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Additional Information

EETP-MAC: Energy Efficient Traffic Prioritization for Medium Access Control in Wireless Body Area Networks

Fasee Ullah[1], Abdul Hanan Abdullah[1], Omprakash Kaiwartya[1], Jaime Lloret[2], Marina Md Arshad[1]

[1]Faculty of Computing, Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor Bahru, Malaysia
[2]Universidad Politecnica de Valencia, 46022 Valencia, Spain

Corresponding Author: omprakash@utm.my

Abstract Wireless body area network (WBAN) has witnessed significant attentions in the healthcare domain using biomedical sensor-based monitoring of heterogeneous nature of vital signs of a patient's body. The design of frequency band, MAC superframe structure, and slots allocation to the heterogeneous nature of the patient's packets have become the challenging problems in WBAN due to the diverse QoS requirements. In this context, this paper proposes an Energy Efficient Traffic Prioritization for Medium Access Control (EETP-MAC) protocol, which provides sufficient slots with higher bandwidth and guard bands to avoid channels interference causing longer delay. Specifically, the design of EETP-MAC is broadly divided in to four folds. Firstly, patient data traffic prioritization is presented with broad categorization including Non-Constrained Data (NCD), Delay-Constrained Data (DCD), Reliability-Constrained Data (RCD) and Critical Data (CD). Secondly, a modified superframe structure design is proposed for effectively handling the traffic prioritization. Thirdly, threshold based slot allocation technique is developed to reduce contention by effectively quantifying criticality on patient data. Forth, an energy efficient frame design is presented focusing on beacon interval, superframe duration, and packet size and inactive period. Simulations are performed to comparatively evaluate the performance of the proposed EETP-MAC with the state-of-the-art MAC protocols. The comparative evaluation attests the benefit of EETP-MAC in terms of efficient slot allocation resulting in lower delay and energy consumption.

Keywords: Wireless body area network, Medium access control, Energy efficient, Traffic Prioritization

1. Introduction

According to a recent report by the World Health Organization (WHO), the deadly diseases causing major deaths include heart attack, stroke, cancer, and respiratory, particularly in lower and middle income countries [1]. The aged people and patients with symptoms of these diseases require continuous monitoring of their abnormalities, and thus, cost of treatment and care is significantly higher for these diseases. Recent developments in Wireless Body Area Network (WBAN) attest the potentials in reducing the cost of treatment along with significant improvement in quality of patient care [2]. WBAN is an innovative technology which detects abnormalities of patient's health condition well before life threatening situation [3]. It can instruct deaf and blind people as personal assistance [4, 5], and monitors physical organs of sportsman on playground [6] and soldiers on battlefield [7, 8]. It comprises of number of Biomedical Sensors (BMSs) and a Body Coordinator (BC) [9]. BMSs are responsible for monitoring different vital signs of patient body including respiratory rate, heartbeat, blood pressure, glucose level, temperature, ECG, EEG, EMG, and SPO_2 [10, 11]. The sensors are connected to a BC following star network topology. The sensors can be implanted, attached or placed near to patient body [12] as depicted in Fig. 1. BC is responsible for taking critical decisive suggestions based on intelligent computation on the collected patient data from BMSs [13].

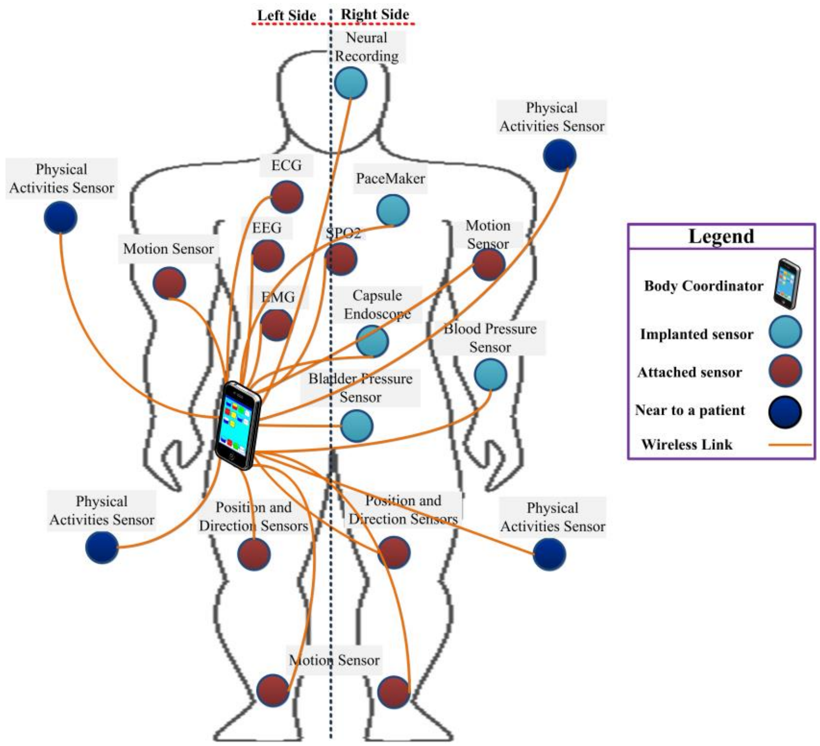

Fig. 1: Example of the Monitoring of Human Body with Support of BMSs

In WBAN, various classification of a patient's data have been explored including routine and abnormal data, medical continuous, non-medical continuous and medical routine data, emergency and non-emergency data [14-16]. The emgerency data represents abnormalities in patient data, exceeding the boundaries of normal reading, e.g., high temperature and low blood pressure. The non-emergency data represents normal information of patients, e.g., number of walking steps, total sleep hours. The patient data from BMSs is required to access channels for efficient transmission of data to BC. The super-frame structure of IEEE 802.15.4 Medium Access Control (MAC) provided 16 slots for channel access. It comprises of a beacon, Contention Access Period (CAP), Contention Free Period (CFP) and Inactive Period (IP) [17, 18]. Each sensor needs to contend during channel assignment in CAP to access channel. BC allocates CFP slots to medical experts for data transmission whereas CAP to BMSs. However, dedicated slots without contention have not been provided for emergency data in 802.15.4 MAC. Due to the the unavailability of contention free dedicated slots, collision, and delay in data transmision occurs, and it results in higher energy consumtion of BMSs. In 802.15.4, the beacon Interval (BI) and Super-frame Duration (SD) is not sufficient for transmitting data in the same SD. BMSs need to wait for the next session of BI for transmitting data. The limited sixteen slots and smaller active slot duration are the major causes of the performance degradation in 802.15.4 in realistic medical enviroments.

Due to the aforementioned challenges ultimately resulting in higher energy consumption in BMSs, the design of 802.15.4 MAC has been modified in literature majorly focusing on superframe structure. In [16], contention based dedicated slots allocation in CFP have been considered. Specifically, this MAC aborts non-emergency data from allocated slots on the arrival of emergency data. This reduces the performance of MAC protocol in terms of higher energy in retransmission of the aborted packets. In [19], the CFP period has been divided into fixed and extend CFP slots. The allocation of these slots to BMSs is based on broadcasting of the notification frame to BMSs.

The waiting of BMSs drop the patient's data and consume a higher energy by retransmitting of the dropped packets. In [23], a clustering technique has been considered for categorizing CFP into notification, fixed and extend CFP slots for a patient's data. With cluster based transmission, BMSs and BC consume maximum energy due to contention leading delay. In [20], CFP has been categorized into two groups and allocation of these dedicated slots based on the contention without carrying of emergency data. The contention causing collision with highest delay and BMSs consume more energy by retransmission of the collided data packets. In [21], the channels of the CAP period have been classified into different three phases and in the same way the patient's data has been divided into three types. Each BMS perform contention to access the designated channel and the allocation of CFP period based on the winning of CAP period. The same challenging problems has been observed as mentioned [20]. In [22], guard-band has been used to avoid channel interferences but the same contention has been used for accessing of the CAP's channel without the important of the life-critical data. In [15], the interference engine and de-fuzzification based fuzzy logic rules have been implemented on the design of superframe of MAC. BC broadcasts a beacon containing "set" to abort data transmission of other BMSs in the detection of emergency data as suggested in [24]. This degrades performance of MAC protocol in terms of collision, delay with lowest data reliability and energy consumption is high. In [25], CAP slots have been categorized into four phases and assigned to different types of a patient's data. Each category of data contends to access channel and some data is restricted not to access phases of other BMSs if these slots not occupied. This degrades performance of MAC protocol if emergency-based BMS wants to transmit data but it cannot transmit due to design restrictions. The 0 and 1 based superframe of MAC has been suggested with broadcasting issue [26]. In the aforementioned MAC protocols, higher energy consumption in BMSs is one of the major issue due to the non-prioritization of patient data traffic. The un-prioritized traffic lead to transmission issues leading towards higher energy consumption due to the longer waiting delay.

In this context, this paper proposes an Energy Efficient Traffic Prioritization for Medium Access Control (EETP-MAC) protocol, which provides sufficient slots with higher bandwidth and guard bands to avoid channels interference causing longer delay. Specifically, the design of EETP-MAC is broadly divided in to four folds:

- Firstly, patient data traffic prioritization is presented with broad categorization including Non-Constrained Data (NCD), Delay-Constrained Data (DCD), Reliability-Constrained Data (RCD) and Critical Data (CD).
- Secondly, a modified superframe structure design is proposed for effectively handling the traffic prioritization.
- Thirdly, threshold based slot allocation technique is developed to reduce contention by effectively quantifying criticality on patient data.
- Forth, an energy efficient frame design is presented focusing on beacon interval, superframe duration, and packet size and inactive period.
- Simulations are performed to comparatively evaluate the performance of the proposed EETP-MAC with the state-of-the-art MAC protocols.

The rest of this paper is organized as follows. Section 2 reviews related literature on MAC protocols for WBANs focusing on energy consumption. Section 3 presents the detail design of the proposed EETP-MAC. Section 4 discusses comparative performance evaluation, followed by conclusion made in Section 5.

2. Related Works

In this section, a critical review on MAC protocol design for WBAN is presented focusing on energy consumption. The channels overlapping/interference and the allocation of a higher bandwidth of the frequency spectrums are the challenging problems in the heavy heterogeneous nature of a patient's data which have not been considered in the existing research of the WBAN MAC. The design and allocation of channels are based on the existing radio frequency spectrums that are operated at 868 MHz, 915 MHz, and 2.4 GHz [27]. The 868 MHz provides one frequency spectrum and is designed for European countries. The channel transfer rate is 20 kbps for 868 MHz. The 915 MHz provides ten frequency spectrums and provides 40 kbps channel rate. This type of frequency spectrum is designed for the US states. The 2.4 GHz provides sixteen frequency spectrums and provides a higher 250 kbps channel data rate. With this higher channel support, it is designed for world and 802.15.4 MAC layer uses 2.4 GHz for wireless communication [28]. However, the suggested MACs for WBAN do not focus on the design problems of channels using 2.4 GHz that are channel overlapping, collision, channel bandwidth utilization, and a guard band between channels.

