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Priority-Based Adaptive MAC for Wireless Body Area Networks in Unlicensed Bands

Graduate School of Chosun University

Department of Computer Engineering

Sabin Bhandari

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비면허 대역 무선 인체 네트워크를 위한 우선순위 기반 적응형 MAC

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Advisor: Prof. Sangman Moh, Ph.D.

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ACRONYMS

WBAN	Wieless Body Area Network
CE	Consumer Electronics
MAC	Medium Access Control
CSMA/CA	Carrier Sense Multiple access with Collision Avoidance
QoS	Quality of Service
ISM	Industrial, Scientific,and Medical
IEEE	Institute of Electrical and Electronics Engineers
ECG	Electrocardiogram
EEG	Electroencephalography
PHY	Physical
CRBAN	Cognitive Radio Body Area Network
NS-2	Network Simulator -2
CAP	Contention Access Period
CFP	Contention Free Period
GTS	Guaranteed Timeslots
SO	Superframe order
BO	Beacon Order
SD	Superframe Duration
BI	Beacon Interval
FFD	Full Function Device
RFD	Reduced Function Device
ED	Energy Detection
BC	Beacon Channel
DC	Data Channel

ABSTRACT

Priority-Based Adaptive MAC for Wireless Body Area Networks in Unlicensed Bands

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In recent years, wireless body area networks (WBANs) are widely used in various applications such as healthcare systems and consumer electronics. In WBANs, various sensors and actuators are placed, on or inside the human body and connected wirelessly. Unlike the other wireless networks, WBANs have specific requirements; however, the standard protocols such as IEEE 802.11 and IEEE 802.15.4 cannot fulfill all the requirements. Consequently, many medium access control (MAC) protocols have been studied, most of which are derived from the IEEE 802.15.4 superframe structure with some improvements and adjustments to effectively address the stringent requirements of WBANs. Nevertheless, they do support differentiated quality of service (QoS) for various forms of traffic coexisting in a WBAN. In particular, a QoS-aware MAC protocol is highly necessary for WBANs in unlicensed ISM (Industrial, Scientific, and Medical) bands because different wireless services such as Bluetooth, WiFi, and Zigbee may cause great interference. In this thesis, we propose the priority-based adaptive MAC protocol for WBANs that allocates time slots dynamically based on the traffic priority. Furthermore, multiple channels are effectively utilized to reduce access delay in a WBAN in the

presence of coexistent systems. The WBAN coordinator dynamically adjusts channel access patterns according to interference environments. Our performance evaluation results show that the proposed MAC outperforms the IEEE 802.15.4 MAC and conventional priority-based MAC in terms of average transmission time, throughput, energy consumption, and data collision ratio.

한 글 요 약

비면허 대역 무선 인체 네트워크를 위한 우선순위 기반 적응형 MAC

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최근 무선 인체 네트워크(WBAN)가 헬스케어 및 정보가전과 같은 다양한 분야에서 광범위하게 사용되고 있다. WBAN 에서는 다양한 센서와 구동기가 인체 내외부에 부착되고 무선으로 연결된다. 타 네트워크와 달리 WBAN 은 고유의 요구사항을 갖는데, IEEE 802.11 및 IEEE 802.15.4 와 같은 표준 프로토콜들은 모든 요구사항을 충족하지 못한다. 이로 인해 많은 매체 접근 제어(MAC) 프로토콜이 연구되고 있으며, 이들 대부분은 IEEE 802.15.4 슈퍼프레임 구조로부터 유도 개발되어 개선되었다. 그럼에도 불구하고, 하나의 WBAN 에 공존하는 다양한 형태의 트래픽에 대하여 차별화된 서비스 품질(QoS)을 지원하지 못하는 한계가 있다. 특히, 비면허 ISM 대역을 사용하는 WBAN 에서는 공존하는 Bluetooth, WiFi, Zigbee 등과 같은 타 서비스가 큰 간섭을 유발할 수 있으므로 QoS 인지 MAC 프로토콜이 절실히 필요하게 된다. 본 논문에서는 WBAN 을 위한 우선순위 기반 적응형 MAC 프로토콜을 제안한다. 제안한 프로토콜은 트래픽

우선순위에 기반을 두고 타임 슬롯을 동적으로 할당한다. 더욱이 타 시스템이 공존하는 경우에 WBAN 에서의 지연시간을 줄이기 위하여 다중 채널을 효과적으로 활용한다. 또한 WBAN 제어기는 채널 접근 패턴을 간섭 환경에 따라 동적으로 조절한다. 성능 평가 결과에 의하면, 제안한 MAC 프로토콜은 IEEE 802.15.4 MAC 및 기존의 우선순위 기반 MAC 프로토콜에 비해 평균 전송시간, 전송률, 에너지 소모, 데이터 충돌 비율 등에서 우수한 성능을 나타낸다.

I. INTRODUCTION

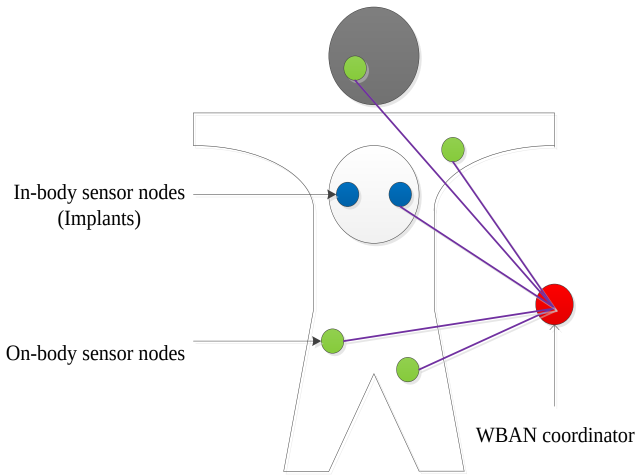

Figure 1. The general organization of a WBAN.

With the rapid advancements of physiological sensors and wireless communications, the area of wireless sensor networks has grown significantly supporting a range of applications including medical and healthcare services. A wireless body area network (WBAN) is a special-purpose sensor network designed to connect various sensors and actuators located on, in and around the human body for continuous monitoring of vital signs such as heart-rate, temperature, blood pressure, electrocardiogram (ECG), electroencephalography (EEG), etc [1]. The general organization of a WBAN is shown in Figure 1. Quality of service (QoS), flexibility, and cost effectiveness are important goals to be achieved for healthcare applications and medical monitoring in WBANs. Different sensors placed in different parts of the human body collect critical and non-critical information and send the information to the coordinator. Moreover, different actuators placed within the vicinity on or inside the human body to communicate with the coordinator. Low delay, high reliability, low power consumption, negligible electromagnetic interface with the human body, and effective communications are the main issues for effective health monitoring systems. The inside or vicinity of the human body is the challenging environment for the design of adaptable, dynamic and flexible protocols in WBANs.

The MAC protocol play a crucial role to provide QoS supports and prolonging the lifespan of a network by controlling the packet collisions, overhearing, control packet overhead, and idle listening [2, 3]. The IEEE 802.15.4 standard exhibiting a desirable feature for WBAN has been discussed and applied in different WBAN platforms [4]. However, there are several limitations in meeting specific requirements and considerations for the successful implementation in medical as well as in consumer electronic (CE) products. In recent years, there have been many significant developments on MAC protocols for WBANs. The number of MAC protocols are already used for the specific purposes, but they can adopt in WBANs with certain modification to fulfill the specification of WBANs. The IEEE 802.15.6 standard [5] defines the physical (PHY) and medium access control (MAC) layers to provide the various ubiquitous services for both medical/healthcare applications and other non-medical applications with varying requirements. The MAC layer in the IEEE 802.15.6 standard aims to support a low-complexity, low-cost, ultra-low power, and highly reliable wireless communication for use in close proximity to or inside the human body .

The different PHY and MAC layer design approaches to develop efficient and reliable mobile health (m-health) services for WBANs are discussed and surveyed in [6]. In [7,8], the various issues concerning channel modelling, coexistence, energy consumption, MAC layer issues, and design features are analyzed and summarized. A number of MAC protocols have been proposed for WBANs, but few have been developed for cognitive radio body area networks (CRBANs). The development of a MAC protocol for CRBANs is a promising area of research. The recent development trends in MAC protocols for CRBANs and open research issues and challenges are presented in [9].

A. Research Objective

Despite the promising applications for healthcare systems, WBANs also impose several challenges in network design and implementation. The design of MAC protocols has a significant impact on energy efficiency, interference, reliability, and QoS provision. High spectrum utilization, reliable communications between nodes, minimum delay, and low energy consumption are key parameters for efficient MAC protocols. One MAC protocol cannot satisfy the requirements of all applications because the protocols are hardware- and application-dependent. The MAC protocol suitable for WBANs must handle specific challenges and issues associated with WBAN topology and node constraints.

In this thesis, we propose a priority-based adaptive MAC (PA-MAC) for WBANs in license-free spectrum based on IEEE 802.15.4. In the proposed MAC, we exploit the channel switching capability of IEEE 802.15.4 radio hardware and operate in beacon enable mode. In beacon enable mode, the WBAN coordinator controls device association,synchronization, and data transmission using periodic beacons. A fixed dedicated channel is assigned for beacon. The beacon channel (BC) is used for transmission and reception of the beacon frames, whereas the rest of the communication is done in the data channel (DC). Moreover, we also prioritized the nodes by using a priority-guaranteed CSMA/CA procedure in the CAP. To support various QoS requirements, we classify data traffic into four priorities and divide the CAP into four sub-phases dynamically. The proposed PA-MAC supports both CAP and CFP. The CFP is used to transfer continuous and large number of data packets to the coordinator.

