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REVIEW

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Medium Access Control (MAC) for Wireless Body Area Network (WBAN): Superframe structure, multiple access technique, taxonomy, and challenges

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Abstract

Health monitoring using biomedical sensors has witnessed significant attention in recent past due to the evolution of a new research area in sensor network known as Wireless Body Area Networks (WBANs). In WBANs, a number of implantable, wearable, and off-body biomedical sensors are utilized to monitor various vital signs of patient's body for early detection, and medication of grave diseases. In literature, a number of Medium Access Control (MAC) protocols for WBANs have been suggested for addressing the unique challenges related to reliability, delay, collision and energy in the new research area. The design of MAC protocols is based on multiple access techniques. Understanding the basis of MAC protocol designs for identifying their design objectives in broader perspective, is a quite challenging task. In this context, this paper qualitatively reviews MAC protocols for WBANs. Firstly, 802.15.4 and 802.15.6 based MAC Superframe structures are investigated focusing on design objectives. Secondly, different multiple access techniques such as TDMA, CSMA/CA, Slotted Aloha and Hybrid are explored in terms of design goals. Thirdly, a two-layered taxonomy is presented for MAC protocols. First layer classification is based on multiple access techniques, whereas second layer classification is based on design objectives and characteristics of MAC protocols. Critical and qualitative analysis is carried out for each considered MAC protocol. Comparative study of different MAC protocols is also performed. Finally, some open research challenges in the area are identified with initial research directions.

Keywords: WBAN, MAC Superframe structure, Nature of patient's data, Scheduling access schemes, Reliability, Energy

Introduction

Google search trend verifies the fact that 'health monitoring' is in the limelight nowadays [1]. Health monitoring has achieved a higher ranking as compared to 'environment monitoring' using sensors. This is due to the significant reduction in healthcare cost by using the technological advancements in health monitoring. The department of economic and social affairs of the United Nations has a report on the vilest health conditions of elderly aged people [2]. The report states that elderly aged people will be 761 million at the age of 60 plus of the total population of world in 2025, which is approximately

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15% of the whole world's population. Since, the elderly aged people require more medical checkup, as they are more in a life threatening situation of various health diseases [3]. These regular health checkup and monitoring of real time health conditions incur higher cost, which is a challenging problem specifically for lower income and developing countries. The report suggests the usage of technological advancements for health monitoring which results in early detection of diseases, and thus, reduction of medical cost.

In health domain, Wireless Body Area Network (WBAN) has got a significant attention in research and applications development, due to the considerable impact on patient-care or patient monitoring via biomedical sensors (BMSs) [4]. The real time health monitoring of patients significantly improves the rate of successful diagnosis in case of life threatening diseases. It also reduces the cost incurred in diagnosis, due to the early detection of diseases [5]. WBAN comprises of small BMSs that are wirelessly connected to a Body Area Network Coordinator (BANC) [6]. BMSs can be broadly divided into three categories, namely; in-body, on-body and off-body sensors [7]. In-body sensors are implanted inside the patient's body, whereas on-body sensors are sewed to the shirt or attached on the skin of a patient's body, and off-body sensors are kept away few centimeters from a patient's body [8]. An operation framework of WBANs with these sensors is presented in Fig. 1. BMSs are deployed to monitor different vital signs of a patient's body in Tier 1. BMSs forward the monitored data of vital signs to BANC. The BANC transmits these data to Tier 2. Tier 2 comprises of a Base Station (BS), and it forwards the outcomes of vital signs to Tier 3 over the dedicated internet communication links. Tier 3 includes a computer server, medical staff and transportation facilities [9]. Through this way, the patient's vital signs are examined by medical staffs, and advice a treatment. The vital signs monitored via BMSs includes heartbeat rate, respiratory rate, EEG, ECG, blood pressure, temperature and glucose level [10]. Each category of vital sign is represented by a specific type of medical data, and is completely different from other categories of vital signs. Therefore, BMSs data is heterogeneous and have different processing requirements by the medical team, which is based on the category of data. The responsibility of a BANC is to allocate slots or channels to the monitored vital signs based on the category of data. Efficient slot allocation is a challenging task due to the resource constraint involved in sensor network such as limited energy, processing power, storage and transmission capability [11].

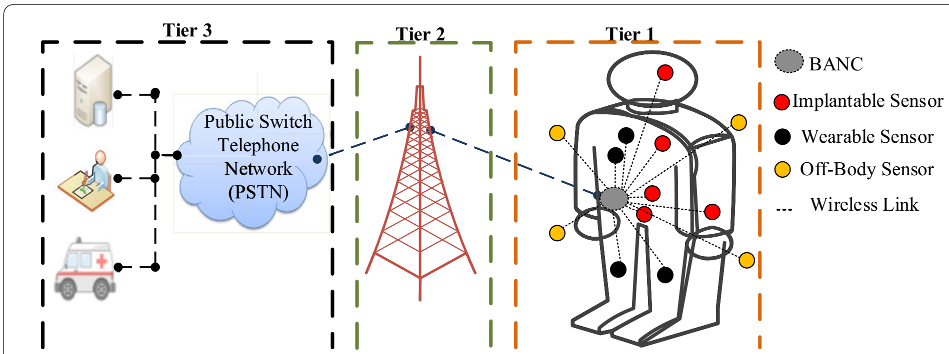

Fig. 1 An overview of communication tiers in WBANs

Various MAC protocols have been suggested for WBANs to address the slot allocation problems. There are two major design decisions have been made in MAC protocols namely, Superframe structure and multiple access (MA) scheme. The first design decision, MAC Superframe structure is based on two IEEE standards namely, IEEE 802.15.4 and IEEE 802.15.6. The Superframe structures have different classification of data, frame format and MA schemes. The second design decision, MA schemes consist of standard schemes and their combinations, which include Aloha, Slotted Aloha, Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and carrier sense multiple access with collision avoidance (CSMA/CA). MAC protocols based on these MA schemes utilize different approaches for slot allocation such as predefined, predefined and prediction, contention, non-contention and urgency, probability, alert and permission. MA scheduling schemes are also known as scheduling access schemes in WBANs which is interchangeably used in the rest of the paper. The allocation of slots to emergency and non-emergency data increases collision in CAP channel accessing. The slot allocation is not an appropriate solution for emergency data. It reduces the performance of MAC protocol in term of insufficient slots for patient's data, delay, retransmission of collided data packets, frequent invocation of beacon interval (BI), minimum duration of Superframe and slots, and higher energy consumption. The recent developments in MAC protocols for WBANs are focusing on these issues.

In this context, this paper qualitatively reviews recent developments on MAC protocol designs for WBANs. The critical investigation focuses on Superframe structure, multiple access scheme, and taxonomy for MAC protocols. The broad picture of the paper is summarized below as major contributions of the work:

- Firstly, MAC Superframe structure is classified into two categories, namely, IEEE 802.15.4 and IEEE 802.15.6. Each category has been qualitatively investigated focusing on frame format, classification of a patient's data, and MA scheduling schemes.
- Secondly, MA schemes are classically explored considering slot allocation and the impact of slot allocation on the various performance parameters.
- Thirdly, a two-layered taxonomy for MAC protocols in WBANs is presented. First layer classification is based on MA techniques, whereas second layer classification is based on design objectives and characteristics of MAC protocols. Comparative study of different MAC protocols is also performed.
- Finally, some open research challenges in the area are identified, and the directions of their solutions are explored.

The rest of the paper is organized as follows. "Related literature reviews" section discusses various survey papers in WBAN focusing on MAC protocols. "MAC Superframe structure" section presents a classification of MAC Superframe structure. "Multiple access scheduling schemes for MAC in WBANs" section discusses MA schemes with their impact on slot allocation. "Taxonomy of MAC protocols for WBANs" section reviews MAC protocols following a taxonomy. "Performance evaluation" section discusses simulation results for performance evaluation. Open research challenges are identified in "Future challenges" section, followed by conclusion made in "Conclusion" section.

Related literature reviews

A survey on WBANs have focused on three layers including routing, MAC and PHY layers considering IEEE 802.15.6 standard [4, 18]. It has described the communication range between BMSs for on and in-body with different considerations. However, the limitations of Superframe structure of IEEE 802.15.4 and PHY layer have not been identified. In [5, 12], authors have discuss applications of WBAN using different sensors for in and on body monitoring of a person. IEEE 802.15.4 MAC Superframe structure has discussed in with using TelOS. It has considered beacon interval (BI), durations of a slot, and Superframe structure. The selection of these metrics has been investigated for energy consumption of BMSs in terms of reliability and delay. A survey on channel interferences, energy, and scheduling access schemes has been conducted considering IEEE 802.15.4 and IEEE 802.15.6 [8]. These performance metrics have been considered based on the importance of the patient's life. The issues on the design and development of low-powered BMSs have been in explored, for monitoring of in and out vital signs of a person in different applications [13]. The issues have been investigated due to the different data rates to transmit the sensory information of a patient for each BMS. Further, the provision of quality of service has been discussed for MAC and PHY layers considering IEEE 802.15.4 and IEEE 802.15.6. A similar survey has been presented focusing on low-powered BMSs [14]. The Superframe structure has been classified into low power listening, contention and TDMA considering MAC protocols studies. Most of the MAC protocols have designed for wireless sensor networks (WSNs). However, the requirements of WBAN are different due to the heterogeneous nature of a patient's data, as compared to the homogeneous nature of data in WSNs.

The frame structure, frequency modulation techniques, and the security authentication have been focused for MAC and PHY layers in IEEE 802.15.6 [15]. The Narrowband (NB), Ultra-wideband (UWB), and Human Body Communications (HBC) are the Superframe structures, have been considered for human beings to animals using Slotted Aloha and CSMA/CA. The application, transport, network, MAC and PHY layers have been considered for Superframe structures of IEEE 802.15.4 and IEEE 802.15.6 in WBAN [16]. These layers have been investigated to establish an association between Superframe structure using Slotted Aloha, CSMA/CA and TDMA. The simulations have been conducted for Superframe structures of Bluetooth, IEEE 802.15.4, and IEEE 802.15.6 in [17]. The performance has been tested on data payload transmission, delay, throughput, and energy consumption using CSMA/CA and Slotted Aloha. Clearly, it has been investigated from simulations that IEEE 802.15.4 has performed better against IEEE 802.15.6 and Bluetooth. Most of the aforementioned surveys on WBAN have been considering multiple layers including physical, MAC, and routing. Contrary to theses generalized surveys, we focus on recent developments in MAC protocols considering Superframe structure, multiple access scheme, and two-layered taxonomy.

MAC Superframe structure

This section classifies MAC Superframe structures into IEEE 802.15.4 [19] and IEEE 802.15.6 [20] as shown in Fig. 2. Each classification is investigated in terms of the Superframe format, classification of a patient's data and MA scheduling access schemes.

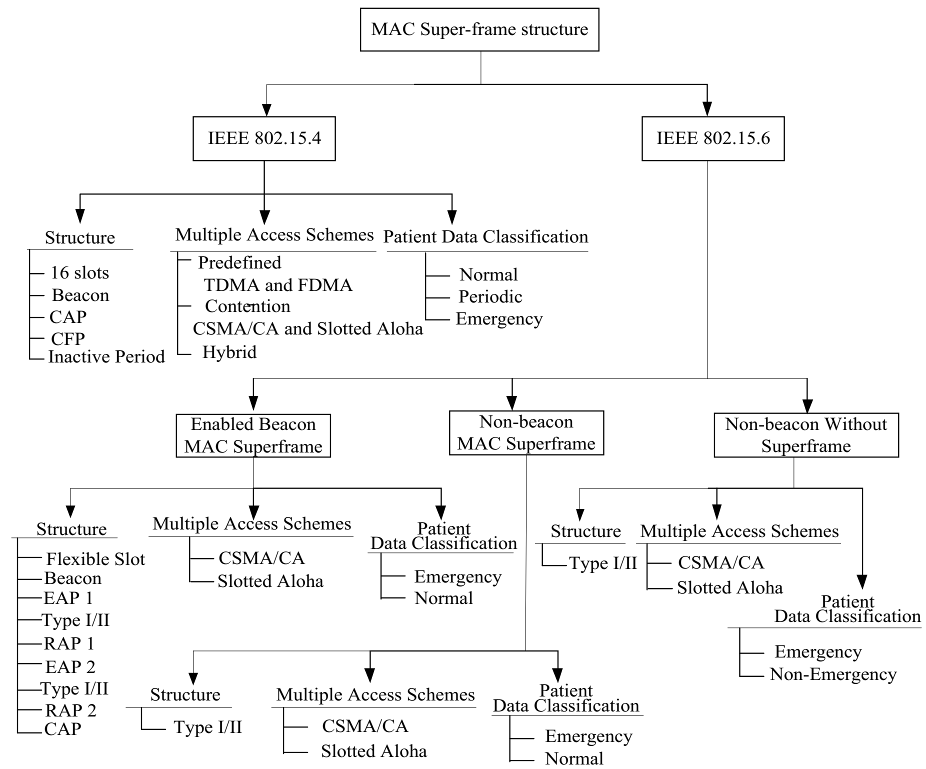

Fig. 2 Classification of MAC Superframe structures

IEEE 802.15.4 based Superframe structure

The BMSs are implanted or attached on the surface of a patient's body for monitoring of various vital signs of a patient. These BMSs are connected to a BANC in the star topology [13]. The patient data are classified into normal, periodic and emergency data. The normal data comprises of a temperature. The periodic data contains the reading of glucose and blood pressure. The emergency data contains a life threatening vital signs information such as low or high threshold value of a heartbeat. Further, the Superframe structure of IEEE 802.15.4 MAC comprises of a beacon, contention access period (CAP), contention free period (CFP) and LPL as depicted in Fig. 3. In IEEE 802.15.4 MAC, all BMSs use CSMA/CA access scheme and the CSM/CA-based BMSs perform contention to access channel in CAP period. During contention, each BMS performs many backoffs and clear channel assessment (CCA) to access channel [14, 21]. The TDMA scheduling access scheme is grouped in CFP period and the CFP period allocates the guaranteed

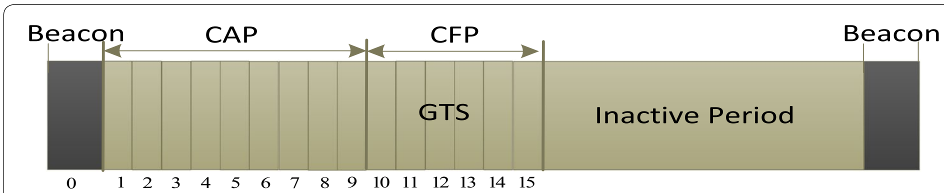

Fig. 3 IEEE 802.15.4 MAC Superframe structure

time slots to transmit the patient's data [22]. However, the BANC allocates the CFP slots to those BMSs who obtain a channel access in CAP period.