The families of 802.11, 802.15 and 802.15.1 [11] do not fit in the healthcare domain due to unavailability of sensing and monitoring of vital signs of a patient. However, 802.15.4 has designed for an environmental detection and has also the sensing capabilities to detect an event and transmits the sensory information to the centralized node. With this sensing capabilities, the existing studies use 802.15.4 MAC [29]. The Superframe structure of 802.15.4 provides 16 slots which comprise of a beacon, CAP, CFP and IP. The BC broadcasts a beacon to all BMSs in the star topology containing the address of BC, synchronization and the next announcement BI. In sychronization, BMSs scan actively channels in CAP period during contention. BI is the total time duration of the superframe structure whereas a BMS can contend and transmit data in the specified time interval to BC. The CFP slots are guaranteed time slot and BC allocates to those BMSs who obtained a channel access in CAP. The IP period uses for a sleep period. Howver, the limitations of 802.15.4 MAC are fixed 16 slots and does not handle life-critical data. The slot allocation is based on the contention and BMSs face higher collision due to contention-based slots allocation and limited slots. BMSs cannot transmit the sensory data in the same BI due to limited slots whereas they need to wait for next session of BI. With these drawbacks, 802.15.4 consumes a higher energy of BMSs with higher delay and collision which is not an acceptable for the life-critical data. Thus, the existing studies have tried to improve the design of MAC Superframe structure of 802.15.4 for heterogeneous nature of a patient data.

The suggested LTDA-MAC protocol [19] provides 6 slots in the CAP period and does not discuss the patient's data. BMSs contend to access slot in the CAP period but they cannot allocate CFP slots in the same BI. With these limitations, BMSs face a higher delay and they need to wait for the next BI. Thus, BMSs have a higher delay with higher collision and deplete a higher amount of energy which is not acceptable for life-critical patient's data. The PLA-MAC protocol [20] classifies the patient data into four classes of emergency and non-emergency data. Four types of patient's data perform contention to access channel in the CAP period. The BC allocates data transfer slot (DTS) slots of the CFP period to those BMSs that accessed a channel access in the CAP period. BMSs must perform CCA to occupy the emergency transfer slot (ETS) slots if the DTS slots are not empty. With this higher delay and lower data reliability, BMSs cannot transmit data in the same slot duration and BI of Superframe structure. Hence, these limitations are not acceptable for life-critical data of a patient. Further, 802.15.4, LTDA-MAC and PLA-MAC do not concentrate on the low and high threshold value of vital signs to transmit on the priority-basis without contention and delay. The adaptive MAC (A-MAC) [22] and Priority-based adaptive Timeslots Allocation (PTA) [21] divide the patient's data into normal and emergency categories. Both types of BMSs perform contention to access channel in the CAP period and follow the same slots allocation procedure as aforementioned. Both protocols do not provide the slots details of the CAP and CFP periods; and also do not concentrate on the low and high threshold values of vital signs. The duration of BI is not sufficient for BMSs to transmit data in the same interval. Moreover, the suggested MACs do not assign dedicated slots to the patient's data leading to collision with lower data reliability and BMSs consume a higher amount of energy. With these limitations, the performance of MAC protocol degrades and is not acceptable for emergency data.

The same contention procedure follows by fuzzy control medium access (FCMA) [15] which classifies the patient's data into non-emergency and emergency. The BC uses certain rules during allocation of the CFP slots which are performed based on the sensory information of BMSs. Similarly, this protocol does not concentrate on the threshold values of vital signs and also does not allocate dedicated slots to emergency data without contention. Further, BMSs cannot transmit data in the same BI and they need to wait for the next session. With limited slots, the collision rate becomes increase and BMSs consume a higher amount of energy which degrades the performance of MAC protocol in terms of lower data reliability. This suggested MAC [24] introduces Emergency Contention Period. Advertisement Beacon, Periodic Contention Access Period, Notification Beacon, and Data Transmission Period by handling emergency and periodic data of a patient. In emergency situation, the BMSs tries to access channel of the Emergency Contention Period and BC informs the whole network about the emergency data by setting the value of a flag is "set" using Advertisement Beacon. Further, BC assigns Data Transmission Period slots if the periodic or non-emergency data has been accessed the Periodic Contention Access Period's channel. The dedicated channels allocation based BMSs content which creates overhead for BMSs in terms of collision, reduces throughput, and consumes a high energy of BMSs. Also, this suggested MAC cannot resolve the conflict of slot allocation between the same types of data. This suggested MAC [25] divides the CAP periods into four phases for the four types of a patient's data that are p1 (emergency data), p2 (on-demand), p3 (normal data), and p4 (non-medical data). The p1 traffic can access all phases of the CAP's period for contention but other traffic types cannot use the allocated slots to p1. In this suggested [26], BC broadcasts 1 or 0 to BMSs whether they can perform contention or not in CAP period.
The ISM frequency spectrum 2.4 GHz is used for worldwide applications that are industrial, scientific and medical low-rate energy consumption devices [30]. The existing MAC protocols use 2.4 GHz frequency spectrum for wireless body area network but they do not concentrate on the design problems of different channels that are the bandwidth and the guard bands between of channels. The second challenging problem is the design of MAC Superframe structure with the handling of non-emergency data, and allocation of dedicated slots to low and high threshold values of vital signs without contention. Third, the contention-based BMSs cannot transmit data in the same BI and they need to wait for the next session of BI. With these limitations, the performance of MAC protocols degrades in terms of higher collision, BMSs retransmit the collided packets with higher delay and BMSs consume a higher amount of energy during contention which suffers the patient's life in a critical situation.

3. Energy Efficient Traffic Prioritization for Medium Access Control

In this section, an energy efficient MAC protocol is proposed. The detail design of EETP-MAC majorly focuses on traffic prioritization, superframe structure, slot allocation, and energy efficient frame design.

3.2 Traffic Prioritization

In this EETP-MAC protocol, the patient's data are classified into four types that are NCD, DCD, RCD and CD. The NCD does not impose any delay or reliability constraints and comprises of regular monitoring of the physiological vital signs that is temperature and glucose level. The DCD contains an audio/video based information of a patient that are motion sensing, telemedicine video imaging and electromyography (EMG). This type of a patient's data accepts a certain amount of packets loss without high-reliability constraint. The RCD comprises of the high threshold values of vital signs that are a high heartbeat, and high respiratory rate which is to be delivered with minimum packet loss and can also tolerate delay. The CD contains a reading of low threshold values of vital signs that are a low heartbeat, low blood pressure, and low respiratory rate. Both types of the life-critical physiological parameters do not accept latency and low reliability. The highest life-critical data is CD and second is the RCD. On the priority-based slot allocation, the EETP-MAC allocates dedicated slots to CD and RCD without contention. While the DCD and NCD-based BMSs perform contention to access channel. The detailed description is provided in the subsequent sections.

The PHY layer of 802.15.4 [31] provides three types of frequency spectrums with different data rates. The first frequency spectrum is 868 MHz and provides one channel with 20 kbps data rate. The second frequency spectrum is 915 MHz and provides ten channels with 40kbps data rate. The third frequency spectrum is 2.4 GHz and can classify this spectrum into different channels with 250 kbps data rate. We divide the frequency spectrum 2.4 GHz into sxiteen sub-frequency spectrums that are 2402 MHZ, 2407 MHZ, 2412 MHZ up to 2477 MHZas depicted in Fig. 2. Each sub-frequency spectrum provides nine channels and the bandwidth of each channel is 9.375 MHz. Moreover, the channel interference/overlapping is removed between two channels with the support of a guard band and its gap between channels is 0.1 MHz. with this guard band, the channels do not interfere with each other and assist them not to corrupt and collide data [32]. The guarad band between main channels is 5.0 MHZ with same benefits. Thus, the proposed EETP-MAC is designed with 128 channels and allocates slots to four types of a patient's data without interrupting the slot allocation processes.

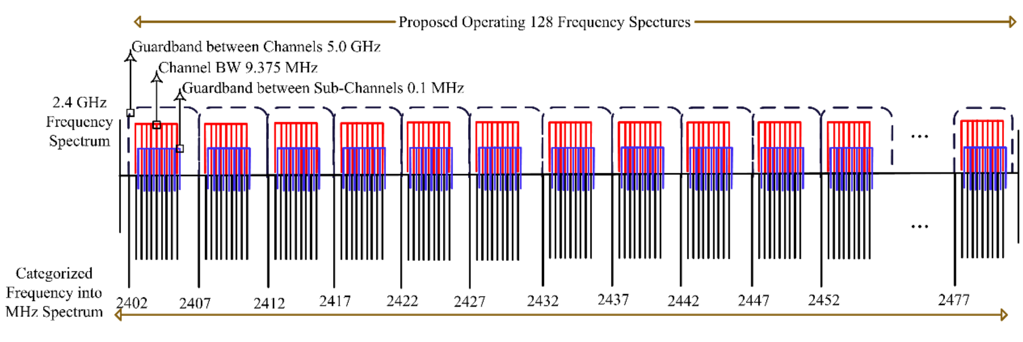

Fig. 2: Operating Frequency Spectrums for the Proposed MAC Protocol

3.2 Superframe Structure

The EETP-MAC protocol works in the beacon-enabled mode. In the beacon-enabled mode, the BC broadcasts a beacon in the network which contains information of the synchronization, address of the BC and next announcement of BI. The proposed MAC protocol is enabled to use Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and Time Division Multiple Access (TDMA) access schemes. The NCD and DCD are non-emergency data whereas these types of

BMSs perform contention to access channel in CAP with the support of CSMA/CA. The TDMA is guaranteed time slots and is placed in CFP period. The guaranteed time slots are allocated to BMSs where they transmit the sensory data of a patient to the medical doctor for an optimal treatment. The RCD and CD are the life-critical emergency data and these types of BMSs are aware of threshold values of vital signs whereas they transmit data to BC without performing contention. The decision of allocation of slots is based on the derived equation as described in section 3.3. Thus, the classification of a patient's data and distribution of traffic load are using these two scheduling access schemes which are suitable for EETP-MAC protocol.

The proposed Superframe structure of the EETP-MAC comprises of a beacon, CAP, Notification (N_t), On-Demand (O-D), Slots for Lowest Threshold Values (SLTVS), Low Threshold Beacon (LT_B), High Threshold Beacon (HT_B), Slots for Highest Threshold Values (SHTVS), Slots for Non-Emergency Traffic (SNET), and IP/Low Power Listening (LPL), as shown in Fig. 3. For the CAP period, the BC allocates twenty-four slots. The B, N_t, O-D, LT_B and HT_B occupy single slot. Similarly, the BC allocate thirty-three slots to SLTVS and SHTVS; thirty-two slots assigns to SNET. The slots N_t, O-D, SLTVS, LT_B, HT_B, SHTVS, and SNET are grouped in the CFP. The first period of the EETP-MAC protocol is a beacon broadcasted to all BMSs in the network for synchronization, address of the BC, the start of SD and next announcement of a BI. BMSs are aware of low and high threshold values of vital signs. If the sensory data of vital signs are in normal conditions, the NCD and DCD-based BMSs perform contention to access channel in CAP period. The allocation of guaranteed SNET slots to non-emergency NCD and DCD-based BMSs are the responsibility of BC when they accessed channels in CAP. The IP is used to save energy. If the BMS does not get a channel access during contention in CAP period, the channel allocation for the packets transmission is handled in the following ways.

- The O-D option can be used when a BMS does not occupy channel in CAP period.
- The particular BMS transmits an alert signal using O-D to BC for allocation of SNET slots.
- The packets of the sender BMSs are stored in the buffer and waits for the next announcement of BI.
- During the wait period, the sender BMSs buffer can overflow and may drop the sensory data or exceed the lifetime of a packet. In this situation, the BC broadcasts N_t alert signal to BMSs to release the occupied SNET slots.
- With this N_t, the BC announces the updated status of the CFP's slots for non-emergency BMSs.

