Comprehensive Review of MAC Protocols for WBAN Applications

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| **Article Info** |  | **ABSTRACT** |
| ***Article history:***  Received month dd, yyyy  Revised month dd, yyyy  Accepted month dd, yyyy |  | This study presents a comprehensive review of the Wireless Body Area Network (WBAN), an emerging and unique technology widely employed in human health monitoring to address the increasing demand for healthcare services. WBAN enables continuous remote monitoring in real-time by utilizing biomedical sensor nodes strategically placed in or around a patient’s body to collect human physical parameters. This paper discusses the key characteristics of WBAN, focusing on their system architecture, types of sensor nodes, and network topology. Furthermore, it examines the communication standards adopted by WBAN technology, specifically the MAC superframe structures according to IEEE 802.15.4 and IEEE 802.15.6 standards. The study delves into various Multiple Access (MA) schemes, including TDMA, CSMA/CA, Polling/Low-Power Listening (LPL), and Hybrid mechanisms, while also providing a comparative analysis of dynamic management MAC protocols. Additionally, the paper investigates the simulation tools utilized in prior research to evaluate the WBAN performances. Finally, it identifies research challenges faced in the domain of WBAN, laying the foundation for future research directions in this burgeoning field of human health monitoring technology. |
| ***Keywords:***  WBAN  Health Monitoring  Sensor Nodes  MAC Superframe  Multiple Access |
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1. **INTRODUCTION**

The Wireless Body Area Network (WBAN) is a specialized network designed for in-body and on-body communications, setting it apart as a sub-class of the Wireless Sensor Network (WSN) with both similarities and significant distinctions [1]. WBAN holds immense potential for enhancing wearable computing applications and e-healthcare technology. They offer continuous monitoring capabilities for a specific duration [2] and can handle Real-Time (RT) traffic, including data, voice, and video, enabling the observation of vital organ functionality [3], [4]. Biomedical sensor nodes, comprising communication boards and antennas, transmit data to a medical system, which then displays, stores, and analyzes the information to identify any medical abnormalities. As these sensor nodes are battery-powered devices with a limited lifespan, a malfunctioning battery leads to the cessation of WBAN operation. Consequently, ensuring energy efficiency becomes crucial for extending the lifespan of sensor nodes. The primary distinguishing characteristic of WBAN lies in their ability to prolong network lifetime through the implementation of efficient low-power techniques on energy-constrained sensor nodes [5].

Given the extensive range of WBAN applications in health monitoring, it is crucial to establish specific technical specifications tailored to different illness types and application scenarios. The key technical requirements of WBAN can be outlined as follows [6], [7], [8]:

1. In normal circumstances, a WBAN is capable of supporting links with a maximum throughput of 10 kbps. However, medical applications typically require a low data rate of less than 300 kbps, while non-medical applications may require transmission rates of up to 10 Mbps.
2. The Packet Error Rate (PER) for 95% of the best-performing links should be less than 10% for a 256-octet payload.
3. WBAN applications should prioritize reliability, latency, and jitter. Both delay and jitter should be kept below 250 ms for non-medical applications. However, medical applications demand a latency requirement of less than 125 ms.
4. WBAN must be capable of functioning in a heterogeneous environment, accommodating different devices and technologies.
5. Power-saving techniques should be implemented to enable WBAN to operate efficiently in power-constrained situations.
6. WBAN must incorporate Quality of Service (QoS) management features and provide priority service to ensure reliable and efficient communication.
7. In-body and on-body WBAN should be able to coexist within range. Sensor nodes should be able to maintain reliable communication even when the user is moving.

The Medium Access Control (MAC) layer plays a critical role in achieving these requirements as it addresses several important issues such as resource allocation, overhearing, idle listening, packet delay, congestion control, data reliability, packet re-transmission, protocol overhead, and collision prevention [9]. The design of the MAC protocol has a significant impact on the overall performance of WBAN, including high data dependability, low packet delay, low collision rate, avoidance of packet re-transmission, minimization of overhearing and idle listening, efficient energy usage, and network performance [10]. The sensor nodes consume substantial energy during wireless connection detection and data processing, which can affect service reliability and energy efficiency. In light of this, this paper aims to investigate various MAC protocols in WBAN, with a particular focus on their dynamic resource management techniques. The main contributions of this paper can be summarized as follows:

1. Provides a comprehensive overview of WBAN characteristics, including the system architecture, sensor node types, network topology, and the communication standards IEEE 802.15.4 and IEEE 802.15.6 that are applicable to WBAN.
2. Investigates various channel access mechanisms specifically tailored for WBAN, considering their unique requirements and constraints.
3. Conducts the comparative study of different dynamic management MAC protocols, evaluating their effectiveness and suitability for WBAN.
4. Evaluates different simulators that are commonly in used for assessing the performance of WBAN, providing insights into their strengths and limitations.
5. Identifies and discusses research challenges in WBAN, thereby contributing to the direction of future studies in this field.

The remainder of this paper is structured as follows: Section 2 examines the characteristics of WBAN, including the system architecture, various types of WBAN sensor nodes, and network topology. Section 3 describes the MAC superframe architecture based on IEEE standards (IEEE 802.15.4 and IEEE 802.15.6). Section 4 categorizes the Multiple Access (MA) schemes relevant to WBAN. The MAC protocols specifically designed for WBAN are reviewed in Section 5. Section 6 provides an evaluation of simulators commonly used in WBAN research. An overview of the challenges in WBAN research is presented in Section 7. Finally, Section 8 concludes the paper and outlines the future direction of WBAN research.

1. **WBAN CHARACTERISTICS**

This section discusses the communication architecture of a WBAN health monitoring system, covering sensor node types and network topology. It explores how sensor nodes interact and exchange information within the network and the specific functionalities and roles of different sensor node types. Additionally, it examines the arrangement and interconnection of sensor nodes in the network, emphasizing the importance of efficient and reliable data transmission.

**2.1. WBAN Architecture**

The communication architecture of WBAN, as depicted in Figure 1, encompasses three distinct functioning sections, each playing a crucial role in enabling effective data transmission and communication within the network [11], [12]:

1. **Tier–1:** The intra-WBAN section focuses on communication within the WBAN. This tier involves interactions among biomedical sensor nodes, enabling them to measure and exchange information among themselves and with the coordinator. Wireless communication standards like Bluetooth (802.15.1), Low-Rate Wireless Personal Area Network (LR-WPAN) (802.15.4), and WBAN (802.15.6) are commonly utilized for collecting and transmitting data from the sensor nodes to the coordinator [13].
2. **Tier–2:** The inter-WBAN section handles communication between the intra-BAN coordinator and other entities, such as the Access Point (AP), multiple coexisting BANs, and enables Body-to-Body (B2B) communication. This tier establishes connectivity, facilitates data exchange between different WBAN, and supports communication between WBAN and external systems or devices.
3. **Tier-3:** Beyond-WBAN represents the communication that extends beyond the boundaries of individual BAN. In this tier, the AP serves as a bridge, transmitting data packets from the WBAN to the corresponding health center or destination using the internet or other communication mediums. This tier ensures seamless data transfer from WBAN to external systems, enabling remote monitoring, analysis, and healthcare services.

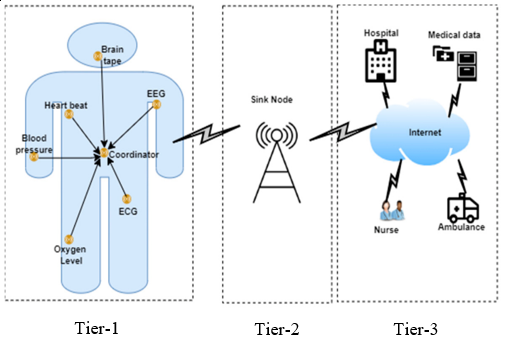


Figure 1. Communication Architecture of WBAN [14]

**2.2. WBAN Sensor Nodes**

In the context of WBAN, nodes can be classified into two distinct classes based on their functionality and implementation. These classifications are essential for understanding the diverse roles and capabilities of the nodes within the network. The categorization of nodes is as follows:

1. **Coordinator*:*** This sensor node type, also known as the Personal Device (PD), sink node, or hub node, plays a critical role in the WBAN system. It serves as the central control unit that manages user interactions and collects information from other sensor nodes within the network. The coordinator is responsible for aggregating data and relaying it to the user through various means, such as an external gateway, display interface, or on-device indicators like Light Emitting Diode (LED). It may be referred to by different names, including body gateway, sink, Body Control Unit (BCU), or Personal Digital Assistant (PDA), depending on the specific context and application of the WBAN system.
2. **Sensor Nodes:** Sensor nodes within WBAN are designed to measure specific physiological parameters from inside or outside the human body. These nodes play a crucial role in collecting relevant data, processing physical signals, and wirelessly transmitting responses for communication purposes. Commercial sensor nodes utilized in WBAN encompass a wide range of applications, including the measurement of vital parameters such as Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyography (EMG), blood pressure, temperature, respiratory rate, glucose level, and more [15], [16]. These sensor nodes are instrumental in providing accurate and RT information for monitoring and analysis in WBAN-enabled healthcare systems. These three communication scenarios in WBAN allow for diverse applications and enable the monitoring of physiological parameters both externally and internally.

A WBAN is established through the deployment of sensor nodes in three distinct communication scenarios [17]. This encompasses the following:

1. **On-Body Communication:** This scenario involves wearable sensors that are positioned on the surface of the human body or placed in close proximity, typically a few centimeters away.
2. **In-Body Communication:** In this scenario, sensor nodes are implanted within the human body, either beneath the skin or within bodily tissue. These nodes are commonly referred to as implanted sensors.
3. **Off-Body Communication:** Sensor nodes in this scenario are positioned at a distance from the human body, typically ranging from several centimeters to up to five meters. Unlike the on-body and in-body scenarios, these nodes do not have direct physical contact with the human body.

**2.3. WBAN Network Topology**

The network topologies commonly used in WBAN are primarily based on a star topology. This star topology employs both single-hop and multi-hop/two-hop configurations for communication [18]. In the single-hop star topology, sensor nodes establish direct connections with the BAN coordinator, as depicted in Figure 2. However, a relay node is introduced in the multi-hop star topology to facilitate communication between the sensor nodes and the coordinator. This can be accomplished either through direct communication or by relaying the data through the intermediary relay node. In terms of the MAC sub-layer parameters, the IEEE 802.15.6 standard [19] pecifies that only one coordinator is allowed to exist within a single BAN. The number of sensor nodes in a BAN can range from 0 to nMaxBANSize, with the standard specifying a maximum size of 64 nodes. This ensures a well-defined and manageable network structure within the BAN, enabling efficient coordination and communication among the sensor nodes and the BAN coordinator.

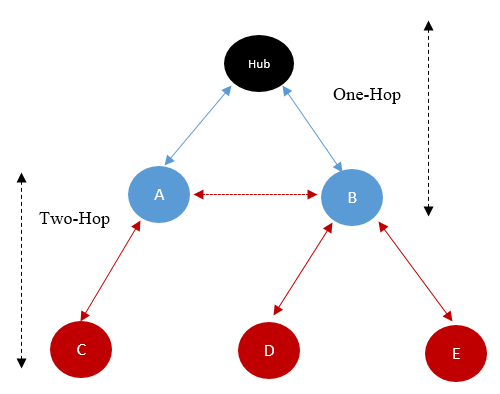


Figure 2. WBAN Network Topology [20]

**3. WBAN COMMUNICATION STANDARDS**

The design of MAC protocols for WBAN applications heavily relies on the MAC superframe structure, which draws from two IEEE standards: IEEE 802.15.4 and IEEE 802.15.6 [21], [22]. These standards provide the foundation for defining the structure of the MAC superframe, which can be tailored to suit the specific requirements and operational characteristics of WBAN. The IEEE 802.15.6 standard plays a significant role as it explicitly specifies the physical (PHY) and MAC layer specifications for WBAN [23]. It is important to note that other standards like IEEE 802.11 Wireless Local Area Network (WLAN), IEEE 802.15, and IEEE 802.15.1 are not well-suited for healthcare applications and do not provide the necessary features and optimizations required by WBAN. Therefore, based on the IEEE 802.15.4 and IEEE 802.15.6 standards, the MAC superframe structure serves as a fundamental design decision for MAC protocols in WBAN.