At the beginning of communication, the BANC broadcasts a beacon to all BMSs in the network which contains information of synchronization, the logical address of BANC, and the next announcement of the beacon interval (BI). In synchronization, BMSs transmit the request for channel association and dissociation to a BANC. The address of the BANC is broadcasted to BMSs for remembering it as the head/coordinator for allocating of channels and data transmission. The BI is the time period whereas each BMS contends and transmits sensory data in the specified amount of time. The inactive period (IP) is used for saving energy when a BMS is not busy for transmitting sensory data. The followings are the limitations of the Superframe structure of IEEE 802.15.4 MAC [23] as follows:

- IEEE 802.15.4 provides limited 16 (0–15) channels.
- All BMSs perform contention to access channel in CAP period.
- Allocation of CFP channels only to those BMSs who obtains a channel access in CAP period.
- During contention for accessing channel, there is no priority-based slot allocated to emergency data and is no differentiation between normal, periodic, and emergency data to assign the first slot on the priority-basis during in the life critical situations.
- No priority based a dedicated slots are occupied for emergency data.
- Due to contention, BMSs consume a higher amount of energy.
- In TDMA, each BMS transmits sensory data in the fixed length of time and drops data if it has a large amount of data (frame).
- Emergency data face a higher delay due to collision, retransmission of the lost packets, and limited time period of a BI.

These limitations severely reduce the performance of a MAC Superframe structure in terms of lower data reliability, collision and a higher amount of energy consumption. Moreover, the standard MAC Superframe structure does not support heterogeneous nature of patient's data which is not appropriate for emergency data. Numerous research contributions have been made that are [24–26]. These papers have modified the Superframe structure of IEEE 802.15.4 MAC according to the need of a patient's data.

IEEE 802.15.6 MAC Superframe structure

There are two types of communication possible for data transmission in WBAN that is one-hop and two-hop with the support of star and mesh topologies, respectively [15]. In one-hop communication, the BANC or hub is a centralized device which is responsible for allocating of slots to BMSs. In two-hop communication, the relay sensors (intermediates sensors) are used to exchange the frames between the sender sensor and BANC when they are far away from access of each other. Since, the use of the intermediate sensors consume a higher amount of energy during transmission of the patient's packet which create overheads in terms of a higher delay and is not feasible during in the life critical situation of a patient. Hence, IEEE 802.15 Task Group 6 (TG6) was decided to design low power sensors to monitor the patient's vital signs and the health conditions of a sportsman in different sports activities. The first draft version of IEEE 802.15.6 for MAC and PHY layers was publicized in 2012 [16]. This draft version describes IEEE 802.15.6 which divides the whole Superframe structure into different channels and beacons. Each channel is assigned an equal time frame to transmit the patient's data. Figure 4 (re-drawn from [15, 27]) shows an overview of IEEE 802.15.6 MAC Superframe structure.

The Superframe structure of IEEE 802.15.6 MAC comprises of three main modules that are MAC header, MAC variable length and frame check sequences (FCS). The MAC header reserves 7 bytes, the variable length reserves 0–255 bytes and FCS reserves 2 bytes as depicted in Fig. 4. The MAC frame body is further categorized into three sub-headers that are (a) Data Freshness which occupies 1 byte to protect data from the reply attack, (b) Message Integrity Code (MIC) occupies 4 bytes to authenticate the frame and maintains the integrity check of a frame, and (c) Data Payload contains data with MIC headers in the frame. Moreover, IEEE 802.15.6 MAC header is categorized into 4 sub-headers. First, the Frame Control occupies 4 bytes and uses to distinguish between control frame and data frame along with an acknowledgment. The second and third headers are the addresses of the receiver and sender sensors, respectively. Each sensor uses 1 byte to store the address. The BANC header is the final header which occupies 1 byte to store the address. The slot allocation to the nature of a patient's data in both IEEE 802.15.4 and IEEE 802.15.6 MACs is the responsibility of a BANC. Therefore, the draft version of IEEE 802.15.6 MAC defines three ways for transmitting the patient's data [4, 15] which are discussed in the following subsections.

Enabled-beacon MAC Superframe structure

The enabled-Beacon MAC Superframe structure comprises of a beacon, exclusive access phase (EAP-I-II), random access phase (RAP-I-II), Type (I–II) and CAP periods as shown in Fig. 5 (re-drawn from [4, 15]). The beacon is used to synchronize BMSs with a BANC. The channel allocation policy to BMSs is based on CSMA/CA or Slotted Aloha

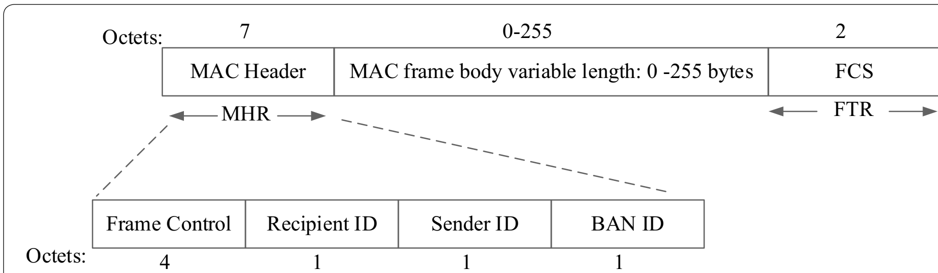

Fig. 4 802.15.6 MAC Superframe structure

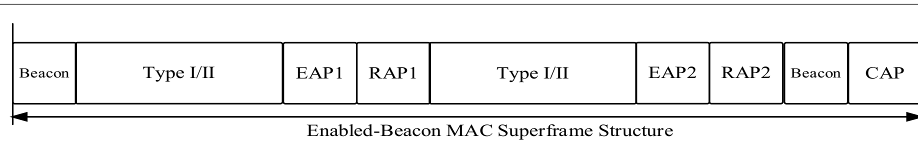

Fig. 5 Enabled-Beacon Mode MAC Superframe

schedule access scheme which are implemented on EAP, RAP and CAP periods. The EAP-I and EAP-II are reserved for life critical a patient's data and these critical data are represented by Type-I in Enabled-beacon MAC. Further, the RAP-I, RAP-II, and CAP periods are reserved for normal and regular monitoring of the health conditions of a patient which is represented as Type-II. The enabled-beacon MAC provides only dedicated slots to emergency and non-emergency data as compared to IEEE 802.15.4 MAC. However, the limitations of IEEE 802.15.6 MAC Superframe structure are the same as aforementioned in IEEE 802.15.4 MAC as challenging problems.

Non-beacon MAC Superframe structure

Figure 6 (re-drawn from [4]) shows the structure of non-beacon MAC Superframe structure. The non-beacon MAC allocates the entire channels (slots) of the Superframe to Type-I or Type-II category of a patient's data. During data transmission, the non-beacon based BMSs do not require synchronization with a BANC. With this advantage, the energy consumption of such BMSs is very minimum. The disadvantage is that the BANC cannot transmit data directly to BMSs but it must first 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 one time which is not an acceptable during life critical situations of a patient.

Non-beacon without Superframe structure

This type of structure of Superframe does not use the predefined periods to transmit all types of a patient's data but it is designed for scenario of Type-II. In this Superframe structure, the slot allocation to BMSs is based on contention or post-contention. The advantage of this structure is that the non-emergency based BMSs do not interrupt contention of emergency-based BMSs. However, the predefined allocation of slots to one type of sensory data is the wastage of slots.

Comparative analysis of MAC Superframe structures

IEEE 802.11, IEEE 802.15, and IEEE 802.15.1 [17] are not capable to monitor and detect early abnormal conditions of a patient. However, IEEE 802.15.4 has the capabilities to monitor and detects abnormal conditions and transmit the sensory data to a BANC with the higher data reliability [28]. Lots of researchers have been modified the Superframe structure of IEEE 802.15.4 MAC and used for WBAN. Table 1 presents characteristics of IEEE 802.15.4 MAC and compares with IEEE 802.15.6 MAC [29].

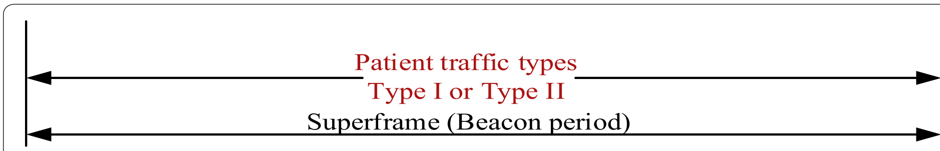

Fig. 6 Non-beacon MAC Superframe

Table 1 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	10–100 m	3–6 m
Network coverage	Scalable	Medium
Support of min-to-max sensors	10–65,000	3–256
Energy consumption	20–35 mW	0.01–40 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	50 kb/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

Multiple access scheduling schemes for MAC in WBANs

The slots allocation activities to BMSs in MAC Superframe structure of IEEE 802.15.4 are carried out with the support of different multiple access (MA) scheduling schemes. The scheduling access schemes can reduce collision, delay, avoids retransmission of the lost packets and energy consumption. Thus, the existing MA schemes in MAC protocols classifies the scheduling access schemes into three main categories; namely, reservation-based, contention-based and hybrid [12, 14]. These three scheduling access schemes assist to allocate slots to heterogeneous nature of a patient's data. The nature of patient's data is divided into three classes as aforementioned. However, the classifications of a patient's data into three classes are not justifiable because these classifications do not discuss low and high threshold values of vital signs and delay-sensitive data. In fact, the existing literature classifies the patient's data into four to five classes [25, 30]. The patient's data are transmitted to the BANC using various scheduling access schemes as discussed in the following sub-sections.

Reservation-based slots allocation

The TDMA scheduling access is the reservation-based slots allocation mechanism and this scheduling access is used for slots of the CFP period of MAC IEEE 802.15.4 Superframe structure [18, 31] as aforementioned in Fig. 3. The body coordinator divides the time frames of CFP period into different predefined time frames. Each BMS waits and transmits sensory data in the allocated predefined time frame as shown in Fig. 7. For example, the nodes 1 and 2 are normal data whereas they transmit in the allocated predefined time frames. The node 3 detects an emergency data (i.e. low or high threshold value) at the same time during data transmission of nodes 1 and 2. In this life-critical situation, the node 3 must wait and transmit emergency data in the predefined allocated

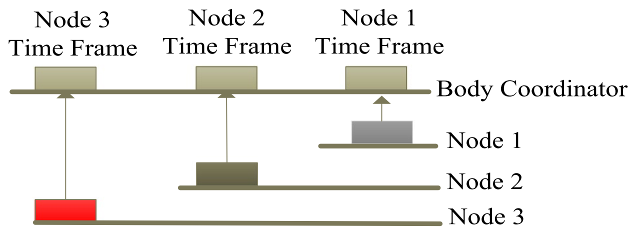

Fig. 7 TDMA-based slots allocation to BMSs

time frame. Hence, the predefined-based time frame allocation is not suitable for emergency data due to the long waiting period which degrades the performance of MAC Superframe structure as well as ruins the patient's life.

Contention-based slots allocation

The most widely adopted scheduling access scheme is the CSMA/CA due to its simplicity, and infrastructure-free for data transmission [18]. The slot allocation policy of CSMA/CA access scheme to BMSs is based on first come first serve (FCFS) mechanism [32] and it is implemented on CAP period of IEEE 802.15.4 MAC Superframe structure. During contention, each BMS performs contention to access slot (channel) in CAP period and all BMSs have the equal probability of accessing CAP slots [33]. Further, the body coordinator allocates the CFP slots to those BMSs who obtain a channel access in CAP period. Due to this challenging problem, the contention-based slot allocation to emergency data is not suitable because of collisions, retransmits the lost packets, a higher delay with lower data reliability and BMSs consume a higher energy [34].

FDMA-based of TDMA slots allocation

The TDMA are the guaranteed timeslots for sending of a patient's data to the medical doctor. Some research articles such as [35] has changed the contention of the BMSs for accessing channel in the CAP period and is using the frequency division multiple access (FDMA) for contention. The FDMA divides channels into different frequencies and timeslots whereas each BMS contends and transmits data within a specific amount of time without a higher of collisions of data packets and delay.

Hybrid-based slots allocation

The hybrid-based slots allocations to BMSs are the combination of TDMA and CSMA/CA scheduling access schemes. The TDMA-based slots are used for emergency-based BMSs whereas these types of BMSs transmit alert signals to the body coordinator during detection of low or high threshold values of vital signs. The non-emergency based BMSs perform contention with the support of a CSMA/CA access scheme for accessing channel in CAP period. The existing studies [25, 30] divide the CFP slots into emergency transfer slots (ETSs), data transfer slots (DTSs) and emergency beacon (EB). The patient's data are divided into Critical data Packet (CP), Reliability data Packet (RP), Delay data Packet (DP) and, Ordinary data Packet (OP) [30, 36]. The CP and RP are the emergency data while DP and OP are non-emergency data. The body coordinator reserves the DTS slots for non-emergency data and allocates to those non-emergency based BMSs who obtains a channel access in CAP period. In a similar way, the emergency-based BMSs transmit alert signals using EB slots during detection of emergency data. The decision of slots allocation on the priority basis depends on the criticality level of sensory data as described as $Priority = \frac{\text{Sensory\_Data}}{G{*}S}$. Where the *Priority* is assigned to four types of a patient's data, *Sensory_data* is the detected data of different vital signs, G is the data generation rate, and S is the size of a vital sign in bytes. However, the proposed protocol does not low and high threshold values of vital signs which is the limitation of this protocol.

