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MOBILE & WIRELESS HEALTH

TraPy-MAC: Traffic Priority Aware Medium Access Control Protocol for Wireless Body Area Network

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Abstract Recently, Wireless Body Area Network (WBAN) has witnessed significant attentions in research and product development due to the growing number of sensor-based applications in healthcare domain. Design of efficient and effective Medium Access Control (MAC) protocol is one of the fundamental research themes in WBAN. Static on-demand slot allocation to patient data is the main approach adopted in the design of MAC protocol in literature, without considering the type of patient data specifically the level of severity on patient data. This leads to the degradation of the performance of MAC protocols considering effectiveness and traffic adjustability in realistic medical environments. In this context, this paper proposes a Traffic Priority-Aware MAC (TraPy-MAC) protocol for WBAN. It classifies patient data into emergency and non-emergency categories based on the severity of patient data. The threshold value aided classification considers a number of parameters including type of sensor, body placement location, and data transmission time for allocating dedicated slots patient data. Emergency data are not required to carry out contention and slots are allocated by giving the due importance to threshold value of vital sign data. The contention for slots is made efficient in case of non-emergency data considering threshold value in slot allocation. Moreover, the slot allocation to emergency and non-emergency data are performed parallel resulting in performance gain in channel assignment. Two algorithms namely, Detection of Severity on Vital Sign data (DSVS), and ETS Slots allocation based on the Severity on Vital Sign (ETS-SVS) are developed for calculating threshold value and resolving the conflicts of channel assignment, respectively. Simulations are performed in ns2 and results are compared with the state-of-the-art MAC techniques. Analysis of results attests the benefit of TraPy-MAC in comparison with the state-of-the-art MAC in channel assignment in realistic medical environments.

Keywords Medium access control · Superframe structure · Traffic prioritization · Wireless body area networks

Introduction

The diabetes and other chronic diseases are the major causes of death of patients in medical care as reported by World Health Organization (WHO) [1]. The aged people and patients need continuous monitoring of diseases which is a costly practice of medical treatment particularly for low-income and developing countries. As another new domain for wireless communication technology [2], Wireless Body Area Network (WBAN) is the cost-affordable solution, and thus, witnessed significant attention in different healthcare applications for the early detection of abnormality of diseases [3]. WBAN consists of tiny Bio-Medical Sensors (BMSs) which are employed to monitor vital signs including heartbeat, ECG, EEG, EMG, blood pressure, respiratory rate, temperature, and glucose [4–6]. The characteristics of these vital signs are known as heterogeneous nature of

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patient data. There are majorly three methods for deployment of BMSs including in-body implantation, on-body wearable, and off-body near placement for monitoring different vital signs of patient as shown in Fig. 1 [7, 8]. In implantation, sensors are inserted inside patient body to monitor kidney, lungs, and liver. In wearable, BMSs are sewed in shirt or placed on patient body to monitor ECG, EMG, and blood pressure. In near placement, BMSs are kept near patient body to monitor body position, running, walking, arm positions, and other physical health conditions. These BMSs are connected with a Body Area Network Coordinator (BANC) following star network topology. Table 1 depicts major implantable and wearable BMSs with data rates, output characterization, topology, and their functionalities.

In literature, monitoring data of patient has been explored using a number of categorization including routine and abnormal data, emergency and non-emergency data [9, 10]. In [11], a classification considers Critical Data Packet (CP), Reliability data Packet (RP), Delay data Packet (DP), and Ordinary Packet (OP) [3]. These classifications have not considered low and high threshold values of vital signs in their emergency data categorization. The classification assists in efficient and effective channel assignment in delivered of patient data to medical doctors without loss and delay with minimum energy consumption of BMSs. The slot allocation policy for patient data of IEEE 802.15.4 MAC is based on the contention in Contention Access Period (CAP) [12, 13]. BANC assigns guaranteed timeslots in the Contention-Free Period (CFP) for data transmission. The contention degrades the performance of 802.15.4 due to the limited channels in Superframe structure resulting in collision, higher delay and lower data reliability in transmission [14, 15]. The retransmission of collided data consumes additional energy. The dedicated channels to emergency data based on the severities of vital signs without contention is not considered. Moreover, 802.15.4 has not considered slots allocation conflict in terms of equivalent level of vital signs, when patient data is transmitted at the same time to BANC.

Various MAC protocols for WSNs have been suggested for addressing the aforementioned challenges by modifying the Superframe structure of 802.15.4 MAC. In [16], the CAP's channels have been divided into four phases and allocation of these channels is based on the contention. In contention, the emergency-based BMS accesses all phases of the CAP period. However, other types of data has not been allowed to contend and access the dedicated channels of emergency data. In [17], the interrupt has been introduced which starts a new session of Beacon interval (BI) any time. However, this suggested MAC stops the slots allocation processes of other BMSs and start new session which reduces the performance of MAC protocol in terms of collision due to the elimination of previous slot allocation. The flag value based channel assignment has been suggested where 1 and 0 represents idle channel and busy channel, respectively [18]. In [19], the dedicated channels have been considered for emergency and non-emergency. However, the allocation of channels is based on the contention without considering severity of data. The slot allocation scheme has no capability to resolve the conflict of slot allocation between the same types of emergency data [19]. The contention has been suggested for emergency and non-emergency based BMSs without allocation of dedicated channels [9]. The contention procedure of 802.15.4 has considered in [10]. Each BMS need to wait for clock synchronization with BANC before contention causing higher delay for emergency data [20]. In [3], the dedicated channels of the CFP period have been assigned after contention. In most of the aforementioned MAC protocols static on-demand slot allocation to patient data has been adopted as the main approach, without considering the type of patient data specifically the level of severity on patient data. This leads to the degradation of the performance of MAC protocols considering effectiveness and traffic adjustability in realistic medical environments. The conflict of slots allocation among BMSs is not considered when BANC receives the equivalent threshold value of vital signs at same time.

In this context, this paper proposes a Traffic Priority-Aware Medium Access Control (TraPy-MAC) protocol. It assigns channels using vital sign threshold value based prioritization of patient data. Specifically, the design of TraPy-MAC is majorly divided into four folds:

- Firstly, a modified super-frame structure is presented using sixty-four slots for enabling contention free slot allocation to emergency patient data.
- Secondly, patient data traffic prioritization is performed aided by low and high threshold value on patient data for reducing contention probability of non-emergency patient data.
- Thirdly, a severity detection algorithm is developed for quantifying criticality on vital sign of patient data, and enabling efficient traffic prioritization.
- Forth, a slot allocation algorithm is developed focusing on severity in vital sign of patient data for effective channel allocation based on the emergent traffic priority.
- Simulations are performed in realistic medical environments for comparatively assessing the performance of the proposed MAC protocols with the state-of-the-art techniques.

The rest of this paper is organized as follows. Comparison of MAC Superframe structures and literatures on MAC protocols have been qualitatively reviewed in Related Work. Traffic Priority-Aware Medium Access Control presents the detail of the proposed TraPy-MAC protocol focusing on the super-frame structure, traffic prioritization, severity detection and slot allocation algorithms. Performance Evaluation discusses comparative performance evaluation considering simulation environments and analysis of results, followed by conclusion made in Conclusion.

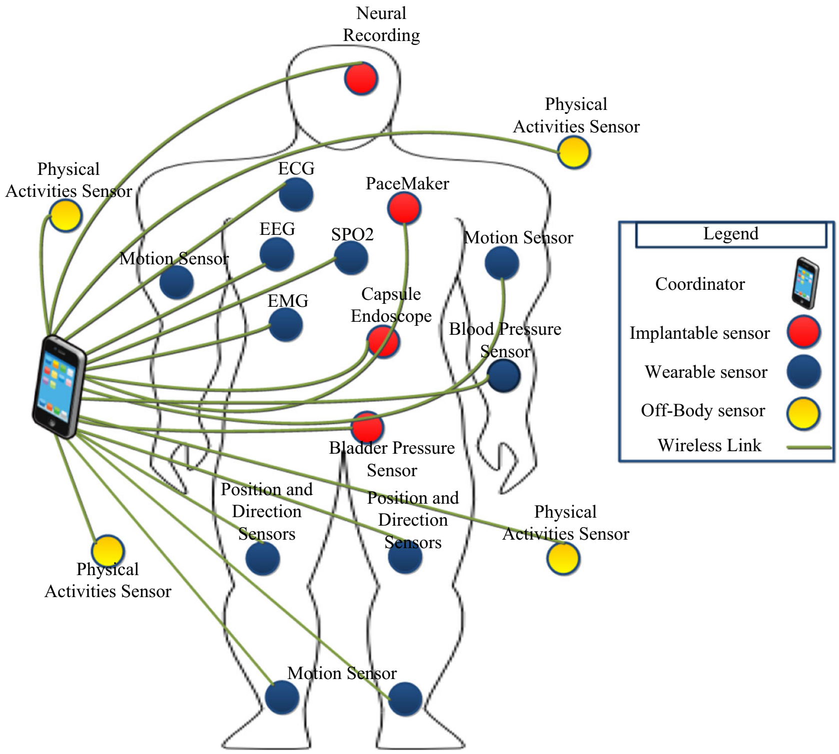


Fig. 1 BMSs monitor health condition of a patient

Related Work

This section presents MAC Superframe structures of IEEE 802.15.4 and IEEE 802.15.6. Both MAC standards are compared based on the features in Superframes in terms of characteristics for WBAN. Moreover, related work section qualitatively reviewed the MAC protocol designs suggested in the literature.