B. Thesis Layout

The rest of the thesis is organized as follows: In chapter II, several existing MAC protocols proposed for WBANs are reviewed and highlighted in terms of the significant features of each MAC protocol. The reviewed MAC protocols are compared with respect to multiple access, performance, advantages and limitations. We also present the open issues and challenges in the design of efficient MAC protocols for WBANs. The proposed MAC protocol is presented in chapter III. The multi-channel utilization, data traffic prioritization, dynamic timeslot allocation, and data transfer procedures are discussed in detail. The analytical approximation of the proposed protocol is described in chapter IV. In chapter V, the performance of the proposed PA-MAC is evaluated via computer simulation and compared with the IEEE 802.15.4 standard protocol and conventional priority-based MAC protocol. Finally, the conclusions of the thesis and future works are provided in chapter VI.

II. RELATED WORKS

In WBANs, different sensors placed in different parts of the human body collect critical and non-critical information and send the information to the coordinator. Also, different actuators placed within vicinity on or inside the human body communicate with the coordinator. Low power consumption, negligible electromagnetic interface with human body, low delay, high reliability and effective communications are the main issues for effective health monitoring systems. There are several attributes to be considered for the design of an effective, reliable and energy-efficient MAC protocol for WBANs. In WBANs, all the nodes of sensors and actuators are operated by small batteries. For long time operation, it is necessary to restrict energy dissipation as low as possible and, thus, the design of energy-aware communication protocols is necessarily required. In the literatures [2, 3], it is found that the main source of energy wastes is data collisions, overhearing, packet overhead, traffic fluctuation and idle listening. Overhearing occurs when one receives a packet that is destined to other nodes. Over-emitting is caused by the prolonged transmission of a message when the destination node is not ready to receive. Transmission of data packets in a channel from multiple sensor nodes results in packet collision. These kinds of packets are dropped and sender nodes retransmit the packets later again, leading to extra energy dissipation. Idle listening incurs when a node listens to an idle channel to receive possible traffic. The physical layer has some limitation for power optimization, but the MAC layer can provide the significant level of energy saving by introducing different scheduling process, signaling technique, optimal packet structure and different channel access scheme.

Channel scheduling is presented in [10] to reduce mutual interference between nodes that belong to the same network. To reduce idle listening, the control channel is differentiated from the data channels with different frequency bands. The channel information is announced using beacon frames, which are broadcasted to allow all the devices to know the assigned channels. However, this scheme does not consider any priority differentiation mechanism.

A novel priority-based channel access algorithm for contention-based MAC protocol [11] is devised to solve the contention complexity problems. The algorithm categorizes the traffic packets into four different levels, and divides the CAP into four sub-phases dynamically. However, in this algorithm the classification of continuous and discontinuous data traffic, and use of GTSs is not considered.

A traffic-aware dynamic MAC protocol (TAD-MAC) for both invasive and non-invasive WBANs is introduced in [12]. In this protocol, each node adapts its wake up interval dynamically based on a traffic status register bank. The dynamic wake up interval scheme saves extra power consumed by idle listening, overhearing, collisions, and unnecessary beacon retransmission.

The low-delay traffic-adaptive MAC protocol (LDTA-MAC) is reported in [13], where GTS time slots are allocated dynamically based on node traffic to overcome the shortcomings of the IEEE 802.15.4 MAC protocol. Similarly, the schemes in [14] prioritized the data traffic based on data's features, and adaptively allocate CFP or CAP for the data according to priority level. However, there is no consideration of traffic priority and back off value of them.

In [15], a traffic load aware sensor MAC (ATLAS) is presented for collaborative body area sensor networks. The superframe structure dynamically varies based on the traffic load and also uses a multihop communication pattern. Nevertheless, there is no consideration about the priority of different packets and back-off classes.

The authors in [16] considered a traffic priority and load-adaptive MAC (PLA-MAC), which provides QoS to the packets according to their traffic priority level. The packets with the higher priority level get better service than the packets with lower priority. Although it considers packet-level priority and reliability, but the condition-based network's channel adaptation is missing.

The traffic adaptive MAC protocol proposed in [17], uses a traffic based wakeup mechanism and a wakeup radio mechanism to accommodate the various kinds of data in a reliable manner. The proposed MAC utilizes the traffic information to enable low power communication. The wakeup tables are established to coordinate the transmission schedule of the nodes, whereas a wakeup radio mechanism is employed for emergency situations.

A schedule-based heartbeat driven MAC protocol (H-MAC) is presented in [18]. This protocol uses the heart rhythm information to perform synchronization and reduces the extra energy costs, but the heart beat information is not always valid due to variations in the patient’s health condition.

A context-aware MAC protocol [19], can switch between normal state and emergency state. The data rate and duty cycle of sensor nodes are dynamically changed to meet the requirement of latency and traffic loads in a context-aware way. The sensor nodes can obtain one or more time slots for periodic or bursty applications according to their traffic characteristics.

In [20], a hybrid and secure priority guarantee MAC protocol (PMAC) for WBANs is proposed. The proposed MAC uses two CAPs for accommodating normal and critical data, whereas one CFP is used for accommodating the large amount of data packets. In addition , a set of security keys is used to prevent illegal access to WBANs.

A MAC protocol specially designed for energy-harvesting WBANs is presented in [21]. The nodes are assigned different priorities and access methods based on the criticality of their data packets and the type of energy harvesting source.

The authors in [22], experimentally investigated the robustness of medical data packet transmission based on the frequency hopping mechanism in heterogeneous environments. The measurement results demonstrate that the transmission reliability requirement depends significantly on the signal strength of the other signals as well as the chosen channel/frequency band. It is a fact that the heterogeneous working requirements of WBAN define different QoS issues, which are specific to that particular application area only. WBAN applications are very sensitive and hence QoS issues in WBAN require more attention and focus and should be taken up more seriously.

A. Characteristics and Design Approaches

Unlike other wireless networks, WBANs have their own inherent characteristics and design requirements. The main outstanding characteristics of WBANs are listed below.

- Each link should support bit rates in the range of 10 Kb/s to 10 Mb/s.
- Packet error rate should be negligible.
- Nodes should be capable of reliable communication even when a person is on body movements, and data should not be lost due to unstable channel conditions.
- Latency, jitter, and reliability should be supported for WBANs applications.
- On- body and in-body WBANs should be capable of coexisting within range.
- WBANs should be capable of operation in heterogeneous environments where networks of different standards cooperate with each other.

- WBANs must incorporate QoS management features.
- To operate in a power constrained environment, power saving mechanisms should be incorporated.

The main approaches adopted in the MAC protocols for WBANs are lower-power listening (LPL), schedule contention, and time division multiple access (TDMA). In this section, each approach is reviewed in detail.

1. Lower-Power Listening (LPL)

In the LPL mechanism, nodes wakeup for a short duration to check the channel activity without receiving data. If the channel is not idle, the node remains in active state to receive data and other nodes go back to sleeping mode. It uses the non-persistent carrier sense multiple access (CSMA) and preamble sampling technique to mitigate idle listening. High energy efficiency is achieved in high traffic conditions through the minimization of the wakeup preamble length. WiseMAC [3] is a low power contention medium access control protocol designed for multi-hop wireless sensor networks. The LPL mechanism has several advantages and disadvantages. The periodic sampling is very efficient for high-traffic nodes. In body nodes, periodic sampling is not preferred due to strict power constraints. WBANs are usually configured as a star topology and the uplink traffic is dominant and, thus, the use of the LPL mechanism may not be an optimal solution.

2. Scheduled Contention

Scheduled contention is a combination of scheduling and contention based mechanism to avoid the problem of scalability and collision. In contention based protocols, contending nodes try to access the channel for data transmission. Therefore, the probability of packet collision is greatly increased. An example of contention based MAC protocols is CSMA/CA in which CCA is performed by nodes before transmitting data. TDMA, code division multiple access (CDMA) and frequency division multiple access (FDMA) schemes are some examples of scheduling mechanisms. But, CDMA and FDMA are not suitable for WBANs because of high computational overhead and bandwidth limitation. S-MAC [2] is proposed for wireless sensor networks. The protocol uses fixed duty cycles to solve idle listening problem. Nodes wake up after a specific time period, as assigned by coordinator, send data and go back to sleep mode again. All the nodes are synchronized and, thus, collision can be easily avoided. S-MAC gives considerably low latency. Energy loss due to collision, overhearing, and idle listening is minimized because nodes are turned on only for data transmission.

3. Time Division Multiple Access (TDMA)

In WBANs, TDMA is the most suitable scheduling scheme due to its sensitivity for synchronization. In TDMA, a superframe consists of a fixed number of time slots allocated to sensor nodes by a central node called coordinator. Traffic rate is one of the key parameters used by the coordinator to allocate time for each contending node. Because slots are pre-allocated to individual nodes, they are collision free. The synchronization process may degrade the performance in terms of energy consumption. H-MAC [18] and Body MAC [23] are the examples of TDMA based MAC protocols.

Reliability, safety and security are the other important metrics besides energy efficiency. Reliability in WBANs depends upon packet transmission delay and packet loss probability. Bit error rate (BER) and packet transmission process may cause packet loss. QoS is another factor for reliable and effective WBANs. The MAC layer plays a great role to achieve high QoS. Other parameters include scalability, topology adaptability, throughput, jitter, latency and bandwidth utilization. The number of nodes to collect necessary information varies according to the network requirements. To support the scalability, WBANs can be easily reconfigured by adding or removing sensor nodes as per requirements. The MAC layer has potential to achieve scalability.

WBANs can be considered as a special type of wireless sensor networks, with their own requirements. To realize communications between nodes in a WBAN, some techniques of wireless sensor networks and ad hoc networks could be adapted. Two types of intra-body and extra-body communications are used in WBANs. In WBANs, sensors communicate with controllers, which is the inter-body model. The sensors, which are wearable, are operating at close proximity to a human body and, thus, the communication must consume less power in order to reduce electro-magnetic effects of radio waves on the human body. The intra-body communication controls the information handling between sensors (or actuators) and the coordinator. The extra-body communication ensures the communication between the coordinator and an external network.

B. Existing MAC Protocols for WBANs

In this section, existing MAC protocols proposed for WBANs are reviewed and highlighted in terms of the significant features of each MAC protocol.

