request and Connection Assignment Frames

The connection request and connection assignment frames are the CM frames for connection establishment between the hub and sensor nodes. These frame types use information units as the payload to communicate the relevant information specific to their procedures. Each information unit contains the element ID which indicates the category of information unit such as the connection request or connection assignment category. Length field represents the number of information modules of length L_{IM} inside the information unit. Figs. 2a and 2b depict the information modules corresponding to the connection request and connection assignment frames respectively. In Fig. 2a, the allocation length denotes the total number of time slots requested in every IBI and allocation period represents the sequence number of D-Beacon at which the allocation may start. The allocation start and allocation end fields in Fig. 2b respectively depict the numbers at which the slot allocation starts and ends. The allocation period in Fig. 2b again denotes the sequence number of D-Beacon at which the allocation starts [11].

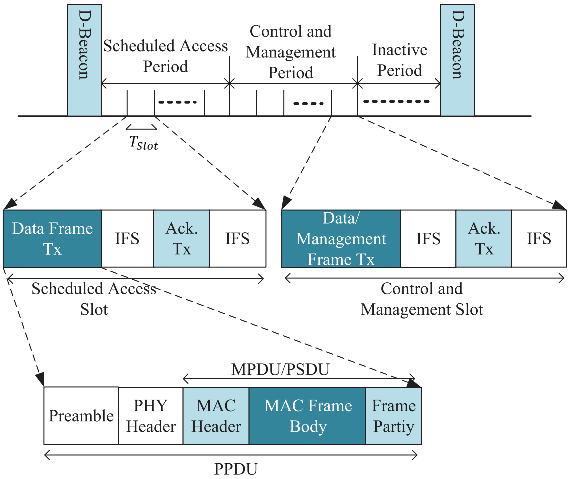
The allocation length field in the connection request information module only indicates the number of requested slots of fixed duration T_{Slot}, such that each allocated scheduled access slot has the slot structure shown in Fig. 1b. Similarly, the allocation start and allocation end fields in connection assignment information module represent the number of allocated slots of pre-defined length T_{Slot}. Therefore, the connection request and connection assignment information modules in the existing SmartBAN standard cannot modify T_{Slot} as per the sensor node traffic demands.

2.3 Connection Establishment and Data Transmission Procedures

For connection initialization, the unconnected node monitors the C-Beacon at the control channel from which the data channel parameters such as slot length parameter (indicated by L_{Slot}) and the number of slots in IBI are acquired. The parameter L_{Slot} specifies the IBI slot duration T_{Slot} beforehand and each data or control frame transmission along with its acknowledgement should take place within this pre-defined slot duration T_{Slot}. The data channel is monitored for D-Beacon which provides the CM period and inactive period start. The



(a) Control channel.



(b) Data channel.

Fig. 1. Channel structure and general MAC frame format. Control channel involves the transmission of C-Beacon. Data channel has D-Beacon, scheduled access, CM and inactive periods. Scheduled access and CM period slot structure consists of PPDU and its acknowledgement set apart by IFS. Each PPDU has PHY-MAC layer overheads along with the data or control information payload.

connection request frame, as mentioned in Section 2.2, is transmitted by the unconnected sensor node during the CM period. The frame is acknowledged by the hub upon a successful reception in the given slot. The hub then sends the connection assignment frame in the upcoming slot or the next IBI during the CM period which is acknowledged by the targeted sensor node in a similar way.

After the connection establishment, data communication between the given node and the hub takes place during scheduled access period [11]. Scheduled access period in IBI is generally contention-free and data PPDUs can be transmitted by the sensor node in the allocated scheduled access slot(s) after the connection establishment. The transmission of data PPDUs is acknowledged by the hub within the same slot. Both the PPDU transmissions and acknowledgements are separated by IFS, as discussed in Section 2.1.

3 MAC Throughput and Energy Consumption Analysis

The MAC throughput associated with each sensor node is defined by its total number of bits transmitted per second. The theoretical MAC throughput TP_{Th} can be found by the multiplication of the number of IBIs sent in one second N_{IBI} and the total data payload size PL sent by the given node in each IBI, as

$$TP_{\text{Th}} = N_{\text{IBI}} \times PL. \tag{1}$$

The first term can be found by the reciprocal of the IBI duration T_{IBI}, therefore (1) becomes

$$TP_{\text{Th}} = \frac{1}{T_{\text{IBI}}} \times PL. \tag{2}$$

The IBI duration for the SmartBAN includes the D-Beacon, scheduled access, CM period and inactive durations and can be written as

$$T_{\text{IBI}} = T_{\text{Beacon}} + T_{\text{SA}} + T_{\text{CM}} + T_{\text{IA}}, \tag{3}$$

where T_{Beacon} is the duration of D-Beacon slot which equals T_{Slot}. T_{SA}, T_{CM} and T_{IA} are scheduled access, CM and inactive durations respectively. Since the entire IBI duration T_{IBI} is divided into the slots of equal size T_{Slot}, so T_{IBI} can also be represented as

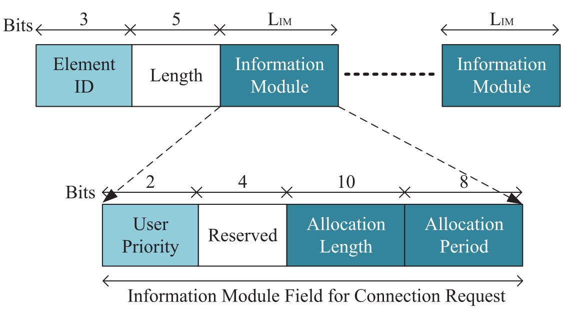
$$\begin{aligned} T_{\text{IBI}} = T_{\text{Beacon}} &+ N_{\text{SA}} \times T_{\text{Slot}} \\ &+ N_{\text{CM}} \times T_{\text{Slot}} + N_{\text{IA}} \times T_{\text{Slot}}, \end{aligned} \tag{4}$$

or

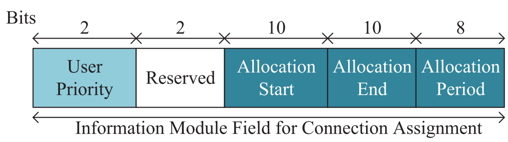
$$T_{\text{IBI}} = N_{\text{Slot}} \times T_{\text{Slot}}, \tag{5}$$

where N_{SA}, N_{CM} and N_{IA} are the number of slots in scheduled access, CM and inactive durations respectively. N_{Slot} is the total number of slots in the entire IBI duration. Substituting T_{IBI} from (4) or (5) in (2), the expression for TP_{Th} becomes

$$TP_{\text{Th}} = \frac{1}{\begin{pmatrix} T_{\text{Beacon}} & +N_{\text{SA}} \times T_{\text{Slot}} + N_{\text{CM}} \\ & \times T_{\text{Slot}} + N_{\text{IA}} \times T_{\text{Slot}} \end{pmatrix}} \times PL, \tag{6}$$



(a) Information module for connection request information unit.



(b) Information module for connection assignment information unit.

Fig. 2. Information modules for (a) connection request and (b) connection assignment. Each of these information modules is appended with “Element ID” and “Length” fields to generate the information unit. Connection request and connection assignment frames send information units as their payloads.

TABLE 2
Payload Size (bytes) for Different L_{Slot} Values and Repetition Modes

$\mathbf{L}_{\mathbf{Slot}}$	Field Value in C-Beacon	$\mathbf{T}_{\mathbf{Slot}}$(ms)	Payload (bytes) No Repetition	Payload (bytes) 2 Repetitions	Payload (bytes) 4 Repetitions
1	000	0.625	8	NA	NA
2	001	1.25	86	35	9
4	010	2.5	243	113	48
8	011	5	555	269	126
16	100	10	1,180	582	283
32	101	20	2,430	1,207	595

or

$$TP_{\mathrm{Th}} = \frac{1}{N_{\mathrm{Slot}} \times T_{\mathrm{Slot}}} \times PL. \tag{7}$$

The SmartBAN is intended to facilitate a maximum throughput of up-to 1000 Kbps [1].