Comparative analysis of MA scheduling schemes

In wireless communication, the data transmission between BMSs and the body coordinator is scheduled with the support of scheduling access schemes [37]. It has been noticed that most of the MAC schemes use TDMA with CSMA/CA scheduling access schemes for allocating of slots in CFP and CAP periods, respectively. The high energy consumption, a higher delay, low throughput and data collision are the most challenging problems during contention for BMSs for accessing channel which degrades the performance of MAC protocol. In a similar way, TDMA-based BMSs wait and transmit data in their predefined time slots. Thus, both scheduling accessing schemes are not suitable for emergency-based BMSs due to contention and the long waiting period. Table 2 [38, 39] presents and compares different functionalities of both scheduling schemes in terms of power, bandwidth, traffic, network, packet delivery and synchronization. However, the energy consumption of CSMA/CA access scheme is higher as compared to TDMA. In fact, we can enhance the performance of both scheduling access schemes with the support of network simulator 2 (NS2) [40].

Taxonomy of MAC protocols for WBANs

In this section, MAC protocols for WBANs have been investigated on the basis of the taxonomy presented in Fig. 8. In this taxonomy, MAC protocol designs are classified in two levels. The first level of classification contains seven categorizes of MAC protocol designs which is based on MA schemes. The second level of classification is further divided into one, two and three sub-categories which are based on the specific slot allocation approach followed in the category. Each of the MAC protocols studied under taxonomy are investigated considering Superframe structure, MA schemes, classification of the patient's data, slot allocation process based on the classification of data and their

Table 2 Comparison of TDMA and CSMA/CA functionalities

Function	TDMA	CSMA/CA
Power consumption	Low	High
Bandwidth utilization	Maximum	Low
Preferred Traffic level	High	Low
Dynamic network	Average	Good
Effect of packet failure	Latency	Low
Synchronization	Essential	N/A

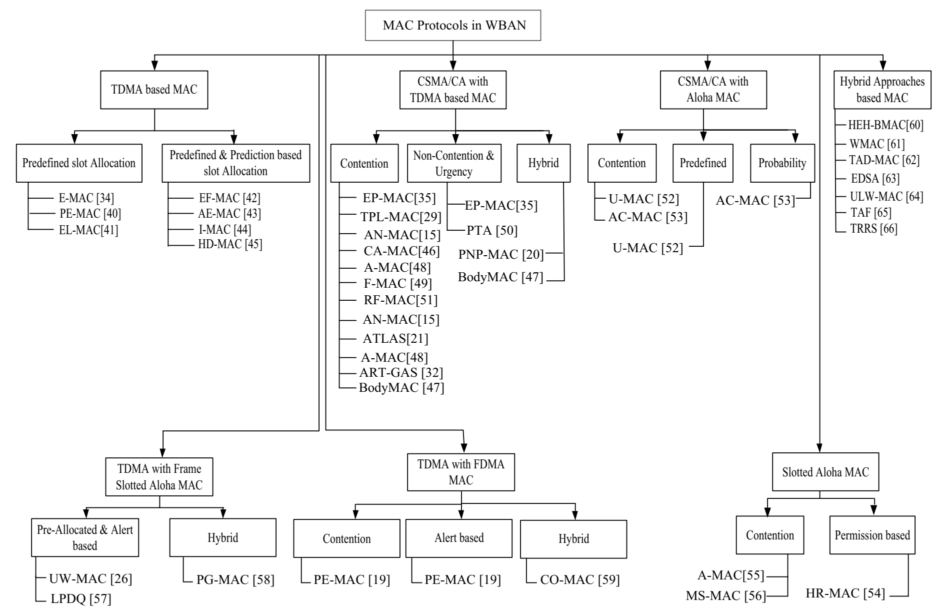

Fig. 8 Taxonomy of MAC protocols for WBANs

impact on performance parameters such as data reliability, delay, throughput, collision and energy consumption.

TDMA based MAC protocols

The TDMA based MAC protocols are divided into predefined and predefined with prediction based slot allocation to a patient's data. Each BMS waits for transmitting data in the predefined time slot. During the wait period, a BMS drops data and consumes a higher energy which degrades the performance of MAC protocol. The predefined slot allocation process is not acceptable for emergency data in terms of the lower data reliability with a higher delay. Lots of research contributions have been made to resolve the addressed problems and are discussed different MAC protocols in the followings.

The TDMA based changeable Superframe structure comprises the *Control data* and *Sensing data* as depicted in Fig. 9 (re-drawn from [34]). The Control data contains a *synchronization, broadcast, power detection, neighboring information upload and scheduling assignment slots*. The *Sensing data* is used for synchronizing clocks of BMSs with the body coordinator before data transmission. Since, the body coordinator broadcasts the *control schedule data* to all BMSs for occupying different slots. These slots are *'power*

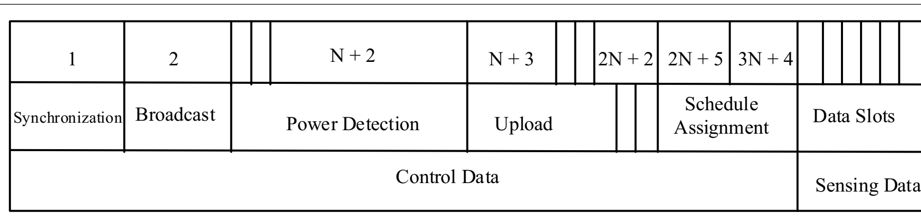

Fig. 9 Energy efficient Superframe structure

detection,' '*information uploading*' and '*schedule assignment*'. During data transmission, the body coordinator uses *neighboring upload slot field* for calculating the path and slot schedule which are transmitted to BMSs with the support of *schedule assignment field*. In this way, each node transmits data in the assigned timeslots with transmission power. However, the suggested scheme [34] uses many control fields which creates overheads for BMSs to execute all fields. The another limitation is that each sensor waits for its turn for transmitting data in the pre-allocated timeslot which is not suitable for emergency data due to a higher delay in the life-critical condition.

The suggested protocol in [41] reduces energy by using state transition with the support of wake-up radio and main radio. The wakeup radio comprises of the sleep and wakeup states. The main radio contains idle (ready) state, Tx and Rx states. The default state of nodes is the sleep state. Both wake-up radio and main radio use wake-up state for periodic data (normal data) and random data (emergency data) transmission, respectively. The limitation of [41] is that each BMS either normal or emergency-based BMS waits and transmits data in the predefined time slot. With the waiting period degrades the performance of MAC protocol in terms of collisions, a higher delay with lower data reliability and higher energy consumption which is not appropriate for emergency data. The second limitation is that the suggested protocol does not differentiate between low and high threshold values of vital signs.

The suggested Superframe structure of MAC comprises of *Control data* and *Sensing data* as depicted in Fig. 10 (re-drawn from [42]). The *control data* contains a *beacon, broadcast, information exchange, upload information,* and *schedule assignment.* The *sensing data field* contains data slots whereas each node sends or receives data in the predefined time slot. In the beginning of communication, the beacon and broadcast are transmitted by the body coordinator to all nodes in the network for *synchronization* and *information exchange, uploading data* and *schedule assignment*, respectively. Since, each node calculates the transmission timeslots and sends back to the body coordinator. The calculation step is processed in the *information exchange phase* and *upload information*. In the *upload information* session, at a time one sensor can upload data and the body coordinator stops other sensors for sending data. However, this scheme [42] consumes a higher energy of sensors due to the outnumbers of control overheads which are used in the data transmission. The blockage of other sensors suffers the patient's life which is not acceptable for real time health domain and also reduces the performance of MAC protocol in terms of a higher delay with lower data reliability.

Table 3 presents the analysis of different MAC protocols in terms of data reliability and energy consumption of nodes during the long waiting period and data transmission. The predefined-based slot allocation to nodes is reducing data reliability in terms of a higher

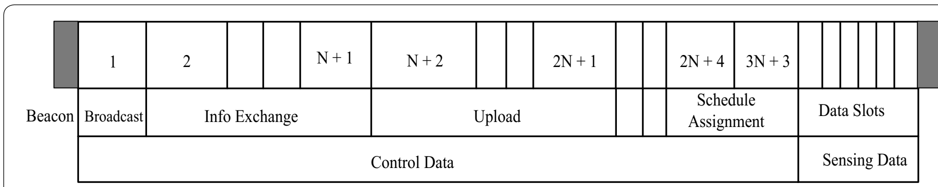

Fig. 10 Energy Efficient MAC Superframe Structure

Table 3 Analysis of the predefined based slots allocation

MAC protocol	Data reliability	Energy consumption	Remarks
E-MAC [34]	Low	High	Each sensor waits and transmits data in the pre-defined time slot. For data transmission, sensors change the format of Superframe according to the needs of a patient's data. With these changes, sensors consume a higher energy during which create overhead to execute all fields of Superframe structure
PE-MAC [41]	Medium	High	Sensors consume more energy in the wakeup radio and main radio state transitions. The waiting based transmission of emergency data in the pre-allocated time increases a chance of dropping data. The Low and high threshold values are not considered in this scheme
EL-MAC [42]	Low	High	Sensor consumes a high energy due to outnumbers of the control overheads and faces a higher delay which is not appropriate for a life critical patient's data

delay which drops patient's data and consumes a higher energy consumption of nodes. Therefore, the predefined scheduling schemes are suitable for non-emergency data and are not suitable for emergency data.

Predefined and prediction based slot allocation

The Medical MAC (MedMAC) protocol [43] is using TDMA scheduling access scheme and classifies the patient's data into 0, 1 and 2 classes. The class-0 comprises of a low-grade data such as temperature and respiratory rate. The class-1 comprises of a medium-grade data such as ECG, EEG and blood pressure while class-2 contains a high-grade data such as EMG, and capsule endoscope. The beacon period of the proposed MAC is used to allocate a dedicated channel to emergency data when a node detects an unpredictable data. During data transmission, each node transmits the request of synchronization to the body coordinator. However, the synchronization, the contention and does not considering the differences between low and high threshold values of two vital signs reduce the performance of MAC protocol in terms of a higher collision, and delay with low data reliability.

The allocation of a slot to nodes is based on first come first serve (FCFS) and each node requires a synchronization with the master node (MN) for data transmission [44]. Since, the monitoring node (MN) forwards the collected data of vital signs to the monitoring system (MS). The slot allocation to nodes on the FCFS approach, the emergency-based sensor drops and it is retransmitted in the extra slot (ES). This protocol [44] consumes a high amount of energy of sensor nodes during retransmission of the collided data and also does not differentiate between low and high threshold values of vital signs. Thus, these parameters reduce the performance of MAC protocol in terms of collision and higher delay with low data reliability.

The Superframe structure of MAC [45] comprises of Exclusive Access Periods (EAP-I/II), and Random Access Periods (RAP-I/II) using Traffic types Type-I and Type-II. The EAP-I and EAP-II are used to transmit emergency data with the support of TYPE-I. The RAP-I and RAP-II are used to transmit normal/periodic data with the support of TYPE-II. Both Types (I, II) inform the master node to allocate the slots when each node transmits data in the pre-allocated time slot. However, the master node blocks other slave nodes during data transmission of the one node in the pre-allocated time slot which consumes a higher amount of energy of other nodes in waiting. Another drawback is that one node can upload information at a time which degrades the performance of the suggested MAC in terms of a higher delay with the higher packets drop.

The heartbeat rhythm MAC (H-MAC) protocol [46] is suggested whereas the body coordinator does not broadcast a beacon but it uses heartbeat rhythm for clock synchronization. The purpose of this process is to avoid periodic synchronization and achieves the minimum energy consumption without turn-on the radio signals. Moreover, the activation of radio signals is based on the heartbeat peak values (high threshold values) and valley (low threshold values) values of a patient which are associated with a blood circulation of the human body. If the blood circulation increases or decreases, the biosensor broadcasts a threshold value and activates the body coordinator to allocate a slot. However, this scheme [46] does not investigate the decision of slots allocation between two sensors if both sensors detect low and/or high threshold values of two vital signs at the same time and transmit to the body coordinator. This challenging problem reduces the performance of MAC protocol in terms of a higher delay and higher energy consumption which is not suitable in the life threatening conditions. Table 4 presents MAC protocols which are analyzing the predefined and prediction based slot allocation to BMSs. This type of slot allocation is suitable for non-emergency based BMSs because the BMSs consume minimum energy with higher data reliability. However, the main drawback of these types of MAC protocols is that they cannot decide to allocate the slot on the priority basis between two vital signs if both sensors detect low and high threshold values and transmit to the body coordinator at the same time. Due to this challenging

Table 4 Analysis of predefined and prediction based slot allocation

MAC protocol	Data reliability	Energy consumption	Remarks
EF-MAC [43]	Low	High	Higher delay and lower data reliability have been noticed during contention of multiple nodes to access channel. This scheme is not suitable to transmit emergency data of more than one sensor at a time. In addition, it does not focus on low and high threshold values of vital signs
AE-MAC [44]	Low	High	Retransmission of the lost packets degrades data reliability. Sensors consume more energy in the waiting state for a beacon to receive from MN which is not suitable for emergency data
I-MAC [45]	Low	High	Nodes consume a higher energy during the waiting period to transmit data in their own turns because the master node locks the services of other slave nodes which are not suitable in case of emergency data
HD-MAC [46]	Average	Low	Allocation of the slot is based on the heartbeat in the predefined time unit. This protocol is not suitable for life-threatening vital signs due to the long waiting period whereas the body coordinator cannot decide the slot allocation process between two vital signs

problem, the BMSs consume a higher amount of energy and drop sensory data due to long waiting period.