1. IEEE 802.15.4 MAC

The IEEE 802.15.4 MAC protocol was designed for the low data rate applications, and it is the most commonly used MAC in wireless sensor networks [4]. The general characteristics of the IEEE 802.15.4 MAC protocol are: low power consumption, support for low latency devices, star or peer-to-peer operation, and dynamic device addressing. The IEEE 802.15.4 MAC protocol operates in three frequency bands; 16 channels in the 2.4 GHz ISM band, 10 channels in the 915 MHz ISM band, and 1 channel in the European 868MHz band. In IEEE 802.15.4 , two operational modes are defined; beacon enable mode and non-beacon enable mode. In the beacon enabled mode, communication is synchronized and controlled by the network coordinator. A superframe consists of active and inactive periods. The active period is further divided into three parts; beacon, contention access period (CAP) using slotted CSMA/CA, and a contention free period (CFP) as shown in Figure 2. The CFP contains up to seven guaranteed timeslots (GTS). All the communications must be taken place during the active parts, and devices can sleep in an inactive part to conserve the energy. The structure of superframe is determined by the network coordinator using two parameters; superframe order (SO) and beacon order (BO). The SO is used to describe the length of superframe duration (SD), whereas BO defines the beacon interval (BI). There are mainly two types of devices in IEEE 802.15.4; full function device (FFD) and reduced function device (RFD). The FFD can support all the network functions and operate as the network coordinator as well as an end device, whereas RFD can only use as an end device. The FFD performs the energy detection (ED) to detect the peak energy of the channel and select the appropriate channel for data transmission.

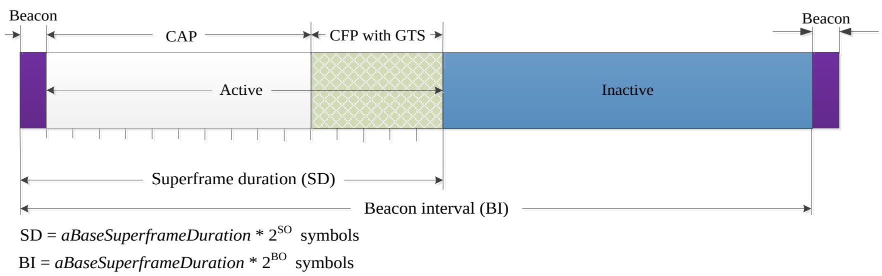

Figure 2. IEEE 802.15.4 superframe.

2. TAD-MAC

The traffic aware dynamic MAC (TAD-MAC) protocol [12] targets both invasive and noninvasive WBANs by considering a hybrid network topology which includes a star topology for in-body networks and a mesh topology for on-body networks. In TAD-MAC, every node adapts its wake up interval (WUInt) dynamically. A traffic status register bank (TST-bank) contains the traffic statistics and continuously update the WUInt of receiving nodes. In the invasive networks, nodes communicate directly with the coordinator and contain a TSR-bank for all the transmit nodes. For the noninvasive networks, all nodes contain the TSR-bank of neighbor nodes. The basic principle of the TAD-MAC protocol, which is initiated by the receiving node, is shown in Figure 3. In the second phase, the receiving node (coordinator) has adapted its WUInt schedule so that the idle listening is minimized [12].

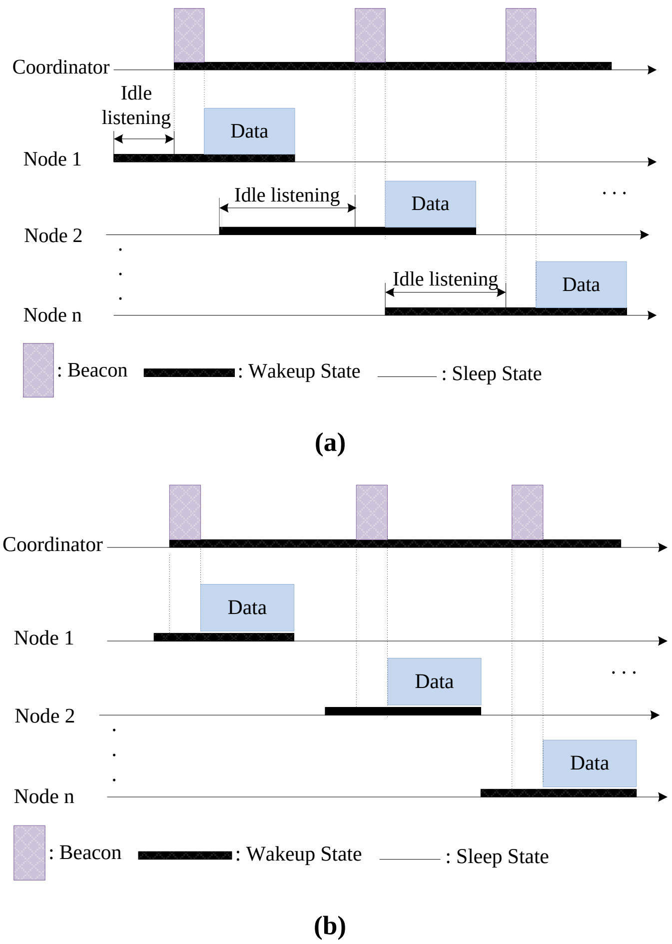

Figure 3. Two phases of TAD-MAC: (a) evolution phase before convergence and (b) steady state phase after convergence.

3. Traffic-adaptive MAC (TaMAC)

The TaMAC protocol [17] uses a traffic based wakeup mechanism and a wake up radio to accommodate normal, emergency, and on-demand traffic in a reliable manner. In TaMAC, channels are bounded by the superframe structure. The superframe contains a beacon, a configurable contention access period (CCAP), and a contention free period (CFP) as shown in Figure 4.

Figure 4. TaMAC superframe structure.

The CCAP period contains a few mini-slots (3 or 4) of equal duration for short data transmission. The slotted ALOHA protocol is used because the CSMA/CA protocol encounters unreliable CCA and heavy collision. The CFP period contains a series of GTSs used for data transmission. The TaMAC protocol uses two channel access mechanisms: a traffic based wakeup mechanism for normal traffic conditions and a wakeup radio mechanism for emergency/on-demand traffic.

In the traffic based mechanism, initial traffic-patterns are predefined and the operation of each node is based on the traffic pattern. The traffic based wakeup table is maintained by the coordinator. The nodes are assigned predefined traffic patterns and wake up whenever they have data to send/receive; otherwise, they remain in sleep mode. This avoids the unnecessary power consumption caused by idle listening and overhearing. If more than one node has the same traffic pattern, then resources are allocated to a high priority node. The data transmission starts in the GTS slot and ends up with an acknowledgement from the coordinator. To compensate for the clock drift between the coordinator and nodes, the nodes wake up a bit earlier than the exact beacon event.

In the wakeup radio mechanism, the nodes for emergency traffic or the coordinator for on demand traffic send wakeup radio signals to each other. It also updates the traffic based wakeup table. TaMAC utilizes the traffic information to enable low-power communication.

4. Heartbeat-driven MAC (H-MAC)

H-MAC is a TDMA based protocol for WBANs to improve energy efficiency by exploiting heartbeat rhythm information for synchronization [18]. The nodes do not need to receive periodic information to perform synchronization. All rhythms represented by peak sequences are naturally synchronized since they are driven by the same source, i.e., the heartbeat. An algorithm is introduced for detection of heartbeat rhythm peak. Each biosensor extracts heartbeat rhythm information from its sensory data. A star network topology is assumed. The network coordinator is the common receiver of the all data transmission. TDMA assigns dedicated time slots to each biosensor to guarantee collision free transmission.

In H-MAC, efficiency is achieved by TDMA approach by reducing idle listening and avoiding the collisions. Although H-MAC protocol reduces the extra energy cost for synchronization, it is not accessible to all the sensors. Also, the TDMA slots are dedicated and are not traffic adaptive. The guard band in TDMA for avoiding collisions encounters low bandwidth efficiency.

5. Context Aware MAC

The context aware MAC protocol [19] was designed to guarantee the critical and emergency data. To save energy, a TDMA based MAC frame structure is used, which is shown in Figure 5 and consists of two parts: beacon and data transmission.

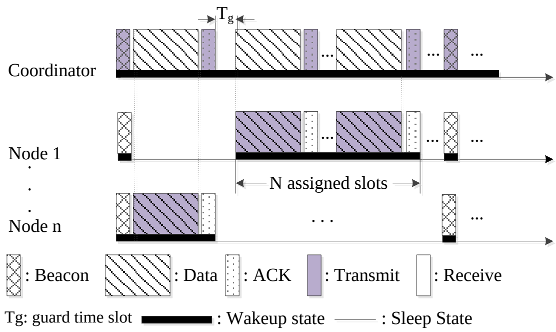

Figure 5. TDMA MAC frame structure.

In the context aware MAC, a centrally controlled TDMA based scheme is used to address the problems of collision, idle listening and overhearing because the sensor nodes only transmit data in their dedicated slots. In beacon slot, coordinator assigns slots for each sensor node by broadcasting a beacon packet. Data slots are assigned to sensor nodes for contention free data transmission. Sensor nodes can obtain one or more slots for periodic or bursty applications depending on their traffic characteristics. This on-demand slot allocation mitigates the frame overhead caused by fixed slot allocation where nodes with low transmission frequency hold reserved slots in every frame.

All sensor nodes wake up at the beacon slot of a new frame for the purpose of checking if there is a new beacon packet. If no beacon packet is sensed, sensor nodes return to sleep and will not wake up until their assigned slots are available. The frame structure is unchanged and the normal state will be periodically repeated if coordinator broadcast a new beacon packet. If a new beacon packet is received, it indicates the coordinator has detected abnormal situation by data processing and analysis within the previous frame and hopes to trigger emergency state. Then, all sensor nodes take the updated information about slot allocation, and a new frame structure is formed. Those sensor nodes which are of most relevance to the monitoring context obtain higher duty cycle, which implies more slots for transmitting data. At the same time, these nodes also increase their sample rate to fulfill emergency monitoring task. Other unconcerned nodes, however, may mitigate available bandwidth and sample rate, or even cease data transmission, resulting in reduction of energy wastage. The emergency state lasts until coordinator broadcasts another new beacon packet altering the system back to normal state.