The data payload transmitted by a sensor node depends upon the number of slots allocated to it in each IBI as well as the slot duration T_{Slot}. Since each slot includes PPDU transmission duration T_{Tx}, two IFS of length T_{IFS} and acknowledgement duration T_{Ack}, therefore

$$T_{\mathrm{Tx}} = \frac{T_{\mathrm{Slot}} - T_{\mathrm{Ack}} - 2 \times T_{\mathrm{IFS}}}{REP}, \tag{8}$$

where REP is the number of times an identical PPDU is repeated. Within T_{Tx}, the PHY and MAC overheads are also transmitted along with the data payload. Hence, the effective payload size in bits for a single slot becomes

$$PL = T_{\mathrm{Tx}} \times R_{\mathrm{Sym}} - K_{\mathrm{Overhead}}, \tag{9}$$

where R_{Sym} is the symbol rate. For uncoded SmartBAN transmissions, $K_{\mathrm{Overhead}} = K_{\mathrm{Preamble}} + K_{\mathrm{PHY}} + K_{\mathrm{Parity}} + K_{\mathrm{MAC}}$. K_{Preamble}, K_{PHY}, K_{Parity} and K_{MAC} respectively denote the number of bits in preamble, PHY header, frame parity and MAC header. [11] and [18] can be referred for the computation of PHY-MAC overheads, T_{Ack} and T_{IFS}.

Table 2 summarizes the payload size in bytes for different L_{Slot} values and repetition scenarios, calculated using (8) and (9). It can be observed that the amount of payload transmitted in a single slot decreases with the reduction in slot length. The minimum slot length T_{Min} provides the PPDU transmissions only once. No PPDU repetitions are allowed because with 0.625 ms slot duration, the amount of related PHY-MAC overheads to constitute a complete PPDU cannot be transmitted more than once. According to (6) and (7), TP_{Th} decreases with the increase in IBI duration which in turn increases due to the higher number of slots N_{Slot} and/or longer slot duration T_{Slot}. However (6) and (7) also reflect that the throughput increases if more PL is accommodated per IBI transmission. Since larger slot durations allow the transmission of more payload in a single round therefore, the MAC throughput theoretically improves for increased slot durations, keeping N_{Slot} constant. This is depicted in Fig. 3 which provides the aggregated theoretical MAC throughput TP_{Th}, found using (6), (7), (8) and (9), with respect to the

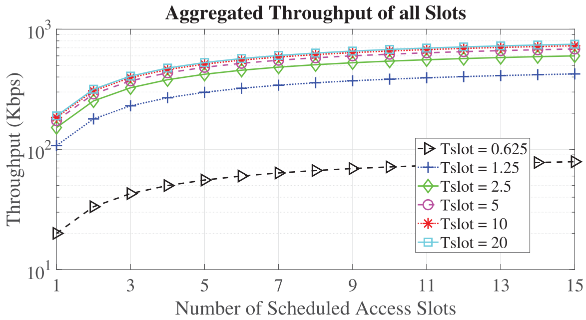


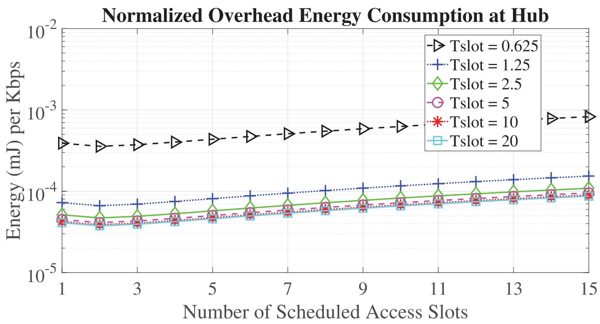
Fig. 3. Aggregated theoretical MAC throughput (Kbps) with respect to the number of scheduled access slots.

number of slots in scheduled access duration. One D-Beacon slot, two slots in CM period and one slot in inactive duration are assumed in the IBI duration for plotting these results. The throughput results provided in Fig. 3 indicate that with the increase in individual slot durations T_{Slot}, the payload PL increases which in turn increases the theoretical throughput TP_{Th}. But increasing the number of slots in IBI (N_{Slot}) beyond a certain limit does not result in higher throughput because of the corresponding increase in IBI duration. Moreover, there is no significant difference in the throughput attained with longer slot durations of 5 ms and 10 ms compared to the 2.5 ms slot. The reason for this is that as the slot size increases to 5 ms or 10 ms, the IBI duration also increases significantly. Therefore, less number of IBIs are transmitted in one second, thus saturating the overall increase in throughput.

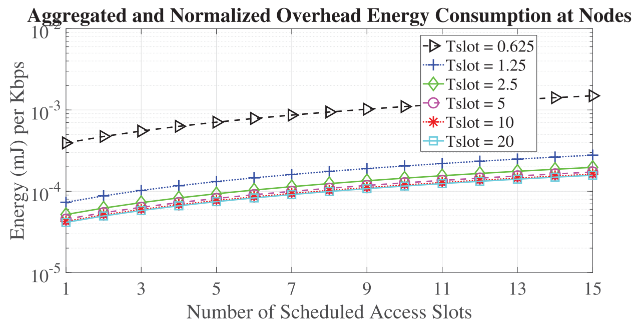
The total energy consumed during the active transmission and reception at both the sensor nodes and hub is the summation of energies utilized in the data payload and overheads communication. While the energy consumed during the data payload transmission leads to the enhanced effective throughput, the frequent transmission of PHY-MAC overheads and data acknowledgements results in high overhead energy consumption. The primary source of overheads in each scheduled access time slot consists of PHY-MAC layer headers and the subsequent acknowledgements sent by the hub. Therefore, the resulting energy consumption at each sensor node due to overheads in scheduled access time slot can be written as

$$\begin{aligned} E_{\mathrm{OHnode}} = {} & 3_{\mathrm{V}} \times T_{\mathrm{B}} \times I^{\mathrm{Rx}}_{\mathrm{mA}} + 3_{V} \times \frac{K_{\mathrm{Overhead}}}{R_{\mathrm{Sym}}} \times I^{\mathrm{Tx}}_{\mathrm{mA}} \\ & + 3_{V} \times T_{\mathrm{Ack}} \times I^{\mathrm{Rx}}_{\mathrm{mA}}, \end{aligned} \tag{10}$$

where $I^{\mathrm{Tx}}_{\mathrm{mA}}$ and $I^{\mathrm{Rx}}_{\mathrm{mA}}$ are the current consumptions in mA at the transmission and reception respectively. T_{B} is the beacon transmission duration. The first term in (10) denotes the energy consumption due to the reception of D-Beacon at the IBI beginning. The second term corresponds to the energy consumption during the PHY-MAC layer overheads transmission by the sensor node. The third term represents the energy consumption due to the reception of packet acknowledgement sent by the hub. 3_{V} represents the hub or sensor node's supply voltage. It is chosen as 3 volts because for the nRF52832 BLE device [19], considered in simulations throughout the article, the supply voltage range is 1.7 volts to 3.6 volts. Moreover, the values of supply voltages are



(a) Normalized PHY-MAC overhead energy consumption (mJ) at the hub.



(b) Aggregated and normalized PHY-MAC overhead energy consumption (mJ) at the sensor nodes.