Super-Frame Structure

The MAC Superframe structure of IEEE 802.15.4 [12] comprises of a beacon, CAP, CFP and LPL/ IP. In IEEE 802.15.4 MAC, all BMSs use CSMA/CA access scheme and perform contention to access channel in CAP period. The BANC broadcasts a beacon to all BMSs in the network containing information about synchronization, the address of the BANC, and the next announcement of the beacon interval (BI). In synchronization, BMSs transmit the request for channel association and dissociation to BANC. The address of the BANC is broadcasted to BMSs for remembering it as the head/coordinator to allocate channels and transmit data. The BI is the time period, where each BMS contends and transmits sensory data in the specified amount of time. The IP is used for sleep mode to save energy when a BMS is not being transmitting data. However, the limitations of IEEE 802.15.4 MAC [21] are the limited 16 channels, contention-based channel allocation to BMSs, no dedicated slot allocation based on the severities/criticalities of threshold values without contention, delay with lower data reliability, retransmission of the collided data packets, could not resolve the conflict of slots allocation between same detected threshold values of vital signs, and high energy consumption of BMSs in contention. These limitations severely reduce the performance of the MAC Superframe structure which is not appropriate in emergency situations.

The first draft version of IEEE 802.15.6 for MAC and PHY layers was publicized in 2012 [22]. It presented three types of MAC Superframe structures. The first type is the enabled-Beacon MAC, consisting of a beacon, Exclusive Access Phase (EAP-I-II), Random Access Phase (RAP-I-II), Type (I-II) and CAP period [7–23]. The channel allocation policy to BMSs is based on the contention using CSMA/CA or slotted Aloha schedule access scheme. These scheduling access schemes are implemented on EAP, RAP, and CAP periods. Further, the TYPE-I is denoted for critical data and TYPE-II is denoted for non-critical data. However, the limitations of IEEE 802.15.6 MAC Superframe structure are contention based channels allocation to BMSs regardless having of emergency or non-emergency data, no classification of emergency data into low and high threshold values; and no allocation of dedicated slots for emergency data in the life-critical situations. These degraded performance of MAC protocol have been discussed in IEEE 802.15.4 MAC. The second type of MAC is the Non-beacon MAC [7], allocating the entire channels of Superframe to Type-I or Type-II data. The disadvantage is that the BANC cannot transmit data directly to BMSs, but it needs first to transmit an activation alert signal to the recipient BMS. The second disadvantage is that the non-beacon MAC allocates slots to one type of a patient's data at the same time, which is not an appropriate solution in the life-critical situations. The last type is the Non-Beacon without Superframe using predefined periods to transmit TYPE-II data. In this Superframe, the slot allocation to BMSs is based on the contention or post-contention. The limitation of the predefined based slot allocation to one type of data is the wastage of slots.

IEEE 802.15.4 has the capabilities to monitor, detect abnormal conditions, and transmit the sensory data to a BANC with the higher data reliability [24]. Lots of researchers have been modified the Superframe structure of IEEE 802.15.4 MAC and used for WBAN. Table 2 presents characteristics of IEEE 802.15.4 MAC and is comparing with IEEE 802.15.6 MAC. The applications of both MAC standards are different, but due to sensing and monitoring strength of IEEE 802.15.4 MAC, is used to monitor vital signs of a patient's body. IEEE 802.15.4 MAC Superframe structure is flexible in terms of coverage and supports a maximum number of sensors as compared to IEEE 802.15.6 MAC. The limitation of 802.15.4 MAC is a high amount of energy consumption as compared to IEEE 802.15.6. However, the duty cycles reduce the energy consumption of sensors [20]. Both MAC standards use ISM (Industrial, Scientific and Medical) frequency bands for data transmission. The medium for data transmission in IEEE 802.15.6 uses the surface of a human body for wearable sensor and for the implantable sensors uses tissues or skin which damage the skin or tissues of a human body as compared IEEE 802.15.4 uses air as a medium. Moreover, IEEE 802.15.6 MAC is configured with a high data rate. The reason is that the human body is composed by a very large portion of water and fat. Therefore, the data are normally not possible to travel from one sensor to another inside the body. The existing MAC schemes in the literature section show that IEEE 802.15.4 MAC is used for in-body, and on-body data transmission without damage of tissues and skin. The judgment is that IEEE 802.15.4 uses the Specific-Absorption Rate (SAR) eq. [25] for in-body communication which measures the temperature of the sensors before data transmission. The discussion concludes that IEEE 802.15.6 WBAN is the subset of IEEE 802.15.4 WSN and will provide all the benefits to the health domain that have been provided by IEEE 802.15.4 WSN.

MAC Protocols

The suggested Adaptive MAC (A-MAC) [26] and Priority-based adaptive Timeslots Allocation (PTA) [27] protocols consider normal and emergency data. Both types of data perform contention to access channel in the CAP period regardless of importance of emergency data. The BANC allocates guaranteed time slots to those BMSs that obtained a channel access using contention. However, both proposed protocols do not allocate a dedicated slot to emergency data without performing contention. In addition, they do not consider low and high threshold values of vital signs. The suggested Fuzzy Control Medium Access (FCMA) [10] uses the same contention process of channel allocation to BMSs as described in [26]. Further, the slot allocation policy of this MAC protocol is based on predefined rules, which are verified against sensory data of a BMS. Due to the contention-based channel allocation causes collision and BMSs consume high energy by reducing data

Table 1 WBAN Sensors and their functions

Sensor type	Placement	Data Rate	Output characterization	Topology	Task
Accelerometer	Wearable	High	Continuous	Star	Show an orientation of an object in X, Y and Z angles
Gyroscope		High	Continuous		Sense rotation
Blood pressure		High	Discrete		Measures maximum and minimum threshold values
EEG/ECG/EMG		High	Continuous		Measure voltage differences
Humidity		Very Low	Discrete		Observe humidity changes
Blood oxygen saturation (CaO_2)		Very Low	Discrete		Measure absorption ratio in blood oxygen saturation
Pressure		High	Continuous		Measure pressure values
Respiration		High	Continuous		Measure breathing of the patient
Visual sensor		Low/ High	Discrete/ Continuous		Collect attributes of an object such length, location, area
Glucose		High	Discrete		Measure the blood circulation rate in the body
Temperature		Very Low	Continuous		Measure the coolness or hotness of a body
Artificial retina	Implantable	High	Continuous		Collect information from the environment and convert it to the electrical signals
Artificial cochlea		High	Continuous		Implant in ears and helps to convert voice signals into pulses
Camera pill		High	Continuous		Swallow the pill in order to monitor various parts of a body

reliability. These causes reduce performance of MAC protocols in terms of delay, which is not appropriate solution for emergency data. This suggested A-Traffic Load Aware Sensor (ATLAS) [28] protocol classifies the patient data into low-load, moderate-load, high-load and over-load. The same process of contention is followed in this MAC as used in [26, 27]. The data is forwarded using cluster-head to the gateway and then gateway transmits to the central node, which causes delay with high energy consumed by BMSs. Also, this protocol creates overheads due to heavy traffic which is not suitable for low and high threshold values of vital signs that have not been classified accordingly. This suggested Adaptive and Real-Time GTS Allocation Scheme (ART-GAS) [29] protocol divides the patient data into LOW, MEDIUM and HIGH. Using this data, the CSMA/CA hit is successful when a BMS gets access of channel. Otherwise, it is known as CSMA/CA hit-miss. The same challenging problems have been observed in this protocol as discussed in IEEE 802.15.4. The Low-delay Traffic-adaptive Medium Access Control (LTDA-MAC) protocol [21] deals with normal and emergency data. Both of a patient's data uses contention to access channel as similarly highlighted in the aforementioned protocols. The contention creates overheads for nodes causing high delay due to collision with low data reliability and BMSs consume a high energy. These challenging problems affect the performance of MAC protocol and are not suitable for emergency data due to a high amount of delay. Another limitation is that this scheme does not allocate dedicated slots to emergency data without performing contention. The slotted aloha algorithm is used to allocate a channel to critical and non-critical data in the proposed an urgency-based MAC (U-MAC) protocol [30]. Both types of data need wait to transmit data in the pre-reallocated time slots. In waiting period, the nodes consume higher amount of energy which affects data reliability with higher delay and is not appropriate for critical data. The low and high threshold values of vital signs have not been considered in this protocol as similarly observed in other protocols. This suggested R-MAC [9] protocol considers emergency and routine data. The allocation of channel to emergency data is based on the wakeup of main radio of BANC. However, the contention-based slot allocation and conflict of slot allocation to the same threshold values of vital signs have not been considered when a BANC receives threshold values at same time. The delay with lower data reliability and BMSs consume high energy are the challenging problems noticed in this protocol. This suggested Traffic-Aware Dynamic MAC (TAD-MAC) protocol [31] uses *before convergence* and *steady state* phases with support of the Traffic Status Register (TSR) bank. In the *before convergence* phase, each BMS verifies traffic load from TSR bank and waits for a beacon from the BANC before data transmission. In the *steady state* phase, the BANC learns various activities of nodes from TSR bank. This learning and waiting of nodes consume a higher amount of energy which reduces the performance of MAC protocols in terms of lower data reliability with higher data collision. Also, this protocol does not consider low and high threshold values of vital signs for emergency data.