The distinctive feature of the context aware MAC is optional synchronization which is used to decrease the synchronization overhead. A sensor node encapsulates local clock information into a data packet. When the coordinator receives the data packet, it takes the clock information and compares that with its local clock information. If the time interval between two clocks exceeds the guard time slot, a parameter called clock offset is set as the interval; otherwise, no operation occurs. The coordinator then encapsulates clock offset into ACK packet and sends it to corresponding sensor node. The sensor node can adjust local clock relying on the value of clock offset after receiving ACK packet. In addition, all the computing tasks are distributed to the coordinator which is less energy constrained and, thus, sensor nodes simply need to passively extract and adjust clock information.

The context aware MAC protocol has lower latency and lower power consumption as compared to IEEE 802.15.4 MAC. This is because the increased bandwidth in emergency state provides extra transmission opportunities for packets buffered in normal state. In IEEE 802.15.4 MAC, data collisions caused by CSMA/CA become more serious with higher traffic load. The context aware MAC protocol does not respond to emergency immediately, but it still shows a good performance in latency.

6. BodyMAC

BodyMAC is a TDMA based MAC protocol [23]. Its design objective is to achieve energy efficient and flexible operation in terms of bandwidth allocation and to support a sleep mode to fulfill the requirements of WBANs. In [23], it is assumed that WBANs would use a star topology, especially for implanted devices. A TDMA-based frame structure with uplink and downlink subframes is defined. The MAC frame is adaptive and flexible with respect to sleep mode for improving the efficiency of the sleep mode.

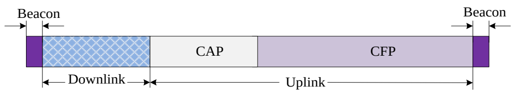

Figure 6. BodyMAC frame structure.

The MAC frame in BodyMAC has three parts: beacon, downlink and uplink as shown in Figure 6. Beacon is used for MAC layer synchronization and description of the MAC frame structure. The downlink part is reserved for transmission from a gateway to nodes. It can be either unicast data for a specific node or broadcast data for all the nodes in the network. The uplink part has two sub-parts: contention access period (CAP) and contention free period (CFP). CAP is based on CSMA/CA, and the nodes contend in CAP for the transmission of MAC control packets. The gateway controls the allocation of slots in CFP. The GTS in CFP is dedicated to one node. The duration of downlink, CAP and CFP are adaptively configured by the gateway based on the current traffic characteristics.

Frequent state switching of radio states costs extra energy and bandwidth in terms of transmission gaps. The inclusion of uplink and downlink in the same MAC frame structure can save energy by reducing the switching time between transmitting and receiving states. The dedicated slot allocation in CFP is completely collision free. This improves the successful packet transmission possibility and hence saves energy. The main characteristic of data transmission in BodyMAC is that downlink and uplink are asymmetric. The three types of data resources are defined: burst bandwidth, periodic bandwidth, and adjust bandwidth. The burst bandwidth defines a temporary period of bandwidth which only lasts for several MAC frames and will be recycled gradually by the gateway. The periodic bandwidth is assigned to allow a node to have access to the channel exclusively within a portion of each MAC frame or few MAC frames. The adjust bandwidth defines the amount of bandwidth to be added or reduced from the previous periodic bandwidth.

Idle listening is a major part of waste energy when nodes have to stay awake to receive potential data. An efficient sleep mode is introduced to turn off a node's radio, especially for the nodes supporting low duty cycle applications. A good sleep mode mechanism should perform a proper tradeoff between flexibility and energy efficiency. A sleep mode must be capable of event reporting during critical conditions. Even during the sleep duration, a node is capable of transmitting data packets to the gateway if it has been allocated GTS resources. GTS can also be used as a synchronization procedure.

BodyMAC uses flexible and efficient bandwidth allocation schemes and sleep mode to meet the requirements of dynamic applications in WBANs. It is observed in [23] that BodyMAC offers better performance in terms of the end-to-end packet delay and energy saving compared to IEEE 802.15.4 MAC.

7. Scalable and Robust MAC

Based on the integrated superframe structure of IEEE 802.15.4, a modified MAC for WBANs with focus on the simplicity, dependability and power efficiency is introduced in [24]. The support of multiple physical layers (PHYs) including ultra-wide band (UWB) is taken into account. Also, mini slotted ALOHA is used in contention access period (CAP) for enhancing the efficiency of contention. The sufficient slot allocation in the contention-free period (CFP) makes the proposed protocol adaptive to different kinds of traffic.

Channel sensing cannot be guaranteed in all frequency bands and scenarios. For example, in a UWB system, usually the channel sensing is not reliable due to the low signal to noise ratio (SNR). Dynamic environment with human movement also influences the sensitivity of the channel sensing. As a result, unreliable channel sensing leads to hidden node problem in CSMA or channel sensing error. In the place of CSMA/CA, ALOHA based mechanism is chosen for simplicity and the contention efficiency.

Figure 7 shows one slot in a superframe, which consists of four mini-slots. A command frame (Cmd) or an acknowledgment (ACK) frame may use one mini-slot. To respond to multiple short commands, a group ACK can be used.

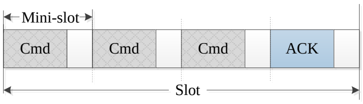

Figure 7. Mini-slot concept.

To increase the success probability of the transmission, all the data packets claimed QoS requirement are transmitted in the CFP of a superframe. According to the specifications of IEEE 802.15.4, a GTS may occupy more than one slot period. However, only up to seven of these GTSs can be allocated to devices in a superframe. So, IEEE 802.15.4 cannot support more than seven devices with CFP traffic simultaneously. An adaptive slot allocation method in CFP is introduced to support more devices and to guarantee QoS. The time duration of CFP is adaptive to traffic, so it may be zero if there is no CFP traffic. At the maximum limit, it may occupy the whole active portion of the superframe. If a device wants to join a WBAN, it reports the information such as data rate, sampling interval, etc. to the coordinator in the process of association. Then, the coordinator allocates sufficient slots at the appropriate superframe indicated by beacon. After the device transmits data packets, the allocated slots will be released for other devices. For dynamic occupancy and release, a WBAN can support more devices using the dedicated flexibility of GTSs.

8. TDMA Based Directional MAC

The TDMA based directional MAC protocol in [25] uses TDMA and multi-beam antenna approach together to provide spatial division multiple access (SDMA), which has clear advantage over FDMA, CSMA, TDMA, etc. In this approach, the human body is divided into four sectors keeping body area network coordinator (BAN_C) as its center. Each sector has its own transceivers that are capable of simultaneous transmission, and directionality is used on only BAN_C. The use of multi-beam directional antennas makes each sector independent of others and also benefits in the form of spatial reuse, extended range and energy saving. The protocol uses two BAN coordinator: one for normal and urgent traffic and another for urgent traffic only. Multi-beam directional antennas are capable of simultaneous transmission in four directions [25]. After finishing transmission of the data, every node goes to sleep. The superframe structure is shown in Figure 8.

The three types of WBAN traffic are considered: normal traffic, urgent traffic and on-demand traffic. For the normal traffic, each receiver of BAN_C will receive data from different sector nodes simultaneously. Nodes of the same sector will have different time slots reserved because, in a single time slot, BAN_C can receive data from each of the sector. For the urgent traffic, if there is an urgent data in the reserved time slot of a node, the node will send data to main BAN_C; otherwise, the node will send data to secondary BAN_C. For on-demand traffic, the wake up radio will be used by BAN_C to wake up the destined node, which will either be in sleep mode or in transmitting mode. Then, the data transmission will take place.

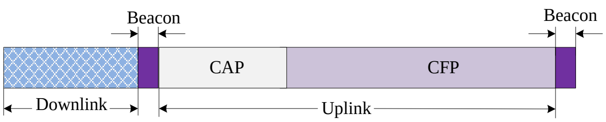

Figure 8. TDMA based directional MAC superframe.

C. Comparison and Discussion of Existing MAC protocols

In this section, a detailed comparison of the MAC protocols designed for WBANs is discussed. In Table 1, the MAC protocols reviewed in the previous section are compared with respect to multiple access, performance, advantages and limitations.

Table 1. Comparison of the MAC protocols designed for WBANs.

Protocol	Multiple access	Performance	Advantages	Limitations
WiseMAC [3]	Non-persistent CSMA and preamble sampling	• Power efficient as compared to IEEE 802.15.4 • Useful for normal traffic conditions and not suitable for low duty cycle nodes	• Adaptive and scalable to different traffic conditions • Mobility support	• Decentralized listen and sleep mode • Long overhearing and no mechanism to adapt to changing traffic patterns
TAD-MAC [12]	Adaptive to wake-up interval based on the traffic variations	• Outperforms the other protocols in fixed and variable traffic • Supports hybrid topology suitable for both invasive and noninvasive WBAANs	• Dynamic adaptation resulting in ultra-low energy consumption from idle listening, overhearing, collisions and unnecessary wake-up beacon transmission	• For variable traffic, there is a significant degradation in performance of non-dynamic environments in terms of energy consumption, quality of service and latency.
TaMAC [17]	TDMA (A superframe contains a beacon, CCAP and CFP.)	• Better performance than WiseMAC and IEEE 802.15.4 in terms of delay and power consumption • Good for normal traffic and low power applications	• Low delay • Accommodates normal, emergency and on-demand traffic in a reliable manner • Traffic-based wake up mechanism to increase energy efficiency	• Inefficient for dynamic topology
H-MAC [18]	TDMA	• Outperforms S-MAC [2] and IEEE 802.15.4 in terms of network lifetime	• Improve energy efficiency by exploiting heartbeat rhythm to perform time synchronization for TDMA • Time synchronization without having to turn on their radio to receive periodic timing information from a central controller	• Single point of failure because it depends upon the human heart for synchronization