Fig. 4. PHY-MAC overhead energy consumption (mJ) normalized to the aggregated theoretical MAC throughput (Kbps) with respect to the number of scheduled access slots.

generally taken the same for all the transceivers in a given WBAN [20]. Subsequently, the overhead energy consumption at the hub in scheduled access communication is due to the transmission of D-Beacon and packet acknowledgements and the reception of PHY-MAC layer overheads appended with the payload. It can be mentioned as

$$\begin{aligned} E_{\text{OHhub}} =& 3_{\text{V}} \times T_B \times I_{\text{mA}}^{\text{Tx}} + \sum_{N_{\text{SA}}} \Big\{ 3_{\text{V}} \times \frac{K_{\text{Overhead}}}{R_{\text{Sym}}} \\ & \times I_{\text{mA}}^{\text{Rx}} + 3_{\text{V}} \times T_{\text{Ack}} \times I_{\text{mA}}^{\text{Tx}} \Big\}. \end{aligned} \tag{11}$$

According to (10) and (11), each time a node is assigned an extra slot for data transmission, the related PHY-MAC headers, preamble and acknowledgement overhead energy is also consumed by both the hub as well as the sensor nodes. We calculated overhead energy consumption results for both the hub and sensor nodes and normalized them to the effective theoretical throughput, shown in Fig. 3 (per Kbps). These results are illustrated in Figs. 4a and 4b respectively. Generally the energy consumption is normalized to the total number of bits or bytes transmitted. But we provide the energy consumption results normalized to the throughput for two reasons. 1) The energy utilized in transmission and reception is meant to increase the overall data throughput as well. 2) The normalization of energy consumption to the effective throughput also serves the same purpose with better analysis because the throughput, by definition, refers to the number of bits transmitted in one second. It can be observed that the normalized overhead energy consumption at both the hub and sensor nodes becomes higher as the number of slots in IBI increase and the slot size decreases.

One of the methods for managing the throughput requirements, without allocating the extra slots to high data rate sensor nodes and increasing the IBI size as well as the frequent transmissions of PHY-MAC overheads and acknowledgements, is slot reassignment. Slot reassignment refers to the periodic allocation of the unused slots of low data rate sensor nodes to the high data rate sensor nodes. The slot reassignment frames are also transmitted as information units appended with PHY-MAC overhead, from the hub to the sensor nodes, as discussed in Section 2.2. During slot reassignment procedure, the hub first informs all the sensor nodes of possible slot re-allocations in D-Beacon and then sends the slot re-assignment frame during the CM period of the IBI [11]. So, the additional energy consumption at each sensor node because of the slot reassignment during the run time can be described as

$$E_{\text{SRaSnode}} = 3_{\text{V}} \times \frac{\begin{pmatrix} K_{\text{Overhead}} & +K_{\text{ID}} + K_{\text{L}} \\ & +N_{\text{SRas}} \times K_{\text{SRas}} \end{pmatrix}}{R_{\text{Sym}}} \times I_{\text{mA}}^{\text{Rx}}, \tag{12}$$

where K_{ID}, K_{L}, K_{SRas} and N_{SRas} represent the element ID field size in bits, length field size in bits, slot re-assignment information module size in bits and the number of sensor nodes which receive the slot reassignment frame [11] respectively. In a similar manner, the related extra energy consumption at the hub due to slot reassignment frame transmission becomes

$$\begin{aligned} E_{\text{SRaShub}} = 3_{\text{V}} \times \frac{\begin{pmatrix} K_{\text{Overhead}} & +K_{\text{ID}} + K_{\text{L}} \\ & +N_{\text{SRas}} \times K_{\text{SRas}} \end{pmatrix}}{R_{\text{Sym}}} \\ \times I_{\text{mA}}^{\text{Tx}}. \end{aligned} \tag{13}$$

Consequently the execution of slot reassignment also leads to extra energy consumption at both the sensor nodes and the hub.

The energy consumptions at the nodes and the hub associated with the payload transmission during the scheduled access period are given as

$$E_{\text{PLnode}} = 3_{\text{V}} \times T_{\text{PL}} \times I_{\text{mA}}^{\text{Tx}}, \tag{14}$$

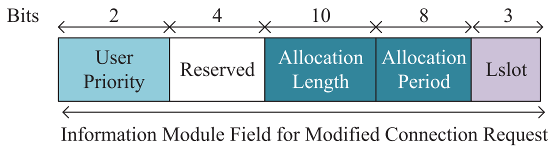
and

$$E_{\text{PLhub}} = \sum_{N_{\text{SA}}} 3_{\text{V}} \times T_{\text{PL}} \times I_{\text{mA}}^{\text{Rx}}, \tag{15}$$

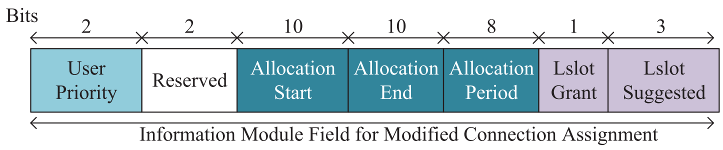
where T_{PL} is the time duration for payload transmission and equals $\frac{\text{PL}}{R_{\text{Sym}}}$.

4 FETRO MAC Scheme With Variable Slot Length

In view of the results given in Figs. 3, 4a and 4b as well as the discussion provided in Section 3, the main issues with



(a) Information module for modified connection request information unit.



(b) Information module for modified connection assignment information unit.

Fig. 5. Suggested information modules for connection request and connection assignment in FETRO MAC. Additional fields associated with the requested and granted L_{Slot} are added.

the base-line scheduled access MAC are: i) Allocating extra slots to high data rate sensor nodes for throughput management not only decreases the throughput (due to long T_{IBI}) but also increases the PHY-MAC overhead and acknowledgement energy consumption, ii) Performing slot reassignment periodically also results in the extra overhead energy consumption due to slot reassignment frame transmission, and iii) Increasing the overall slot duration to accommodate the high data rate sensor nodes also increases the IBI duration which in turn results in the throughput saturation as shown in Fig. 3. These phenomena motivate the design of a MAC algorithm in which high data rate sensor nodes make data transmissions in longer slots while the slot durations assigned to low data rate sensor nodes should be small. It should be noted that the existing connection request or connection assignment frames can only notify about the number of allocated slots, whose duration T_{Slot} is already defined and broadcast in C-Beacon. The existing frame format cannot modify slot duration (T_{Slot}) depending upon the sensor node data rate requirements on the run-time. To overcome these issues with fixed slot duration scheduled access MAC in SmartBAN, this section elaborates on the FETRO MAC protocol. The variable slot length execution in the SmartBAN reduces the PHY-MAC and slot reassignment overheads as well as frequent acknowledgement transmissions for subsequently enhancing the throughput at a reduced overhead energy consumption.

In the proposed FETRO scheme, the slot durations are primarily allocated based on the amount of payload an individual node intends to send. The payload is determined by the sensor node's sampling rate and bit resolution. For example, an inertial measurement unit (IMU) sensor samples data at the rate of 1 KHz and uses a bit resolution of 16 bits per sample, so a payload of 16 kilo bits shall be generated per second [1] which is also the data rate requirement of the given sensor. If the sampling rate and bit resolution of the same sensor type are decreased, the payload and the required sensor data rate shall also be reduced. As discussed in Section 3, the longer slot duration can carry more payload in a single transmission and smaller slot duration is sufficient to carry smaller payloads. Therefore, each sensor node provides its own required L_{Slot} value at the time of connection establishment, depending upon the sensor node's data rate requirement, sampling rate and bit resolution. For high data rate sensor nodes, more number of minimum slot units can be combined to create a longer T_{Slot} which communicates more data payload simultaneously with less PHY-MAC and acknowledgement overheads. While for low data rate sensor nodes, shorter T_{Slot} can be allocated which prevents the wastage of scheduled access resources and does not increase T_{IBI} unnecessarily.