CSMA/CA with TDMA based MAC protocols

This section explains CSMA/CA with TDMA based MAC protocols in WBAN. As discussed the challenging problems of IEEE 802.15.4 MAC, the [36] modifies the Superframe structure of MAC and classifies the patient's data into Emergency Data (ED), Periodic Data (PD), and Normal Data (ND). During contention of sensors if the channel is busy then ND-based sensor waits for a random amount of time and performs many backoffs. The PD-based sensor uses TDMA access scheme to transmit data. Further, this study uses an equation that is $\text{Priority} = \frac{\text{Data type}}{\lambda_t * \text{P}_{\text{size}}}$ which calculates the criticality levels of sensory data and differentiates between ND and PD for declaring it as ED as represented by data type. The λ_t is the generation rate of the packet and P_{size} is the length of the generated data. However, the CSMA/CA and TDMA scheduling schemes reduce the performance of MAC protocol in terms of contention for emergency-based sensors due to the long waiting period during slots allocation process which is not an appropriate practice. Another limitation of this protocol does not differentiate between low and high threshold values of vital signs and also does not resolve the conflict of slots allocation if two sensors transmit the same types of data at the same time to the body coordinator.

The Priority-based Load Adaptive MAC (PLA-MAC) [29] protocol classifies the patient's data into Critical data Packet (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 second the priority of data for allocating 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 patient's data that can delay. The suggested Superframe comprises of a beacon, CAP, notification, CFP, and LPL. The CFP period is further divided into Emergency Data Transfer Slots (ETSs) and Data Transfer Slots (DTSs). At the beginning of channel allocation, all nodes perform contention to access channel in CAP period. The body coordinator allocates ETS slots to those emergency-based sensors who obtain a channel access in CAP period. The non-emergency based sensors can occupy ETS slots but they must perform a CCA to ensure collision-free data transmission. However, the suggested protocol [29] consumes a higher energy of sensors during contention period and does not different between low and high threshold values of vital signs. The contention reduces the performance of MAC in terms of a higher delay with low data reliability which is not suitable for emergency data.

The preemptive and non-preemptive MAC (PNP-MAC) protocol [25] classifies the patient's data into emergency alarm, medical continuous, medical routine, non-medical continuous and file transfer. The suggested MAC Superframe structure comprises of an advertisement, Beacon, DTS and ETS. The DTS and ETS slots are grouped into CFP period. Each node performs contention to access channel in the CAP period. The body coordinator allocates DTS slots to those sensors who achieve a channel access in CAP period. Moreover, the body coordinator preempts the low-priority data, i.e. the non-medical continuous from the DTS slots and assigns the slots of DTS on the arrival of the high priority data if there is no empty slot available in DTS. In this moment, the body coordinator transmits a request message to all nodes to de-allocate the slots of the

DTS and updates their status. The allocation of ETS slots in the life critical conditions if all slots in DTS are not empty. The limitation of this scheme is the preemption of the non-critical data from DTS slots on the arrival of critical data which is the drawback of this scheme in terms of the preempted nodes drop data. The energy consumption of the nodes is higher due to contention and does not differentiate between critical and non-critical data to allocate a separate channel without performing of contention.

The Superframe structure of Low-delay Traffic-adaptive Medium Access Control (LTDA-MAC) [15] comprises of a beacon, fixed CAP, CFP, extended dynamic CFP and inactive sleep state. At the beginning of communication, the body coordinator broadcasts a beacon to all nodes in the network for clocks synchronization. During a channel allocation period, each node competes for a slot in the fixed CAP period along with the requesting of dynamic CFP slot from a body coordinator. The body coordinator allocates the fixed CFP and extended CFP slots to those nodes who gets a channel access in the fixed CAP slot. The limitation of this scheme is that the body coordinator transmits a notification alert to all nodes for stopping data transmission. With this stopping of data, the throughput of the MAC is reduced in the terms of a higher dropping of a patient's data, a higher delay, and re-transmission of the dropped packet which consumes a higher energy of nodes. Thus, these issues badly reduce the performance of MAC protocol which cannot allocate the slots to emergency data in an appropriate time.

The MAC Superframe structure of A-Traffic Load Aware Sensor (ATLAS) [26] comprises of a beacon, CAP, CFP and IP. The sensory data is transmitted from sensors to cluster-head (S-to-CH) and cluster-head to the gateway (CH-to-G) using multi-hops. The CH synchronizes the clock with nodes during slots allocation process. The allocation of slots to sensory data is based on the traffic load which is divided into low, moderate, high and overload traffic load. The CAP slots and IP of the Superframe structure are assigned to low load traffic. The gateway assigns CAP, IP and CFP slots to moderate traffic load. For high load data, the gateway assigns CFP and IP. While the CFP slots are assigned to overload data. In fact, the drawback of this protocol [26] is the higher delay in transmitting data to sensor-to-cluster and cluster-to-gateway which consumes a higher energy of the nodes and is not suitable in the life critical situations of a patient.

The Adaptive and Real-Time GTS Allocation Scheme (ART-GAS) [32] provides 'service differentiation' and 'GTS' slot allocation. Since, the 'service differentiation' offers two types of services that are 'data-based priority' and 'rate-based priority'. The 'data-based priority' devices contain emergency data and these types of emergency data allocate slots on the priority basis. The rate-based priority means data is generated recently with a high rate and needs a higher attention to transmit it. In this suggested protocol, each device is configured with different priorities such as CSMA/CA hit-miss and GTS hit-miss. These two priorities are used to avoid the wastage of the GTS slots. However, the contention consumes more energy of emergency-based sensors and reduces the performance of MAC protocol with lower data reliability in terms of collision, delay and retransmission of the collided packets.

The suggested Superframe structure comprises of a beacon, Emergency-TDMA (ETDMA), Medical Contention Access Period (MCAP), Normal-TDMA (NTDMA), CAP, and Emergency Slot (ES) [47]. The ETDMA slots are reserved for emergency data during an alarming situation. In a similar way, the MCAP slots are used for allocating channels when outnumbers of nodes are the alarming situations. For periodic and normal data, the NTDMA slots are occupied. The following steps are used for allocating of a slot to emergency data as follows:

1. The emergency-based node tries during contention to transmit emergency data in CAP slots. However, the successful rate of emergency data transmission in CAP slot is comparatively very low because the normal-based nodes also perform contention.
2. In the case of failure, the particular node informs the hub in ES slot about an alarming situation. The collision may also occur in ES slot due to the multiple requests transmitted by other nodes.
3. In these situations, the nodes drop the packets if data transmission counter is reached to the maximum threshold values.

The drawback of this protocol [46] is high energy consumption during contention to access channel whereas the dropping ratio of packets of nodes exceed. Another limitation is that the proposed protocol changes the order of fields of the proposed MAC Superframe structure which creates overheads for emergency data.

The suggested BodyMAC protocol [47] comprises of a beacon, downlink and uplink. The downlink is used for a unicast, broadcast message, and control command. The uplink is used for CAP and CFP slots for sending data to the gateway. The suggested protocol maintains 'control-bandwidth' and 'data-bandwidth' requests. The 'control-bandwidth' request is used by a node when a node contains more than one control packets and wants to transmit to the gateway. Similarly, the 'data-bandwidth' request generates by the sender node and transmits it to the gateway. The bandwidth of slots is divided into' burst bandwidth', 'periodic bandwidth', and 'adjust-bandwidth'. The 'adjust-bandwidth' is assigned to nodes on-demands while other types of bandwidth are assigned to nodes on the temporary basis. However, this protocol [47] consumes a higher energy during contention to access channel which is not suitable for a patient's data due to permission-based transmission and reception. The overall performance is not satisfactory in terms of a high energy consumption and low data reliability.

The suggested MAC Superframe structure of an Adaptive MAC (A-MAC) [48] contains a beacon/synchronization, CFP, CAP, guard-band, and time slot [48]. The suggested protocol uses *data* and *control packets*. The *data packets* contain the patient's data and the *control packets* contain the channel packet, Time Slot Request (TSR), TSR Reply (TSRR), Synchronization Acknowledgment (SYN-ACK), Data Request (DR) packet, and ACK (acknowledgment). During data transmission, the nodes transmit the *TSR packet* to the coordinator node (CN) for the allocation of slots. On the successful allocation of slots, the CN replies with a *TSRR* to nodes. Further, the node transmits a request of *SYN-ACK* for allocating of slots if a node needs a slot before the predefined timeslot. The DR assists in transmitting on-demand data. However, the suggested A-MAC does not allocate dedicated slots to emergency data and consumes a higher energy of BMSs during contention to access channel. The control packet creates overheads and degrades the performance of MAC in terms of collision and delay with lower data reliability.

The Fuzzy Control Medium Access (FCMA) [49] implements acquisition, fuzzy logic control, and implementation phases for handling the non-real time data, normal real-time data, abnormal data, and emergency data of a patient body. The *data acquisition phase* is used to collect data from the deployed sensors. When a body coordinator receives the patient's data then it uses the fuzzy rules to decide whether to assign CAP or CFP slots. This activity is performed under the *fuzzy logic control phase*. In the CAP period, the fuzzy rules manage the *Contention Window Size* for *priority data* and *data rate*. The *priority data* represents the patient's data such as normal, abnormal and emergency. While *data rate* represents the severity of a patient's data such as low, medium and high. The suggested mechanism is suitable for emergency data, but sensors consume a higher amount of energy during contention to access channel. The sensory data is delayed during the decision making for allocating of slots to sensors.

The Priority-based adaptive Timeslots Allocation (PTA) protocol [48] divides the CAP slots into phase-1, phase-2, and phase-3 timeslots. The phase-1 slot is assigned to emergency data and is represented by C1 (critical). The phase-2 slot is assigned to continuous and discontinuous data and is represented by C2. In the same way, the phase-3 slot is assigned to an audio/video data and is represented by C3. The allocation of CAP timeslots to the phase-2 and phase-3 based traffic depends on contention of nodes. The phase-1 slot is occupied for emergency traffic and cannot occupy by any other type of traffic. The drawback of this protocol is higher energy consumption during contention of nodes for accessing channel which is not suitable for emergency data in terms of a higher delay with lower data reliability.

The Radio Frequency Identification (RFID) based MAC (R-MAC) protocol classifies the patient's data into emergency and routine data [51]. The emergency and routine-based sensors perform contention to access channel using CSMA/CA access scheme. Moreover, the suggested MAC Superframe structure comprises of a Configurable CAP (CCAP) slot, CFP guaranteed slots, and IP or LPL. During emergency data, the sensor will perform contention and will wait for a clear channel access. Since, the body coordinator allocates CFP slots to those nodes who gets a channel access in CCAP period. However, there is no slot allocate during alarming situations and each sensor contends to access channel. In these situations, the performance of the suggested protocol is reduced in terms of a higher delay with higher energy consumption.

Table 5 investigates the techniques used for slot allocation to sensors that are contention, non-contention, and urgency. The patient's data are categorized into different classes and each type of a patient's data performs contention for accessing channel in CAP period. The body coordinator allocates slots of the CFP period to those nodes who obtains a channel access in CAP period. With this contention, the energy consumption of nodes is high which reduce data reliability. In TDMA-based approach, each node waits for transmitting data in the predefined time slot. Both types of scheduling access schemes are not optimal solutions for emergency data. Hence, the optimal solution is that the emergency-based node should transmit an alert signal in the guaranteed time slot for allocating of slot without contention. With this type of data transmission avoids the conflict of the priority-based slot allocation between two vital signs.

CSMA/CA with Aloha based MAC protocols

This section describes the hybrid scheduling access schemes which are the combination of CSMA/CA and Aloha. An Urgency-based MAC (U-MAC) protocol [53] is used to

Table 5 Analysis of CSMA/CA with TDMA based slot allocation MAC protocols

MAC protocol	Data reliability	Energy consumption	Remarks
EP-MAC [36]	Low	High	Sensors consume a high energy during contention. The high delay is noticed due to the clock synchronization which is not suitable for emergency data. Another limitation of not differentiating between low and high threshold values of vital signs
TPL-MAC [30]	Low	High	All sensors perform contention for accessing channel in CAP period which effects data reliability and consumes a higher energy of nodes which is not an appropriate solution in the life critical situation
PNP-MAC [25]	Low	High	Sensors consume a high energy when they contend for slots in CAP. Preempts other data on the arrival of high priority data from the allocated slots which reduces the performance of data reliability due to preemption and sensors consume more energy
AN-MAC (LTDA-MAC) [23]	Low	High	Nodes consume a high energy during contention to access channel. Notify other nodes to terminate data transmission if there is no empty slot available in CFP which is not an appropriate solution for emergency data
ATLAS [26]	Low	High	Allocation of slots depends on the traffic load. The higher delay is faced to transmit data from sensors-to-cluster and cluster-to-gateway. This process consumes a high amount of energy which is not suitable for emergency data in terms of outnumbers of emergency data
ART-GAS [32]	Low	High	The different classification of a patient's data is represented by low, middle, and high. The suggested MAC does not define the priority to allocate dedicated slots in the alarming situations. With this shortcoming, the performance of the suggested MAC is reduced
CA-MAC [47]	Low	High	High energy consumption is noticed due to contention and data collision which affects the performance of slots allocation to emergency data in the alarming situation
Body-MAC [49]	N/A	High	Sensors consume a high energy during contention to access channel and is not suitable for the nature of a patient's data due to permission-based slots allocation and data transmission. Gateway is always ACTIVE which also consumes a high energy
A-MAC [50]	Low	High	There is no slot allocated for emergency-based sensors which consume more energy during contention to access channel. The control packets create overheads and reduce the data reliability

Table 5 continued

MAC protocol	Data reliability	Energy consumption	Remarks
F-MAC [51]	Low	High	Sensors consume more energy during contention to access channel. The rules based assignment of the GTS slots produces a higher delay during the verification of different conditions
PTA [48]	Low	High	The reserved slots for emergency-based BMSs cannot assign to non-emergency based BMSs if these are empty. This limitation wastes resources in terms of higher number of collisions of the packets, delay with lower data reliability and BMSs consume more energy
RF-MAC [52]	Low	High	Nodes perform contention to access channels in CAP period. With these contentions of nodes reduce the performance of MAC protocol in terms of a higher delay and higher energy consumption

assign priority-based slots to the critical data as compared to non-critical data. The Slotted Aloha channel access method is used with the support of an enabled-beacon control. At the beginning of data transfer, each node allocates a timeslot whereas a node can transmit critical and non-critical data. Therefore, 'G' is the total number of packets which are ready for transmission at the initial time slot as described as $G = \sum_{x=1}^{x=X} \sum_{n=0}^{n=r_x} C_x^n$ [53]. Where 'x' is the traffic index, 'n' is the retransmission of the lost traffic and its range is from 1, 2, 3 to r_x. The C_x^n is the number of critical and non-critical patient's data in the packet. The X (capital) is the supported traffic classes of the C_x^n whereas G is the successful packet delivery transmission which must be equal to 1. However, each node transmits critical and non-critical data in the pre-allocated time slots which reduce data reliability with higher data collision. Another limitation is nodes consume a higher energy during contention and reduces the performance of MAC protocol.