Table 1. ***Continued.***

Protocol	Multiple access	Performance	Advantages	Limitations
Context Aware MAC [19]	TDMA	• Lower latency and lower power consumption as compared to IEEE 802.15.4 MAC.	• Context awareness; i.e., adopts different transmission strategies depending on environmental conditions, patient activity, data rate, etc. • Optional synchronization to decrease the synchronization overhead	• Does not respond to emergency immediately; i.e., slow adaptation to changes
Body MAC [23]	TDMA	• Better result in terms of end-to-end packet delay and energy consumption as compared to IEEE 802.15.4 • Suitable for normal and high traffic conditions	• Low overhead and high throughput • Adaptive to uplink and downlink • Good packet delivery rate • Energy efficient sleep mode	• All nodes need to listen to the long preamble.
Scalable and robust MAC [24]	Mini slotted ALOHA in CAP and adaptive slot allocation in CFP	• Provides scalability and robustness compared to IEEE 802.15.4 by using revised CAP and CFP schemes	• Specially designed mini-slot method to increase contention efficiency • Simple for implementation to chip makers • Contention-free scheme for guaranteeing QoS	• Unclear energy efficiency
TDMA based directional MAC [25]	TDMA and SDMA with multi-beam antennas	• Prioritized service for different nodes according to their application requirements	• Differentiates between normal and urgent traffic using two network coordinators • Spatial reuse, extended range and energy saving thanks to multi-beam antennas	• Unclear performance improvement (Neither analysis nor simulation result is given.)

Frequency division multiple access (FDMA) and code division multiple access (CDMA) protocols are unsuitable in the context of wireless sensor networks due to the limited frequency bands and computational capability. As a result, many protocols studied so far are based on the TDMA scheme. In WBANs, the TDMA based protocols based on star topology are used to mitigate idle listening, overhearing and collisions. Because slots are pre-allocated to individual nodes, they are contention free but not adaptive, flexible and scalable. In [19], an optional synchronization scheme is introduced to reduce the overhead caused by frequent synchronization in TDMA. CSMA/CA is scalable with no time synchronization constraint and also shows good adaptation to topology changes as in [3]. However, additional energy consumption for collision avoidance and overhead are the main drawback of CSMA/CA. The ALOHA can be used in the place of CSMA/CA because channel sensing is not accurate in implanted sensors as in [24]. Based on the network topology and the limited number of sensor nodes in WBANs, TDMA could be considered as suitable solution for medium access in WBANs.

Frequent state switching of radio states costs extra energy and bandwidth in terms of transmission gaps, the inclusion of uplink and downlink in the same MAC frame structure can save energy by reducing the switching time between the transmitting and receiving states. Most of the MAC protocols are proposed to avoid energy dissipation due to collision, idle listening and overhearing. The other objectives for efficient multifunctional MAC protocols are reliable communication, reduce synchronization cost, minimum delay, and bandwidth utilization.

Different proposed MAC protocols have their own pros and cons in the context of real WBAN applications. However, the selection of a MAC protocol depends on the application, hardware and deployment scenarios.

D. Open Issues and Challenges

In this section, we present open issues and challenges in the design of efficient MAC protocols for WBANs. There are numerous challenges in a wireless body area network, a few of which are as follows:

1. Security and Privacy

Security and privacy issues are the major concerns in every field. WBANs enable the collection of life-critical data for better medical services. However, they preset new and unique security and privacy challenges. Addressing security in WBANs faces different difficulties. WBANs inherit most of the well-known security challenges from wireless sensor networks. However, the typical characteristics of WBANs, such as severe resource constraints and harsh environmental conditions, pose additional unique challenges for security and privacy support [26]. It is very important to identify the adequate levels of security challenges and their potential solutions.

2. Cognitive Radio Capability

Cognitive radio (CR) is a paradigm for opportunistic access of licensed parts of the electromagnetic spectrums by unlicensed users. The CR technology enables unlicensed users (or secondary users, SUs) to access underutilized licensed (or white space) spectrum opportunistically whenever licensed users (or primary users, PUs) are in idle state [27]. CR has unique attributes of learn, sense, and adapt. Some CR schemes are proposed for the medical wireless body area networks [28-30]. The MAC protocol for WBANs with cognitive radio capabilities is another promising research area that needs to address more extensively in the future.

3. Energy Harvesting

In WBANs, the replacement of batteries is not practical. Energy harvesting will have a great impact on the lifetime of future WBANs. Common sources of energy harvesting include mechanical, thermal, electromagnetic, natural and human body energy. Nowadays, energy harvesting devices efficiently and efficiently capture, accumulate and store energy to power sensor nodes [31]. The sources of energy can be utilized by means of an energy efficient protocol to extend network lifetime.

4. Reducing Interference

Reducing interference in WBANs is another important challenge. For example, the accurate detection of the physical locations of biomedical devices may be helpful for reducing the mutual interference. A radio frequency identification (RFID) based transceiver is used in [32] in order to detect the respective physical locations of biomedical devices. RFID transceiver may be suitable for WBANs due to the lower power transceiver, but it may cause interference to biomedical devices. Without accurate physical location offered by RFID, however, there may be a greater challenge to reduce mutual interference between different sensors and medical devices.

5. Enhancing QoS

QoS provision is also a major concern. QoS requirements vary according to application and operating environment. QoS support is a challenging issue because of the numerous resource constraints, such as limited power, bandwidth, memory, processing power, etc., in WBANs. Priority-based scheduling schemes can be applied to provide context-based QoS differentiation.

III. PRIORITY-BASED ADAPTIVE MAC (PA-MAC)

In this chapter, the proposed PA-MAC is presented in detail. The multi-channel utilization, data traffic prioritization, dynamic timeslot allocation, and data transfer procedures are discussed in the following subsections.

A. Utilizing Multiple Channels

In the proposed priority-based adaptive MAC, we exploit the channel switching capability of IEEE 802.15.4 MAC radio hardware. Therefore, we implement the two different channels: dedicated beacon channel (BC) and data channel (DC). The dedicated BC is available for exchange of control information such as channel assignment broadcasts and access requests between coordinator and sensor nodes. The dedicated BC is used during the beacon frame transmission, whereas the rest of the communication is done through the DC. During the beacon period, a node switches its channel to the BC and returns to its original DC at the end of the beacon period as shown in Figure 9. The widely used transceivers for short range and low power WPANs e.g. CC2420 and the more advance CC2500, have the channel switching times only 300 μs and 90 μs respectively [33]. The DC information is conveyed to the sensor nodes by piggybacking the channel information in the beacon payload of the beacon frame as in Figure 10. The entire network information can be determined by just scanning the BC [34]. In 2.4 GHz ISM band, the interference from high power WLAN transmission is dominant. The channels 13 and 14 of IEEE 802.11 operating in the 2.4 GHz ISM band are not used by most of WLAN systems in North America. Therefore, the channel 25 or 26 of IEEE 802.15.4 WPAN would be free from WLAN interference and can be used as the dedicated BC. Although, this scheme protects the beacon from WLAN interference, but the interference by

IEEE 802.15.1 or other IEEE 802.15.4 WPANs may still exist. However, the WPANs are generally operated with lower transmission power; the interference with these systems is less concern [35]. The coordinator continuously senses all the channels in the pool of candidate channels. The coordinator assigns the white spaces as transmission slots to the body nodes. The coordinator may choose and remain tuned to an idle channel until it becomes unavailable or degraded by the activities of coexisting systems.

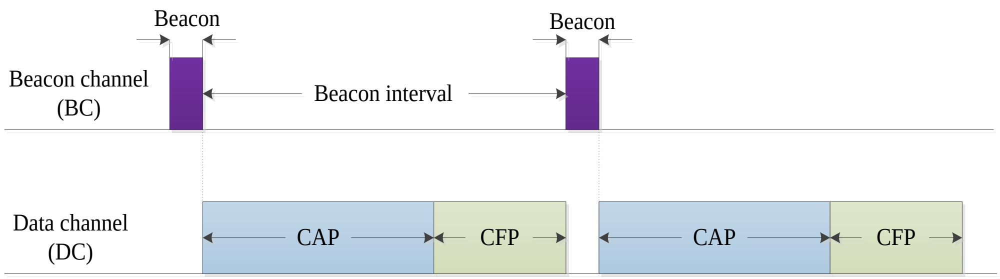

Figure 9. Channel switching mechanism.

Frame control	Sequence number	Addressing fields	Auxiliary security header	Superframe specification	GTS fields	Pending address fields	Data channel	Beacon payload	FCS

Figure 10. Data channel field in IEEE 802.15.4 beacon frame.

B. Data Traffic Prioritization and Dynamic Timeslot Allocation

The medical and non-medical applications are the two major categories in WBANs. The medical applications include the healthcare and diagnosis assistance relate signal monitoring, whereas the non-medical applications cover the consumer electronic (CE) related signals. In medical applications, the emergency vital signals are directly related to the life of the patient, and it should be regarded as the first priority service. The priority levels for the different kinds of data traffic are shown in Table 2.

Table 2. Different levels of traffic priority.

Traffic category	Priority	Example
Emergency traffic	P_1 (highest)	Emergency alarm signal
On-demand traffic	P_2	Continuous medical signal (e.g., EEG, EMG)
Normal traffic	P_3	Discontinuous medical signal (e.g., temperature, blood pressure)
Non-medical traffic	P_4 (lowest)	Audio/Video/ Data

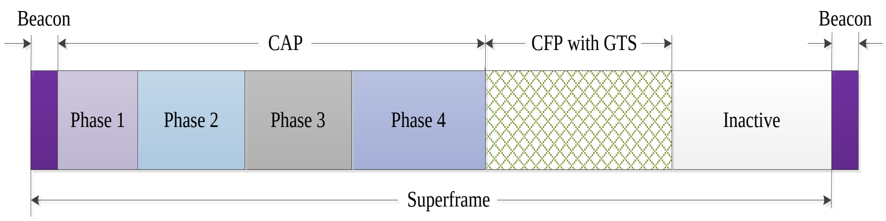

Figure 11. Superframe structure of the proposed MAC.