The hub sends its response, indicating the acceptance (grant) of the requested L_{Slot}, retainment of its own L_{Slot} or the suggestion of another L_{Slot} value. The hub decision and response in this context is again determined by the available resources like available energy, duty cycling status, number of connected sensor nodes and the presence of relay node. For example, if the hub is operating on low power mode and has to retain a duty cycling of less than 50 percent, it may reject a slot duration which increases the duty cycle of the hub. It should be noted that the FETRO MAC is effective if there are massive variations in the data rate requirements of the different sensor nodes in a given use case. The example applications would be "Precise Athlete Monitoring" use case in which both the EMG (hundereds of Kbps) and IMU (upto 16 Kbps) measurements are taken for the athlete and "Rescue and Emergency Monitoring" use case in which both low data rate measurements like GPS and pulse monitoring (few bps data rate) as well as high data rate voice communication (upto 100 Kbps) are required [21]. In such scenario, the proposed FETRO MAC will optimize the throughput by allocating the suitable slot duration to each sensor node and shall also reduce the overhead energy consumption, resulting due to extra slot allocation and slot reassignments for throughput management.

4.1 FETRO MAC Connection Request and Connection Assignment Frames

FETRO MAC is implemented by providing the few necessary modifications in the primary SmartBAN MAC frame format which are: i) Rather than broadcasting the number of slots in IBI N_{Slot} within C-Beacon and D-Beacon at the beginning, the number of minimum slot duration (T_{Min}) units, i.e., N_{Min} should be broadcast by the hub, ii) The allocation length field in connection request information module, as given in Fig. 2a, should indicate the number of minimum slot units (of length T_{Min}) requested by the sensor node, and iii) The allocation start and allocation end fields in connection assignment information module, as shown in Fig. 2b, should respectively represent the numbers at which the minimum slot unit allocation starts and ends. These modifications will ensure the necessary synchronization between the hub and the sensor nodes when the individual slot duration of each sensor node is different.

The FETRO MAC with variable slot length is executed by providing a minor ad-on to the connection request and the connection assignment information modules in the existing SmartBAN, as given in Figs. 2a and 2b respectively. The modified information modules for connection request and connection assignment information units are illustrated in

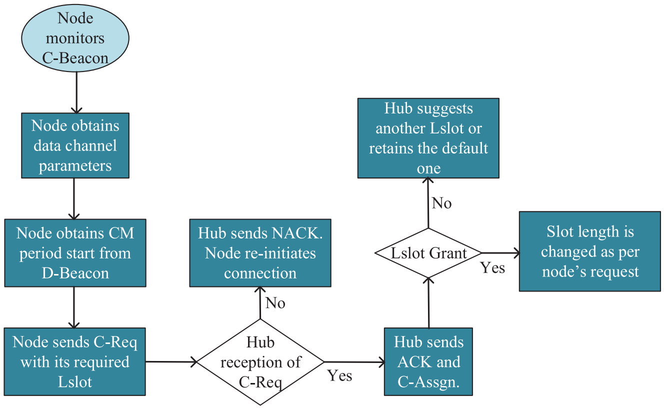


Fig. 6. Connection initialization in FETRO MAC protocol. The modified connection request frame by the node indicates the desired L_{Slot} and the modified connection assignment frame by the hub responds with the grant or refusal of the requested L_{Slot}.

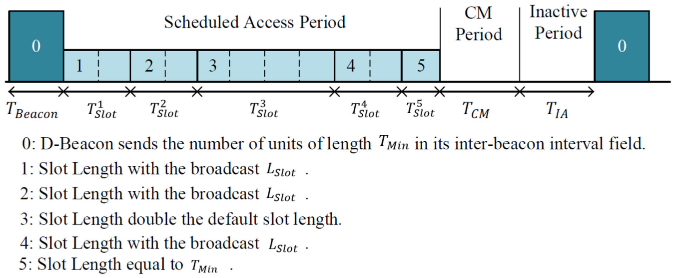


Fig. 7. IBI operation with different slot duration in FETRO MAC. Each slot has frame transmission duration and acknowledgement duration separated by IFS in scheduled access period. The duration of each slot T_{Slot} is an integer multiple of T_{Min} for retaining the synchronization at each node.

Figs. 5a and 5b respectively. A three-bit field L_{Slot} is added in the modified connection request information module. The L_{Slot} field along with the element ID field, length field and PHY-MAC overheads constitutes the connection request frame, as mentioned in Section 2.1. This added field is necessary to indicate the slot duration assigned to a particular sensor node. Using the L_{Slot} parameter in modified connection request and connection assignment information modules, the way of combining the given number of minimum slot duration T_{Min} units is determined.

4.2 Connection Establishment Procedure and IBI Operation in FETRO MAC

Similar to the default connection establishment mechanism in SmartBAN, the sensor node trying to connect monitors the C-Beacon over the control channel and acquires the information about the data channel and other network parameters. Later, the sensor node monitors the data channel and D-Beacon for the CM period start to send its connection request frame. The node requests the L_{Slot} value, required by its payload, in the modified connection request frame which is acknowledged by the hub. Then the hub responds with a connection assignment frame, which includes an "L_{Slot} Grant" field to signify the allocation status of the requested L_{Slot} value, with "1" referring the provision of the requested L_{Slot} value and "0" depicting the refusal of the requested L_{Slot}. In the second scenario, the hub either suggests its own "L_{Slot}" to satisfy the node throughput requirements or retains the L_{Slot} broadcast in the C-Beacon. The "L_{Slot} Suggested" field is only present when the hub suggests its own slot length. The entire procedure for connection establishment in FETRO MAC with variable slot length is embodied in Fig. 6. The received connection assignment frame by the node is acknowledged and the communication starts taking place from the mutually agreed IBI between the sensor node and the hub.

The synchronization among other sensor nodes which are allocated different slot durations and the hub in FETRO MAC can be maintained with the help of the fact that the slot durations T_{Slot} for the increasing L_{Slot} values are the integer multiples of the T_{Min}, as can be seen in Table 2. The proposed idea in FETRO MAC focuses on having a flexible and dynamic T_{Slot} assignment by keeping intact the existing integer multiple characteristic of slot durations represented by L_{Slot} values. The strategy here is that the D-beacon would broadcast the number of minimum length units N_{Min}, that are present within the IBI, in its "inter-beacon interval field" [11], where T_{Min} is the minimum time slot duration possible in SmartBAN MAC. This would allow the sensor nodes to adjust their wake-up intervals irrespective of the L_{Slot} broadcast in the C-Beacon and the remaining slot sizes which are exclusively allocated to the other sensor nodes. An illustration of the IBI in the FETRO MAC scheme is shown in Fig. 7 in which the slots "1", "2" and "4" follow the L_{Slot} broadcast in the C-Beacon whereas the slot number "3" has a duration equal to the twice of default slot length. Slot "5" has the duration equal to T_{Min}. Every slot has the frame transmission duration, acknowledgement duration and two IFS. The D-Beacon broadcasts the N_{Min}, i.e., the number of minimum time slot duration T_{Min} units in its "inter-beacon interval field" for the sensor nodes to adjust their wake-up intervals accordingly.

4.3 FETRO MAC Throughput and Energy Consumption Analysis

With the scheduled access slot duration distinctive to each node, the related throughput at every node in FETRO MAC technique also changes as every node sends a different payload, defined by its slot duration. The IBI with several distinct slot durations becomes

$$T_{\text{IBI}} = T_{\text{Beacon}} + \sum_{i=1}^{N_{\text{SA}}} T^i_{\text{Slot}} + T_{\text{CM}} + T_{\text{IA}}, \tag{16}$$

where T^i_{Slot} is the duration of individual scheduled access slots and $i = 1, 2, \ldots, N_{\text{SA}}$. The FETRO MAC throughput associated with the slot duration T^i_{Slot} will therefore be written as

$$TP^{\text{FETRO}}_{\text{Th}} = \frac{1}{\left(T_{\text{Beacon}} + \sum_{i=1}^{N_{\text{SA}}} T^i_{\text{Slot}} + T_{\text{CM}} + T_{\text{IA}}\right)} \times PL^i, \tag{17}$$

where PL^i is the payload size which is defined by the scheduled access slot duration T^i_{Slot}. The data frame transmission duration and the effective payload size in bits for a single slot also change accordingly as

$$T^i_{\text{Tx}} = \frac{T^i_{\text{Slot}} - T_{\text{Ack}} - 2 \times T_{\text{IFS}}}{REP}, \tag{18}$$

and

$$PL^i = T^i_{\mathrm{Tx}} \times R_{\mathrm{Sym}} - K_{\mathrm{Overhead}}, \tag{19}$$

respectively. The above equations indicate that allocating the slot duration according to the sensor nodes' data rates in FETRO MAC leads to a better repletion of the individual data rate requirements at each sensor node.