A cross-layer based IEEE 802.15.6 Superframe structure is employed for transmitting the patient's data on the reliable and an efficient path [54]. The proposed protocol is developed for extended star topology and divides the patient's data into Emergency data (EM), Delay Sensitive packets (DS) and General Monitoring packets (GM). The body coordinator allocates the slots EAPI and EAPII to EM and DS-based sensors during data transmission, respectively. GM-based sensors employ RAP (I,II) and CAP slots for data transmission. The slot allocation priority to EM is highly preferred as compared to other two types of data which consume minimum energy. However, the data delivery reliability for EM suddenly goes down when all BMSs continuously transmit data. Another limitation is that this protocol [54] does not discuss threshold values of vital signs. Table 6 presents the analysis of CSMA/CA with aloha based slot allocation to sensory data. The contention and predefined based slot allocation reduce data reliability and consume a higher amount of energy of nodes due to collision and a long wait, respectively. However, the probability based slot allocation reduces contention and avoids predefined time slots. With this optimal solution, the energy consumption is reduced, but it does not solve the conflict of slots between two emergency-based nodes. Hence, the

Table 6 Analysis of CSMA/CA with Aloha based slot allocation MAC protocols

MAC protocol	Data reliability	Energy consumption	Remarks
U-MAC [53]	Low	High	The slot allocation is based on the contention and predefined time slot. The energy consumption is high which degrades the data reliability in terms of a higher delay with collision and does not acceptable for critical data
AC-MAC [54]	High	Low	The patient's data are distributed to different channels, but GM data cannot access the channel which has reserved for EM. This restriction improves the performance of MAC in terms of lower energy consumption with higher data reliability

recommended solution is to allocate dedicated slots to low and high threshold values of vital signs without interrupting the contention of other nodes.

Slotted Aloha based MAC protocols

An urgency based Distributed Queuing Body Area Network (DQBAN) MAC protocol [55] is suggested with *Collision Resolution Queue (CRQ)* and *Data Transmission Queue (DTQ)*. The *CRQ* provides a channel access to those sensors which has emergency data of vital signs. While *DTQ* is employed to allocate collision-free channels to emergency sensors. The suggested protocol uses fuzzy logic rules in helping to specify the criticality level of vital signs and residual energy of a node. The drawback of [55] is that it cannot decide to allocate slots between two sensors if both detect the same types of emergency data at the same time.

The suggested Superframe structure of MAC protocol comprises of a beacon, emergency access period (EAP), normal access period (NAP), guaranteed access period (GAP) and acknowledgement [56]. The EAP period is associated with uplink and downlink. The uplink is employed to transmit data from BMSs to the body coordinator. The downlink is employed to transmit data between the body coordinator and BMSs. During an emergency situation, the BMSs transmit a message to EAP period using contention and the coordinator replies back with the allocation of GAP slots. However, the energy consumption of this scheme [56] increases if more BMSs are added to the network which affects the data reliability in terms of higher data delay and collision.

The Discrete Time Markov Chain mode is employed together with Slotted Aloha slots in the non-saturated conditions which can access finite number of BMSs (users) [57]. The slot allocation to the higher priority BMSs is given a higher ranking as represented by CP_{max} [57]. The data reliability degrades with higher data collision if more BMSs contend to access a slot. However, this scheme does not concentrate on the patient's data and energy consumption of BMSs is high during contention. Most of the MAC schemes allocate slots on the basis of contention as depicted in Table 7. The slot allocation conflict is the same challenging problem as noticed in this analysis. Thus, the permission-based slot allocation is an optimal solution to reduce the energy consumption and supports to increase data reliability.

Table 7 Analysis of Slotted Aloha based slot allocation MAC protocols

MAC protocol	Data reliability	Energy consumption	Remarks
HR-MAC [55]	High	Average	The energy consumption is minimum and allocates error-free slots to BMSs. The drawback is that it cannot decide a slot allocation if the same types of two emergency data occurred at the same time
A-MAC [56]	Low	High	The contention-based slot allocation and does not specify the patient's data in this scheme. The data reliability is reduced if more BMSs are added to network
MS-MAC [57]	Low	High	The suggested protocol does not discuss patient's data and consumes a higher energy of BMSs during contention to access slot. The data reliability decreases if more BMSs contend to access a slot

TDMA with Frame Slotted Aloha based MAC protocols

The following contributions design the MAC protocol in WBAN which are based on TDMA with Frame Slotted Aloha (FSA) scheduling access schemes. The Traffic adaptive MAC (TaMAC) protocol [28] is suggested to handle normal data, emergency and on-demand data. The suggested Superframe structure comprises of CCAP and CFP periods. The CCAP provides Mini-slots to transmit data in the short duration. In the TaMAC protocol, the wake-up of traffic-pattern is employed for non-emergency data. While wake-up radio is employed for emergency and on-demand traffic. In an emergency situation, the sensor transmits an alert signal to the body coordinator and the body coordinator replies with allocation of a channel. The energy consumption is low but sensors wait to transmit data in their predefined time slot which is the drawback of this protocol [28] due to outnumber of states in the state-transaction diagram. Another limitation is that the predefined based slot allocation to normal and emergency data is not acceptable due to the long wait where sensors drop data.

The Low-Power Distributed Queue (LPDQ) [58] scheme uses *LPL*, *Distributed Queue (DQ)* and *Channel Hopping (CH)* for ensuring the collision-free transmission, minimize the delay and reduce energy consumption. The suggested protocol comprises of network synchronization and data transmission phases [58]. In the network synchronization phase, all nodes are in *LPL* state whereas they periodically wake up and turn-on their radios to assure activities in the network. The *DQ* and *CH* are employed in the data transmission phase. The data transmission phase provides a fixed time structure where all nodes must transmit their packets by using an access request period (ARP). However, each sensor transmits an ARP message and waits to occupy channel which reduces the performance of MAC in terms of higher delay, ACK, retransmission of the lost packets, and high energy consumption. Another limitation of this scheme does not concentrate on a patient's data.

The MAC Superframe structure of [59] comprises of active and inactive parts whereas body coordinator divides channels into application-specific control and traffic-specific data channels. The active part is further divided into a beacon, timeslot-has reserved for periodic traffic (TSRP), timeslot-has reserved for bursty traffic (TSRB), control channel access (AC) AC1 and AC2 as shown in Fig. 11 (re-drawn from [59]). The uplink channels AC1 and AC2 are used to transmit medical and consumer electronics (CE) data, respectively using slotted-Aloha access scheme. In the life-critical situation, the body

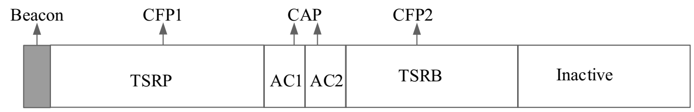

Fig. 11 Priority based Superframe structure

coordinator assigns AC1 channel to the high priority data. For contention-based slot allocation, the body coordinator calculates how many nodes are performing contention as described in $\Delta N = \min\{N\lambda L_f, N\}$ [59]. Where N is the total available nodes, λ is the traffic average arrival rate, and L_f is the waiting duration for the next announcement of Superframe. However, the suggested MAC protocol [59] consumes a higher amount of energy of sensors during maintaining the sessions of control ad data channels which creates overheads. The second limitation is that this scheme does not define low and high threshold values of vital signs.

The long waits of BMSs in the predefined timeslots drop the patient's data and BMSs consume more energy in this period as described in Table 8. These types of BMSs are instructed to wake up periodically and verify events in the network. However, the desirable solution is to transmit an alert command to the body coordinator during emergency situation where this process assists to resolve the conflict of slot allocation between two vital signs.

TDMA with FDMA based MAC protocols

This section presents different MAC protocols with combination TDMA and FDMA scheduling access schemes. The table-based wakeup for normal data and the radio-chip based wakeup for emergency data are introduced [24]. The patient's traffic is classified into normal, on-demand and emergency data. With radio-chip wake up of on-demand and emergency sensors transmit request for slots allocation with few conditions. First, the body coordinator transmits a wake-up authentication code (WAC) packet to emergency and on-demand traffic sensors, respectively. Second, the particular sensor compares the received WAC packet with its own generated WAC packet. Third, if the data packets of both are matched, then data communication link is established and updates the counter. Fourth, if WAC code does not match or sensors do not have enough energy

Table 8 Analysis of TDMA with Frame Slotted Aloha based Slot allocation

MAC protocol	Data reliability	Energy consumption	Remarks
UW-MACs [28]	Average	Low	Does not different between low and high threshold values and drops emergency data if other types of sensors occupy slots. Each node waits to transmit data in its predefined time slot
LPDQ [58]	Low	High	Each sensor transmits an ARP and waits for the channel which increases delay. The sensors re-transmit the packet, and wakes up periodically to verify any activity in the network which consumes a higher energy
PG-MAC [59]	Low	High	The sensors follow the control header and then data channels which consume a higher energy of BMSs. No priority is defined for low and high threshold of vital signs

to transmit their data, then both on-demand and emergency-based sensors drop data. However, this authentication process is the expensive practice in the life-critical alarming situations whereas sensors consume a higher energy and drop the life-threatening data.

The suggested MAC [35] uses TDMA with FDMA and provides two channels during data transmission from BMSs to the body coordinator. The TDMA scheduling access scheme is implemented on the distributed algorithm and provides *control* and *data sections*. The body coordinator uses a *control section* which supports a beacon to transmit in the network for synchronization. With this synchronization, the body coordinator allocates slots to BMSs. The BMSs transmit data in the *data section* when they receive a slot allocation message from the body coordinator. The FDMA divides slots into different frequencies and time-slots for data transmission. The suggested protocol [35] does not consider the patient's data but energy consumption is minimized with collision-free data transmission. Table 9 shows that non-emergency based nodes use contention and emergency-based nodes transmit alert commands for informing the body coordinator in the life-threatening conditions. The energy consumption and data reliability are achieved with these processes because the patient's data are categorized and each type of data is transmitted in the required slot. Further, an alert based data transmission avoids contention and consumes minimum energy but it does not resolve the slot conflict during allocation to emergency data if both types of a patient's data are the same status. For example, if a node H detects low threshold values of a heartbeat and a node R detects the high threshold value of the respiratory rate. In this situation, both nodes inform the body coordinator at the same time and the body coordinator cannot decide which of them should give a higher and lower priority to allocate slots.

Hybrid approaches based MAC protocols

The hybrid based MAC protocols design new scheduling access schemes for allocating slots to different types of a patient's data. This section explains each hybrid approach in the following subsections.

Polling and contention-based slot allocation

The Human Energy Harvesting Medium Access Control (HEH-BMAC) protocol is suggested with objectives to re-charge the batteries of wireless nodes from the harvesting

Table 9 Analysis of TDMA with FDMA based slot allocation MAC protocols

MAC protocol	Data reliability	Energy consumption	Remarks
PE-MAC [24]	High	Low	The energy consumption of BMSs is low and provides a higher data reliability due to distribution and allocation of the separated channels to each type of a patient's data
CO-MAC [35]	High	Low	Each type of a patient's data is allocated a separated channel during contention and transmission. By this process, the energy consumption is reduced and increases the chance of data transmission higher in terms of data reliability

energy of a human, uses ID-polling timeslot for emergency data and the probabilistic contention (PC) for normal data [60]. The body coordinator node is placed in the center and assigns the Monitoring Interval ($MIT_{ID\text{-}BN}$) to each body node (BN) in assisting to calculate the packet Inter-Arrival Time (IAT_{BN}) and constant energy harvesting rate (KEH). The body coordinator inserts an offset in $MIT_{ID\text{-}BN}$ for avoiding a collision in the packet inter-arrival time with increasing or decreasing the polling time of a node. In PC mode, the body coordinator broadcasts the 'Control Packet' (CP) to nodes whereas the nodes define their threshold values (Xi) for data packet transmission. Further, the node transmits data and gets an acknowledgment reply from the body coordinator if $Xi < CP$. If the node does not receive the CP's packet, then the body coordinator waits for the predefined interval and sends it back with changing the threshold values. However, the packet collision occurs if more than one node have the same threshold values for data transmission, whereas the energy consumption of the nodes become high.

The [60] protocol does not predict in advance which node detects an emergency and non-emergency data to allocate slots for data transmission accordingly. During data collision, the body coordinator adjusts the threshold values of the sender sensors to build a gap between their timing and data transmission. With this process, the data reliability of MAC protocol becomes degraded in terms of delay and consumes a higher energy of nodes. However, this protocol does not define low and threshold values of vital signs which is not suitable for emergency data.

Polling based slot allocation

The suggested BodyQoS protocol comprises of an *Admission Control, QoS scheduler and Virtual MAC (VMAC)* [61]. The functionalities of *admission control* and *QoS scheduler* are implemented on the master node (aggregator) and slave nodes (sensors). The *admission control* and *scheduler* for a master node are handled by the aggregator. For a slave node, the *admission and scheduler* are handled by sensor nodes. The benefits of *admission control* are: (i) the node transmits the request for new QoS channel reservation which can be accepted or rejected. The acceptance or rejection is based on the availability of bandwidth, (ii) polling of individual sensor to access channel, and (iii) measures the criticality level of a patient's data. In the *QoS scheduler*, there are three types of traffic considered that are aggregator to a sensor, Sensor to the aggregator and best effort delivery. The *VMAC* is used to connect the transport layer with MAC layer. The suggested protocol [61] consumes a higher amount of energy of sensors because most of the activities are performed on sensors. Another limitation of this protocol is that each sensor waits for verifying the availability of slots to transmit data which reduces the performance of the suggested MAC in terms of collision with a higher delay.