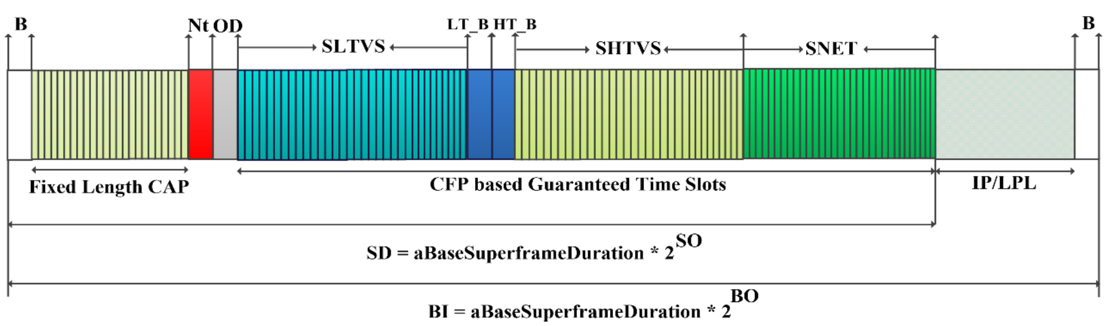

Fig. 3: Superframe Structure of EETP-MAC

3.3 Slot Allocation

The emergency data is RCD and CD which contain information of high and low threshold values of vital signs, respectively. During detection of an emergency data, the particular BMSs do not contend to access channels but they transmit alert messages of the life-critical data to BC in the allocated slot of LTV_B or HTV_B. The BC calculates the threshold values of the vital signs and on the priority-basis allocates slots to BMSs as expressed in Eq. (1).

$$Priority_{Threshold_{Val}}(i) = \frac{Detec\_Threshold_{Value}(i)}{Generation_{Rate} * P_{Size}(i)} \tag{1}$$

Where $Priority_{Threshold_{Val}}(i)$ is on the priority-based slot allocation to BMSs, $Detec\_Threshold_{Value}(i)$ is the detected threshold value of a vital sign which can be low or high, $Generation_{Rate}$ is the time of data generated, and $P_{Size}(i)$ is the size of detected vital sign in bytes.

On the EETP-MAC protocol based BMSs, the BMSs are aware of low and high threshold values of vital signs that are low heartbeat rate is ≤ 50 beats/min, high heartbeat rate is ≥ 120 beats/min, low respiratory rate is ≤ 11 breath/min, and high respiratory rate is ≥ 20 breath/min [33]. In detection of low threshold value of a vital sign, the particular BMS transmits an alert signal to LTV_B slot of the BC for allocation of SLTVS slots. The BC replies back and allocates the SLTVS slots. In the same way of the detection of high threshold values, the BMS informs the BC using slot of HTV_B and BC replies by allocating of SHTVS slots. These types of BMSs do not perform contention and also require a higher attention to allocate slots without delay and low reliability.

If the BC receives alert signals of the same types of two BMSs at the same time. Then the allocation of the SLTVS or SHTVS slots are assigned under the following conditions.

- In the case of the low threshold value, the BC compares the ranges of two low threshold values, generation rates and size of the packet. For example, if a BMS_heart detects 47 beats/min with generation rate is X_i (recently detected) and the second BMS_respiration detects 4 breath/min with generation rate is Y_j (earlier detected). In this life-critical situation, the BC assigns the first slot on the priority-basis to BMS_respiration. The reason is that the respiration rate is more than in the life-critical situation and has generated earlier as compared to BMS heart.
- In the case of high threshold values, the BC assigns the first slot to the higher values of a vital sign as compared to the lower values of a vital sign. For example, if a BMS_heart detects 133 beats/min with generation rate is P_i (recently detected) and the second BMS_respiration detects 22 breath/min with generation rate is T_j (earlier detected). In this life-critical situation, the BC assigns the first slot on the priority-basis to BMS_heart as the values of heartbeat are on the highest range as compared to the BMS_respiration values.

With these conditions and life-critical situations, the BC resolves the conflict of slots allocation between BMSs which assists for saving the patient's life from serious damage. The NCD and DCD-based BMSs sleep in the LPL mode and monitor vital signs to save energy. In the same way, the RCD and CD-based BMSs can also sleep in LPL to save energy when there is no life-critical situation. The BC activates IP if BMSs need more slots for data transmission.

3.4 Energy Efficient Frame Design

The EETP-MAC frame structure comprises of MAC header, payload and frame check sequence (FCS). The MAC header uses 5 to 11 bytes, FCS uses 2 bytes and the payload length is dependable on the packet's size as depicted in Fig. 4. The slots are configurable and are of equal length in SF.

The SF structure depends on BI and SF Duration (SD). The BI comprises of active and inactive parts of the superframe structure whereas it measures the total time duration between the current duration of a beacon and the announcement of a next beacon for superframe. The whole active part is the SD that includes a beacon, CAP, N_t, O-D, SLTVS, ET_B, HT_B, SHTVS, and SNET. Further, the BI and SD are associated with beacon order (BO) and superframe order (SO), respectively as shown in Fig. 3. The BO determines the time duration of the whole superframe structure as expressed in Eq. (2). Similarly, SO determines the time duration of the active part of superframe as expressed in Eq. (3).

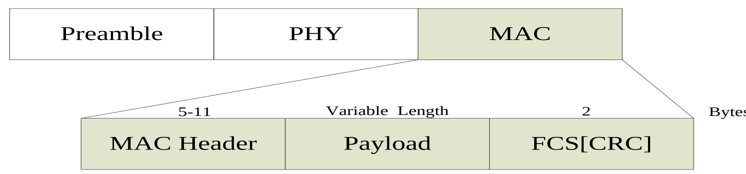

Fig. 4: The frame structure

$$BI = aBaseSupframeDuration \times \ 2^{BO} \tag{2}$$

$$SD = aBaseSuperFrameDuration \times \ 2^{SO} \tag{3}$$

Where $aBaseSuperFrameDuration$ is a dynamic value which represents the number of symbols in Superframe. The value of BO must be greater or equal to SO and both parameters must satisfy the following condition as expressed in Eq. (4).

$$0 \leq \mathrm{SO} \leq \mathrm{BO} \leq 128 \tag{4}$$

The following subsections assist in finding the duration of BI, SD and the packet size in the Superframe duration.

3.4.1 Beacon Interval

To calculate the time duration of the proposed EETP-MAC, BI can be expressed in Eq. (5).

$$BI = \frac{(aBaseSupframeDuration \times \ 2^{BO})}{Data\_Rate} \tag{5}$$

Where $aBaseSlotDuration$ is represented in symbols (durations) and provides a constant value. The $aBaseSlotDuration$ can be calculated in the following way as expressed in Eq. (6).

$$aBaseSupframeDuration = aBaseSlotDuration \times anumSuperframeSlots \tag{6}$$

The $anumSuperframeSlots$ represents the total number of slots in SF where the proposed EETP-MAC provides 128 slots.

After determining different design parameters of BI, Eq. (5) and Eq. (6) are expressed as shown in Eq. (7).

$$BI = \frac{(aBaseSlotDuration \times anumSuperframeSlots \times \ 2^{BO})}{Data\_Rate} \tag{7}$$

The resultant values of BI and SD are divided by data rate where the data rate is the amount of time required between two machines to transfer data. The higher data rates are used for saturated, mission-critical systems and high traffic load networks such as continuous monitoring of vital signs of a patient and online video streaming [34]. The minimum data rates are 5 kbps and 10 kbps. These data rates increase the idle listening time and generate the small size of packets. With 20 kbps and 40 kbps of higher data rate reduce the idle listening time and transmit considerably a higher amount of data packets [34]. Hence, the proposed model is implemented with 20 kbps data rate.

3.4.2 Superframe Duration

The same steps are followed for calculation of SD as expressed in Eq. (7) for BI except with one changes that are the replacement of BO with SO as described in Eq. (8).

$$SD = \frac{(aBaseSlotDuration \times anumSuperframeSlots \times 2^{SO})}{Data\_Rate} \tag{8}$$

The design parameters for a slot duration depends on the SD and the size of patient's data packet depends on the slot duration. For the EETP-MAC protocol, we use data rates 20 kbps and 40 kbps for SD. For slots in Superframe structure, we use 2^k which represents the total number of slots in Superframe and the value of k comprises of 4, 5, 6, 7, and 8. Hence, the total number of slots in Superframe structure are 16, 32, 64, 128, 256, and 512. With these parameters, we can easily calculate a slot duration in Superframe as expressed in Eq. (9).

$$A\ Slot\ Duration = \frac{SD}{Total\ no.of\ slots\ in\ superframe} \tag{9}$$

3.4.3 Packet Size and Inactive Period

The packet size in a slot can be calculated by the following as expressed in Eq. (10).

$$Packet\ Size\ in\ a\ Slot = A\ Slot\ Duration \times data\ rate \tag{10}$$

To find the IP in Superframe structure, BI and SD act a significant role in calculating IP as expressed in Eq. (11).

$$Inactive\ Period\ (IP) = Beacon\ Interval\ (BI) - Superframe\ Duration\ (SD) \tag{11}$$

The BI represents the whole superframe structure (active + inactive parts) and is calculated with the support of BO as described in Eq. (2). Similarly, the SO represents the active parts of the Superframe structure which are calculated with the support of SO as described in Eq. (3). The value of BO must be greater or equal to SO as described in the following conditions.

- If the value of BO = SO which is BO=SO=1, 2, 3, 4…. This concludes that there is no an inactive period and all the slots are active in the Superframe structure.
- If the value of BO > SO which is BO=2, 3, 4… and SO=1, 2, 3…. This concludes that Superframe contains an inactive portion and uses only active slots of Superframe duration (SD).
- The values of BO < SO are not possible because SO is the sub-part of BO and BO represents the whole Superframe structure.

The time period of BI is reduced by 50% if all slots are activated (BO=SO). In this situation, the BC announces quickly a new BI before the actual timing of the SF Duration as compared to BO > SO. With this reduction, the performance of MAC protocol degrades in terms of higher collision, delay with lower data reliability and higher energy consumption of BMSs. Hence, the EETP-MAC protocol uses BO > SO for implementation.

3.5 Analysis of Energy Consumption

In this section, we analyze energy consumption and packet delivery delay of the EETP-MAC. It is assumed in WBAN that *n* number of BMSs have used to monitor vital signs and outputs of the monitored vital signs are sent to BC, which is expressed in Eq. (12).

$$WBAN = \{BC, BMS_1, BMS_2, BMS_2, \ldots, BMS_n\} \tag{12}$$

The complexity analysis of energy consumption of the non-emergency based BMSs during contention for accessing channels in the CAP period, as expressed in Eq. (13).

$$Beacon_{Frame} = \frac{BI\ (Tx_E + Rx_E) + Beacon_T + BMS_{TX-Time} + BMS_{Rx-Time}}{BI} \tag{13}$$

Where $Beacon_{Frame}$ is the ratio of time of receiving frame from BC, *BI* stands for Beacon Interval, Tx_E is the amount of energy consumption in receiving of beacon, Rx_E is the amount of energy consumption in transmission of the contention beacon, $Beacon_T$ is the time of beacon transmitted, $BMS_{TX\text{-}Time}$ is the time of transmission of the contention beacon to BC, and $BMS_{RX\text{-}Time}$ is the time of receiving of the BI from BC.

The average energy consumption of non-emergency based BMSs in CAP period as described in Eq. (14), as follows:

$$E_{CAP} = \frac{Beacon_{Frame} + ACK_{Time} + (2 + backoffs) * BMS_{Rx-Time} + 2 * backoffs * CCA}{BMS_{generation\_rate}} \tag{14}$$

Where ACK_{Time} is the time of acknowledgement, *backoffs* is the number of tries during contention to access channel, each BMS have to perform twice *CCA* to ensure collision free access of channel and E_{CAP} is the total average energy consumed in the contention by BMSs.