The overhead energy consumption for the sensor nodes and hub in FETRO MAC strategy can be easily computed using (10) and (11) respectively. The energy consumption associated with the payload transmission in scheduled access period can be calculated using (14) and (15) respectively for the sensor nodes and hub. Note that the transmission of additional fields to define L_{Slot} in the modified connection request and connection assignment frames leads to a slight increase in energy consumption only at the time of connection establishment (as mentioned in Sections 4.1 and 4.2) in FETRO MAC. However, it can significantly reduce the overhead energy consumption which occurs periodically and frequently because of the "extra slot allocation" and "slot reassignment" techniques in conventional SmartBAN MAC for accommodating the high data rate sensor nodes' throughput requirements.

5 Performance Evaluation

This section evaluates the performance of the existing SmartBAN MAC schemes for throughput management, such as the provision of extra slots and slot re-assignment, as well as the proposed FETRO MAC technique. The channel models and radio link modeling assumed in the simulation setup and the application use-case scenario are described as well.

5.1 Radio Link and Channel Modeling

We assume four different channel models for computing the pathloss values, i.e., static IEEE CM3B model with additive white Gaussian noise (AWGN) [16], dynamic IEEE CM3B (deterministic) channel model with AWGN [22], static IEEE CM3B model with fading [16] and deterministic channel model with fading. The static AWGN and Fading channel models are the standard for WBAN communication developed over the ISM 2.4 GHz frequency band, widely termed as IEEE CM3B [16]. The static channel models (both AWGN and fading) are derived using the measurement campaigns in which nodes are placed on a static human body and the received signal is then modeled mathematically. Therefore, the static channel models do not take into account the human body mobility in pathloss calculations [22].

The integration of the effects of human body mobility in pathloss computation considers all the losses that occur due to human body shadowing under non-line of sight (NLOS) links. The biomechanical mobility traces are used to provide the on-body link distances and link types which are line of sight (LOS) or NLOS. Therefore deterministic channel model is considered for evaluating the realistic pathloss values. In the deterministic channel model with AWGN, dynamic distances and link types are generated for several on-body links between the sensor nodes and hub. As opposed to the static IEEE CM3B model dynamic distances are taken as input distances for pathloss calculation in the deterministic model. The space-time varying link types identify the given link as either LOS or NLOS links. An additional NLOS factor of 13 percent is added to the computed pathloss value with time-varying distances, for NLOS link condition, otherwise the pathloss remains unchanged [22]. The realistic channel model with fading can be derived by taking the CM3B channel model with fading [16] as the baseline, integrating the dynamic distances and adding the space-time varying link-related pathloss values. The deterministic channel model with fading, therefore, includes all the losses that occur due to short-term fading and the human body shadowing under mobility.

After determining the pathloss results, a radio link modeling is performed which includes the computation of signal-to-noise ratio (SNR), bit error rate (BER) and packet error rate (PER) calculations. For the radio link modeling, an identical approach is followed in this article as was proposed in [17] with slight modifications in the BER expressions. The Gaussian Frequency Shift Keying (GFSK) modulation technique with the bandwidth-bit period product BT and modulation index h of 0.5 [18] is used at SmartBAN PHY layer. Therefore, the theoretical expression to compute the BER at the SmartBAN PHY layer is given by [23, Eq. (10)] under AWGN channel. Whereas the upper bound to calculate the BER at the SmartBAN PHY layer under fading channel is written as [23, Eq. (11)]. The details of the computations from the BER to the PER and the packet reception status can be found in [17].

5.2 Use Case Description

We assume a health monitoring application scenario for the performance assessment of the conventional SmartBAN MAC and the proposed MAC protocol. It is a health and fitness monitoring use case which involves simultaneous monitoring of ECG, EMG and pulse oximetry signals. Similar type of patient monitoring use cases are extensively discussed in the Section 2 of [24]. The sensor nodes in the given medical use-case generate constant bit rate traffic which is deterministic and therefore, the scheduled access MAC schemes are the most suitable ones for handling this traffic category. Both the MAC schemes in the existing SmartBAN standard as well as the proposed FETRO MAC are based on the scheduled access.

The ECG node contains three channels with ten bits resolution at 750 Hz sampling rate, leading to 7.5 Kbps data rate per channel [25], [26]. The EMG sensor consists of a single channel sampled at 30 KHz rate with eight bits of precision [25], [26], giving a data rate of 240 Kbps. For pulse oximetry measurement, a sensor module with a total data rate of 1.92 Kbps is considered [27]. The total throughput required by this health and fitness monitoring application, therefore, sums upto 264.42 Kbps. Given the individual data rate requirements of the sensor nodes, a slot duration of 0.625 ms would be enough to support the data rates of the majority nodes except of the EMG sensor. However for performance evaluation, we consider three different values of T_{Slot} in the conventional SmartBAN MAC which are 0.625 ms, 1.25 ms and 2.5 ms. Furthermore, the slot durations of 5 ms, 10 ms and 20 ms are not considered in the performance analysis because there is no significant difference in the theoretical

TABLE 3
Use Case Scenario for Performance Evaluation [25], [26], [27]

Health and Fitness Monitoring Application	
Sensor Type	Throughput Requirements
EMG (1 channel)	240 Kbps
ECG (3 channels)	7.5 Kbps
Pulse Oximeter Sensor	1.92 Kbps

throughput results with these slot sizes compared to the 2.5 ms slot, as depicted in Fig. 3. The sensor types, number of nodes and their throughput requirements for the given use-case are summarized in Table 3.

For each considered slot duration, we assume three different conventional SmartBAN MAC strategies to manage the throughput requirements of the health and fitness monitoring application. The first one is the reference scheme, in which each channel/node is allocated a single scheduled access slot, and hence there would be five slots in the scheduled access period. There are two slots in the CM period for management operations and one slot in inactive duration in all MAC strategies. This results in the IBI period of 5.625 ms and 178 IBIs per second with 0.625 ms slot, 11.25 ms IBI and 89 IBIs per second with 1.25 ms slot and 22.5 ms IBI and 44 IBIs per second with 2.5 ms slot. In the reference scheme with 0.625 ms slot, each ECG and EMG channel sends data at every IBI while the pulse oximeter makes transmission after every 5 IBIs. The EMG node sends data at every IBI in the reference scheme with 1.25 ms and 2.5 ms slot durations. ECG channels send data after every 8 and 11 IBIs with 1.25 ms and 2.5 ms slot durations respectively. While the pulse oximeter node makes transmissions after 22 and 29 IBIs with 1.25 ms and 2.5 ms slot durations correspondingly.