The Priority-based Load Adaptive MAC (PLA-MAC) [3] protocol classifies the patient's data into Critical data Packet

Table 2 Comparison of IEEE 802.15.4 and 802.15.6 based on Superframe.

Characteristics	IEEE 802.15.4	IEEE 802.15.6
Domain-Specific Task	Sensors applications to monitor and detect an events from environments like Home temperature monitoring, pipeline leakage detection, and battlefield, etc.	Specially designed for healthcare related domains
Nature of data	Homogenous	Heterogeneous
Network deployment range	10 to100 Meter	3 to 6 Meter
Network coverage	Scalable	Medium
Support of min-to-max sensors	10 to 65,000	3 to 256
Energy consumption	20 mW to 35 mW	0.01 mW to 40 mW
Frequency band	ISM	ISM and other approved by medical authorities for in/on-body such as UWB PHY
Data transmission medium	Air	Air, on-body, in-body
Data transmission rate	20 Kb/s to Max 250 Kb/s	50Kb/s to Max 10 Mb/s
Safety precautions for deployed environment	Varies situation to situation but uses SAR in WBAN	Yes, use SAR for measuring of temperature in/out organs of a patient
Scheduling access scheme	CSMA/CA, TDMA, FDMA, Aloha	CSMA/CA, TDMA, FDMA, Aloha
Controls overhead	Low	Average
Channel allocation mechanism to end-devices	Contention, polling and alert based	Contention and post-allocation

(CP), Reliability data Packet (RP), Delay data Packet (DP) and Ordinary Packet (OP). The CP is the first highest critical data and needs to allocate the first available channel. The RP is the second priority of data to allocate channel without loss of the packet. The DP is the third priority of data which must be delivered on time. The OP is the fourth priority of a patient's data that can delay. The suggested Superframe comprises of a *beacon, CAP, notification, CFP,* and *LPL*. Further, the CFP period is divided into *Emergency Data Transfer slots* (ETSs) and *Data Transfer Slots* (DTSs). At the beginning of channel allocation, BMSs perform contention to access channel in CAP period. The BANC allocates ETS slots to the emergency-based BMSs whey they obtained a channel access in CAP. The non-emergency based sensors can occupy ETS slots but they need to perform a CCA to ensure collision-free data transmission. Moreover, this protocol uses an equation that calculates criticalities of the detected vital signs and declares either the patient data is normal or emergency data after contention. However, the suggested protocol does not classify emergency data into low and high threshold values, contention-based channel allocation to all BMSs, does not resolve the conflict of slots allocation between BMSs when a BANC receives the same threshold values of vital signs at the same time. These reduce the performance of MAC protocol in terms of high delay with lower data reliability, and retransmission of lose packets is causing of high energy consumption of BMSs. The Superframe structure of MAC scheme-1 [20] comprises of a beacon, CAP, CFP, Emergency Beacon (EB), and IP periods. The proposed scheme-1 divides the patient data into Normal Data (ND), Periodic Data (PD), and Emergency Data (ED). The ND data contains a reading of routine checkup of a patient body such as temperature and glucose. The PD is the request message of a medical doctor which is generated to know the health condition of a patient body based on audio/video. ED contains the highest priority data of a vital sign such as ECG, heartbeat, and respiratory rate. In contention, if the BMS wins the contention then the BANC broadcasts a special beacon for that emergency BMS and allocates slot of the IP period. The decision of data either it is normal or emergency data uses the same equation as used in [3]. However, this scheme-1 considers one type of emergency data and this emergency data does not classify into low and high threshold values. Another drawback is that this scheme cannot resolve the conflict of slots allocation challenging problems as addressed in [3]. Moreover, the PD interrupts the contention of ND and emergency-based BMSs because the doctor can access data of any BMS. These problems degrade performance of MAC in terms of low data reliability due to interruption of PD data, does not consider low and high threshold values of vital signs, and BMSs need clocks synchronization with BANC before data transmission. The Priority-Adaptive MAC (PA-MAC) [16] is proposed by dividing the CAP period into four phases and is introducing Beacon Channel (BC) and Data Channel (DC). The patient's traffic is classified into p1 (emergency data), p2 (on-demand), p3 (normal data), and p4 (non-medical data). The allocation of slots is based on the contention using CSMA/CA scheme. BC handles the three-way handshaking process between BANC and BMSs that included: the channel assignment broadcasts and access requests. In contention, the p1 type of traffic accesses all phases of CAP period. The p2 type of traffic can only access phases 2 to 4. For p3 traffic BMSs can occupy channels of phases 3 and 4. While p4 traffic can occupy channels of phase 4. The distribution of channels among four types of the traffic is the wastage of resource of BANC if any BMS is not having intension to transmit traffic, which cannot occupy any other BMSs, such as p2 and p3. The contention-based channel allocation increases collision causing delay, reduces throughput, and consumes a high energy of BMSs. These limitations and is not allocating dedicated channels to p1 traffic of a patient's data degrade the performance of MAC protocol which is not tolerable as addressed above. Also, this scheme cannot resolve the conflict of slot allocation between the same types of detected data of vital signs which are transmitted at the same time to the BANC. A Multi-Channel MAC (MC-MAC) [18] is proposed to reduce delay and improve the throughput by introducing new fields in the beacon frame. The beacon consists of sender address, beacon period length, Random Access Period (RAP) end, RAP start, Channel state, and inactive duration. This suggested MAC classifies 2.4 GHz frequency into different sub-frequency to avoid channel interference and collision of data. Before contention of BMSs to access channel, the BANC broadcasts a beacon frame to BMSs about the availability of channel by using channel state with flags 1 (channel available) or 0 (channel not available). With this beacon, the BMSs contend or need to wait for next interval of beacon. The BANC allocates channels to BMSs by using contention but the performance of MAC protocol is degraded in terms of increasing delay, reducing throughput, and consumes a high energy of BMSs which is not tolerable for emergency data in the life-critical situations. The proposed MAC of this paper [19] introduces Emergency *Contention Period (ECP), Advertisement Beacon (AB), Periodic Contention Access Period (PCAP), Notification Beacon (NB),* and *Data Transmission Period (DTP)* to handle emergency and periodic data of a patient. In emergency situation, the emergency-based BMSs contend to access channel in the ECP period and the BANC informs the whole network about the emergency data by setting the value of a flag is "set" with the support of AB message. The periodic or non-emergency based BMSs uses PCAP using contention and the BANC allocates DTP slots to those BMSs that obtained a channel access in PCAP. Also, the allocation of DTP slots is based on the transmission of NB. This suggested MAC scheme provides dedicated channels to emergency and non-emergency data but slot allocation is based on the contention which increases collision, reduces throughput, and consumes a higher energy of BMSs. In addition, this scheme cannot resolve the conflict of slot allocation between the same types of emergency data when a BANC receives at same time.

Traffic Priority-Aware Medium Access Control

In this section, a traffic priority based MAC protocol is proposed focusing on superframe structure, traffic prioritization, severity detection and slot allocation algorithms.