The average energy consumption of emergency-based BMSs using alert signal is expressed in Eq. (15).

$$E_{Tx} = \left(\frac{Generation_{time} + BMS_{Tx-Time}}{BMSs\_generation\_time}\right) * BMS_{E-Tx} \tag{15}$$

Where E_{Tx} is the amount of energy consumed in transmission of alert signal, $Generation_{time}$ is the time of detection abnormality of a vital sign, $BMS_{Tx\text{-}Time}$ is the time of transmission of detected data, $BMS_{E\text{-}Tx}$ is the energy consumed by BMS in transmission and *BMS_generation_time* is the time of reception of a vital sign at side of BC.

The data packet delivery delay of non-emergency based BMSs in the contention using CAP is expressed in Eq. (16).

$$CAP_{Time} = T_{BMS-CSMA/CA} + T_{Data} \quad (16)$$

Where CAP_{Time} is the amount of time required to occupy channel in CAP period, $T_{BMS-CSMA/CA}$ is the required to BMS for performing contention in CAP period, and T_{Data} is the time of data transmission. Using Equation of [35] is to describe $T_{BMS-CSMA/CA}$ as expressed in Eq. (17).

$$T_{BMS-CSMA/CA} = BMS_{Tx-Time} + backoffs * CCA_{CAP} + \delta(backoffs, BO_{Time}(\beta)) \quad (17)$$

The amount of time required is to transmit data in the designated slots of CFP period as expressed in Eq. (18).

$$T_{CFP} = \frac{BI-CAP_{Time}}{2} + T_{BMS-CSMA/CA} + T_{Data} \quad (18)$$

Where T_{CFP} is the required time of data transmission in CFP period and T_{Data} is the time of data transmission.

The data packet delivery delay based on emergency-based BMSs is carried out in Eq. (19).

$$U_{Data} = \frac{T_{Alert}+ACK_B}{BI} \quad (19)$$

Where U_{Data} is the detected abnormal data which can be low or high threshold value, T_{Alert} is the time of sent alert signal of the detected low/high threshold values, ACK_B is the acknowledgement sent back to BMS and BI is the interval in which BMS transmit data to BC.

4 Performance Evaluation

In this section, simulations are performed for evaluating the performance of EETP-MAC in realistic medical scenario. It is majorly divided into three folds. Firstly, simulation setting are discussed. Secondly, performance evaluation metrics for medical environment are defined. Thirdly, comparative analysis of simulation results is presented.

4.1 Simulation Setting

The simulation is performed in NS-2 and is categorized into two phases. Phase one simulates 16, 32, 64, 128, 256, and 512 slots of MAC Superframe structure. With these slots, the simulations are grouped under conditions BO = SO and BO > SO with data rates 20 kbps and 40 kbps. With BO = SO condition, the values of BO equal to SO that is 1, 2, 3 … 19. Similarly, BO > SO, the values of BO are 2, 3, 4 … 20 and the values of SO are 1, 2, 3 … 19. In the second phase of simulation, the performance of the proposed EETP-MAC protocol is compared with state-of-the-art MAC protocols that are 802.15.4 MAC [17], LTDA-MAC [19], and PLA-MAC [20]. Table 1 shows parameters list for both phases of simulations. Moreover, there are sixteen BMSs are deployed and connected with a BC in the star topology for monitoring different vital signs of a patient that are ECG, EEG, Blood Pressure, Blood flow, respiration, heartbeat, blood PH, temperature, EMG, Glucose, motion sensor, pacemaker, capsule endoscopy, cochlear and artificial retina. All these BMSs are static and the simulation coverage area is 3 * 3 m. The simulation runs for 1800 seconds.

Table 1: Simulation Parameters

Parameter	Value	Parameter	Value
Channel Rate	250 kbps	Sending Data Rates	20 kbps & 40 kbps
Number of Slots in SF (default)	16,32,64,128,256,512	MAC Payload size	1920 bytes
Number of Slots in SF (Activated an inactive period)	32,64,128,256,512,1024	Buffer size of BC	2000 bytes

BO & SO values (case 1)	1 to 19 (BO==SO)	Buffer size of a BMS	1920 bytes
BO & SO values (case 2)	2 to 20 for BO and 1 to 19 SO when (BO >SO)	Max PHY Packet Size	127 bytes
Slot Duration	Variable	TurnaroundTime	12 Symbols
CCA Time	8 symbols	UnitBackoffPeriod	20 symbols
Max Frame Retries	4	macAckWaitDuration	54
MAC Beacon Order	Variable	macMinBE	3
Time of SF Duration	variable	Time of BI	Variable
MAC Minimum backoff exponent	3	MAC Maximum backoff exponent	5
Number of nodes	16	BC	1
Traffic Type	CBR	Power Consumed in Sleep state	0.005 mW
Power Consumed in Transmission state	27-220 mW	Power Consumed in Receive state	1.8 mW
Duration of Turn-On radio to Transmit/Receive data	0.8 ms	Power required for radio to switch from transmitting state to receive state & vice versa	0.4 ms

The extensive simulations have been performed for two phases. In phase one, a different number of slots of Superframe structure are simulated to measure the success rate vs traffic load and average energy consumption of BMSs. In phase two, the proposed EETP-MAC consists of 128 slots with different active parts in the Superframe duration. Both phases use data rates 20 kbps and 40 kbps. The SNET slots are guaranteed time slots and occupy thirty-two slots for NCD and DCD-based BMSs. The SLTVS and SHTVS slots are reserved for life-critical emergency data and each of them occupies thirty-three slots in the CFP period. Moreover, the Priqueue model is used for emergency data that allocates a slot based on the priority to the life critical data. In addition, the Priqueue helps during allocation of the CAP slots to non-emergency data based on first come first serve.

4.2 Simulation Metrics

The following simulation metrics are used for the performance evaluation of the proposed Superframe structure of EETP-MAC with state-of-the-arts MAC protocols.

- *Success Rate:* The BMSs monitor vital signs of a patient and transmit the sensory data to the slots of Superframe structure under the supervision of BC. This metric is calculated as the total number of packets successfully received and is divided by the total number of packets generated by BMSs.
- *Energy consumption:* The energy consumption of BC and BMSs are the lowest in the proposed EETP-MAC protocol as compared to state-of-the-arts MAC protocols. It can be defined as the amount of energy is consumed by BMSs in different states that are in transmit, receive, sleep and LPL.
- *Average Packet Delivery Delay:* BMSs monitor different vital signs of a patient body and generate sensory data. At the time of generation, BMSs transmit them to the concerned slots of the Superframe structure of BC. Thus, it is the time duration between a sender BMS and time of reception at the BC.
- *Average Delivery Delay for Delay-Driven Packets:* The delay-driven packets are CD and RCD and these types of packets need to be delivered in the specified time period. The EETP-MAC protocol assigns dedicated slots to both types of emergency data without performing contention. In an emergency situation, the emergency-based BMSs transmit an alert signal to BC for requesting of allocation of slots. If these delay-driven packets are not delivered in the specified time, the life of a patient can seriously affect.
- *Throughput:* In network communication, it is the amount of data that can be transmitted successfully per unit time (bps). Hence, we calculate in the kbps that are transmitted to BC successfully and is divided by the total number of BMSs.

4.3 Analysis of Results

This section presents the results analysis of slots of the MAC Superframe structures which comprises of 16, 32, 64, 128, 256, and 512. Eqs. 7 to 11 are used to evaluate the results as described in the following subsections.

4.3.1 The impact of BI and SD on the Slots of MAC Superframe structures

Table 2 presents the MAC Superframe structure of 16 slots with transfer data rates 20 kbps and 40 kbps. With BO = SO means that the input values of BO and SO are the same that are 1, 2, 3 …19. With BO > SO means that the input values of BO start from 2, 3, 4 … 20 and the values of SO start from 1, 2, 3 …19. BO helps in calculation of BI while SO helps in calculation of SD. Further, SD measures the slot duration of the Superframe structure as addressed in Eq. (7-11). While BI assists in an announcement of a next interval. The values of BO=SO reduce the timing of BI by 50% as compared to BO > SO and BC announces the next BI very frequently as shown in the first column of Table 2. This reduction of 50% time and frequently invoking of a new BI show that the BC has activated an inactive period of Superframe as shown in the fourth column and compares to the column eight. In this situation, the maximum number of data packets drop by BMSs and BMSs consume a higher amount of energy for retransmission of the dropped and collided data due to the short interval time of BI. The SD (in seconds) and a slot duration (in seconds) in both cases BO=SO and BO > SO have the same timing due to the same data rate used. Hence, the 16 slots of Superframe structure is not sufficient due to the activation of the whole Superframe for heterogeneous nature of the patient's which degrades the performance of MAC protocol in terms of allocation of minimum duration of the Superframe (SD) and the minimum duration of a slot.

In the situation BO > SO, BMSs cannot transmit data due in the same SD and a slot duration as discussed in BO = SO. The reason is that each BMS requires a bit higher amount of time to transmit data which is not possible for long generated data of ECG, and EMG. For limited 16 slots of Superframe, BI increases or decreases only time for invoking of a new beacon which is the minimum time for the long generated data transmission.

With 40 kbps transfer data rate has the same challenging issues for 16 slots of Superframe structure as addressed with 20 kbps. For 16 slots of Superframe structure with 40 kbps data rate reduce the 50% timing as compared to 20 kbps data rate. In these situations, the performance of MAC Superframe degrades in terms of higher collision, a higher number of retransmission of the lost packets with higher delay, and higher amount of energy consumption.

Table 2: Superframe Structure of 16 Slots with data rates 20 kbps and 40 kbps

Data Rate 20 kbps								Data Rate 40kbps								Packet Size in a Slot (Byte)
BO==SO				BO>SO				BO==SO				BO>SO				
BI (sec)	SD (sec)	A Slot Duration (sec)	IP (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	IP (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	IP (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	IP(sec)	
0.096	0.096	0.006	0	0.192	0.096	0.006	0.096	0.048	0.048	0.003	0	0.096	0.048	0.003	0.048	15
0.192	0.192	0.012	0	0.384	0.192	0.012	0.192	0.096	0.096	0.006	0	0.192	0.096	0.006	0.096	30
0.384	0.384	0.024	0	0.768	0.384	0.024	0.384	0.192	0.192	0.012	0	0.384	0.192	0.012	0.192	60
0.768	0.768	0.048	0	1.536	0.768	0.048	0.768	0.384	0.384	0.024	0	0.768	0.384	0.024	0.384	120
1.536	1.536	0.096	0	3.072	1.536	0.096	1.536	0.768	0.768	0.048	0	1.536	0.768	0.048	0.768	240
3.072	3.072	0.192	0	6.144	3.072	0.192	3.072	1.536	1.536	0.096	0	3.072	1.536	0.096	1.536	480
6.144	6.144	0.384	0	12.288	6.144	0.384	6.144	3.072	3.072	0.192	0	6.144	3.072	0.192	3.072	960
12.288	12.288	0.768	0	24.576	12.288	0.768	12.288	6.144	6.144	0.384	0	12.288	6.144	0.384	6.144	1920
24.576	24.576	1.536	0	49.152	24.576	1.536	24.576	12.288	12.288	0.768	0	24.576	12.288	0.768	12.288	3840
49.152	49.152	3.072	0	98.304	49.152	3.072	49.152	24.576	24.576	1.536	0	49.152	24.576	1.536	24.576	7680
98.304	98.304	6.144	0	196.608	98.304	6.144	98.304	49.152	49.152	3.072	0	98.304	49.152	3.072	49.152	15360
196.608	196.608	12.288	0	393.216	196.608	12.288	196.608	98.304	98.304	6.144	0	196.608	98.304	6.144	98.304	30720