In the second strategy, extra slots are provided to the high data rate sensor nodes. With 0.625 ms, 1.25 ms and 2.5 ms slot durations, the high data rate EMG node is allocated three, one and one extra slots respectively. Whereas the slot allocations for ECG and pulse oximeter nodes remain the same. This results in the entire IBI duration of 7.5 ms and 133 IBIs per second with 0.625 ms slot, 12.5 ms IBI duration and 80 IBIs per second with 1.25 ms slot length and 25 ms IBI duration and 40 IBIs per second with 2.5 ms slot. The ECG and EMG nodes make transmission at every IBI whereas the pulse oximeter node sends data after every 4 IBIs with the slot duration of 0.625 ms. The EMG node makes transmissions at every IBI when extra slots are assigned with 1.25 ms and 2.5 ms slot durations. The intervals between the successive transmissions for ECG channels become 7 and 10 respectively with 1.25 ms and 2.5 ms slot durations. Whereas the pulse sensor sends data after every 26 and 20 IBIs with 1.25 ms and 2.5 ms slots respectively. It should be noted that the number of extra slots assigned to the high data rate sensor node are not increased beyond one for longer slot durations because it increases the IBI duration which in turn would decrease the throughput, according to the theoretical throughput results indicated in Fig. 3.

The slot reassignment strategy has a similar IBI duration as the reference SmartBAN MAC scheme but the unused slots of ECG channels and pulse oximeter node are strategically reassigned to manage the EMG channel transmissions.

TABLE 4
Simulation Setup Parameters

RF Parameters [19]	
Transmitter Power (dBm)	0
Receiver Sensitivity (dBm)	-96
Current Consumption Tx ($I^{\mathrm{Tx}}_{\mathrm{mA}}$)	5.3
Current Consumption Rx ($I^{\mathrm{Rx}}_{\mathrm{mA}}$)	5.4
Current Consumption (idle) ($I^{\mathrm{Idle}}_{\mu\mathrm{A}}$)	1.2
Bandwidth per channel (MHz)	2
Information Rate (Kbps)	1000
Modulation type	GFSK (h = 0.5 and BT = 0.5)
PHY/MAC Parameters[11][18]	
Minimum slot length (T_{Min})	625μs
Interframe spacing (IFS)	150μs
Acknowledgement Duration (T_{Ack})	128μs
Beacon Duration (T_{B})	104μs
Beacon Duration with slot reassignment (T_{B})	128μs
Symbol Rate (R_{Sym})	10^6
MAC header (K_{MAC})	7 octets
PHY header(K_{PHY})	5 octets
Preamble (K_{Preamble})	2 octets
Frame Parity (K_{Parity})	2 octets
Element ID and Length fields ($K_{\mathrm{ID}} + K_{\mathrm{L}}$)	1 octet
Slot Reassignment information module (K_{SRas})	4 octets
Number of slots in CM period (N_{CM})	Two
Number of slots in inactive period (N_{IA})	One

Finally, in the proposed FETRO MAC with variable slot length, a slot duration of 2.5 ms is assumed for EMG channel while the remaining nodes retain a slot length of 0.625 ms since this slot length is enough to manage their throughput requirements. With an IBI of 7.5 ms, EMG and ECG nodes send data at subsequent IBIs. While the pulse oximeter node keeps a transmission periodicity of 4 IBIs in the suggested FETRO MAC protocol.

5.3 Simulation Setup

The trace file that provides space-time varying distances and link types for the deterministic channel models (with and without fading) assessment of this application scenario is about 59 seconds long and contains several mobility patterns such as walking, sitting and hand motions. The pathloss values for the static CM3B channel models (with and without fading) are repeated for the identical duration to give the performance evaluation at a similar time span. The simulation with this trace file is repeated 100 times to give more reliable results. For the performance assessment of conventional SmartBAN MAC strategies and FETRO MAC, we consider transmission power levels of "0dBm", defined for nRF52832 BLE device [19]. The sensor nodes and the hub go into an idle mode while not performing any active transmission or reception, except during the T_{Tx} of the scheduled access and CM slots when the hub has to remain in the active mode for any other possible frame reception. The other relevant RF specifications and PHY-MAC parameters are summarized in Table 4. All the simulations are performed using the MATLAB script files.

5.4 Simulation Results

This sub-section elaborates the simulation results for the given simulation setup and the use-case scenario in terms of

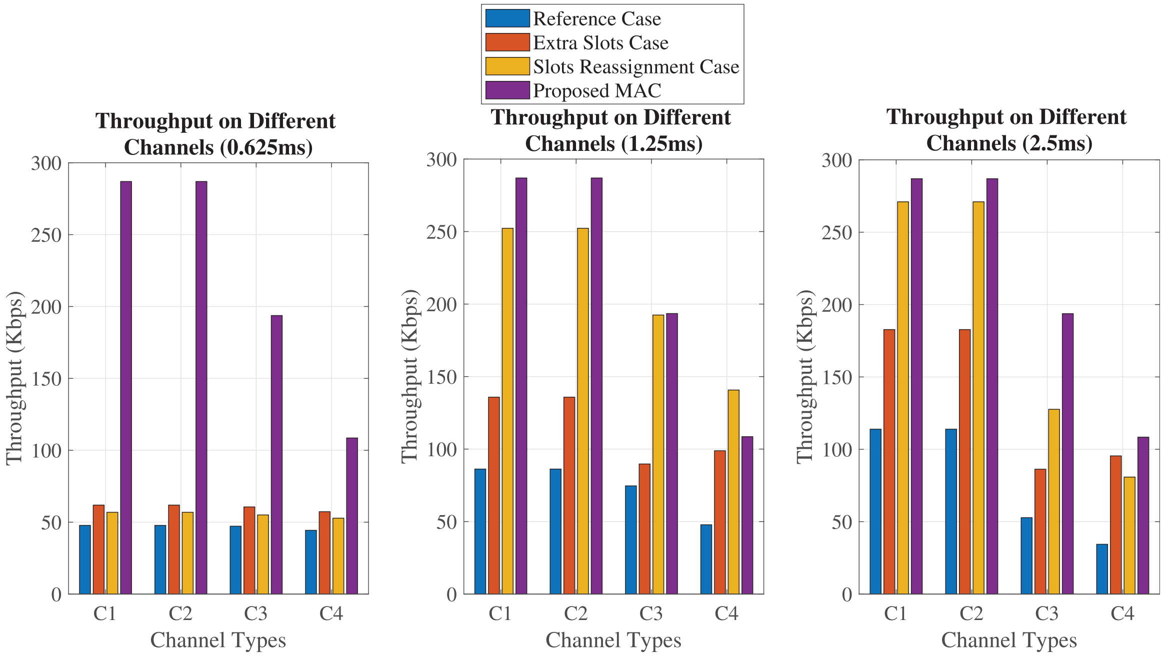


Fig. 8. Throughput on different channel types (Kbps), health and fitness monitoring applications. C1: Static AWGN channel, C2: Deterministic AWGN channel, C3: Static fading channel, and C4: Deterministic fading channel.

the throughput attained at the receiving end as well as normalized the energy consumption per Kbps due to payload transmission and overheads. The throughput results under ideal channel conditions for the baseline SmartBAN and FETRO MAC schemes can be calculated using (4) and (17) respectively. But the practical WBAN channels greatly impact the effective throughput attained at the receiver. The effective throughput under the given channel conditions, such as AWGN or fading and static or deterministic, can be computed as

$$Th_{\mathrm{Pr}} = \frac{N_{\mathrm{Rx}}}{T_{\mathrm{Trace}}}, \tag{20}$$

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 given in Section 4.3.