Super-Frame Structure

The TraPy-MAC Superframe structure consists of a beacon (B), CAP, Notification (N), Contention Slot (CS), CFP, DTS, Emergency-Beacon (EB), ETS, and IP/LPL as shown in Fig. 2. The proposed Superframe provides sixty-four slots. We assign fifteen slots to CAP and four slots is to CS. Similarly, the BANC assigns twenty-one slots to DTS and twenty slots is to ETS. The B, N, and EB is assigned a single slot. Moreover, the TraPy-MAC is based on the beacon-enabled mode and provides contention-free allocation of guaranteed timeslots (GTSs) to support transmission of emergency data. At the beginning of data transmission, the BANC broadcasts a beacon frame containing address of the BANC, synchronization, and announcement of a new Beacon Interval (BI). The address represents the BANC as central node of the topology. Each BMS uses synchronization and is actively scanning for channels in the CAP period. BI defines the time duration between two consecutive beacons. It comprises of active and inactive periods as shown in Fig. 2. The active period is represented as Superframe Duration (SD), which divides different timeslots for data transmission that is B, CAP, N, CS, DTS, ETS, and EB. The LPL mode is used by BMSs to save energy when there is no data transmission being performed. The SD and BI are associated with Superframe Order (SO) and Beacon Order (BO), respectively, which is transmitted by BANC in the beacon frame to BMSs. SO manages the durations of the active periods of the TraPy-MAC as described in Eq. 1. While BO manages the durations of the whole Superframe of TraPy-MAC, as described in Eq. 2.

$$SD = \mathrm{aBaseSuperframeDuration} * 2^{SO} \tag{1}$$

$$BI = \mathrm{aBaseSuperframeDuration} * 2^{BO} \tag{2}$$

Equations 1 and 2 use *aBaseSuperframeDuration*, which shows the minimum duration of slots in TraPy-MAC. The *backoff Exponent* (BE) period calculates the backoff delay for accessing channel and tries to reduce collision. Therefore, BE depends on size of the Contention Window (CW) as described in Eq. 3.

$$CW = 0\ \ To\, 2^{BE}-1 \tag{3}$$

IEEE 802.15.4 provides a minimum value of BE (*macMinBE*) that is 3. The maximum value of BE (*aMaxBE*) is 5. We set value of *aMaxBE* is 4 because CAP period provides sufficient slots. Therefore, the minimum size of CW is 0 to 7 and maximum size of CW is 0 to 15 for accessing CAP.

Traffic Prioritization and Contention Reduction in Slot Allocation

This paper categorizes the patient's traffic into OP, DP, RP, and CP. OP contains a normal reading of vital signs, that is normal temperature and glucose level. This data can be delayed without reliability constraints. DP comprises of audio/video based information of a patient such as sleeping position, run, walking, and hands shaking. It accepts minimum delay with loss. RP contains reading of high threshold values of vital signs that are high respiratory rate and high blood pressure. The RP data need to be delivered with minimum packet loss and delay. CP comprises of low threshold values of vital signs such as low heart rate and low respiration. This type of data does not accept any delay and packet loss that need to be delivered with higher reliability. Moreover, OP and DP are non-emergency data and allocation of DTS slots is based on the contention. In emergency situations, OP and DP-based BMSs do not contend to access channel, but they transmit alert signals using EB slot of BANC.

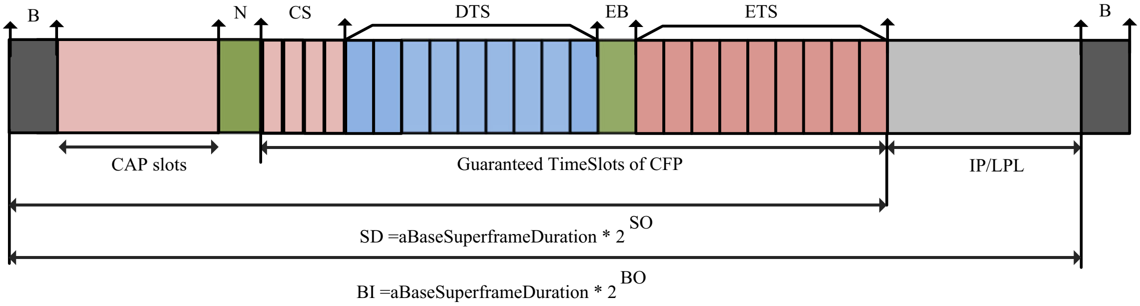


Fig. 2 The proposed superframe of TraPy-MAC

The contention-based slot allocation to BMSs increases collision of data packets, which causes delay with lower reliability due to retransmission of the loss packets and BMSs consume a high energy. The TraPy-MAC provides sufficient time period for non-emergency based BMSs to contend and transmit data without waiting for next announcement of BI. Figure 3 shows the process of the reduced contention during allocation of slots for non-emergency data with the support of Eq. 3. In contention, each BMS tries for accessing channel in rounds maximum 0 to 15 times. The BANC allocates DTS slots to those BMSs that obtained a channel access in CAP. Further, the BMS uses CS slot for data transmission if it does not get channel access by exceeding threshold value of the contention. For accessing CS, the BMS performs twice Clear Channel Assessment (CCA) to ensure collision-free transmission of data using slot N of the TraPy-MAC if that BMS could not get access channel. Moreover, the medical doctors can retrieve reading of any BMS with the support of slot N and transmit data using DTS slots. The Contention-based channel access probability is derived as shown in the following.

The contention-based BMSs are OP and DP transmit data in CAP with a probability of successful channel allocation S with maximum (*aMaxBE*) 4 backoff as expressed in Eq. (4).

$$S = \sum_{C=1}^{4} p\,(1-p)^{C-1} \tag{4}$$

Where S is the probability of the successful channel access, C is the backoff with maximum 4 times and p is the probability of a clear channel access. The probability of clear channel access accomplishes with the support of CCA time period p for n number of BMSs in the network as expressed in Eq. (5).

$$p = (1-q)^{n-1} \tag{5}$$

Where p is the time period used in CCA, and q is the successful transfer of data of non-emergency based BMS n in CCA, which can be calculated as expressed in Eq. (6).

$$q = \frac{\text{average time channel allocation}\,\mathit{to\,a\,BMS}\,\text{in the fixed time period}}{\text{fixed time period}} \tag{6}$$

Under the TraPy-MAC protocol, Eqs. (4) and (5) can be re-written for OP and DP, and these two types of BMSs access channel in the CAP period as expressed in Eqs. (7)–(9).

$$p_1 op = (1-q)^{n_{op}-1} \tag{7}$$

$$p_2 op = (1-q)^{n_{op}-1}\,(1-q)^{n_{Dp}} \tag{8}$$

$$p_3 Dp = (1-q)^{n_{op}}(1-q)^{n_{Dp}-1} \tag{9}$$

Where p (p_1, p_2) is the probability of obtaining a clear channel access with the support of CCA and n is the number of BMS performing contention to access channel.

S_1 and S_2 are the successful data transmission from CAP period to DTS slots as expressed in Eqs. (10) and (11), respectively.

$$S_1 = \frac{1}{T_1}\sum_{c=1}^{4} p_1\ op\ (1-p)^{c-1} + \frac{T_2}{T_1}\sum_{c=1}^{4} p_2\ op(1-p)^{c-1} \tag{10}$$

$$S_2 = \frac{T_2}{T_1-1}\sum_{C=1}^{4} p_2\ DP(1-p_1)^{C-1} \tag{11}$$

Where T_1 and T_2 are the length of timeslot to transmit data in the CAP.

Detection of Severity on Vital Sign

The Heart Rate (HR), Respiratory Rate (RR), Blood Pressure (BP), and Temperature (Temp) [37] are vital signs for survival of the normal life of patients. This paper classifies the severities of vital signs into low, normal values, and high threshold values as shown in Table 3. The low threshold values vital signs are in the life-critical situations as compared to the high threshold values. The reason is that the values of low threshold of vital signs move towards zero values while high values of vital signs are away from ranges of low values. Table 3 is based on real values of a patient and we assume that BMSs are programmed in an intelligent-way to detect abnormal reading and inform the BANC. For this purpose, the algorithm 1 is proposed that is Detection of Severities of Vital Signs (DSVS). It is assumed that n numbers of BMSs monitor vital signs. In detection of low or high or both values, the BMS sends an alert signal to the EB slot of the BANC. The BANC replies by allocation of ETS slots as described in the proposed

DSVS algorithm 1. The alert based communication with a BANC does not interrupt the contention of non-emergency data. The BMS goes in the LP monitoring of a vital sign if these are not conditions.