393.216	393.216	24.576	0	786.432	393.216	24.576	393.216	196.608	196.608	12.288	0	393.216	196.608	12.288	196.608	61440
786.432	786.432	49.152	0	1572.864	786.432	49.152	786.432	393.216	393.216	24.576	0	786.432	393.216	24.576	393.216	122880
1572.864	1572.864	98.304	0	3145.728	1572.864	98.304	1572.864	786.432	786.432	49.152	0	1572.864	786.432	49.152	786.432	245760
3145.728	3145.728	196.608	0	6291.456	3145.728	196.608	3145.728	1572.864	1572.864	98.304	0	3145.728	1572.864	98.304	1572.864	491520
6291.456	6291.456	393.216	0	12582.912	6291.456	393.216	6291.456	3145.728	3145.728	196.608	0	6291.456	3145.728	196.608	3145.728	983040
12582.912	12582.912	786.432	0	25165.824	12582.912	786.432	12582.912	6291.456	6291.456	393.216	0	12582.912	6291.456	393.216	6291.456	1966080
25165.824	25165.824	1572.864	0	50331.648	25165.824	1572.864	25165.824	12582.912	12582.912	786.432	0	25165.824	12582.912	786.432	12582.912	3932160

We want to show the effects of active and inactive periods of Superframe structure when BO > SO and BO = SO with data rate 20 kbps. We consider the values of BO = 8 and SO = 7. The calculations are performed with the assistance of Eq. (7-9) and Eq. (11). In Fig. 5, the W represents a slot duration (*aBaseSlotDuration*), X represents SD (active periods of Superframe structure), Y represents IP and Z represent BI interval of the Superframe. The values of X becomes equal to the values of Y when BO > SO. Hence, in this situation the BMSs use active periods of the Superframe structure. If the condition BO = SO, the BC activates an inactive period (Y) of the Superframe which reduces 50% timing of the active periods (X) of Superframe as well as of BMSs during contention for channel access and emergency-based BMSs transmission of sensory data. The activation of full slots of Superframe structure is the activation of double slots of Superframe as noticed from the values of X and Y which are equal to the value of Z if BO=SO as described in Fig. 5. The limited 16 slots and the activation of the whole Superframe structure reduce the time interval for data transmission, which degrades the performance of the MAC Superframe structure in terms of higher collision, higher number of retransmission of the collided data, higher delay and higher amount of energy consumption of BMSs.

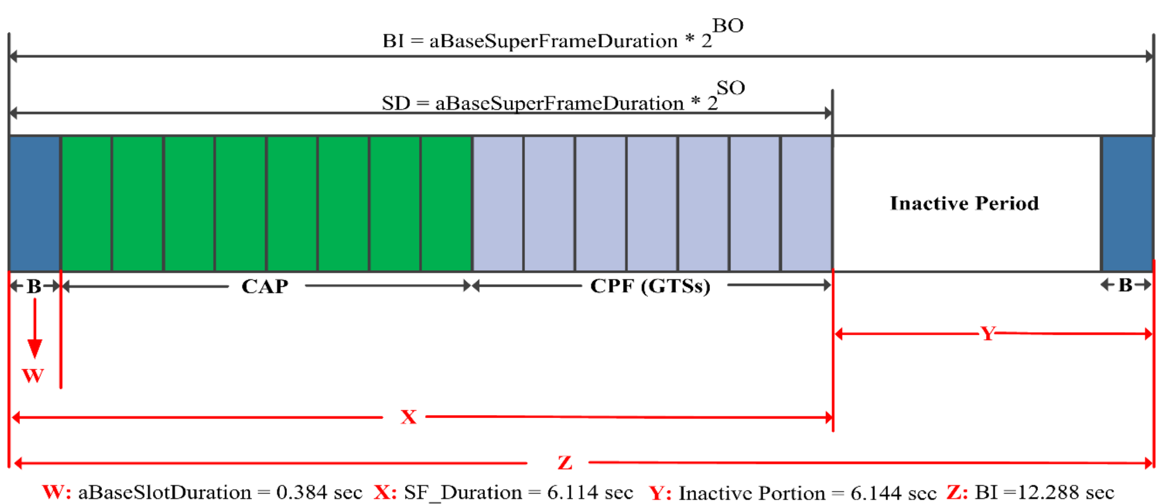

Fig. 5: Comparison of the Active and Inactive Periods of Superframe Structure

As the number of slots increases in the MAC Superframe structure, the timing of BI increases if BO > SO. But this timing of BI is reduced by 50% if BO = SO. With this condition BO = SO, the time is distributed among all the slots (active and inactive periods) of Superframe and in the returns the higher collision happen, retransmission of the collided packets, higher delay and higher amount of energy consumption of BMSs. These design parameters reduce the performance of MAC protocol which is not acceptable for saturated and high traffic load of WBAN as examined in Tables 3-7. It has also been noticed from the experimental results that the maximum number of slots that are 256, and 512; and the minimum number of slots that are 16, 32, and 64 in the Superframe structure increase and decrease the waiting time of contention-based BMSs and emergency-based BMSs during transmission of sensory data, respectively. Hence, the most favorable and acceptable solution for the efficient design of MAC Superframe is 128 slots with condition BO > SO which performs better in terms of minimum collision, minimum retransmission of the lost packets, lowest delay with higher data reliability and consumes the minimum energy of BMSs.

Table 3: 32 Slots Superframe Structure with data rates 20 kbps and 40 kbps

Data Rate 20kbps				Data Rate 40kbps				Packet Size in a Slot (Byte)
BO==SO	BO>SO			BO==SO	BO>SO			
BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	
0.192	0.384	0.192	0.006	0.096	0.192	0.096	0.003	15
0.384	0.768	0.384	0.012	0.192	0.384	0.192	0.006	30
0.768	1.536	0.768	0.024	0.384	0.768	0.384	0.012	60
1.536	3.072	1.536	0.048	0.768	1.536	0.768	0.024	120
3.072	6.144	3.072	0.096	1.536	3.072	1.536	0.048	240
6.144	12.288	6.144	0.192	3.072	6.144	3.072	0.096	480
12.288	24.576	12.288	0.384	6.144	12.288	6.144	0.192	960
24.576	49.152	24.576	0.768	12.288	24.576	12.288	0.384	1920
49.152	98.304	49.152	1.536	24.576	49.152	24.576	0.768	3840
98.304	196.608	98.304	3.072	49.152	98.304	49.152	1.536	7680
196.608	393.216	196.608	6.144	98.304	196.608	98.304	3.072	15360
393.216	786.432	393.216	12.288	196.608	393.216	196.608	6.144	30720
786.432	1572.864	786.432	24.576	393.216	786.432	393.216	12.288	61440
1572.864	3145.728	1572.864	49.152	786.432	1572.864	786.432	24.576	122880
3145.728	6291.456	3145.728	98.304	1572.864	3145.728	1572.864	49.152	245760
6291.456	12582.912	6291.456	196.608	3145.728	6291.456	3145.728	98.304	491520
12582.912	25165.824	12582.912	393.216	6291.456	12582.912	6291.456	196.608	983040
25165.824	50331.648	25165.824	786.432	12582.912	25165.824	12582.912	393.216	1966080
50331.648	100663.296	50331.648	1572.864	25165.824	50331.648	25165.824	786.432	3932160

Table 4: 64 Slots Superframe Structure with data rates 20 kbps and 40 kbps

Data Rate 20 kbps				Data Rat 40 kbps				Packet Size in a Slot (Byte)
BO==SO	BO>SO			BO==SO	BO>SO			
BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	
0.384	0.768	0.384	0.006	0.192	0.384	0.192	0.003	15
0.768	1.536	0.768	0.012	0.384	0.768	0.384	0.006	30
1.536	3.072	1.536	0.024	0.768	1.536	0.768	0.012	60
3.072	6.144	3.072	0.048	1.536	3.072	1.536	0.024	120
6.144	12.288	6.144	0.096	3.072	6.144	3.072	0.048	240
12.288	24.576	12.288	0.192	6.144	12.288	6.144	0.096	480
24.576	49.152	24.576	0.384	12.288	24.576	12.288	0.192	960
49.152	98.304	49.152	0.768	24.576	49.152	24.576	0.384	1920
98.304	196.608	98.304	1.536	49.152	98.304	49.152	0.768	3840
196.608	393.216	196.608	3.072	98.304	196.608	98.304	1.536	7680
393.216	786.432	393.216	6.144	196.608	393.216	196.608	3.072	15360
786.432	1572.864	786.432	12.288	393.216	786.432	393.216	6.144	30720
1572.864	3145.728	1572.864	24.576	786.432	1572.864	786.432	12.288	61440
3145.728	6291.456	3145.728	49.152	1572.864	3145.728	1572.864	24.576	122880
6291.456	12582.912	6291.456	98.304	3145.728	6291.456	3145.728	49.152	245760
12582.912	25165.824	12582.912	196.608	6291.456	12582.912	6291.456	98.304	491520
25165.824	50331.648	25165.824	393.216	12582.912	25165.824	12582.912	196.608	983040
50331.648	100663.296	50331.648	786.432	25165.824	50331.648	25165.824	393.216	1966080
100663.296	201326.592	100663.296	1572.864	50331.648	100663.296	50331.648	786.432	3932160

Table 5: 128 Slots Superframe Structure with data rates 20 kbps and 40 kbps

Data Rate 20kbps				Data Rate 40kbps				Packet Size in a Slot (Byte)
BO==SO	BO>SO			BO==SO	BO>SO			
BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	
0.768	1.536	0.768	0.006	0.384	0.768	0.384	0.003	15
1.536	3.072	1.536	0.012	0.768	1.536	0.768	0.006	30
3.072	6.144	3.072	0.024	1.536	3.072	1.536	0.012	60
6.144	12.288	6.144	0.048	3.072	6.144	3.072	0.024	120

12.288	24.576	12.288	0.096	6.144	12.288	6.144	0.048	240
24.576	49.152	24.576	0.192	12.288	24.576	12.288	0.096	480
49.152	98.304	49.152	0.384	24.576	49.152	24.576	0.192	960
98.304	196.608	98.304	0.768	49.152	98.304	49.152	0.384	1920
196.608	393.216	196.608	1.536	98.304	196.608	98.304	0.768	3840
393.216	786.432	393.216	3.072	196.608	393.216	196.608	1.536	7680
786.432	1572.864	786.432	6.144	393.216	786.432	393.216	3.072	15360
1572.864	3145.728	1572.864	12.288	786.432	1572.864	786.432	6.144	30720
3145.728	6291.456	3145.728	24.576	1572.864	3145.728	1572.864	12.288	61440
6291.456	12582.912	6291.456	49.152	3145.728	6291.456	3145.728	24.576	122880
12582.912	25165.824	12582.912	98.304	6291.456	12582.912	6291.456	49.152	245760
25165.824	50331.648	25165.824	196.608	12582.912	25165.824	12582.912	98.304	491520
50331.648	100663.296	50331.648	393.216	25165.824	50331.648	25165.824	196.608	983040
100663.296	201326.592	100663.296	786.432	50331.648	100663.296	50331.648	393.216	1966080
201326.592	402653.184	201326.592	1572.864	100663.296	201326.592	100663.296	786.432	3932160