5.4.1 Throughput Analysis

The aggregated throughput results of all the sensor nodes in the given health and fitness monitoring applications for the given 59 seconds trace duration are presented in Fig. 8. We refer to the "static AWGN channel" as "C1", deterministic AWGN channel" as "C2", "static fading channel" as "C3" and the "deterministic fading model" as "C4" in all the performance evaluation results. This is the effective throughput attained by the packet transmissions of all the sensor nodes for different channel types with several slot durations compared against the proposed FETRO MAC strategy. The throughput results of the extra slot and the slot reassignment cases are better than the reference SmartBAN case under all channel conditions and MAC slot durations. Also, the throughput outcomes for all the MAC scenarios with fixed slot durations, i.e., reference, extra slot allocation and slot re-assignment cases, are not significantly changed under different channel types for 0.625 ms slot duration. This is because with smaller slot durations of 0.625 ms, the payload size is also very small (8bytes, as mentioned in Table 2), leading to lower PER values even under extremely poor channel conditions [23]. This leads to the reception of almost all the transmitted bits, resulting in higher throughput under static as well as dynamic channels, with and without fading. But all the MAC scenarios with fixed slot durations fail to achieve a total throughput of 264.42 Kbps using the 0.625 ms slot length.

For 1.25 ms slot duration, the reference SmartBAN MAC and the SmartBAN MAC with extra slots fail to attain the throughput requirements under all the channel conditions because of the transmission of insufficient payload and increased IBI duration respectively. However the throughput is significantly improved with slot reassignment strategy under the static and deterministic AWGN channels. It is because the unused slots of other nodes/channels are reallocated to the EMG for maximum resource utilization within the smaller IBI duration. The same trends in throughput can be observed with 2.5 ms slot duration under the static and deterministic AWGN channels. The throughput results degrade under the static and deterministic fading channels with 1.25 ms and 2.5 ms slot durations because of the transmission of large payload at once which results in higher PER values under poor channel conditions [23].

Referring to (17), with an IBI of 7.5 ms and the allocated slot size of 2.5 ms in FETRO MAC, EMG can achieve a total throughput of 258.55 Kbps in total (243 bytes in a single transmission, $243 \times 8 \times 133$). Each of the 3 ECG channels can obtain a total throughput of 8.5 Kbps (8 bytes in a single transmission, $8 \times 8 \times 133$). While the pulse oximeter which makes transmission after every 5 IBIs achieves a throughput of 2.128 Kbps (8 bytes in a single transmission, $8 \times 8 \times 133/4$). This leads to a total theoretical throughput of 286.178 Kbps in FETRO MAC which is certainly within the bounds as shown by Fig. 8. Both the static CM3B and the deterministic

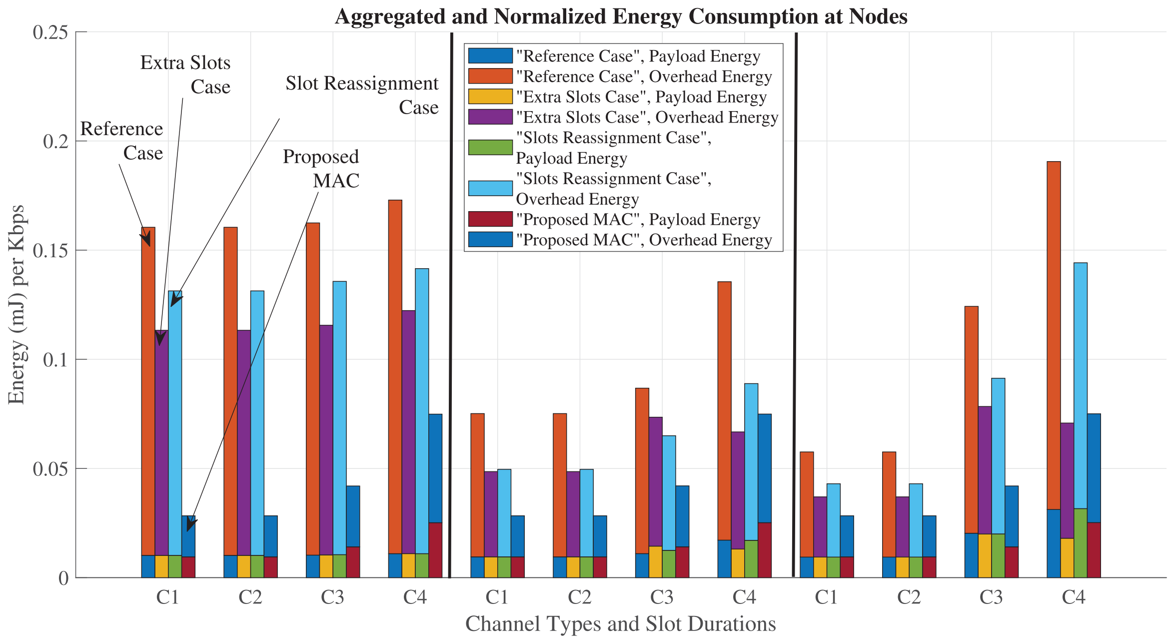


Fig. 9. Node energy consumption (mJ) per Kbps, health monitoring and fitness applications. C1: Static AWGN channel, C2: Deterministic AWGN channel, C3: Static fading channel, and C4: Deterministic fading channel.

AWGN channels have considerably high throughput of more than 275 Kbps for the proposed FETRO MAC protocol with variable slot length. It clearly demonstrates the potential of the suggested MAC scheme in fulfilling the total throughput requirements of the use-case considered. The effective throughput results for FETRO MAC respectively become 195 Kbps and 110 Kbps for the static CM3B and the realistic channel models with fading. This phenomenon can be explained by the two facts. One is the transmission of larger payload size (234 bytes) in the slot allocated to the EMG node. Other is the BER calculation on Rician fading channel, taking an upper bound expression [23, Eq. (11)] which gives the highest possible error rate results. With the upper bound results of BER, the related PER also takes the maximum values which in turn decreases the total number of received bits N_{Rx} and the attained throughput Th_{pr} under the fading channels.

The provision of variable slot durations within an IBI makes the scheduled access MAC highly adaptable according to the throughput requirements of the individual sensor nodes in FETRO MAC. For example, with 0.625 ms slot length extra slot allocation SmartBAN scheme, EMG is allocated 4 slots in total with 3 of them as extra slots. There are 133×4 ACK transmissions and 133×4 overhead transmissions (for 133 IBI per second) for transmitting the EMG payload. Also there are 2 IFS within each slot which results in 8 IFS for a single EMG transmission with extra slots and 133×8 IFS per second. In FETRO MAC, these numbers are reduced to 133 ACK transmissions, 133 overhead transmissions, and 133×2 IFS per second for EMG node. Therefore, there is an overall reduction of extra 399 ACK transmissions, 399 packet overhead transmissions and 798 IFS which collectively lead to a significantly high throughput with the proposed scheme. FETRO MAC also helps preventing the wastage of scheduled access resources due to the allocation of unnecessary longer slot durations to low data rate sensor nodes.

5.4.2 *Node Energy Consumption Analysis*

The aggregated and normalized energy consumption per Kbps can be found as the ratio of total energy utilized in the entire trace duration (mentioned in Section 5.3) and the attained effective throughput. Fig. 9 illustrates the aggregated payload and overhead energy consumption per Kbps results for all the sensor nodes. The aggregated energy of all the sensor nodes is summed up for the entire trace duration and normalized to the effective throughput, as shown in Fig. 8. The energy can also be normalized to the number of bits or bytes transmitted successfully in the entire trace duration. But here the energy is normalized to the effective throughput which again refers to the number of bits transmitted successfully per second. The results are presented for the similar channel types and slot durations, as mentioned in Sections 5.1 and 5.2. Furthermore, the energy consumption results of the conventional SmartBAN MAC scheduling strategies with 0.625 ms, 1.25 ms and 2.5 ms slot durations are compared against the proposed FETRO MAC. Since the motivation behind FETRO MAC is the reduction of overhead energy consumption, therefore we provide comparison taking overhead energy consumption per Kbps as the primary metric.

For 0.625 ms slot duration and under all the given channel types, employing FETRO MAC decreases the normalized overhead energy consumption by 84.6, 80.9 and 83 percent in comparison with the reference, extra slot allocation and slot reassignment SmartBAN MAC schemes respectively on average. The allocation of three extra slots to manage the EMG node throughput requirements incorporates the additional PHY-MAC layer and acknowledgement overhead energy consumption at node, as given by (10). The slot reassignment strategy has high overhead energy consumption with 0.625 ms slot because of more frequent slot re-allocations to handle high data rate EMG sensor node.