Algorithm 1: DSVS (Detection of Severity on Vital Signs)

Notations

Sen_{ith}: Number of Sensor $_{i \ldots in}$
Rd_off_{ith}: Sensor $_{i \ldots in}$ monitor vital sign in LP
$Monitor\_V\_S_{jth}$: Monitor vital signs j …j_k
L_{th}: Low threshold value
H_{th}: High threshold value
BANC: Body area network coordinator
$BANC_{EB}$: Emergency Beacon slot of Superframe structure of a BANC
$Sen_{ith}\_Trans_{AS}$: Sen_{ith} transmit alert signal to a BANC
BANC_All_ETS: BANC allocates ETS slot to sensor
$BANC_{ACK}$: Acknowledgment of a BANC of a requested service
$Sen_{ith}\_Trans\_TH\_Val$: Sensor $_{i \ldots in}$ transmit the detected LOW/HIGH threshold values U_{us}_value: Detection of unusual event

Input

heartbeat, respiratory rate, blood pressure, temperature

Process

```
START
Begin_$Sen_{ith}$
$Sen_{ith} \leftarrow Rd\_Off_{ith}$
$Sen_{ith} \leftarrow Monitor\_V\_S_{jth}$
For ($Sen_{ith} \leftarrow 1$, $Sen_{ith} \leftarrow Monitor\_V\_S_{jth}$, $Sen_{ith}$ ++ )
    If ($Sen_{ith} \in Monitor\_V\_S_{jth} == L_{th}$ or $H_{th}$) then
        $BANC_{EB} \leftarrow Sen_{ith}\_Trans_{AS}$
        $Sen_{ith} \leftarrow BANC_{ACK}$
        $Sen_{ith} \leftarrow BANC\_All\_ETS$
        $BANC \leftarrow Sen_{ith}\_Trans\_TH\_Val$
    Else
        Print ($U_{us}\_value$) and Go to LP
    end if
endloop
EXIT
END
```

Output: Detection of severity of a vital sign and informing BANC use alert signal

In emergency situations, BMSs detect abnormal readings of vital signs of a patient that can be low or/and high threshold values, such as low blood pressure and high heartbeat rate. These emergency data of a patient need to be delivered to BANC with higher reliability without contention. The contention causes collision, delay with retransmission of the collided packets, and BMSs consume maximum energy. The existing studies on MAC protocols do not consider these challenging issues. For this purpose, this paper classifies threshold values of vital signs into low and high threshold values; and normal values, as depicted in Table 3. The low threshold-based BMS is represented by CP and high threshold-based BMS is represented by RP. In detection of threshold values, the particular BMS (CP or RP or both) transmits an alert signal to EB slot of the BANC and BANC allocates ETS slots based on the priority. Hence, this paper is introduced Eq. 12 which assists in allocation of ETS slots on the priority-basis as expressed below.

$$\text{Slot}_{\text{\_Prioritization}} = \frac{\text{Severity\_of\_Vital\_}sign}{S_{\_B} * G_{\_Re/Ea}} \tag{12}$$

Where $Slot_{\_Prioritization}$ defines the priority of ETS slots allocation between low and high threshold values of vital signs. The *severity_of_vital_sign* is the criticality of the detected vital sign and $S_{\_B}$ is the size of the detected vital sign. The $G_{\_\mathrm{Re}/Ea}$ represents generation rate of a vital sign which can be detected recently (*Re*) and early (*Ea*). Equation 12 resolves the conflict of slots allocation among BMSs when a BANC receives alert signals of BMSs in EB slot at same time. For this purpose, **ETS S**lots allocation based on the **S**everities of **V**ital **S**igns (ETS-SVS) algorithm 2 is proposed and presented in next section.

Severity Based Slot Allocation

This section presents ETS-SVS algorithm 2 which allocates ETS slots to the severities of the detected vital signs based on the priority and also assists in avoiding of conflict of slots allocation.

Algorithm 2 ETS-SVS: **ETS S**lots allocation based on the Severities of Vital Signs

```
Notations
        BANC: Body area network coordinator
        $Sen_i$: BANC receives emergency data from single sensor
        $Sen_i$ and $Sen_j$: BANC Receives_Two_Sensors_emergency_Data
        $BANC_{EB}$: Emergency Beacon slot of a Superframe structure of BANC
        $TH_V$: Threshold Value
        $L_{th}$: Low threshold value
        $H_{th}$: High threshold value
        $G_{\_Re}$: sensor generates Recently threshold value of a vital sign
        $G_{\_Ea}$: sensor generates Early threshold value of a vital sign
        $S_{\_B}$: Detected data size in bytes
        BANC_Alc_ ETS (X): BANC allocates ETS (x) slot to emergency data
Input
        heartbeat, respiratory, ECG
Process

        1.  For (BANC ← each BMS transmit $TH_V$) do
        2.    If ($BANC_{EB}$ ← $Sen_i$-$TH_V$ or $Sen_j$-$TH_V$) then  // BANC receives emergency data from single sensor
                  If ($Sen_i$ or $Sen_j$-$TH_V$ ← $L_{th}$ or $H_{th}$ && $G_{\_Re}$ or $G_{\_Ea}$ && $Si_{\_B}$) then
                      $Sen_j$ or $Sen_i$ ← BANC_Alc_ ETS (X)
                  Else
                      Go to sleep mode
                  End If
        3.    Else If($BANC_{EB}$ ← $Sen_i$-$TH_V$ && $Sen_j$-$TH_V$ ) then //BANC receives two sensors emergency data

                   // Both BMSs detect Low threshold
        4.        If ($Sen_i$_ $L_{th}$ && $G_{\_Ea}$ &&  $S_{i\_B}$ = $Sen_j$_ $L_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                      $Sen_i$ ← BANC_Alc_ ETS ($X_1$) AND $Sen_j$ ← BANC_Alc_ ETS ($X_{1+a}$)
        5.        If ($Sen_i$_ $L_{th}$ && $G_{\_Re}$ &&  $S_{i\_B}$ < $Sen_j$_ $L_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                      $Sen_j$ ← BANC_Alc_ ETS ($X_1$) AND $Sen_i$ ← BANC_Alc_ ETS ($X_{1+a}$)
        6.        If ($Sen_i$_ $L_{th}$ && $G_{\_Ea}$ &&  $S_{i\_B}$ > $Sen_j$_ $L_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                      $Sen_i$ ← BANC_Alc_ ETS ($X_1$) AND $Sen_j$ ← BANC_Alc_ ETS ($X_{1+a}$)
        7.        If ($Sen_i$_ $L_{th}$ && $G_{\_Re}$ &&  $S_{i\_B}$ = $Sen_j$_ $L_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                      $Sen_i$ ← BANC_Alc_ ETS ($X_1$) AND $Sen_j$ ← BANC_Alc_ ETS ($X_{1+a}$)

                  // Both BMSs detect High threshold
        8.        If ($Sen_i$_ $H_{th}$ && $G_{\_Ea}$ &&  $S_{i\_B}$ = $Sen_j$_ $H_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                      $Sen_i$ ← BANC_Alc_ ETS ($X_1$) AND $Sen_j$ ← BANC_Alc_ ETS ($X_{1+a}$)
        9.        If ($Sen_i$_ $H_{th}$ && $G_{\_Re}$ &&  $S_{i\_B}$ < $Sen_j$_ $H_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
```

```
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
10.         If ($Sen_{i\_}H_{th}$ && $G_{\_Ea}$ && $S_{i\_B} > Sen_{j\_}H_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                $Sen_i \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_j \leftarrow BANC\_Alc\_ETS(X_{1+a})$
11.         If ($Sen_{i\_}H_{th}$ && $G_{\_Re}$ && $S_{i\_B} = Sen_{j\_}H_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                $Sen_i \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_j \leftarrow BANC\_Alc\_ETS(X_{1+a})$

            // Seni detects Low threshold and Senj detects High threshold
12.         If ($Sen_{i\_}L_{th}$ && $G_{\_Ea}$ && $S_{i\_B} > Sen_{j\_}H_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                $Sen_i \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_j \leftarrow BANC\_Alc\_ETS(X_{1+a})$
13.         If ($Sen_{i\_}L_{th}$ && $G_{\_Re}$ && $S_{i\_B} < Sen_{j\_}H_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
14.         If ($Sen_{i\_}L_{th}$ && $G_{\_Ea}$ && $S_{i\_B} > Sen_{j\_}H_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
15.         If ($Sen_{i\_}L_{th}$ && $G_{\_Re}$ && $S_{i\_B} > Sen_{j\_}H_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                $Sen_i \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_j \leftarrow BANC\_Alc\_ETS(X_{1+a})$

            // Both BMSs detect High threshold
16.         If ($Sen_{i\_}H_{th}$ && $G_{\_Ea}$ && $S_{i\_B} < Sen_{j\_}L_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
17.         If ($Sen_{i\_}H_{th}$ && $G_{\_Re}$ && $S_{i\_B} < Sen_{j\_}L_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
18.         If ($Sen_{i\_}H_{th}$ && $G_{\_Ea}$ && $S_{i\_B} > Sen_{j\_}L_{th}$ && $G_{\_Re}$ && $S_{j\_B}$) then
                $Sen_i \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_j \leftarrow BANC\_Alc\_ETS(X_{1+a})$
19.         If ($Sen_{i\_}H_{th}$ && $G_{\_Re}$ && $S_{i\_B} < Sen_{j\_}L_{th}$ && $G_{\_Ea}$ && $S_{j\_B}$) then
                $Sen_j \leftarrow BANC\_Alc\_ETS(X_1)$ AND $Sen_i \leftarrow BANC\_Alc\_ETS(X_{1+a})$
20.         Else
                Go_To_Sleep_Mode and Monitor vital signs
        End If
    Endfor
Output: allocation of ETS slots to $Sen_i$ and $Sen_j$ based on the severity of vital signs
```