Table 6: 256 Slots Superframe Structure with data rates 20 kbps and 40 kbps

Data Rate 20kbps				Data Rate 40kbps				Packet Size in a Slot (Byte)
BO==SO	BO>SO			BO==SO	BO>SO			
BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	
1.536	3.072	1.536	0.006	0.768	1.536	0.768	0.003	15
3.072	6.144	3.072	0.012	1.536	3.072	1.536	0.006	30
6.144	12.288	6.144	0.024	3.072	49.152	3.072	0.012	60
12.288	24.576	12.288	0.048	6.144	98.304	6.144	0.024	120
24.576	49.152	24.576	0.096	12.288	196.608	12.288	0.048	240
49.152	98.304	49.152	0.192	24.576	393.216	24.576	0.096	480
98.304	196.608	98.304	0.384	49.152	786.432	49.152	0.192	960
196.608	393.216	196.608	0.768	98.304	1572.864	98.304	0.384	1920
393.216	786.432	393.216	1.536	196.608	3145.728	196.608	0.768	3840
786.432	1572.864	786.432	3.072	393.216	6291.456	393.216	1.536	7680
1572.864	3145.728	1572.864	6.144	786.432	12582.912	786.432	3.072	15360
3145.728	6291.456	3145.728	12.288	1572.864	25165.824	1572.864	6.144	30720
6291.456	12582.912	6291.456	24.576	3145.728	50331.648	3145.728	12.288	61440
12582.912	25165.824	12582.912	49.152	6291.456	100663.296	6291.456	24.576	122880
25165.824	50331.648	25165.824	98.304	12582.912	201326.592	12582.912	49.152	245760
50331.648	100663.296	50331.648	196.608	25165.824	402653.184	25165.824	98.304	491520
100663.296	201326.592	100663.296	393.216	50331.648	805306.368	50331.648	196.608	983040
201326.592	402653.184	201326.592	786.432	100663.296	1610612.736	100663.296	393.216	1966080
402653.184	805306.368	402653.184	1572.864	201326.592	3221225.472	201326.592	786.432	3932160

Table 7: 512 Slots Superframe Structure with data rates 20 kbps and 40 kbps

Data Rate 20kbps				Data Rate 40kbps				Packet Size in a Slot (Byte)
BO==SO	BO>SO			BO==SO	BO>SO			
BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	BI (sec)	BI (sec)	SD (sec)	A Slot Duration (sec)	
3.072	6.144	3.072	0.006	1.536	3.072	1.536	0.003	15
6.144	12.288	6.144	0.012	3.072	6.144	3.072	0.006	30
12.288	196.608	12.288	0.024	6.144	98.304	6.144	0.012	60
24.576	393.216	24.576	0.048	12.288	196.608	12.288	0.024	120
49.152	786.432	49.152	0.096	24.576	393.216	24.576	0.048	240
98.304	1572.864	98.304	0.192	49.152	786.432	49.152	0.096	480
196.608	3145.728	196.608	0.384	98.304	1572.864	98.304	0.192	960
393.216	6291.456	393.216	0.768	196.608	3145.728	196.608	0.384	1920
786.432	12582.912	786.432	1.536	393.216	6291.456	393.216	0.768	3840
1572.864	25165.824	1572.864	3.072	786.432	12582.912	786.432	1.536	7680
3145.728	50331.648	3145.728	6.144	1572.864	25165.824	1572.864	3.072	15360
6291.456	100663.296	6291.456	12.288	3145.728	50331.648	3145.728	6.144	30720
12582.912	201326.592	12582.912	24.576	6291.456	100663.296	6291.456	12.288	61440
25165.824	402653.184	25165.824	49.152	12582.912	201326.592	12582.912	24.576	122880
50331.648	805306.368	50331.648	98.304	25165.824	402653.184	25165.824	49.152	245760
100663.296	1610612.736	100663.296	196.608	50331.648	805306.368	50331.648	98.304	491520
201326.592	3221225.472	201326.592	393.216	100663.296	1610612.736	100663.296	196.608	983040
402653.184	6442450.944	402653.184	786.432	201326.592	3221225.472	201326.592	393.216	1966080
805306.368	12884901.89	805306.368	1572.864	402653.184	6442450.944	402653.184	786.432	3932160

The slot duration and Superframe duration (SD) are the same in BO=SO and BO >SO with their respective data rates. With higher data rate, the transfer speed for transmission of a patient's data is higher and transmits data in 50% less timing as compared to the lower data rate. Fig. 6 and Fig.

7 explain the performance of MAC Superframe structure which consists of 16, 32, 64, 128, 256, and 512 slots. For 16 slots of MAC Superframe structure, the collision of a patient's data starts very quickly in both conditions (a) BO > SO and (b) BO = SO. This happens in (a) due to limited 16 slots and the BC announces a new BI very frequently. With a higher collision in (a), BMSs retransmit the collided packets which increase delay with lower data reliability and degrades the performance of MAC protocol. In condition (b), the BC actives an inactive period and distributes the timing of SD to all active slots (active + inactive slots) of Superframe. The activation of all slots reduces 50% timing of BI and the BC announces a new BI earlier as compared with BO > SO. This short time period affects data reliability performance of MAC Superframe structure where all BMSs cannot contend to access channel and transmit data in the short time. With this short time, the collision becomes high and BMSs retransmit the collided data packet with higher delay as depicted in Fig. 6 and Fig. 7.

The MAC Superframe structure of 32 and 64 slots have the same challenging problems as addressed of Superframe structure of 16 slots. Comparatively, the performance of 64 slots of MAC Superframe structure is better as compared to 32 slots of MAC Superframe structure, as shown in Fig. 6 and Fig. 7. The performance degradation of 32 slots of MAC Superframe structure starts quickly when the traffic loads reach to 2.7 as compared to 64 slots of Superframe structure starts down at traffic load 3.1. Most of the reasons have been discussed as aforementioned for 16 slots of Superframe and the other reason is that each BMS exchanges eleven types of commands with a BC in the beacon-enabled mode for transmitting the patient's data as depicted in Fig. 8. With these exchange of messages, BMSs face higher collision, higher delay with lower data reliability and BMSs consume a maximum amount of energy.

The 128 slots of the MAC Superframe outperforms as compared to 16, 32, and 64 slots but the collision starts suddenly at average traffic load of 3.8, as shown in Fig. 6 and Fig. 7. The 256 and 512 slots of the MAC Superframe structure outperform as compared to all slots but the activation of 256 slots become 512 slots and the activation of 512 slots becomes 1024 slots. The success rate of both 256 and 512 slots is 100% with the ignorable collision. However, the activation of all slots and the designing of slots beyond of 128 consumes a higher amount of energy of BMSs because an inactive period of Superframe is used for sleeping. With a higher number of slots also increase the idle listening time of BMSs and BC invokes the new BI after a long time as noticed in the simulation.

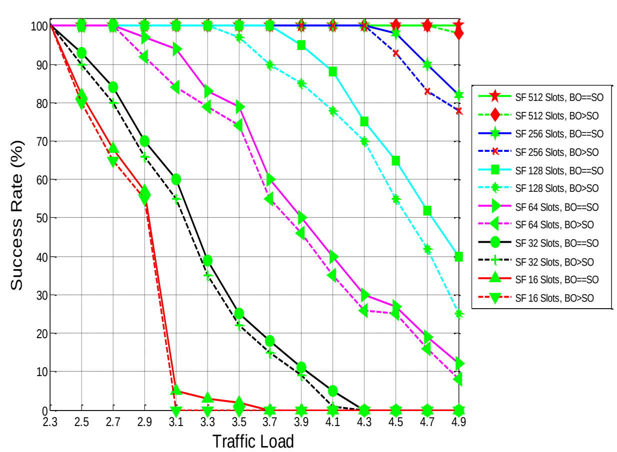

Fig. 6: Success Rate vs Traffic Load with Data Rate 20 kbps

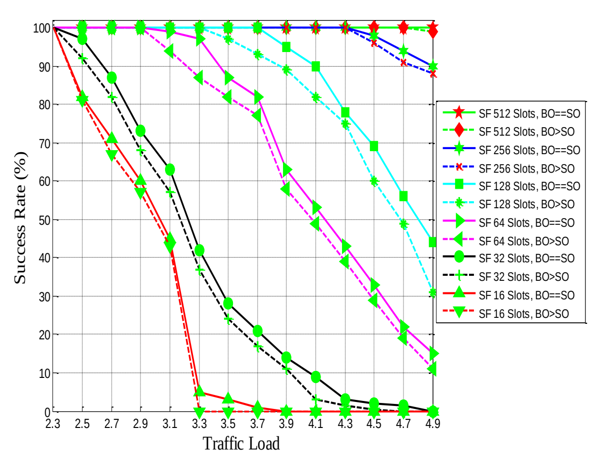

Fig. 7: Success Rate vs Traffic Load with Data Rate 40 kbps

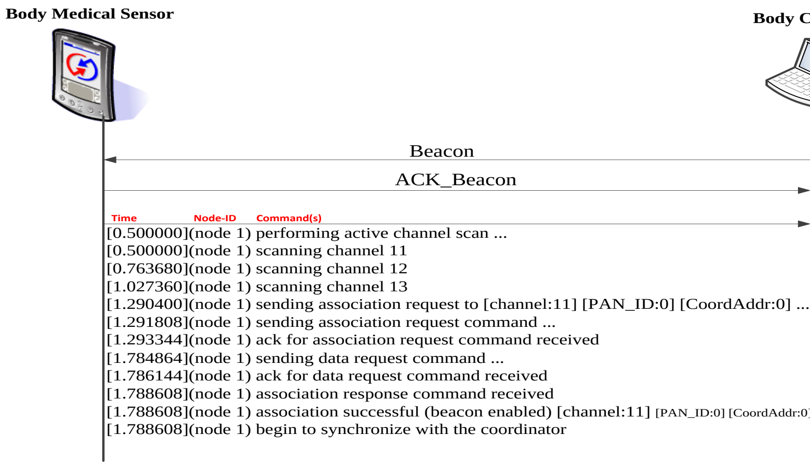

Fig. 8: BMSs Communication in Beacon-Enabled mode

4.3.2 Energy Consumption impacts on different Slots of MAC Superframe structures

The heterogeneous nature of a patient's data in WBAN requires a sufficient energy during monitoring of vital signs and frequently transmission of sensory data to BC. Fig. 9 shows the energy consumption of BMSs with the whole active slots which is the combination of active and inactive periods and the default (active) slots of MAC Superframe structure. The energy consumption of BMSs is twice if BO = SO is used as described values of X, Y, and Z in Fig. 5. In this situation, the BC actives an inactive period of the Superframe structure whereas the highest energy consumption of BMSs has been seen for 16 slots of MAC Superframe structure as depicted in Fig. 9. The reason behind is that the BC distributes the timing of 16 slots among 32 slots of Superframe structure and BC announces the new beacon interval very frequently as compared to BO > SO for 16 slots. With this significant change in the slots arrangement, the performance of MAC Superframe structure is degraded in terms of higher collision, higher delay with the lowest data reliability, higher number of the retries for submission of the collided data and BMSs consume sufficient amount of energy. The high energy consumption of 16 slots of MAC Superframe structure is due to limited slots which create overhead for heterogeneous nature of a patient's data in terms of higher collision, higher delay with lowest data reliability and high energy consumption of BMSs during contention and emergency-based transmission of life-critical data. These types of challenging problems are not acceptable for life-critical data. Further, the energy consumption of 32 slots of the whole active slots (inactive + inactive slots) of Superframe structure is a bit minimum as compared to the whole active of 16 slots, as shown in Fig. 9. However, the energy consumption of the whole active 32 slots is higher as compared to the default 32 slots and the remaining slots of Superframe structures. Hence, the lowest energy consumption is of 512 slots of Superframe structure, the second and third lowest energy consumption is of 256 and 128 slots, respectively. It is concluded from the experimental results that for high load heterogeneous nature of a patient's data requires 128 slots of MAC Superframe structure which is more suitable to enhance the performance of MAC protocol without compromising data reliability and higher energy consumption of BMSs. The reason is that the higher slots that are 256 and 512 increase the idle listening time and BC announces a new BI after a long time of period. In this situation, those BMSs that have performed five times backoff for channel access, they have need to wait for a long time period for next announcement of BI. Thus, the energy consumption of BMSs is high due to a long time period which suffers the patient's life.