In IEEE 802.15.4 MAC, the performance of a CAP significantly influences the collision probability and the final throughput. If the nodes are densely deployed in a narrow region, contention complexity is increased; and leads to high collision ratio and high energy consumption. The main goal of the proposed MAC is to provide QoS and low power consumption for various applications by dispersion of contention complexity. Here, we divide the CAP into four sub-phases for each priority level of traffic as shown in Figure 11. The traffic of priority P_1 can access the channel through all phases ; whereas, node that transmits traffic of priority P_4 can only use phase 4. The P_2 priority traffic can access the channel from phases 2 to 4. Similarly, P_3 can access channels through Phases 3 and 4. In order to avoid the waste of timeslot, the length of sub-phases are calculated dynamically by using the equation (1)[11].

$$l_i = \sum_{k=0}^{i-1} l_k + L_{CAP} * (N_i/N_T) \qquad (1)$$

where l_i is the length of sub-phase i $(i = 1,2,3,4)$ taken from the starting point of CAP, L_{CAP} is the length of CAP, N_i is the total number of nodes in the traffic category of priority P_i , N_T is the total number of nodes, and l_0 is initially set to zero . To learn the information of node's priority classes, we modify the IEEE 802.15.4 association request command as shown in Figure 12. Furthermore, we assume that each node only supports one type of data. When newcome nodes join in the network, the coordinator owns the ability to sense changes in the number of nodes of each class in CAP of previous superframe, and calculate the value of number of nodes in each traffic category. The medical services must satisfy 125ms or less delay and CE services have to satisfy 250ms or less delay requirement. Based on these delay requirements, the average transmission delay of each category is calculated by equation (2).

$$D_k^i = \alpha * D_{k-1}^i + (1-\alpha) * d_k^i \qquad (2)$$

where d_k^i is the delay of k-th packet in the traffic category of priority P_i and α is equal to 0.125. If the delay threshold gets exceeded, CAP is divided into sub-phases of a number of exceeded categories+1.

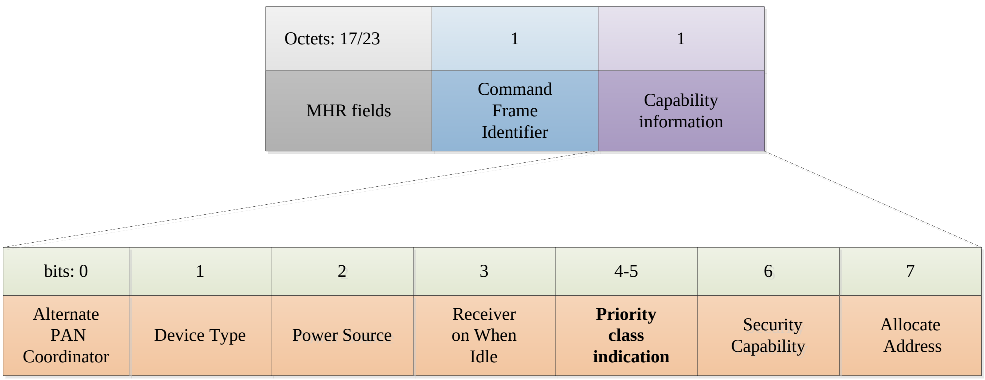

Figure 12. Association request command.

C. Data Transfer Procedure

In IEEE 802.15.4 MAC, superframe consists of a CAP and a CFP. The CAP is suitable for the transfer of command message and short data, whereas the CFP is implemented for the continuous data.In the CAP, each node transmits its packets to a coordinator by using CSMA/CA procedure. In the CFP, each node transmits its packets to the coordinator by using the dedicated guaranteed time slots (GTSs) without contention with the other nodes. In order to transmit packets in the CFP, each node transmits the request packet for CFP to the coordinator in the CAP using CSMA/CA procedure. When the coordinator successfully receives the GTS request packet, it allocates the GTS to the node accordingly. The data from P_1 and P_3 nodes are transmitted immediately after accessing the channel in the CAP. However, the P_2 and P_4 nodes send the GTS request command in the CAP to apply GTS allocation. The algorithm for slot allocation of the coordinator and data transfer procedure for different traffic priorities are shown in Figures 13 and 14, respectively.

Algorithm for the CAP allocation

1. **while** (!End of CAP)
2. **if** (An associate request command packet is received from a node)
   2.1 Calculate the number of nodes with different traffic priorities as
   $N_i \leftarrow N_i+1$,where N_i is the total number of nodes in the traffic category of priority P_i and i is an integer that varies from 1 to 4.
   end if
   end while
3. Calculate the lengths of sub-phases as
   $l_i = \sum_{k=0}^{i-1} l_k + L_{CAP} * (N_i/N_T)$, where l_i is the length of sub-phase i from the starting point of CAP, L_{CAP} is the length of CAP, N_T is the total number of nodes, and l_0 is initially set to zero .
4. Broadcast the beacon frame

Figure 13. Algorithm for the CAP allocation.

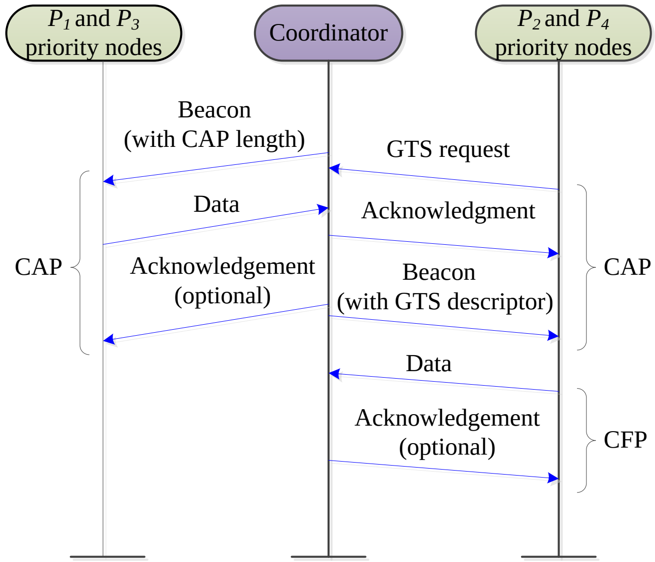

Figure 14. Data transfer procedure.

IV. ANALYTICAL APPROXIMATION OF PA-MAC

In this chapter, we presented the analytical approximation of channel status, energy consumption, and average delay of proposed PA-MAC.

A. Channel Status

The low power and low rate transmission of WBANs nodes do not change the access pattern of coexisting systems contending on a shared ISM band. The channels in the ISM band alternate between the busy state, i.e. occupied by a coexistent network, and remain in the idle state when no coexistent system is accessing the channel. The channel state can be characterized by two-state Markov chain. The average length of idle and busy periods depends on the channel usage pattern of the coexisting systems. The length of busy and idle periods for ith licensed channel follows an exponential distribution with means equal to λ_i and μ_i [36]. The probability that the channel i is busy or idle at any time instant is given by,

$$P_{i(busy)} = \frac{\lambda_i}{\lambda_i+\mu_i} \text{ , and } P_{i(idle)} = \frac{\mu_i}{\lambda_i+\mu_i} \qquad (3)$$

The WBAN has access the medium as long as one of the n candidate channels is found idle, and it loses its all access when all channels become busy due to the activities of coexisting systems. The inactive state occurs with the probability,

$$P_{inactive} = \prod_{i=1}^{n} P_{i(busy)} \qquad (4)$$

In this inactive state, all the WBAN operations and services are interrupted. When at least one channel becomes idle, the WBAN transits to the active state and its services are resumed. The probability of at least one channel becomes idle is calculated by,

$$P_{active} = 1 - \prod_{i=1}^{n} P_{i(busy)} \tag{5}$$

B. Energy Consumption

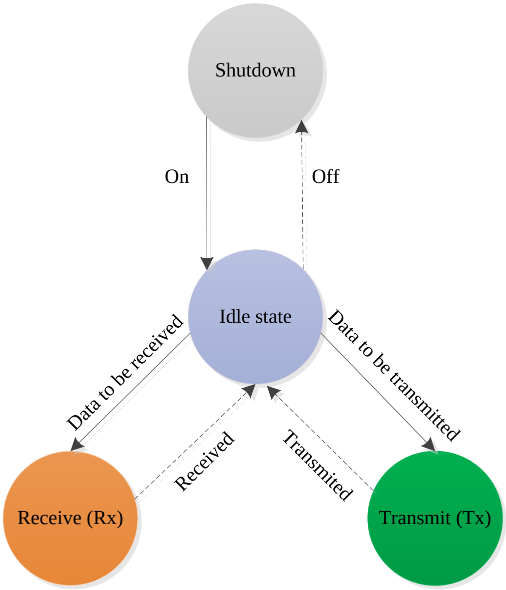

Figure 15. State transition of the transceiver.

Energy efficiency is one of the key measurement parameters for the reliable and efficient MAC protocol design.The energy consumption is based on the transceiver's activity; the transition state of the transceiver is shown in Figure 15. To minimize the energy consumption, idle and wakeup state plays a vital role.We assume the constant energy consumption regarding, sensing and processing units. Let E_C be the total consumed energy in one cycle, E_I is energy consumed in an idle state, and E_W is energy consumed in a wakeup state. Then,

$$E_C = E_I + E_W \tag{6}$$

The average total energy consumption for the n number of cycle is given by,

$$E_{T(avg)} = \sum_{C=1}^{n} E_c \quad (7)$$

The energy is a function of time and power, and power itself is a function of voltage and current. In an idle state, nodes consume less energy as compared to wakeup state.

$$E_I = T_I * P_I = T_I * I_I * V \quad (8)$$

$$T_I = T_F - T_W \quad (9)$$

where T_F is the total time frame duration, T_I is an idle time duration, P_I is power consumed in an idle state, and I_I is the current drawn in an idle state from voltage source V.