Explanation of Steps of ETS-SVS

There are *n* BMSs monitoring vital signs of a patient as depicted in line 2 of this algorithm 2. This algorithm 2 presents two scenarios. The first scenario is based on the single BMS while second scenario is based on two BMSs, as shown in lines 3 and 4, respectively. The single BMS detects threshold value (TH_v) of a vital sign either it is low (L_{th}) or high (H_{th}). In this life-critical situation, that BMS sends an alert signal of the emergency situation to EB slot of the Superframe structure of TraPy-MAC. Then, BANC verifies threshold values of the detected vital sign as described in Eq. 12 and allocates ETS slots. Further, the threshold values in the second scenario has categorized into four groups that are low, High, Low to High, and High to Low. From lines 5 to 8 depict that both BMSs i.e. Sen_i and Sen_j detect low threshold values with different generation rates. If both BMSs generate data with E_a, then BANC allocates first slot on the priority-basis to Sen_i and second is to Sen_j, as shown in line 5. The BANC allocate first slots to Sen_j if Sen_i detects threshold value with R_e and Sen_j detects threshold value with E_a because Sen_j detects earlier and needs to be transmitted immediately before Sen_i, as shown in line 6. Sen_i detects threshold value with E_a and Sen_j detects threshold value with R_e, as shown in line 7. BANC allocate first slot to Sen_i and then is to Sen_j because Sen_i detects earlier than Sen_j. As shown line 8 that both BMSs generate low threshold with same R_e. In this case, BANC allocates first slot to Sen_i and then is to Sen_j. Lines 9 to 12 show that both BMSs detect high threshold values. The BANC allocates first slot to Sen_j if this BMS generates data with E_a. Otherwise, the priority of first slot allocation is assigned to Sen_i. Lines 13 to 16 depict that Sen_i detects low threshold and Sen_j detects high threshold. BANC allocates first to that BMS if the BMS detects low threshold value with E_a. From lines 17 to 20 show that both BMSs detect high threshold. BANC allocates slots in ascending to BMSs if both BMSs generate data with equality i.e. E_a or R_e. On other hand, BANC allocates first slot to that BMS if a BMS generates data with E_a. BMSs go to in monitoring of vital signs in sleep mode if these are not the relevant conditions.

Energy Consumption in BMSs

The BANC turns off its radio signal and goes into IP period when there is no data transmission being performed. BMSs

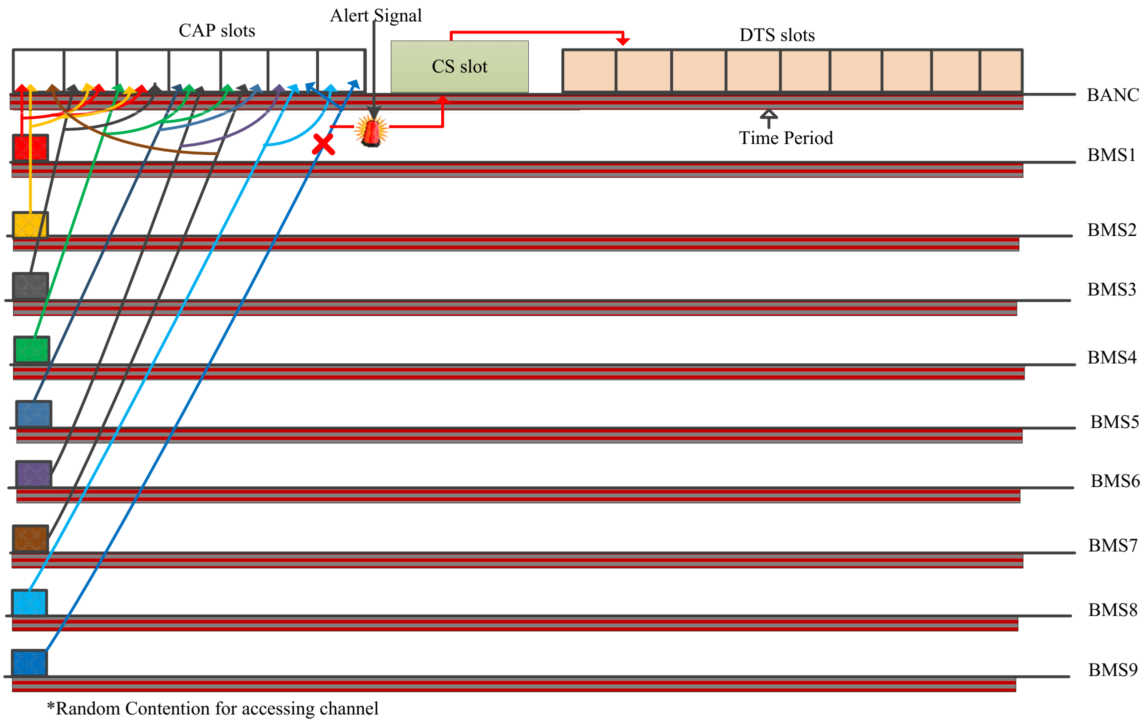


Fig. 3 Reduced contention based slots allocation

monitor vital signs in low power and consume minimum energy. The reduced duty-cycle mode [27] has been used to consume minimum energy of BMSs in contention for accessing of CAP's channels. This model presents four states that are shutdown, Ready, Tx (Transmission), and Rx (Reception), as presented in Fig. 4.

We assume that a BMS transmits one packet in Tx. The required consumed energy in the Ready, Rx, and Tx states are calculated with the support of Equations13, 14, and 15, respectively, in the following.

$$T_{\text{Ready}} = TSR + \left(T_{\text{contention}} - T_{Rx} - T_{Tx}\right) \tag{13}$$

$$T_{Rx} = TS + T_{\text{beacon}} + 2(C+1)T_{CCA} + 2C\,TS \tag{14}$$

$$T_{Tx} = T_{\text{pckt}} \tag{15}$$

Where *TSR* (**T**ransition from **S**hutdown to **R**eady) measures different changes in the shutdown to Ready states, *TS* (**T**ransition **S**witch) switches states from Ready to Tx and vice versa of BMSs, $T_{contention}$ is time period required for BMS to contend, C is the average back-off, T_{CCA} is the duration for clear channel assessment, and T_{pckt} is the duration of the packet transmission. The $T_{contention}$is associated with OP and DP data which has been presented in section 3.3.

The total energy consumption (E_{Total}) in the CAP to transmit a packet, as expressed in Eq. 16.

$$E_{\text{Total}} = T_{\text{Ready}}\,P_{\text{Ready}} + T_{RX}\,P_{TX} + T_{TX}\,P_{TX} \tag{16}$$

Where T_{Ready} is the energy consumed at the time of data transmission in the Ready state, P_{Ready} is the power required to stay in the Ready state, T_{RX} and T_{TX} are energy consumed in reception and transmission of packet, respectively. The energy consumption of the TraPy-MAC is the minimum in the contention and alert-based data transmission of BMSs.

Performance Evaluation

The performance of the TraPy-MAC protocol is compared with IEEE 802.15.4 MAC, PLA-MAC and MAC Scheme-1. Simulation experiments are performed in NS2 with different simulation parameters as shown in Table 4. There are 15

Table 3 Classification of threshold values of vital signs

Vital Sign	Low Values	Normal Values	High Values
HR	0–50 beats/min	51–119 beats/min	120–180 beats/min
RR	0–11 breaths/min	12–19 breaths/min	20–60 breaths/min
BP	(70–90)÷(40–60)	(90–120)÷ (60–80)	(140–190) ÷ (90–100)
Temp	-----	37 °C	38 °C to 40 °C & above

BMSs connected with a BANC in the star topology to monitor vital signs as described in Table 5. All deployed BMSs are in static mode and simulation area is 4*3 m. NS2 is configured with physical layer according to the narrowband PHY specification as presented in Table 4. Simulation runs for 500 s.

Simulation Environment

The TraPy-MAC protocol provides 64 slots which are extendable up to 128 slots. We assume that DP and OP-based BMS generate number of packets in ranges 60% to 70%. CP and RP-based BMSs generate packets in ranges 30% to 40%. Further, the propagation type is *TwoRayGroundused* selected which uses two different slots for contention and emergency situation. The *Priqueue* preempts non-emergency data from allocated slots and assigns to emergency data. BO is configured with 8 and SO is configured with 7. All MAC protocols use these configurations. We consider that PLA-MAC and MAC scheme-1 provide 128 slots in their MAC Superframes. IEEE 802.15.4 provides 16 slots. Moreover, BI provides 49.152 s for the whole Superframe and SD is 24.576 s for active slots in the TraPy-MAC. The Slot duration is 0.384 s whereas a BMS easily transmits long report of ECG without waiting for next BI. PLA-MAC and MAC scheme-1 based superframes provide 98.304 s for BI and 49.152 s is for SD. IEEE 802.15.4 based Superframe provides 12.288 s for BI and 6.144 s is for SD. All BMSs are connected in the star topology with BANC. Simulation experiments is listed in Table 4.