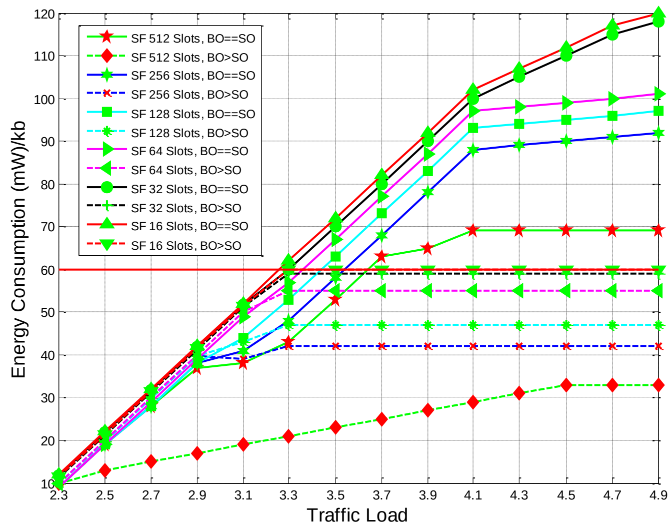

Fig. 9: Average Energy Consumption per BMS

4.3.3 Phase Two: The Proposed EETP-MAC Protocol

The performance of the EETP-MAC protocol is compared with IEEE 802.15.4 [29], LTDA-MAC [19], and PLA-MAC [20]. The values of BO=10 and SO=9 are configured in NS-2 under package 2.34 for all MAC protocols. IEEE 802.15.4 MAC provides 16 slots with BI is 49.152 seconds (983040 symbols), SD is 24.576 seconds, and a slot duration is 1.536 seconds. The LTDA-MAC provides 32 slots in the MAC Superframe structure with BI is 98.307 seconds (1966080 symbols), SD is 49.152 seconds, and a slot duration is 1.536 seconds. The proposed EETP-MAC and PLA-MAC provide 128 slots in the MAC Superframe structure. However, their provided functionalities and working directions of slots allocation to different types of a patient's data are dissimilar. The new announcement of BI is after 393.216 seconds (7864320 symbols), SD is 196.608 seconds, and a slot duration is 1.536 seconds.

Fig. 10 depicts the comparison of average packet delivery of the MAC Superframes. Each BMS is given a specific amount of time to transmit the data packet to BC. As more BMSs transmit data packets, the collision increases. The reason is that IEEE 802.15.4 [29] provides limited sixteen slots and sixteen BMSs perform contention to access channel in the available fixed seven slots of CAP period. During contention to access channel, the BC announces the new BI after 49 seconds which does not provide sufficient time for all BMSs to contend and get a channel access. The BC allocates seven guaranteed slots of CFP period to those BMSs that accessed a channel access in CAP. Due to limited slots and the frequent announcement of a new BI, the patient's data confronts the highest delay as the number of data packets increase for transmission to BC as depicted in Fig. 10 which is not acceptable for real-time patient's data. The same situation is also noticed in LTD-MAC [19] whereas few number of data packets are transmitted in the same BI of CAP period and the maximum number of data packets are transmitted in the next announcement of BI. As the number of packets increases for transmission, the collision rate increases as provided thirty-two slots. Both IEEE 802.15.4 and LTDA-MAC [19] do not classify the patient's data into four classes as described in the EETP-MAC protocol. The PLA-MAC protocol [20] reduces delay during contention, allocation of slots and transmission of a patient's data as it provides 128 slots as compared to the addressed protocols. The delay increases gradually after the fifth BMS because all four types of the patient's data perform contention in the fixed slots of CAP, as shown in Fig.

10. The allocation of CFP slots in the PLA-MAC [20] take considerable a higher amount of time as BC cannot allocate slots to all data packets in the same Superframe duration due to the fixed slots in CAP period and contention. The contention increases collision whereas BMSs retransmit the collided data packets which degrade the performance of MAC protocol. With this collision, the BC allocates the CFP slots to BMSs in the next announcement of BI. The lowest average packet delivery delay has noticed in the EETP-MAC protocol. The judgment is that CAP period provides 24 slots to contention-based BMSs and BC allocates the guaranteed slots of CFP periods in the same interval without waiting for the next announcement of BI.

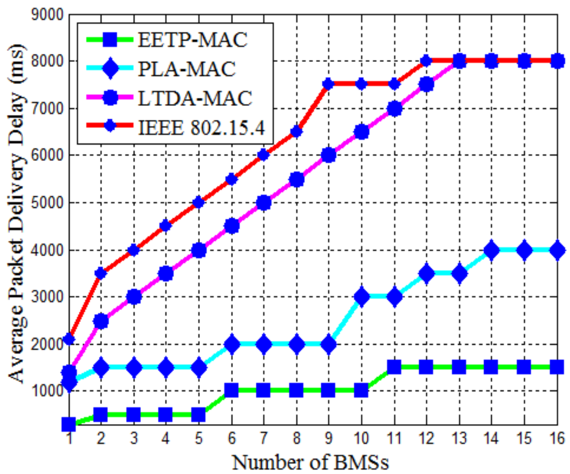

Fig. 10: Average Packet Delivery Delay Versus No. of BMSs

The delay-driven packets in the EETP-MAC are RCD and CD while in PLA-MAC [20] are RP and CP. These delay-driven packets need to be delivered in the specific amount of time to BC. IEEE 802.15.4 MAC [29] and LTDA-MAC [19] protocols do not allocate dedicated slots to emergency data and the allocation of slots to the life-critical data are based on the contention as aforementioned. Similarly, the PLA-MAC uses contention in the CAP period for allocating of slots to both delay-driven life-critical data. This protocol provides dedicated DTS and ETS slots for delay-driven packets but BC allocates dedicated slots to those BMSs that accessed a channel access in the CAP period. Due to this reason, the collision becomes high and the BC takes considerably a higher amount of time during preemption of the non-emergency data from the dedicated slots on the arrival of delay-driven data packets as depicted in Fig. 11. Further, the transmission of delay-driven packets in the PLA-MAC [20] is transmitted in the next BI as the BC re-allocates slots for delay-driven packets. The proposed EETP-MAC provides dedicated slots SLTVS and SHTVS for delay-driven CD and RCD data packets, respectively. The detection of low or high threshold values of vital signs, the particular BMS does not contend for channel accessing but it transmits an alert signal to the slot of BC i.e. LT_B or HT_B for allocation of guaranteed time slot. As shown in Fig. 11, the EETP-MAC allocates dedicated slots to emergency-based BMSs without performing of such preemption activities and is a considerably minimized delay for delay-driven packets.

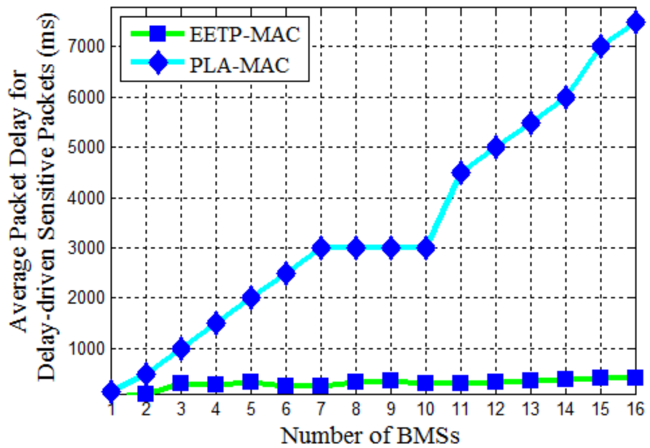

Fig. 11: Average Packet Delivery Delay for Delay-driven Sensitive Packets Versus No. of BMSs

Throughput can be defined as the number of successfully received data packets by the BC in per unit time. As the number of BMSs increases for data transmission, the throughput of all protocols increase. The throughput of IEEE 802.15.4 MAC protocol grows gradually in increasing order up to BMS 7 as this protocol provides seven slots in the CAP period. Afterward, the throughput of IEEE 802.15.4 becomes constant and does not grow in increasing order as shown in Fig. 12. The LTDA-MAC provides fixed slots in the CAP period and supports the maximum throughput for 9 BMSs. The throughput of LTDA-MAC also becomes invariant as more BMSs transmit data whereas they exceed the traffic load in the allocated slots of CAP period. The throughput of PLA-MAC protocol is better as compared to IEEE 802.15.4 MAC and LTDA-MAC as shown in Fig. 12. The PLA-MAC protocol provides 20 slots in CAP period and the throughput gradually increases up to 9 BMSs. Similarly, this protocol also exceeds the traffic load and the throughput becomes invariant. The reason is that all four types of a patient's data perform contention in the fixed 20 slots of CAP. The EETP-MAC provides 24 slots and in the non-emergency situations, all four types of BMSs perform contention in the CAP period. In an emergency situation, only two types of BMSs perform contention. Thus, the throughput of the EETP-MAC outperforms as compared to all MAC protocols, as shown in Fig. 12.

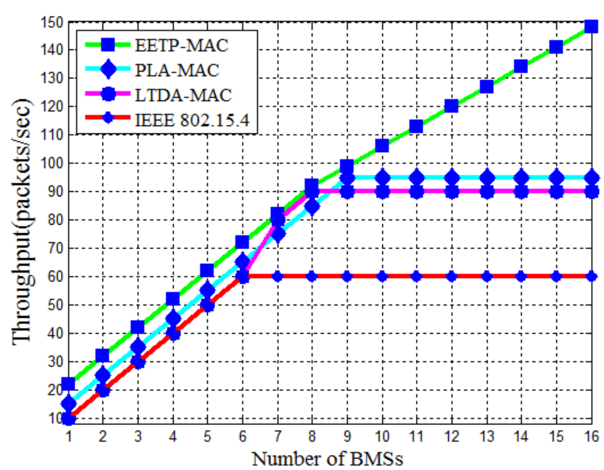

Fig. 12: Throughput Versus No. of BMSs

Fig. 13 evaluates the energy consumption of BCs for 16, 32 and 128 slots of their respective MAC Superframe structures. IEEE 802.15.4 provides fixed 7 slots in the CAP period whereas the sixteen BMSs perform contention to access channel. The contention is reached to the highest peak due to limited 16 slots whereas the collision ratio grows to the highest point. Moreover, the BC announces a new BI after 49 seconds which is not sufficient time for BMSs to contend and transmit data in the same BI. Thus, the energy consumption of BC is the highest. The energy consumption of BC in the LTDA-MAC increases gradually due to limited slots in CAP period, high traffic load, and the BC announces a new BI after 98 seconds whereas all sixteen BMSs do not success to contend and transmit their data in CFP period. The PLA-MAC and the proposed EETP-MAC provide 128 slots and their energy consumption is low as compared to the aforementioned MAC protocols. The PLA-MAC provides 20 slots in the CAP period and the energy consumption is high due to the contention of four types of a patient's data and the BC keeps active all slots of MAC Superframe structure. As the traffic load exceeds the certain thresholds, the energy consumption becomes high. The EETP-MAC provides 24 slots in the CAP period and the energy consumption is the lowest as compared to the addressed MAC protocols. The reason behind is that only two types of non-emergency data perform contention in the CAP period and in an emergency situation, the BC activates the dedicated slots of the CFP period.