In wakeup time duration T_W , nodes consume switching energy E_{SW} , transmission energy E_{TX} , reception energy E_{RX}.

$$E_W = 2 * E_{SW} + E_{TX} + E_{RX} \quad (10)$$

To switch between ideal and wakeup state, transceiver consumes energy E_{SW},

$$E_{SW} = T_{SW} * P_{SW} = T_{SW} * I_{SW} * V \quad (11)$$

where nodes draw I_{SW} current from a voltage source during T_{SW} switching time duration and P_{SW} is switching power.Let L be the length of the packet (control or data), T_{TX} be time needed for single byte transmission, and I_{TX} be the amount of currents drawn from during the packet transmission. Energy consumed during transmission is given by,

$$E_{TX} = L * T_{TX} * P_{TX} = L * T_{TX} * I_{TX} * V \quad (12)$$

Similarly, energy consumed at the receiver end is calculated as,

$$E_{RX} = L * T_{RX} * P_{RX} = L * T_{RX} * I_{RX} * V \quad (13)$$

where P_{TX} and P_{RX} are the power consumption during transmission and reception of the packets, T_{RX} be time needed for single byte reception, and I_{RX} be the amount of currents drawn from during the packet reception.
So, the total average energy consumed is given by,

$$E_{T(avg)} = \sum_{C=1}^{n}(T_I * P_I + 2 * T_{SW} * P_{SW} + L * T_{TX} * P_{TX} + L * T_{RX} * P_{RX}) \quad (14)$$

C. Transmission Time

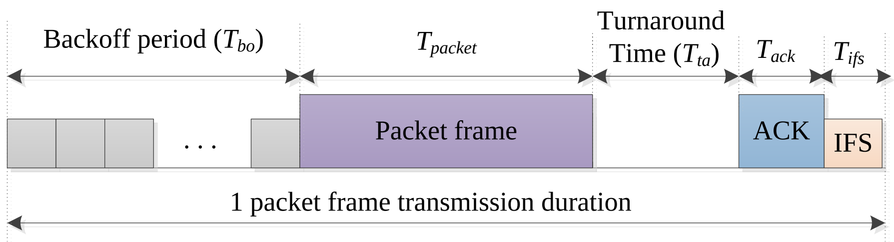

Figure 16. IEEE 802.15.4 frame transmission sequence.

The data frame transmission sequence in shown in Figure 16. The T_{bo} is the total backoff time (i.e. channel access delay), T_{packet} is the data packet transmission time, T_{ta} is transceiver's turnaround time, T_{ack} is an ACK frame transmission time, and T_{ifs} is time for inter frame space (IFS). The IFS could be either SIFS or LIFS depending upon the size of MAC frame. The average transmission delay T_l , is the time needed to transmit a packet from node to coordinator ,and can be calculated as [37],

$$T_l = T_{bo} + T_{packet} + T_{ta} + T_{ack} + T_{ifs} \tag{15}$$

For the n number of maximum backoff periods, The probability that node can successfully access the channel is given by,

$$P_s = \sum_{i=1}^{n} P_c(1-P_c)^{(i-1)} \tag{16}$$

where the P_c is the probability that a node access the idle channel at the end of a backoff period. For the m number of nodes in the network, the P_c is given by,

$$P_c = (1-q)^{(m-1)} \tag{17}$$

The q is the probability that a network device is transmitting at any time. The average number of backoff period R is calculated as [37],

$$R = (1-P_s)n + \sum_{i=1}^{n} iP_c(1-P_c)^{(i-1)} \tag{18}$$

The packet transmission time T_{packet}, is given by,

$$T_{packet} = \frac{L_{PHY}+L_{MHR}+L_{payload}+L_{MFR}}{R_{data}} \tag{19}$$

where L_{PHY} is the length of the PHY header in bytes, L_{MHR} is the length of the MAC header in bytes, $L_{payload}$ is the length of data bytes in the data packet, L_{MFR} is the length of MAC footer in bytes, and R_{data} is the data transmission rate.

V. PERFROMANCE EVALUATION

In this chapter, the performance of the proposed PA-MAC is evaluated via computer simulation and compared with the IEEE standard 802.15.4 and conventional priority-based MAC in terms of average transmission time, network throughput, average energy consumption, and a collision ratio.

A. Simulation Environment

The performance of the proposed PA-MAC is evaluated, and compared with IEEE 802.15.4 standard using the ns-2 network simulator version 2.35. The ns-2 simulator is a discrete event simulator targeted at networking research, provides a substantial support for simulation of various network protocols over wired and wireless networks [38]. The 20 percentage of the total nodes generate the emergency traffic. Meanwhile, each of on-demand traffic and non-medical traffic category also constitutes 20 percent of total nodes, and normal traffic occupies 40 percentage of total traffic generated during each simulation. The physical layer parameters are defined according to the IEEE 802.15.4 standard. We have assumed that the several biomedical sensors are implanted or attached to the human body. The sensor nodes are randomly deployed within an area of 4 meter radius around the central coordinator, and the data are transmitted by one hop. All nodes intend to transmit the first packet randomly during the contention access period. The small scale fading has been neglected and is assumed that the packet loss is solely due to the collision. The Poisson arrival is used to approximate the random packet arrival process. For the medical traffic, a payload size of 40 bytes is used, due to the lower end to end latency and acceptable packet delivery rate [11,37]. The emergency traffic occurs randomly, and the packet size is same as the normal medical traffic. The network parameters used in the simulation are summarized in the Table 3.

Table 3. Simulation parameters.

Parameter	Value
Channel rate	250 kbps
Frequency band	2.4 GHz
Symbol times	16 µs
Superframe duration	122.88 ms
Transition time	192 µs
aUnitBackoffPeriod	20 symbols
macMaxCSMABackoffs	5
macMinBE	3
macMaxBE	5
Idle power	712 µW
Transmission power	36.5 mW
Reception power	41.4mW

B. Simulation Results and Discussion

The overall performance of the average transmission time is illustrated in Figure 17. In the proposed MAC, a fixed dedicated channel is assigned for beacon. The WBAN utilizes the signal channel statically; the channel access opportunities suffer less interference and interruptions. Moreover, the proposed PA-MAC and the conventional NPCA-MAC performs slotted CSMA/CA with a priority-based channel access policy, whereas IEEE 802.15.4 MAC protocol operates slotted CSMA/CA without a priority-based channel access policy. Thus, as in Figure 17, the overall average transmission time of the IEEE 802.15.4 protocol had the largest delay as compared to the proposed PA-MAC and NPCA-MAC. Additionally, the PA-MAC shows the better performance than the NPCA-MAC as the number of node increases.

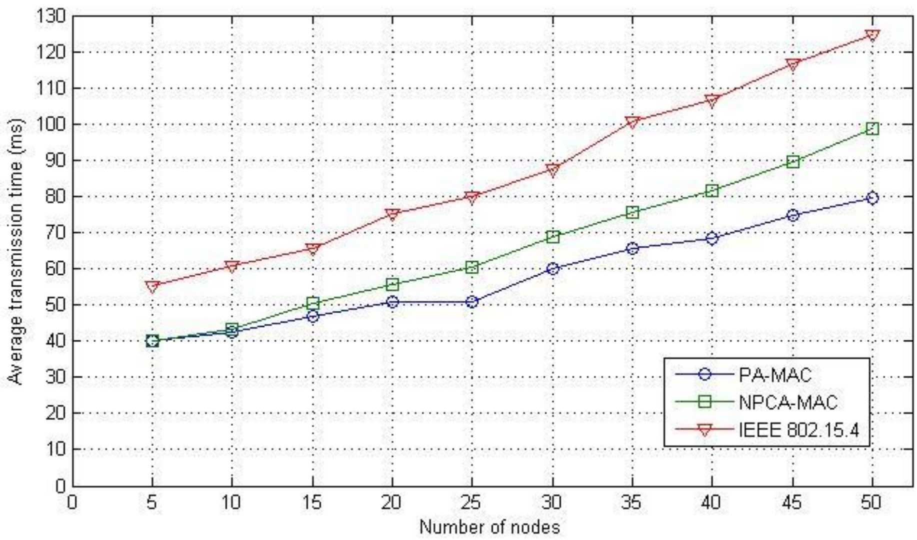

Figure 17. Average transmission time.

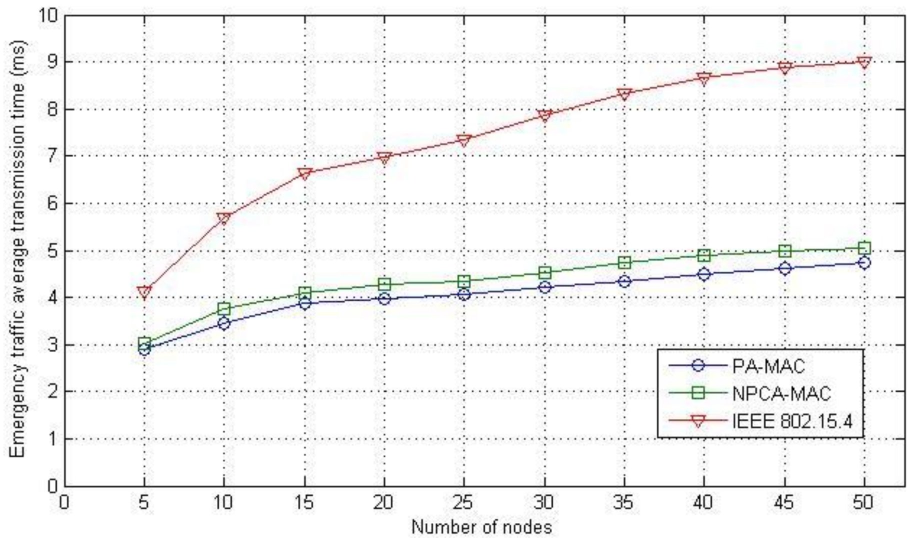

Figure 18. Emergency traffic average transmission time.