Sensor Input The TraPy-MAC protocol is suitable for heterogeneous nature of a patient's data in WBAN because of sufficient and dedicated assignment of slots. These slots reduce collision, delay, and consumes minimum energy of BMSs. Further, ECG, EEG, blood pressure, respiratory rate, heartbeat rate, temperature, and glucose are BMSs for monitoring of health condition of a patient. The data is generated and is transmitted at different frequencies with different data rates due to heterogeneous in nature, as shown in Table 5.

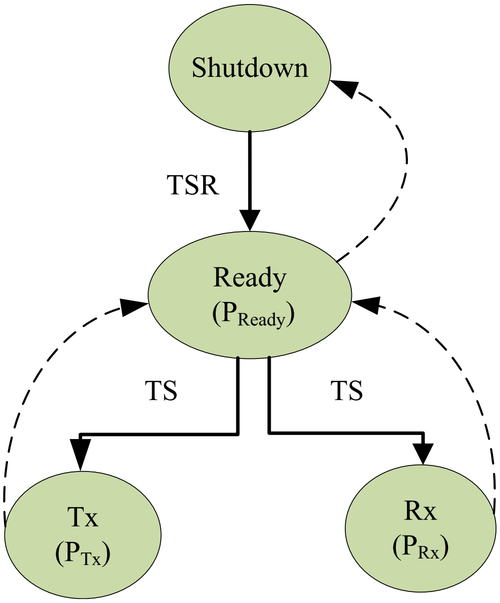


Fig. 4 State Transition Diagram for Transceiver

Simulation Metrics

The simulation performance metrics are defined in below.

- **Packet Delivery Delay**: The non-emergency based BMSs perform contention to access channel while emergency-based BMSs do not perform contention but they transmit alerts in detection of emergency data. Thus, the packet delivery delay is the amount of received data packets at the BANC from different BMSs which can be defined as expressed in Eq. 17.

$$\text{Delay}(ms) = \frac{\sum(T_d - T_s)}{\sum P_n} \tag{17}$$

- **Throughput**: The number of the generated packets of emergency and non-emergency based BMSs are successfully received by BANC in per second in its allocated slots of TraPy-MAC. It can be expressed in as shown in Eq. 18.

$$\text{Throu}_{-Net}(\text{kbps}) = \frac{\sum P_{\text{rece}}}{\sum T_{\text{generted}}} \tag{18}$$

Where $\sum T_{generated} = \sum (T_{generated} - T_s)$

- **Energy Consumption**: BMSs monitor vital signs of a patient's body in sleep mode and wake up to transmit the abnormal thresholds. The energy consumption can be defined as it is the difference between initial and final energy consumption by total number of BMSs that can be expressed in Eq. 19.

$$\text{Energy}(E) = \frac{\sum_{i=1}^{\text{BMSs}} (E_{\text{initial}} - E_{\text{final}})}{No.\text{of} \quad \text{BMSs}} \tag{19}$$

Analysis of Results

The performance of the TraPy-MAC is compared with the state-of-the-art MACs in terms of average packet delivery delay, delivery delay for delay-driven packets, throughput, and energy consumption, in the following.

The TraPy-MAC provides sufficient and dedicated slots to emergency and non-emergency data. The contention of non-emergency based BMSs has been reduced for accessing channel in CAP period. The reduced contention decreases collision

Table 4 NS2 simulation parameters

Parameter	Value	Parameter	Value
Frequency band in MHz/carrier frequency	2400–2483.5	Propagation type	TwoRayGround
Packet component	PHY service data unit (PSDU)	Queue type	PriQueue
Frame Size (default)	127 bytes		
Modulation technique	$^{\pi}/_{2}$ -DBPSK	Traffic type	CBR
Symbol rate	600 kbps	Beacon duration	3.2 ms
Nodes & BANC	15 & 1	Maximum number of backoff	4
Simulation area	4*3 m	Power consumed in transmission state	27 mW [32]
Simulation time	500 s	Power consumed in sleep state	0.005 mW
Data packet size	50 bytes	Power consumed in receive state	1.8 mW
Data packet duration	15.5 ms	Duration of Turn-ON radio to transmit /receive data	0.8 ms
Channel data rate	20 kbps	Power required for radio to switch from transmission state to receive state and vice-versa	0.4 ms
MAC protocols	TraPy-MAC, MAC scheme-1, PLA-MAC, IEEE 802.15.4	Topology	Star
No. of Slots in TraPy-MAC	64	No. of CAP slots in the TraPy-MAC	10
CAP slots in IEEE 802.15.4 MAC, PLA-MAC and MAC scheme-1	8 slots	No. of DTS slots in TraPy-MAC	16
No. of EB slot in TraPy-MAC	1	No. of ETS slots in TraPy-MAC	20

Table 5 Sensor parameters [33, 34]

Sensor	Signal Frequency in Hz (max)	Data Rate (bps)
ECG	250	5000
EEG	200	4000
Blood Pressure	50	1000
Blood flow	20	400
Respiratory	10	200
Heart beat	6	120
Blood PH	2	40
Temperature	0.1	120 [34]
EMG [34]	0–10,000	320,000
Glucose [34]	50	1600
Motion [34]	500	35,000
Pacemaker	300	12
Capsule Endoscopy (Solenoid) [35]	218,000	2 frame/s [36]
Cochlear	5	100
Artificial Retina	20	400

and delay with higher data reliability, as shown in Fig. 5. Also, if the BMSs do not get access of channel, then they do not drop the patient's data by using CS slots to access DTSs. The sufficient and dedicated slots, reduced contention; BMSs need not to wait for next BI and SD in the TraPy-MAC, are the advantages which reduces delay for packet delivery as compared to PLA-MAC, MAC scheme-1, and IEEE 802.15.4. The PLA-MAC based BMSs also use contention and contention reduces performance of the MAC in terms of collision due to limited slots in CAP, long waiting time period for next announcement of SD and BI, as depicted in Fig. 5. MAC scheme-1 does not provide dedicated slots to a patient's data and allocation of slots to BMSs based on the contention. That's why, the degraded performance of this MAC is shown due to repeated values of contention in the next round of contention. IEEE 802.15.4 has also shown the degraded performance because of limited slots, limited time period of BI and SD; and higher collision of data of BMSs noticed, as shown in Fig. 5.

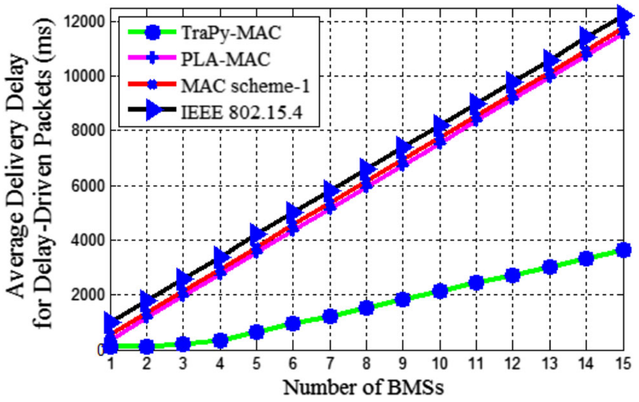


Fig. 6 Packet delivery delay for delay-driven packets vs no. of BMSs

The CD and RCD are emergency data considered in the TraPy-MAC. These data cannot accept delay with packets lost and need to be delivered to BANC. In detection of low and high threshold values of vital signs, BMSs do not perform contention to access channel but they send alert signals using EB slot of the BANC. The BANC sends an acknowledgment containing of ETS slots allocation. Moreover, the BANC allocates a slot to BMS without verifying other parameters as presented in Eq. 12 if it receives an alert signal from single BMS. If BANC receives alert signals from two BMSs at the same time, then BANC calculates severities of the detected threshold values and assigns slots based on the severities of vital signs as described in algorithm 2 with the support of Eq. 12. The existing MAC studies do not resolve the conflict of slots allocation among the same types of generated data of BMSs at same time. These features such as dedicated and sufficient slots allocation; alert-based slots allocation, sufficient time period of BI and SD