Preamble based slot allocation

The Traffic-Aware Dynamic MAC (TAD-MAC) protocol [62] is suggested for in-body and on-body traffic communication. The suggested protocol uses '*Before convergence*' and '*After convergence*' phases. In the '*Before convergence*' phase, each node cannot transmit data and must wait for a beacon signal from the body coordinator. The body coordinator learns various wakeup states of nodes from a beacon signal and uses the wake-up interval (WUInt) under the *convergence phase*. The WUInt and the node traffic information are maintained in Traffic Status Register (TSR) bank. On the successful delivery of data, the recipient node replies with '1'. Otherwise, it replies with '0' which indicates the failure of data to sender node. This scheme [62] faces a higher delay in transmitting data and consumes a higher amount of energy of the node during the wait period for a beacon which is not acceptable in emergency situation.

Node ID based slot allocation

An *Efficient Dynamic Scheduling Approach (EDSA)* is suggested and compares with *Time Division Beacon Scheduling (TDBS)* [63]. The comparison of both schemes is based on the allocation of dynamic slots and assignments of addresses to nodes. The *TDBS* scheme assigns addresses and slots to nodes in the predefined time interval whereas each node waits for a long period of time. While *EDSA* scheme uses static and dynamic algorithms to assign addresses and slots to nodes. The addresses and time slots allocation are assigned to each node using static algorithm in the predefined schedule. Both slot allocation processes are verified from the table which is maintained under the supervision of a personal area network coordinator (PANC). The advantage of the dynamic algorithm is collision-free processing without delay and achieves a higher data reliability. Moreover, the slot allocation procedure in the dynamic algorithm is based on the first come first serve but the static algorithm assigns slots to each node in sequence and each node waits for its predefined time. As compared static algorithm to a dynamic algorithm, the dynamic algorithm outperforms and allocates collision-free slots without the verification of sequence of nodes. In the static algorithm, the nodes consume a higher amount of energy during the waiting period for allocation of slots. Another limitation is that this scheme does not differentiate between low and high threshold values of vital signs.

Slot allocation based on the criticality level of a patient's data

An ultra-light weight and low power complexity MAC protocol is suggested with the support of three-way handshakes between a body coordinator and nodes [64]. The CSMA/CA access scheme can avoid data collision but this scheme creates overheads and increases a higher delay during data transmission due to RTS, CTS, DATA and acknowledgment (ACK). Thus, the suggested protocol [64] replaces the functionalities of CSMA/CA access scheme with '*Data Request' (DR), DATA and ACK*. The *DR* maintains the address of each node whereas a node waits for DR message from the body coordinator before data transmission. During data transmission of a node-1 to the body coordinator, all nodes turn-off their radio signals and change their states to the sleep states. Since, the body coordinator replies back with piggybacking message (ACK + DR2) to a node-1 when the body coordinator receives DATA. The [64] tries to change the control signal messages of the CSMA/CA scheme access but each node waits for a DR message before data transmission. Hence, the energy consumption of the suggested scheme is enhanced but the allocation of slots to nodes is based on the contention which reduces data reliability of sensory data in terms of a higher delay which is not acceptable for emergency data.

Urgency based slot allocation

The table-based, aggregation and fuzzy logic based proposed approaches are used to find the criticality levels of respiratory rate (RR), heartbeat rate (HR), and mental status (MS) [65]. The RR and HR are further classified into low_critical, high_critical and normal values. The MS is represented by responsiveness (means ok) and non-responsiveness. The lower threshold value of a vital sign is more in life-critical situation as compared to high threshold value. The reason is that the low threshold value approaches towards zero value while the high critical threshold value is far away from the ranges of low threshold values. Hence, the first priority of a slot allocation is given to low threshold values. The table approach represents the tabular representation and assigns the priority on the basis of criticality level of threshold values. The aggregation based approach calculates the average of three vital signs and takes decision as described in $C_{agg} = \frac{C_{RR} + C_{HR} + C_{MS}}{3}$. The fuzzy logic is the third approach and uses member functions for representing vital signs. The purpose of the member function is to extract the knowledge from threshold values. However, this scheme does not consider other vital signs of a patient, energy consumption and data reliability in the resource constraints environment of WBAN.

Permission based slot allocation

The master node uses *Transmit Slot (TX)*, *Receive Slot (RX)*, *Receive to Synchronize (RXS)* and *Stand By slot (SB)* [66] to transmit the patient's data as shown in Fig. 12 (re-drawn from [66]). All nodes in the network are in *SB* or *RXS*. During *SB* state, the node hears the transmission of the sender node and becomes active to receive the packets if the intended packets are coming to it. However, the suggested protocol allocates slots to nodes in the predefined pattern and each node transmits data in the predefined time slot. The master node blocks data transmission of other nodes when one node is busy for data transmission. Due to this blockage problem, the nodes consume a higher amount of energy and reduce data reliability which is not appropriate for emergency data.

Performance evaluation

The simulation is performed using NS2 and compares the performance of the MAC protocols in terms of average packet delivery delay, the average delay for delay-driven packets, throughput and energy consumption of BMSs. Table 10 shows the simulation parameters list of LTDA-MAC [15], PNP-MAC [20], PLA-MAC [20], and IEEE 802.15.4 MAC [12] protocols. The number of available slots in the MAC Superframe structure of LTDA-MAC is 32, IEEE 802.15.4 provides 16 slots, and PNP-MAC and PLA-MAC both provide 128 slots. The common parameters list of simulation is provided which have used in the four MAC protocols as aforementioned. The operating frequency is 2.4 GHz and the channel sending rate is 250 kbps. Moreover, all twelve BMSs are static

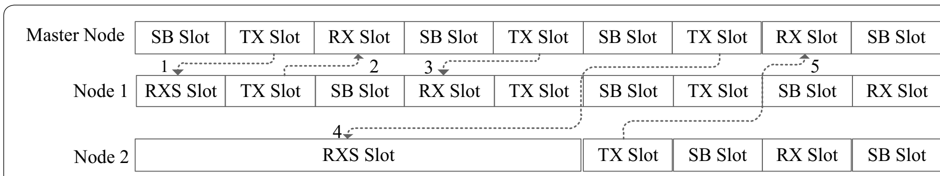

Fig. 12 The Master and Slave Nodes data exchange scenario

Table 10 Simulation parameters list

Common parameters list		Common parameters list	
Parameter	**Value**	**Parameter**	**Value**
Operating frequency	2.4 GHz	*LTDA-MAC* [15]	
Channel rate	250 kbps	Total no. of slots in Superframe	32
CCA time	8 symbols	Slots in CAP	6
Max frame retries	4	Transmit power	36.5 mW
Traffic type	CBR	Receive	41.4 mW
Turnaroundtime	12 symbols	*PLA-MAC* [29]	
UnitBackoffPeriod	20 symbols	Total no. of slots in Superframe	128
macAckWaitDuration	54	Slots in CAP	20
Topology	Star	BO	6
PNP-MAC [20]		*IEEE 802.15.4 MAC* [12]	
Total no. of slots in Superframe	128	Total no. of slots in Superframe	16
BO	6	BO	6
SO	3	SO	3
Slot size	7.68 ms	Slot size	7.68 ms
CAP	8 slots	CAP	8 slots
CFP (PNP)	116 slots	CFP	7 slots
MACMinBE	3	MACMinBE	3
MACMaxBE	5	MACMaxBE	5
MACMaxCSMACABackoffs	4	MACMaxCSMACABackoffs	4

and connected with a body coordinator in the star topology. The simulation area is 3×2 m and simulation runs for 200 s.

The average packet delivery delay of PLA-MAC, PNP-MAC, LTD-MAC and IEEE 802.15.4 MAC are compared as shown in Fig. 13. These four MAC protocols allocate slots to all nature of a patient's body based contention in the CAP period. Thus, the body coordinator allocates the guaranteed timeslots of the CFP period to those BMSs who obtain a channel in the CAP period. Each BMS is allocated a certain amount of time in which the BMS contends and transmits data. The contention and transmission of data

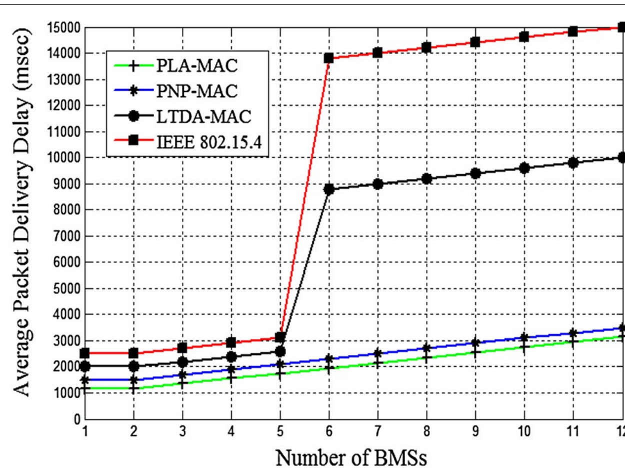

Fig. 13 Average packet delivery delay VS number of BMS

depend on the values of beacon order (BO) and Superframe order (SO). The BO is the interval between two successive beacons of the MAC Superframe structure whereas SO is the time duration of the active slots of the MAC Superframe structure. Since, the beacon order $BO = 6$ and $SO = 3$ are configured for IEEE 802.15.4 MAC Superframe structure. The allocated channels for contention in IEEE 802.15.4 MAC are 8 in the CAP period. As more BMSs contend for accessing channel in CAP period of IEEE 802.15.4 MAC, the packet delivery delay is increased due to contention as more BMSs contend. This is because of the limited channels, retransmission of the lost packets, and limited time of Superframe duration which is *1.536 s* and a slot duration is *0.012 s*. Another reason is that all BMSs cannot contend and transmit data in the same beacon interval (BI) but they wait for the next announcement of BI. As compared IEEE 802.15.4 MAC, the LTDA-MAC outperforms in terms of reduced delay of the packets but the delay increases when the traffic loads exceed the number of available slot in LTDA-MAC Superframe structure. The PNP-MAC classifies the patient's data into five classes and each class has assigned a unique priority. With this unique priority is denoted for allocating of slots on the priority-basis during contention for accessing channel. The packet delivery delay is reduced by PNP-MAC and outperforms as compared to IEEE 802.15.4 MAC and LTDA-MAC because the BI provides 128 slots, dedicated slots to different types of a patient's data and a sufficient timing for BMSs for accessing channel in CAP period which is $BI = 19.668\ s$. However, the packet delivery delay increases of PNP-MAC due to preemption of the non-emergency data from allocated slots on the arrival of the emergency data. The PLA-MAC uses the same configuration as used in PNP-MAC but it does not perform preemption techniques as addressed in PNP-MAC. The PLA-MAC outperforms as compared all MAC protocols discussed. The PLA-MAC protocol classifies the patient's data into four types which fulfills the needs of a patient. With this classification, each patient's data have assigned dedicated slots and the allocation of slots is based on the criticality level of a patient which reduce the packet delivery delay.

The average delivery delay for delay-driven packets is compared of PLA-MAC with PNP-MAC as shown in Fig. 14. Both MAC protocols provide 128 slots with allocating

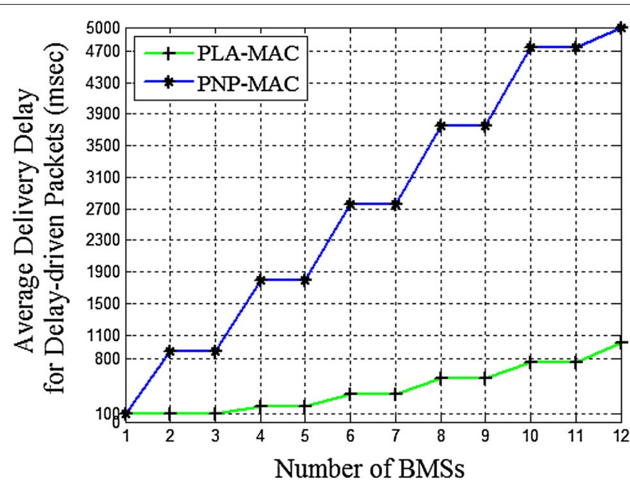

Fig. 14 Average delivery delay for delivery-driven packets VS number of BMS

of dedicated slots for non-emergency and life-critical emergency data. However, the contention-based slot allocation to BMSs reduces the performance of MAC in terms of collision, retransmission of the lost packets with a higher delay which is not acceptable for life-critical patient's data. These problems have noticed in PNP-MAC because this MAC first removes the non-critical data from the allocated slots and then assigns these slots to emergency data. During preemption of the non-emergency data from slots, the life-critical data based BMSs face a higher delay because of contention of other BMSs and in this way the delay increases as the traffic load exceeds. As compared PLA-MAC to PNP-MAC, the PLA-MAC outperforms by allocating separate and dedicated slots for non-emergency and emergency data in the CFP period. Further, this PLA-MAC is not practicing the preemption technique due to which the life-critical data are not delayed as shown in Fig. 14.

Figure 15 presents the throughput of the existing MAC Superframe structures. The throughput of IEEE 802.15.4 MAC reduces when the data packets sending of BMSs are increased. The reason for this reduction is because of the limited channels in MAC Superframe structure, contention-based channel allocation, a higher number of collisions, and retransmission of the collided packets with a higher delay. The second reason is the waiting period whereas BMSs cannot transmit data in the same BI and they wait for the announcement of next BI. The throughput of LTDA-MAC is better as compared to IEEE 802.15.4 MAC but the throughput reduces of LTDA-MAC as more BMSs contend and transmit data to the body coordinator. This LTDA-MAC has the same problems as highlighted in IEEE 802.15.4. Further, the reduction of throughput of PNP-MAC is due to preemption of sensory data of one BMS on the arrival of sensory data of another BMSs. However, the PNP-MAC outperforms in allocating of slots and transmission of sensory data of BMSs as compared to LTDA-MAC and IEEE 802.15.4. The final PLA-MAC allocates dedicated slots to emergency and non-emergency data whereas each type of BMS transmits data in those dedicated slots. With these advantages, the throughput of PLA-MAC is the highest as compared to the rest of MAC protocols as shown in Fig. 15.