In NPCA-MAC, the continuous and discontinuous data transfer procedures, and the use of GTSs are not considered. There is no difference in the transmission of emergency traffic in the proposed MAC and NPCA-MAC. Figure 18 shows the emergency traffic average transmission time for proposed PA-MAC, NPCA-

MAC, and the IEEE 802.15.4 MAC. The main contribution of the transmission delay is due to the channel access delay. The emergency nodes have to transmit a small size data packet in the very small time interval. If the channel becomes extremely busy, the sensor nodes have to backoff more periods to complete to access the channel, and will cause longer channel access delay. Here, we can see that the average transmission time of all three protocol increases with the increased number of sensor nodes. However, the proposed PA-MAC and NPCA-MAC shows the better performance than the IEEE 802.15.4 MAC protocol.

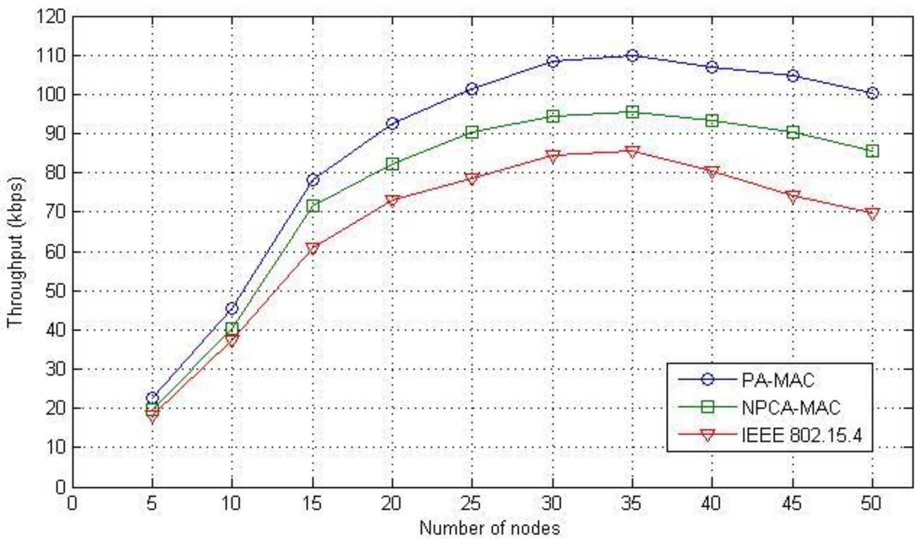

Figure 19. Network throughput.

In Figure 19, the overall performance of network throughput as a function of the number of nodes is illustrated. All three schemes show the similar performance, when the number of sensor nodes are less than 10. The proposed PA-MAC and the conventional NPCA-MAC, however, provide better performance as compared to the IEEE 802.15.4 MAC protocol. In the IEEE 802.15.4 MAC, the collision ratio increases sharply with the number of sensor nodes. Hence, more resources are wasted on data packet collision rather than the effective data transmission. The throughput of all three schemes seems to decrease as the number of nodes exceeds 35, because of high contention complexity and increased packet collision rate. Although the collision rate increases with the number of data packets, the radio resource on data channels is efficiently managed in both PA-MAC and NPCA-MAC according to the data traffic. However, channel access pattern, the prioritization of data traffic, and GTSs allocation for continuous data traffic, the proposed PA-MAC performs better than conventional NPCA-MAC.

The energy efficiency is the key parameter to design the efficient and reliable MAC protocols for WBAN. The energy consumption is related to the nodes behaviors. The network with busy traffic has higher energy consumption as compared to the low traffic activity. To evaluate the energy efficiency comprehensively, the average energy consumption per bit is used. The average energy per bit is given by,

$$E_b = \frac{E_{avg}}{S_b} \tag{20}$$

where E_{avg} is the average energy consumption and S_b is the throughput achieved.

The evaluation of the average energy consumption per bits is shown in the Figure 20. The increasing energy consumption is mainly due to the packet collision and packet retransmission. The energy consumption of the IEEE 802.15.4 MAC protocol is increased sharply with the number of nodes, because of high contention complexity. The high contention complexity causes high packet collision rate and makes a large number of retransmission. The traffic prioritization scheme reduces the contention complexity, and also decreases the packet collision and packet retransmission. The proposed PA-MAC and the conventional NPCA-MAC show the better performance than the IEEE 802.15.4 MAC protocol. This is because the proposed PA-MAC prioritizes channel access and incorporates classification of data transfer procedure, reducing the contention complexity, packet collision, and packet retransmission. Hence, the proposed PA-MAC performs better than the conventional NPCA-MAC and IEEE 802.15.4.

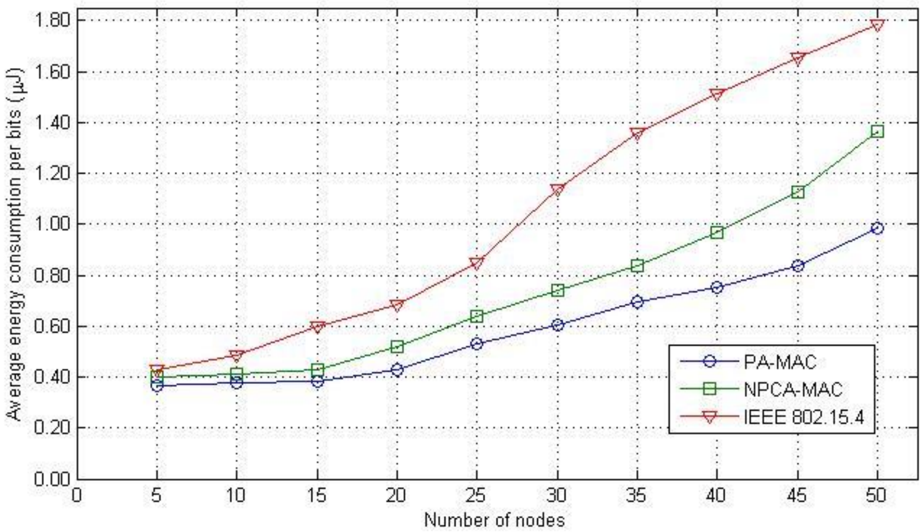

Figure 20. Average energy consumption per bit.

Figure 21 shows the collision ratio of the overall traffic in a network as a function of the number of nodes. The number of collisions increased consequently, with the number of sensor nodes in the WBAN. In the IEEE 802.15.4, slotted CSMA/CA without a prioritization policy did not solve the contention complexity problems, the collision ratio increased discernibly when the number of nodes was greater than 20. The proposed PA-MAC and NPCA-MAC provide the low collision ratio as compare to the IEEE 802.15.4 MAC protocol, due to the prioritization of data traffic and classification of continuous and discontinuous data transfer procedure. And with the features of channel access pattern and GTSs allocation for continuous data traffic, the proposed PA-MAC outperforms conventional NPCA-MAC.

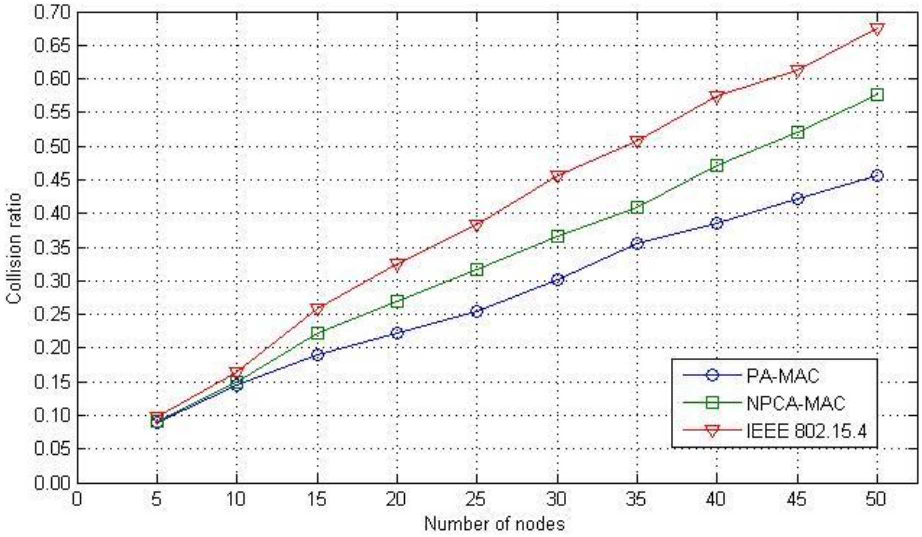

Figure 21. Collision ratio.

VI. CONCLUSIONS AND FUTURE WORKS

The various wireless services such as, IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth), and IEEE 802.15.4 (ZigBee) operate in the industrial, scientific, and medical (ISM) band. The shared nature of ISM band leads to unpredictable service interruptions due to the mutual interference from coexisting systems. The WBANs operating in the highly coexisting interference may suffer from beacon drop,data collision, packet delay, low network throughput, and high energy consumption. To address these issues, we propose a priority-based adaptive MAC (PA-MAC) for WBAN in license-free spectrum. In this proposed protocol, a fixed dedicated channel is assigned for beacon. The beacon channel is used for transmission and reception of the beacon frames, whereas the rest of the communication is done in the data channel. Moreover, we also differentiate the access phase of the CAP and classified the transfer procedure of priority-based traffic in WBANs. The proposed protocol supports both CAP and CFP. The CFP is used to transfer continuous and large number of data packets to the coordinator. According to the simulation results, PA-MAC showed substantial improvements in terms of transmission time, throughput, energy efficiency, and collision ratio compared to the IEEE standard 802.15.4 and the conventional NPCA-MAC.

A possible future work is to apply the cognitive adaptive medium access control mechanism to reduce the delay and packet loss probability in the presence of coexistent systems. By opportunistic extraction of white spaces, the WBAN coordinator dynamically adjusts a channel access pattern according to current coexistent systems, and also improves the WBAN's visibility among coexistent networks.

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