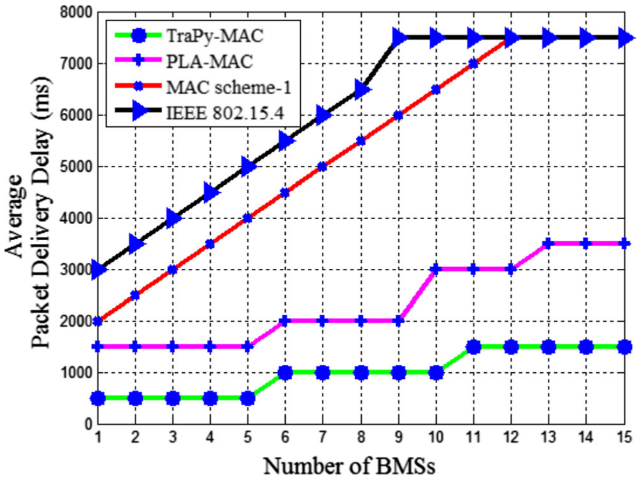


Fig. 5 Average delivery delay vs no. of BMSs

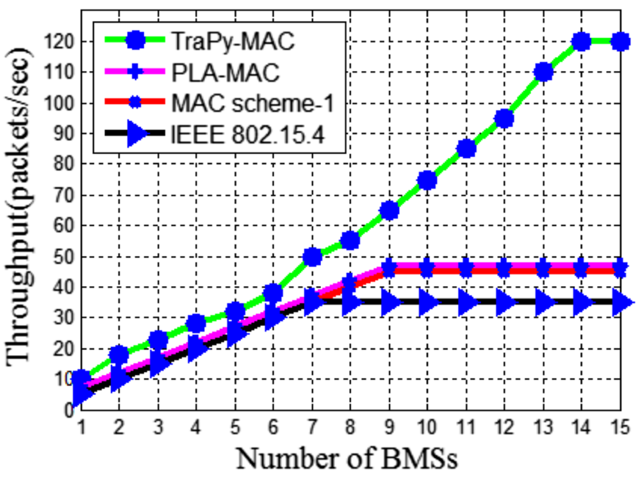
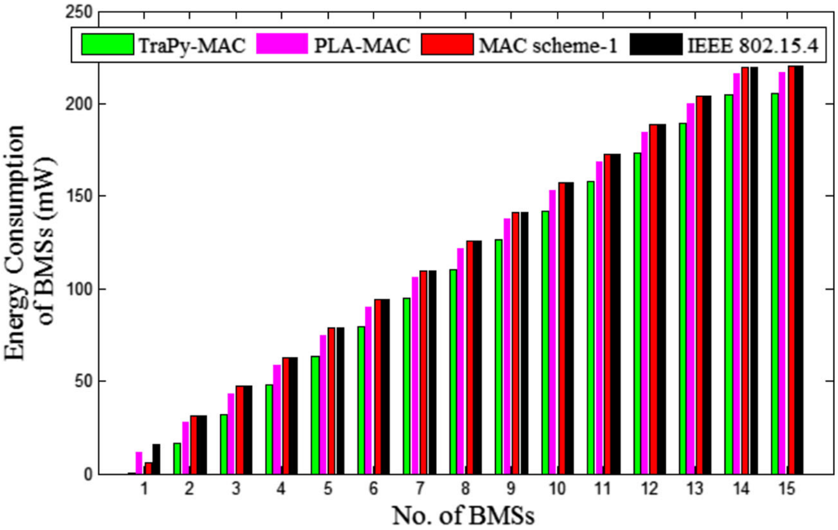


Fig. 7 Throughput vs no. of BMSs

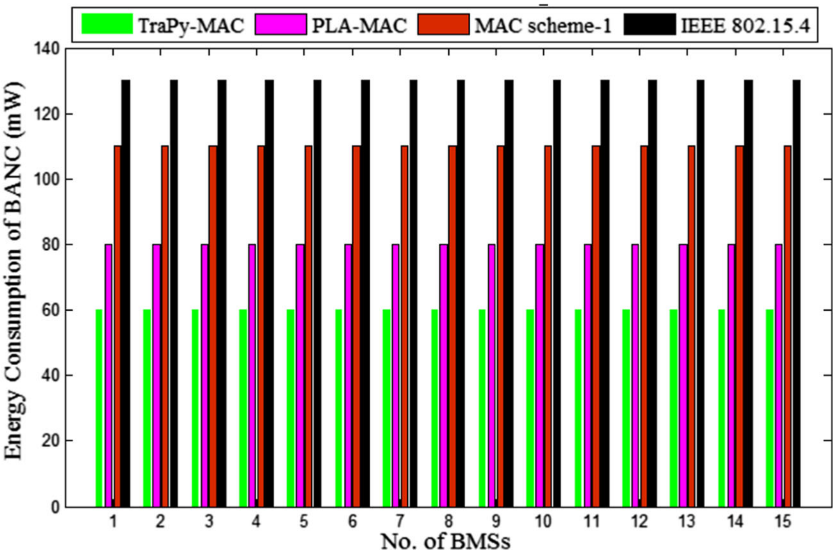
Fig. 8 Energy consumption of BMSs vs no. of BMSs



allocated for BMSs to send alerts and data, are the advantage to transmit data immediately without delay, as shown in Fig. 6. The state-of-the-art MAC protocols allocate slots to emergency-based BMSs based on the contention. PLA-MAC has the same procedure of slots allocation to BMSs based on contention. Later, BANC verified either data is having emergency or non-emergency situation. If it is emergency situation, then it allocates slots of CFP. The same process of slots allocation is followed by MAC scheme-1. In addition, this MAC does not allocate dedicated channel as compared to TraPy-MAC. Due to contention, non-allocation of the dedicated slots using alerts, and long waiting period of BMSs for next announcement of new session of superframes degrade performance of MAC where they cannot transmit life-critical data of a patient on time to BANC, which increases delay and is not acceptable for them, as shown in Fig. 6.

The throughput of the TraPy-MAC has been improved as compared to other MACs. The dedicated slots allocation to emergency and non-emergency data, reduced contention of non-emergency based BMSs, non-dropping of patient's data using CS slot if BMSs do not get access of channels, sufficient time period of BI and SD are the features of this MAC which transmit a maximum amount of data with higher reliability and improves throughput, as shown in Fig. 7. Moreover, the algorithm 2 resolves the conflicting slots allocation among BMSs of the same generated data when a BANC receives the request of slots at the same time. The throughput decreases in PLA-MAC when traffic loads exceeds from ninth BMSs. This degraded performance happens due to contention which causes collision leading to delay with lower reliability and BMSs retransmit the collided data packets. Also, BMSs need to wait for next session of superframe to transmit data which may ruin the lives of patients by reducing throughput of MAC, as shown in Fig. 7. The reduced throughput performance has been observed in MAC scheme-1 with the same reasons. IEEE 802.15.4 has also decreased performance due to contention which leading to

Fig. 9 Energy consumption of BANC vs no. of BMSs



collision. Moreover, the limited slots, minimum time period of BI and SD, and BMSs need to wait for next session of superframe for data transmission. The degraded performance reduce throughput of IEEE 802.15.4, as shown in Fig. 7.

The proposed MAC and existing MACs use low duty cyle model for minimum energy consumption of BMSs as well as BANC. The energy consumption of the TraPy-MAC is obviously minimum due to noval features introduced that are dedicatd and sufficient slots allocation, sufficient time period of BI and SD, reduced contention of the non-emergency based BMSs, do not drop the patient's data by exceeding threshold values of contention, and allocation of DTS with the support of CS. That's why, energy consumption of BMSs is quite minimum, as shown in Fig. 8. The contention policy based channel allocation is casuing collision due to limited slots, BMSs need to wait for next BI and SD, retransmission of the lost packets, and non-allocation of dedicated slots have been observed in PLA-MAC. These reduce performance which consumes a high energy of BMSs, as shown in Fg. 8. The same situation happens with MAC scheme-1 and always keep active slots of superframe by consumping higher energy of BMSs, as depicted in Fig. 8. The limited slots, contention, non-allocation of dedicated slots, dropping of patient's data and retransmission of the dropped data, and BMSs wait to transmit data in new session of superframe consume higher energy of BMSs, as observed in IEEE 802.15.4 and shown in Fig. 8.

The energy consumption of BANC of TraPy-MAC is compared with existing MACs. The TraPy-MAC actives slots of the superframe structure when is needed for BMSs to contend and transmit alert signals. Also, allocation of dedicated slots, reduced contention and sufficient time of supframe reduces energy cosnumption of BANC, as shown in Fig. 9. The state-of-the-art MACs keep active all slots of their superframes due to a large number of contention of BMSs causing collision which effects other performance parameters. That's why, Fig. 9 shows a higher energy consumption of BANC of the existing MACs due to aformentioned problems as compared to TraPy-MAC.

Conclusion

In this paper, a traffic priority based MAC protocol has been presented. The TraPy-MAC provides sufficient and dedicated timeslots to emergency and non-emergency based BMSs. The contention of non-emergency based BMSs has been reduced and do not drop the patient's data by allocation of CS. Also, the detection of emergency data based BMSs do not contend but they transmit alert signals using EB slot of the Superframe. With this slot, BANC allocates slots based on the severities of the detected threshold values of vital signs along with the support of an equation which resolves the conflict of slots allocation and allocates slots based on the severities of vital signs. Simulation has been performed and compared results of the proposed works with the state-of-the-art MACs. The proposed works perform better in terms of reducing packets delay for emergency and non-emergency data, consume minimum energy of BMSs and BANC; and improves throughput.

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