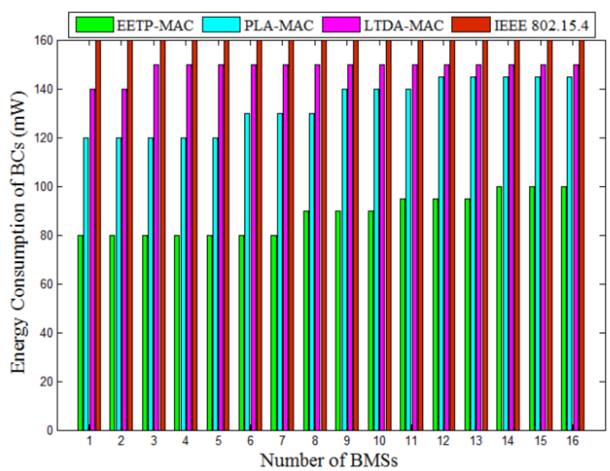

Fig. 13: Energy Consumption of BCs Versus No. of BMSs

The highest energy consumption of BMSs has been noticed in IEEE 802.15.4 and LTDA-MAC as shown in Fig. 14. Both protocols provide limited slots, contention-based slots allocation to all BMSs, no dedicated slots have assigned to emergency data without contention, and all BMSs cannot access a channel in the same BI whereas they need to wait for a new BI. Similarly, the energy consumption of the PLA-MAC gradually increases as the number of traffic load increases due to contention and the long waiting time to access channel in the CAP period. The EETP-MAC protocol consumes the minimum energy of BMSs during contention where this protocol provides dedicated slots to emergency and non-emergency based BMSs without interrupting the slots process. The energy consumption constantly increases as the traffic load increases. All types of BMSs transmit data to the BC in the same BI.

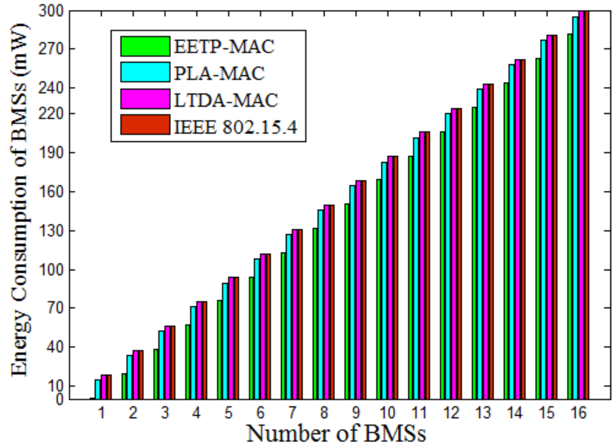

Fig. 14: Energy Consumption of BMSs Versus No. of BMSs

4.3.4 Simulation Effect on different Traffic Loads

The extensive simulations have been performed and compared the results of the proposed EETP-MAC protocol with the state-of-the-art MAC protocols. Now, the performance of the proposed protocol is measured with varying traffic loads from 1 kbps to 7 kbps. The same simulation parameters are used in this part of a simulation as depicted in Table 1 for 12 BMSs.

The proposed EETP-MAC protocol allocates slots to all types of BMSs without delay and four types of a patient's data can get easily slot access in the CFP period as compared to the state-of-the-art MAC protocols, as shown in Fig. 15. The IEEE 802.15.4 provides 7 GTS slots in the CFP and the delay increases as the traffic load increases. In similar, the LTDA-MAC has also higher delay during allocation of GTS slots to BMSs. The PLA-MAC protocol shows considerably a lower delay as compared to IEEE 802.15.4 and LTDA-MAC protocols but the delay increases as if more BMSs transmit data, as shown in Fig. 15.

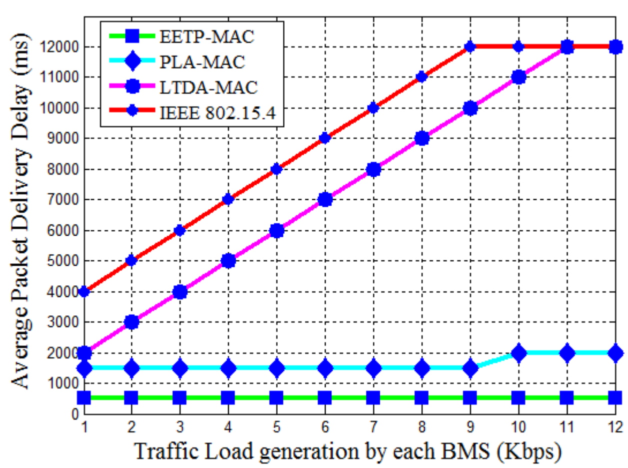

Fig. 15: Average Packet Delivery Delay Versus Traffic load by each BMS

The average delay for delay-driven packets is compared with PLA-MAC protocol as shown in Fig. 16. The highest delay is noticed in the PLA-MAC due to contention-based slots allocation to emergency BMSs. The BC allocates DTS slots of CFP period to those BMSs that accessed a slot of CAP. The emergency-based BMSs must perform CCA to occupy ETS slots if all DTS slots are not empty. The EETP-MAC allocates dedicated slots to the life-critical vital signs without need of contention but BMS transmits an alert signal to the particular slot of a low or high threshold. With this process, the slot allocation delay is reduced to the life-critical data.

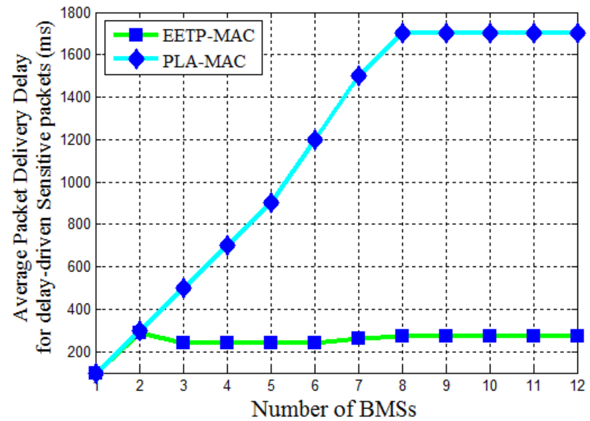

Fig. 16: Average Delay for Delay-Driven Packets Versus Traffic load

Fig. 17 compares the throughput of the proposed EETP-MAC with the state-of-the-art MAC protocols. It has been observed from experimental results that the EETP-MAC protocol transmits data packets in 30 kbps and achieves the maximum throughput without delay because it provides dedicated slots. Moreover, all types of BMSs transmit data in the same BI of Superframe. The slot allocation policy in PLA-MAC is based on the contention whereas each BMS tries to win a channel access. As more BMSs generates traffic, the throughput does not grow and becomes fixed. The reason is that life-critical data perform CCA to ensure collision-free transmission during allocation of ETS slots. The throughput performance of LDTA-MAC is better than IEEE 802.15.4 as IEEE 802.15.4 provides 7 CFP slots and does not increase the throughput from the first transmission due to the limited time of BI and contention-based slot allocation.

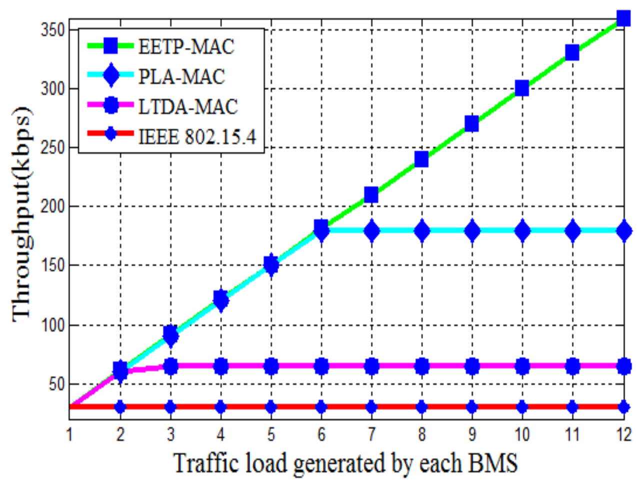

Fig. 17: Throughput Versus Traffic Load

Fig. 18 and Fig. 19 evaluate energy consumption of BCs and BMSs, respectively. The highest energy consumption of the BCs are of IEEE 802.15.4 and LTDA-MAC due to limited slots, a higher number of contention of BMSs to access channel, and the announcement of a new BI repeatedly. With these degradation, the collision ratio is high and the BC consumes a maximum amount of energy. In PLA-MAC, the energy consumption of the BC is minimum as compared to addressed MAC protocols but it is higher than the EETP-MAC. The reason is that the BC of the proposed MAC provides separated and dedicated slots to all types of BMSs without consuming a high amount of energy during slots allocation process in the same BI. As discussed in Fig. 14, the energy consumption of BMSs is the same as depicted in Fig. 19.

The proposed EETP-MAC performs better in terms of maximum throughput, the lowest average packet delay and minimum energy consumption of BMSs during contention and allocation of slots as compared with the state-of-the-art MAC protocols.

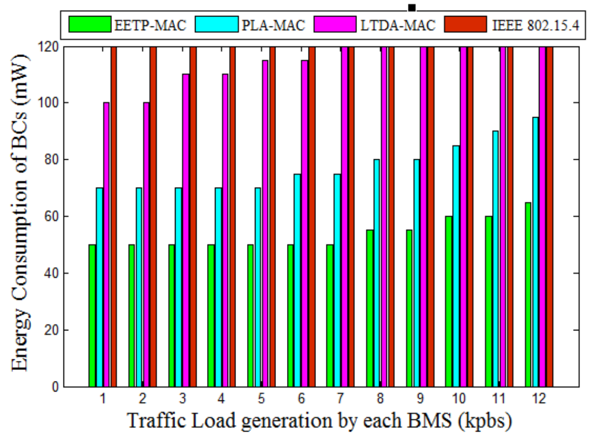

Fig. 18: Energy Consumption of BCs Versus Traffic Load

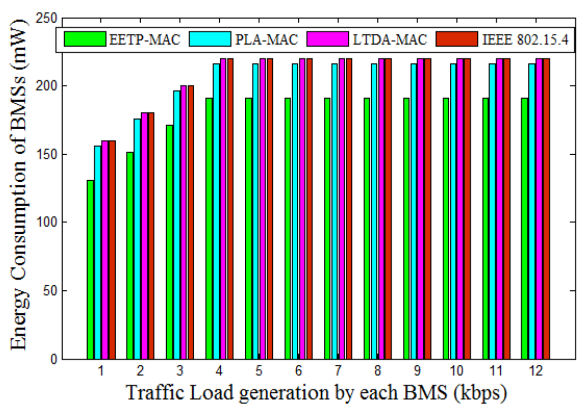

Fig. 19: Energy Consumption of BMSs Versus No. of BMSs

5 Conclusion

WBAN is a dominant technology with the potential of carrying out revolutionary changes in the healthcare domain. The state-of-the-art MAC protocols have deficiencies of the design of MAC Superframe structure in terms of a limited number of slots in the Superframe, contention-based slot allocation to life-critical data and allocation of the CFP slots in the announcement of BI. These issues degrade the performance of MAC protocols in terms of higher collision, delay with lowest data reliability and consumes a high energy by BMSs. To address these challenging issues, a novel EETP-MAC protocol is proposed and compared with existing MAC protocols. The channels of the EETP-MAC are designed to avoid interference with each other which provides sufficient bandwidth to the channels. With dynamic slot allocation, the critical and reliability-oriented packets are transmitted in their dedicated slots of the CFP period without performing any contention. Thus, the reliability of the critical data is assured with the transmission of an alert signal to the particular slot of emergency beacon. The delay and energy consumption of BMSs are minimized with the utilization of the dedicated slots to both types of a patient's data and transmission of data in the same BI. The improvements are due to the uses of a novel design of the MAC Superframe structure which is based on the patient's data prioritization and load adaptation.

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