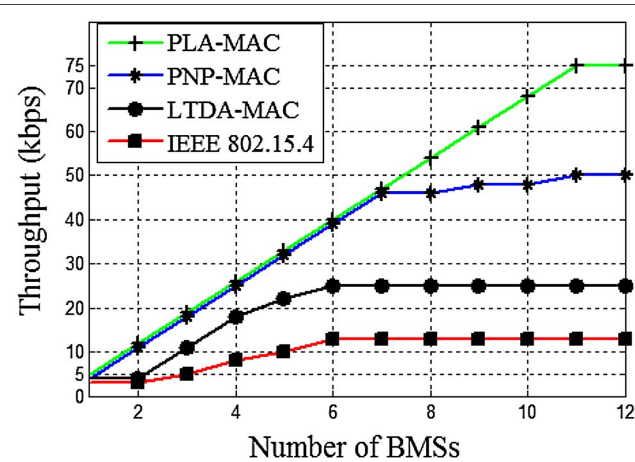

Fig. 15 Throughput VS number of BMS

The high energy consumption of BMSs in the MAC protocols is IEEE 802.15.4 MAC and LTDA-MAC as more BMSs transmit data to the body coordinator as shown in Fig. 16. Both protocols allocate channels to BMSs with the assistance of contention, the limited channels with no separate and dedicated channels for emergency and non-emergency data, and all BMSs cannot contend for accessing CAP period and transmit the patient's data in the same BI. As more BMSs generate more traffic, the chances of the preemption of data increase which consume more energy of BMSs as noticed in PNP-MAC. However, the minimum energy consumption of BMSs has been noticed in PLA-MAC as compared to the remaining MAC protocols as shown in Fig. 16. The reason for the minimum energy consumption of BMSs is dedicated slots to emergency and non-emergency data without interrupting the contention process of each other.

Figure 17 evaluates the energy consumption of the body coordinators of their respective MAC Superframe structures. IEEE 802.15.4 provides fixed 7 slots in the CAP period whereas all types of BMSs whether emergency or non-emergency based BMSs perform contention to access channel. BMSs drop the patients' data when the contention reaches to the highest peak because of the limited 16 slots. With this higher collision of the patient's data, all BMSs wait for contending and transmitting data in the next announcement of BI which consume a higher energy of the body coordinator. The energy consumption of the body coordinator in the LTDA-MAC increases gradually due to limited slots in CAP period, high traffic load, and the body coordinator announces a new BI after 98 s. The PNP-MAC and PLA-MAC provide 128 slots and their energy consumption are low as compared to the aforementioned MAC protocols. However, the energy consumption of PNP-MAC is higher due to the preemption of sensory data from allocated slots for coming sensory data of other BMSs, and provides limited 8 slots in CAP period. With these changing of the order of the patient's data, the body coordinator is actively involved for such types of activities. While PLA-MAC provides 20 slots in CAP period which are sufficient for BMSs to contend and transmit data without actively involving of the body coordinator.

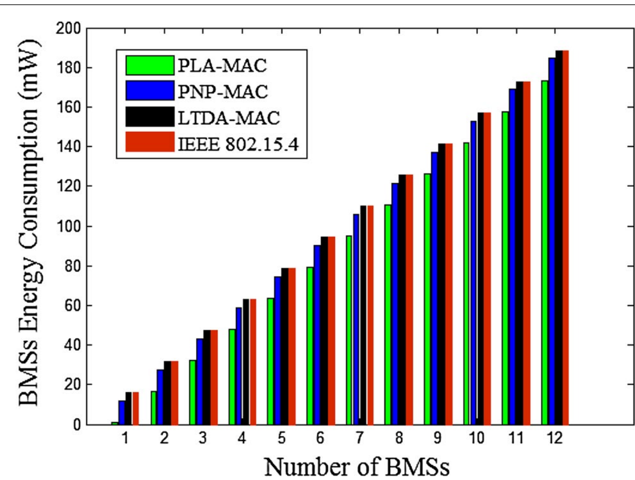

Fig. 16 Energy Consumption VS BMSs

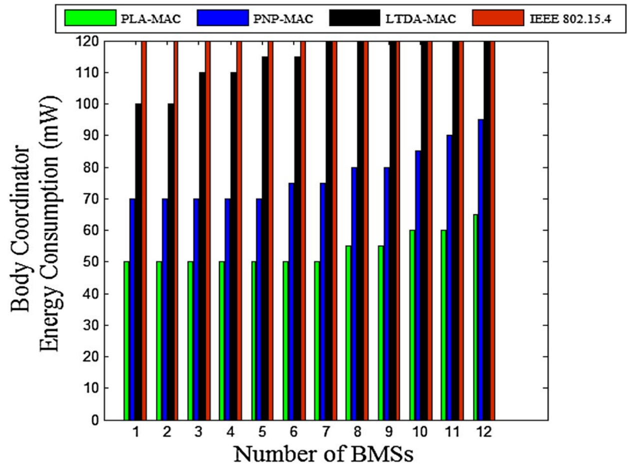

Fig. 17 The body coordinator Energy Consumption VS BMSs

Future challenges

The WBAN is the medical application of WSN and it needs to design an efficient MAC protocol due to their unique requirements and specific characteristics [67]. This paper classifies the challenging and open issues in WBAN in two classes. The first class gives an explanation of different scheduling access schemes which are used in MAC layer for a patient's data. The second class of classification highlights the different routing issues.

MAC layer issues

Suffering of heterogeneous nature of a patient's data in WBAN

There are different types of BMSs used to monitor different vital signs such as heartbeat rate, respiratory rate, EEG, ECG, glucose, temperature, blood pressure. The BMSs transmit the patient's data in different data rates and frequencies which require high processing power, high storage and high energy to transmit to the body coordinator [68]. Hence, the researchers ought to design MAC protocol that fulfills the requirements of the dedicated data rates for BMSs.

Waiting period based slot allocation

The waiting period based slot allocation is performed with the support of TDMA scheduling access scheme whereas the nodes require synchronization before data transmission in the pre-allocated time slots [29]. The emergency-based nodes require a higher care to transmit their data without waiting and synchronization to the body coordinator in the life-critical situations. Thus, the waiting of nodes suffers the patient's life and technologically the nodes consume a higher energy with lower data reliability.

Unconditional contention-based slot allocation

It has been noticed in the existing studies that MAC schemes use CSMA/CA scheduling scheme in which all types of nodes perform contention to access channel in the CAP period [48]. During contention, the non-emergency based nodes do not care of emergency-based nodes to give priority in the allocation of slots which is not acceptable medically for emergency data and technologically the nodes consume a higher amount of energy, higher collision, and re-transmission of the lost packets [57].

Channel access design complexity

The FDMA provides collision-free data transmission but designing of hardware is the most crucial and challenging problem during establishing the communication links between nodes [59].

Threshold values based slot allocation

The existing studies do not decide for allocating of slots on the priority basis to two vital signs if two vital signs are detected with low-to-high or high-to-low threshold values at the same time. As stated in [65] that low threshold of a vital sign is in more life-critical conditions as compared to the high threshold value of a vital sign. Hence to resolve such challenging problem, the MAC Superframe structure needs to add an individual slot for each type of emergency data.

Alert-based slot allocation

The dedicated slot is used to receive an alert signal from the particular BMS and allocate slots in emergency situation. In fact, the node requires three-way handshaking process to establish a communication session with the body coordinator and transmits data [26]. This approach drops the patient's data due to the long waiting period of allocating a slot.

Permission-based slot allocation

The permission-based slot allocation to nodes consume a higher energy with higher delay which degrades the performance of MAC protocol in terms of lower data reliability [66]. These challenging issues are not appropriate for emergency-based nodes whereas they wait for beacons to transmit and receive data.

Preemptive and non-preemptive based slot allocation

On the arrival of emergency data, the body coordinator preempts the non-emergency data from allocated slots and assigns to emergency data [20]. The blockage and removing of non-emergency data from the allocated slots reduces the performance of MAC protocol in terms of lower data reliability with higher dropping of a patient's data, and BMSs consume more energy on the re-transmission of the lost packets.

Hybrid based slot allocation

Most of the existing MAC schemes use TDMA and CSMA/CA scheduling access scheme as hybrid scheduling schemes [36]. Both scheduling schemes are an optimal solution to allocate slots to non-emergency data. However, the contention and predefined access based slots allocation to emergency-based nodes reduces data reliability in terms of a higher data collision, higher re-transmit of the lost packets, and nodes consume a higher amount of energy.

Priority based slot allocation to emergency data in WBAN

The patient's data is classified into emergency, periodic and non-emergency data. The emergency data comprises of low and high threshold values of vital signs such as the heartbeat-based BMS detects a low threshold value and the respiratory rate-based BMS detects a high threshold value [69]. The periodic data is used for on-demand service that is the body coordinator which retrieves data from any BMS and transmits the outcomes to the medical doctor. The non-emergency data comprises of temperature, blood pressure and glucose level. Hence, the emergency data requires a higher attention to giving the first channel access as compared to periodic and non-emergency data [70]. The emergency data are in a life-threatening situation and may suffer the patient's life if it does not allocate the first channel [65]. The researchers ought to re-design MAC and routing protocols with efficient scheduling access schemes in order to transmit emergency data without contention.

General research issues of WBANs

Radiation absorption and overheating in WBAN

The radio frequency (RF), the radiation of biosensors' antenna and the circuitry of sensor node are the three sources of temperature-rise which heat up BMSs during monitoring of vital signs and data transmission to the body coordinator. With this heat up, BMSs damage tissues and skin of a patient's body [71]. Due to these challenging problems, some new routing protocols should need to design for keeping safe the tissues and skin from overheating.

Quality of Service (QoS) in WBAN

The patient's data are classified into critical data, delay sensitive data, reliability-sensitive data and ordinary data [72]. These types of data require a dedicated and guaranteed QoS to transmit without delay and packet loss. The researchers need to suggest and design an efficient QoS for delay sensitive data of WBAN as compared to WSN data.

Path loss in WBAN and WSN

BMSs are implanted inside the patient's body and/or attached on the skin for monitoring of various vital signs. The path loss occurs in WBAN due to fat and various postural movements of a patient's body such as LYING-DOWN, SIT, SIT-RECLINING, STAND, WALK and RUN [73]. The data transmission in WSN is in free space where it has minimum path loss as compared to WBAN. The researchers ought to improve the existing MAC and routing protocols for WBAN to minimize the path loss problems.

Data protection in WBAN and WSN

Both WBAN and WSN transmit data in free space which faces problems of data integrity. The existing security techniques are difficult to apply on the tiny BMSs due to limited memory, storage, energy and processing power [74]. Therefore, it is suggested to develop new and light weight security techniques for protecting the patient's data from an unauthorized access.

High energy consumption

Most of the energy of BMSs is consumed due to contention-based slot allocation, predefined based slot allocation and permission. In order to minimize the energy consumption, the alert based slot allocation to BMS is the appropriate solution for extending the network life time.

Limited resources

The low data storage, low processing power and high energy consumption are the challenging problems of WSN's sensor and these sensors are used in WBAN to monitor the sensitive organs of humans [75]. The manufacturers and designers are suggested to enhance the performance of sensors in terms to minimize the energy consumption, provide high data storage and high processing power.

Conclusion

In this paper, a qualitative review of MAC protocols for WBAN has been carried out by analyzing the designs of Superframe structure, describing multiple access schemes, and presenting a taxonomy based qualitative analysis of the MAC protocols. The design of Superframe structure and multiple access schemes are the two most significant design decisions, from where the optimal prioritization of the patient's data can be obtained for a MAC protocol in WBANs. The optimality in prioritization of a patient's data determines the efficiency of MAC protocol in terms of slot allocation, energy consumption during contention, and reliability of data. It has been observed that the classification of the patient's data in four categories, namely, Critical data Packet (CP), Reliability data Packet (RP), Delay data Packet (DP) and Ordinary data Packet (OP) is the most appropriate classification. The classification consider the requirements including low and high threshold values, on-demand access to a specific vital sign, and normal, emergency and non-emergency data. CSMA/CA scheduling is more appropriate for normal and non-emergency data due to the absence of time constraint, in case of these types of data where contentions are performed for slot allocation. TDMA scheduling schemes are more appropriate for emergency data, where without performing contention, the emergency-based sensor transmits an alert signal to body coordinator for slot allocation. The contention based sensors perform backoffs to access channels, which creates overheads resulting in higher collision, delay, retransition of lost packets, and lower reliability of data.