The overhead energy consumption per Kbps is significantly decreased in all three conventional SmartBAN MAC

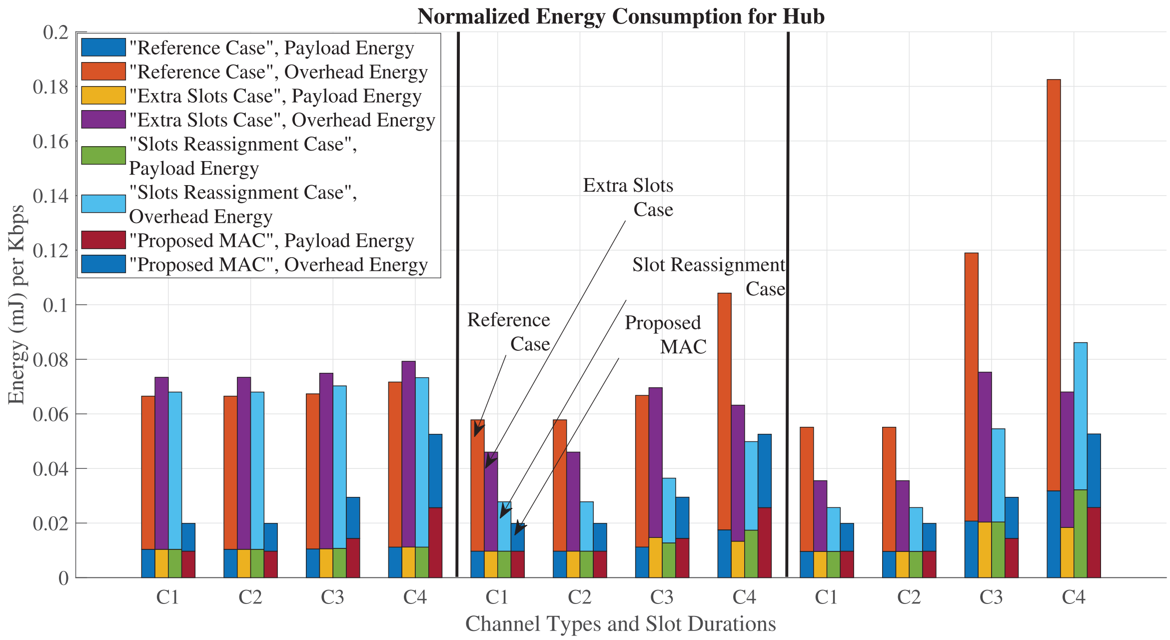


Fig. 10. Hub energy consumption (mJ) per Kbps, health monitoring and fitness applications. C1: Static AWGN channel, C2: Deterministic AWGN channel, C3: Static fading channel, and C4: Deterministic fading channel.

schemes (reference, extra slot, slot reassignment) with 1.25 ms and 2.5 ms slot durations because of the transmission of relatively higher payload with less overheads. Nevertheless, the proposed FETRO MAC reduces the normalized energy consumption per Kbps by 65, 53.3 and 49 percent as compared to the reference, extra slot allocation and slot reassignment SmartBAN MAC scheduling methods respectively, on average, with 1.25 ms slot length. With 2.5 ms slot, the proposed FETRO MAC results in an average decrease of 42.8 percent in overhead energy consumption per Kbps outcomes in contrast to the conventional SmartBAN MAC scheduling methods. The normalized overhead energy consumption per Kbps results for FETRO MAC are increased under the deterministic fading channel because of the related decrease in FETRO MAC throughput results, as previously shown in Fig. 8.

It can also be observed that the normalized overhead energy consumption is much higher than the normalized payload energy consumption but decreases with the increase in slot size. It is because all three base-line SmartBAN MAC strategies utilize a lot of energy in transmitting and receiving overheads (PHY-MAC, acknowledgement, slot reassignment and others) while attaining comparatively low effective throughput. The energy is also consumed when the sensor nodes and hub are in the active state during the CM period for the possible reception of control frames by the other WBAN nodes. So, the longer the slot duration, the higher is the energy to keep the device in the active state. Furthermore the normalized overhead (or payload) energies are much higher for the deterministic fading channel because the corresponding effective throughput is considerably declined under the static and deterministic fading channels.

5.4.3 *Hub Energy Consumption Analysis*

The normalized energy consumption results for hub are depicted for the conventional SmartBAN MAC strategies and compared against the proposed FETRO MAC in Fig. 10 for the identical channel types and slot durations. The hub energy consumption is summed up for the entire trace duration and normalized to the effective throughput, as shown in Fig. 8. The payload and overhead energy consumption per Kbps outcomes for the hub follow a similar pattern as the aggregated and normalized energy consumption per Kbps results for the nodes. Employing the FETRO MAC cuts down the overhead energy consumption per Kbps by 75, 62.5 and 40 percent as compared to the conventional SmartBAN scheduling methods with 0.625 ms, 1.25 ms and 2.5 ms slot durations respectively.

The aggregated and normalized payload energy consumption, as shown in Figs. 9 and 10 for the nodes and hub respectively, is related to the actual data payload transmission by the sensor nodes. The larger the payload transmitted per unit time, the higher shall be the payload energy consumption. However all of the transmitted payload is not received successfully because of the channel losses. The fading channel types (both static and deterministic) have more packet losses compared to the AWGN channel types, resulting in the reduced effective throughput. This phenomenon is also illustrated in the throughput results (Fig. 8) in which the attained effective throughput is comparatively higher under AWGN channel types while the throughput decreases under fading channels for the same MAC procedures. If the aggregated payload energy consumption (at both the sensor nodes and hub) for some MAC algorithm is high and there are negligible channel losses, the higher effective throughput shall normalize it to the same level because all the consumed energy is utilized in the successful packet reception. Likewise, if some MAC technique transmits less payload with more overheads, the lower effective throughput normalizes that low (aggregated) payload energy to yield the same level of normalized energy usage. But under the fading channel types, the effective throughput decreases because of the higher channel losses although the same payload transmission energy is consumed for the given method (at both the sensor nodes and hub) as in the AWGN channels. Therefore, the normalized payload energy consumption performance varies under fading channels for the different methods compared. This throughput degradation under the fading channel types is more obvious for 1.25 ms and 2.5 ms slot durations, as shown in Fig. 8. Therefore, the changes in normalized payload energy consumption (of the methods compared) are also more observable for 1.25 ms and 2.5 ms slots.

6 Conclusion

This paper thoroughly discusses the potential of SmartBAN MAC layer to collectively manage the throughput requirements of the sensor nodes with varying data rates. In this regard, both extra slots allocation and slot reassignment methods are investigated for health and fitness monitoring applications. Either additional slots are allocated to high data rate sensors or empty slots within an IBI are utilized to regulate the proper data transmission in a slot reassignment method. Both of these strategies in existing SmartBAN MAC require more PHY-MAC overheads. The provision of longer slot durations in the simultaneous presence of low and high data rate sensors may lead to the under-utilization of SmartBAN scheduled access resources due to fixed slot length allocation. An innovative FETRO MAC technique with variable slot length is proposed in this article which requires minimal changes in the baseline SmartBAN structure. The suggested variable slot length MAC scheme is based on the adaptation of the slot durations according to the sensors data rate requirements. The proposed FETRO MAC scheme counters the extra energy consumption by reducing the required transmission of several PHY-MAC overheads and offers the best trade-off between the effective throughput and overhead energy consumption per Kbps outcomes.

Acknowledgments

This work was 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, and in part by the Estonian Research Council under Grant PUT-PRG424.

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