Authors' contributions

This research is a group work, and each author has significant contributions. FU carried out the technical review with suggestions from AHA and OK. SK and MMA helped in carrying out revisions of the paper. All authors read, and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

1. Health Monitoring by Google Trend (2015) https://www.google.com/trends/explore#q=Healthmonitoring%2CEnvironmentmonitoring&date=1%2F201072m&cmpt=q&tz=Etc%2FGMT-8. Accessed 10 Jan 2016
2. Ullah S, Chen M, Kwak KS (2012) Throughput and delay analysis of IEEE 802.15.6-based CSMA/CA protocol. J Med Syst 36:3875–3891
3. Oey CHW, Moh S (2013) A survey on temperature-aware routing protocols in wireless body sensor networks. Sensors 13:9860–9877
4. Movassaghi S, Member S, Abolhasan M, Member S (2014) Wireless Body Area Networks: a survey. IEEE Commun Surv Tutor 16(3):1658–1686
5. Milenković A, Otto C, Jovanov E (2006) Wireless sensor networks for personal health monitoring: issues and an implementation. Comput Commun 29:2521–2533
6. Bhoir S, Vidhate A (2014) An improved WBAN MAC protocol. In: 2014 international conference on computer communication and informatics, pp 1–6
7. Rout DK, Das S (2016) Hybrid relaying in ultra-wideband body area networks. Wirel Pers Commun 86(2):435–449
8. Boulis A, Smith D, Miniutti D, Libman L, Tselishchev Y (2012) Challenges in body area networks for healthcare: the MAC. IEEE Commun Mag 50(5):100–106
9. Akbar MS, Yu H, Cang S (2016) Delay, reliability, and throughput Based QoS Profile: a mac layer performance optimization mechanism for biomedical applications in wireless body area sensor networks. J Sens 2016:1–17
10. Kim Y, Lee S (2014) Energy-efficient wireless hospital sensor networking for remote patient monitoring. Inf Sci 282:332–349
11. Xing J, Zhu Y (2009) A survey on body area network. In: 2009 5th international conference on wireless communications, networking and mobile computing, pp 1–4
12. Lai X, Liu Q, Wei X, Wang W, Zhou G, Han G (2013) A survey of body sensor networks. Sensors 13(5):5406–5447
13. Chen M, Gonzalez S, Vasilakos A, Cao H, Leung VCM (2010) Body area networks: a survey. Mob Netw Appl 16(2):171–193
14. Ullah S, Shen B, Riazul Islam SM, Khan P, Saleem S, Kwak KS (2010) A study of MAC protocols for WBANs. Sensors 10:128–145
15. Ullah S, Mohaisen M, Alnuem MA (2013) A review of IEEE 802.15.6 MAC, PHY, and security specifications. Int J Distrib Sens Netw 2013:1–12
16. Filipe L, Fdez-Riverola F, Costa N, Pereira A (2015) Wireless Body Area Networks for healthcare applications: protocol stack review. Int J Distrib Sens Netw 2015:1–23
17. Cavallari R, Martelli F, Rosini R, Buratti C, Verdone R (2010) A survey on Wireless Body Area Networks: technologies and design challenges. IEEE Commun Surv Tutor 3:1–23
18. Kaiwartya O, Abdullah AH, Cao Y, Lloret J, Kumar S, Shah RR, Prasad M, Prakash S (2017) Virtualization in wireless sensor networks: fault tolerant embedding for internet of things. IEEE Internet of Things J PP(99):1–10. doi:10.1109/JIOT.2017.2717704
19. Zhan Y, Xia Y, Anwar M (2016) GTS size adaptation algorithm for IEEE 802.15.4 wireless networks. Ad Hoc Netw 37:486–498
20. Ullah F, Abdullah AH, Kaiwartya O, Lloret J, Arshad MM (2017) EETP-MAC: energy efficient traffic prioritization for medium access control in wireless body area networks. Telecommun Syst 1–23. doi:10.1007/s11235-017-0349-5
21. Rashwand S, Mišić J (2012) Effects of access phases lengths on performance of IEEE 802.15.6 CSMA/CA. Comput Netw 56(12):2832–2846
22. Ullah F, Abdullah AH, Kaiwartya O, Cao Y (2017) TraPy-MAC: traffic priority aware medium access control protocol for wireless body area network. J Med Syst 41(6):93–111. doi:10.1007/s10916-017-0739-y
23. Li C, Hao B, Zhang K, Liu Y, Li J (2011) A novel Medium Access Control protocol with low delay and traffic adaptivity for Wireless Body Area Networks. J Med Syst 35(5):1265–1275
24. Al Ameen M, Liu J, Ullah S, Kwak KS (2011) A power efficient MAC protocol for implant device communication in Wireless Body Area Networks. In: 2011 IEEE consumer communications and networking conference (CCNC), pp 1155–1160
25. Yoon JS, Ahn G-S, Joo S-S, Lee MJ (2010) PNP-MAC: preemptive slot allocation and non-preemptive transmission for providing QoS in body area networks. In: 2010 7th IEEE Consumer Communications and Networking Conference, pp 1–5
26. Rahman MO, Hong CS, Lee S, Bang Y-C (2011) ATLAS: a traffic load aware sensor MAC design for collaborative body area sensor networks. Sens (Basel, Switz) 11(12):11560–11580
27. Khattiya W, Timakul S, Choomchuay S (2013) An error control coding in MAC layer for UWB WBAN. In: 2013 IEEE international conference on signal processing, communication and computing (ICSPCC 2013), pp 1–5
28. Ullah S, Kwak KS (2012) An ultra low-power and traffic-adaptive Medium Access Control protocol for wireless body area network. J Med Syst 36(3):1021–1030
29. Isikman AO, Cazalon L, Chen F, Li P (2011) Body area networks. Mob Netw Appl J 16(2):171–193
30. Anjum I, Alam N, Razzaque MA, Mehedi Hassan M, Alamri A (2013) Traffic priority and load adaptive MAC protocol for QoS provisioning in body sensor networks. Int J Distrib Sens Netw 2013:1–9

31. Zeng D, Guo S (2010) An energy aware MAC protocol for Wireless Personal Area Networks. In: 2010 2nd international symposium on aware computing, pp 171–176
32. Xia F, Hao R, Li J, Xiong N, Yang LT, Zhang Y (2013) Adaptive GTS allocation in IEEE 802.15.4 for real-time wireless sensor networks. J Syst Archit 59(10):1231–1242
33. Razzaque MA, Hong CS, Lee S (2011) Data-centric multiobjective QoS-aware routing protocol for body sensor networks. Sens (Basel, Switz) 11(1):917–937
34. Lin L, Kumar A (2011) An energy efficient MAC protocol for mobile in vivo body sensor networks. In: 2011 3rd international conference on ubiquitous and future networks (ICUFN), pp 95–100
35. Wang R, Wang H, Roman HE, Wang Y, Xu D (2013) A cooperative Medium Access Control protocol for mobile clusters in Wireless Body Area Networks. In: 2013 1st international symposium on future information and communication technologies for ubiquitous healthcare (Ubi-HealthTech), pp 1–4
36. Khan ZA, Rasheed MB, Javaid N, Robertson B (2014) Effect of packet inter-arrival time on the energy consumption of beacon enabled MAC protocol for body area networks Procedia Comput Sci 32:579–586
37. Wang S-L, Chen YL, Kuo AM-H, Chen H-M, Shiu YS (2016) Design and evaluation of a cloud-based Mobile Health Information Recommendation system on wireless sensor networks. Comput Electr Eng 49:221–235
38. Gopalan SA, Kim DH, Nah JW, Park JT (2010) A survey on power-efficient MAC protocols for wireless body area networks. In: Broadband network and multimedia technology (IC-BNMT), 2010 3rd IEEE International Conference on. IEEE, Beijing, China, pp. 1230–1234
39. Marinkovic S, Spagnol C, Popovici E (2009) Energy-efficient TDMA-based MAC protocol for Wireless Body Area Networks. In: 2009 3rd international conference on sensor technologies and applications, pp 604–609
40. Charfi F, Bouyahi M, 1 Laboratoire (2012) Performance evaluation of beacon enabled IEEE 802.15.4 under NS2. Int J Distrib Parallel Syst (IJDPS) 3(2):67–79
41. Al Ameen M, Ullah N, Chowdhury MS, Islam SMR, Kwak K (2012) A power efficient MAC protocol for Wireless Body Area Networks. EURASIP J Wirel Commun Netw 2012(1):33
42. Lin L, Yang C, Wong KJ, Yan H, Shen J, Phee SJ (2014) An energy efficient MAC protocol for multi-hop swallowable body sensor networks. Sens (Basel, Switz) 14(10):19457–19476
43. Timmons NF, Scanlon WG (2009) An adaptive energy efficient MAC protocol for the medical body area network. In: 2009 1st international conference on wireless communication, vehicular technology, information theory and aerospace & electronic systems technology, pp 587–593
44. Calhan A (2016) A Non-Preemptive priority scheduling algorithm for improving priority data transmission delay in wireless body area networks. Adhoc & Sens Wireless Netw 34:59–75
45. Choi JS, Kim JG (2014) An improved MAC protocol for WBAN through modified frame structure. Int J Smart Home 8(2):65–76
46. Li H, Member S, Tan J (2010) Heartbeat-driven medium-access control for body sensor networks. IEEE Trans Inf Technol Biomed 14(1):44–51
47. Rezvani S, Ghorashi SA (2013) Context aware and channel-based resource allocation for Wireless Body Area Networks. IET Wirel Sens Syst 3(1):16–25
48. Shuai J, Zou W, Zhou Z (2013) Priority-based adaptive timeslot allocation scheme for wireless body area network. In: 2013 13th international symposium on communications and information technologies (ISCIT), pp 609–614
49. Fang G, Dutkiewicz E (2009) BodyMAC: energy efficient TDMA-based MAC protocol for Wireless Body Area Networks. In: 2009 9th international symposium on communications and information technology, pp 1455–1459
50. Javaid N, Ahmad A, Rahim A, Khan ZA, Ishfaq M, Qasim U (2014) Adaptive Medium Access Control protocol for Wireless Body Area Networks. Int J Distrib Sens Netw 2014:1–10
51. Zhou J, Guo A, Xu J, Su S (2014) An optimal fuzzy control medium access in Wireless Body Area Networks. Neurocomputing 142:107–114
52. Ullah S (2013) RFID-enabled MAC protocol for WBAN. In: 2013 IEEE international conference on communications (ICC), pp 6030–6034
53. Ali KA, Sarker JH, Mouftah HT (2010) Urgency-based MAC protocol for wireless sensor body area networks. In: 2010 IEEE international conference on communications workshops, pp 1–6
54. Ben Elhadj H, Boudjit S, Fourati LC (2013) A cross-layer based data dissemination algorithm for IEEE 802.15.6 WBANs. In: 2013 International conference on smart communications in network technologies, SaCoNeT 2013, vol 1
55. Otal B, Alonso L, Verikoukis C (2009) Highly reliable energy-saving mac for wireless body sensor networks in healthcare systems. IEEE J Sel Areas Commun 27(4):553–565
56. Liu Y, Harn L, Chang CC (2015) A novel verifiable secret sharing mechanism using theory of numbers and a method for sharing secrets. Int J Commun Syst 28(7):1282–1292
57. Chowdhury MS, Khan P, Jung J, Kwak KS, Engineering C, Korea S (2014) Modeling Slotted Aloha of WBAN in non-saturated conditions. KSII Trans Internet Inf Syst 8(6):1901–1913
58. Tuset-Peiro P, Vazquez-Gallego F, Alonso-Zarate J, Alonso L, Vilajosana X (2015) LPDQ: A self-scheduled TDMA MAC protocol for one-hop dynamic low-power wireless networks. Pervasive Mob Comput 20:84–99
59. Zhang Y, Dolmans G (2009) A new priority-guaranteed MAC protocol for emerging body area networks. In: 2009 5th international conference on wireless and mobile communications, pp 140–145
60. Ibarra E, Antonopoulos A, Kartsakli E, Verikoukis C (2015) HEH-BMAC: Hybrid polling MAC protocol for WBANs operated by human energy harvesting. Telecommun Syst 58(2):111–124
61. Zhou G, Lu J, Wan C-Y, Yarvis MD, Stankovic JA (2008) BodyQoS: adaptive and radio-agnostic QoS for body sensor networks. In: 2008 IEEE INFOCOM—the 27th conference on computer communications, pp 565–573
62. Alam MM, Berder O, Menard D, Sentieys O (2012) TAD-MAC: traffic-aware dynamic MAC protocol for wireless body area sensor networks. IEEE J Emerg Sel Top Circuits Syst 2(1):109–119
63. Al-Ghamdi B, Ayaida M, Fouchal H, Baala H (2014) A slot assignment for Wireless Body Area Networks. In: 2014 IEEE symposium on computers and communications (ISCC), pp 1–8

64. Wang B, Wang L, Huang B-Y, Wu D, Lin S-J, Gu J, Zhang Y-T, Chen W (2009) A low-complexity Medium Access Control framework for body sensor networks. In: 2009 annual international conference of the IEEE engineering in medicine and biology society, pp 2446–2449
65. Ullah F, Khelil A, Sheikh AA, Felemban E, Bojan HMA (2013) Towards automated self-tagging in emergency health cases. In: 2013 IEEE 15th international conference on e-health networking, applications and services (Healthcom 2013), pp 658–663
66. Lamprinos I, Prentza A (2006) Energy-efficient MAC protocol for patient personal area networks. In: Engineering in medicine and biology 27th annual conference, pp 3799–3802
67. Movassaghi J, Abolhasan S, Lipman M (2013) A review of routing protocols in Wireless Body Area Networks. J Netw 8:559–575
68. Ullah S, Higgins H, Braem B, Latre B, Blondia C, Moerman I, Saleem S, Rahman Z, Kwak KS (2012) A comprehensive survey of Wireless Body Area Networks: on PHY, MAC, and network layers solutions. J Med Syst 36(3):1065–1094
69. Chakraborty C, Gupta B, Ghosh SK, Das DK, Chakraborty C (2016) Telemedicine supported chronic wound tissue prediction using classification approaches. J Med Syst 40(3):68
70. Culley JM, Svendsen E, Craig J, Tavakoli A (2014) A validation study of 5 triage systems using data from the 2005 Graniteville, South Carolina, chlorine spill. J Emerg Nurs 40(5):453–460
71. Tang Q, Tummala N, Gupta SKS, Member S, Schwiebert L (2005) Communication scheduling to minimize thermal effects of implanted biosensor networks in homogeneous tissue. IEEE Trans Biomed Eng 52(7):1285–1294
72. Djenouri D, Balasingham I (2009) New QoS and geographical routing in wireless biomedical sensor networks. In: Proceedings of the 6th international ICST conference on broadband communications, networks, and systems, pp 1–8
73. Quwaider M, Biswas S (2009) On-body packet routing algorithms for body sensor networks. In: 2009 first international conference on networks & communications, pp 171–177
74. Braeken A, Porambage P, Gurtov A, Ylianttila M (2016) Secure and efficient reactive video surveillance for patient monitoring. Sensors 16(1):32
75. Khan JY, Yuce MR, Bulger G, Harding B (2012) Wireless Body Area Network (WBAN) design techniques and performance evaluation. J Med Syst 36(3):1441–1457

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