**3.1. IEEE 802.15.4 Standard**

The IEEE 802.15.4 Task Group 4 (TG4) communication standard, published in 2006 [24], is primarily designed for low-power and low-data-rate applications. This standard supports both WSN and WBAN. It operates in two modes of operation: beacon-enabled mode and non-beacon-enabled mode. Figure 3 provides a general overview of the MAC superframe structure of IEEE 802.15.4 in the beacon-enabled mode. The superframe is divided into active and inactive components. The active period is divided into 16 equal time slots for data transmission. It consists of a beacon, a Contention Access Period (CAP), and a Contention Free Period (CFP). The CFP uses the Time Division Multiple Access (TDMA) approach. In contrast with the CFP, the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) approach is used in the CAP. The sensor nodes and body coordinator go into the sleep mode during the inactive period after the CAP and CFP phases.

The non-beacon-enabled mode does not define the superframe, the slot synchronization, and the Guarantee Time Slot (GTS). However, for medium sharing, only the random access mechanism is employed. The data transmission for this type of operation mode uses the unslotted CSMA/CA mechanism. The major disadvantage of IEEE 802.15.4 is the limited GTS for collision free transmission, which is impractical for WBAN applications [25]. Also, the heterogeneous nature of data is additionally forbidden by this standard, making it unsuitable for transmitting emergency data.

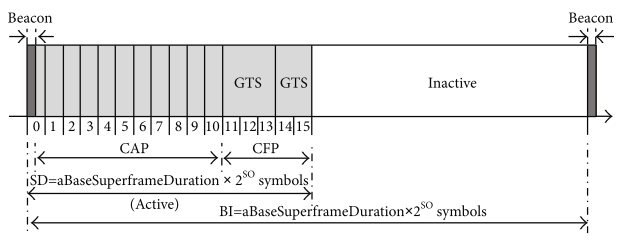


Figure 3. Beacon-Enabled Mode Superframe Structure [24]

**3.2. IEEE 802.15.6 Standard**

In 2012, the IEEE Task Group 6 released a standard called IEEE 802.15.6 [19] to standardise communication among sensor devices linked to a WBAN. This standard can be employed in numerous medical and non-medical fields. It provides ultra-low power, low complexity, excellent reliability, short-range wireless communication within or near the human body, and functioning at low frequencies [26].

As specified by IEEE 802.15.6, three PHY layers are supported by the MAC layer, which are Narrowband (NB), Ultra-Wideband (UWB), and Human Body Communications (HBC) [27]. The NB and UWB are based on radio frequency (RF) propagation, whereas the HBC is based on the non-RF method [6]. The NB PHY supports seven frequency bands ranging from 402–2483.5 MHz for 230 channels, and 402–405 MHz for implantable devices, while 2360–2400 MHz is used for medical applications. The UWB PHY supports frequency bands between 3494.4–9984 MHz. The range of frequency bands for the HBC PHY is between 5–50 MHz, and the central frequency is 21 MHz. A PHY layer of this standard manages the following tasks: radio transceiver activation and deactivation, Clear Channel Assessment (CCA) for the current channel, and data transmission and reception. The chosen physical layer depends on the aim of applications—medical or non-medical and within, outside, or off the human body.

The IEEE 802.15.6 standard consists of three modes of operation: 1) the beacon mode with a beacon-period superframe; 2) the non-beacon mode with a superframe; and 3) the non-beacon mode without a superframe. The most useful mode is the beacon mode with a beacon-period superframe because it synchronises communication among various sensing devices. Figure 4 illustrates the superframe structure of IEEE 802.15.6 in the beacon-enabled mode, which is anticipated to manage heterogeneous traffic loads. It consists of nine different phases, which are the Exclusive Access Phase (EAP 1 and EAP 2), the Random Access Phases (RAP 1 and RAP 2), the Manage Access Phases (MAP 1 and MAP 2), the CAP, and two beacon frames (B). In actual implementation, any access phase can be enabled or disabled to adjust the MAC superframe [28]. According to the standard of IEEE 802.15.6 WBAN specifications, the EAP is designed for highest-priority data, whereas the RAP and CAP are reserved for normal data [29]. In addition, the MAP phases are offered for allocated bilink, uplink, and downlink schedules. Furthermore, the IEEE 802.15.6 standard provides different types of traffic, which is divided into eight different User Priorities (UPs), as tabulated in Table 1.

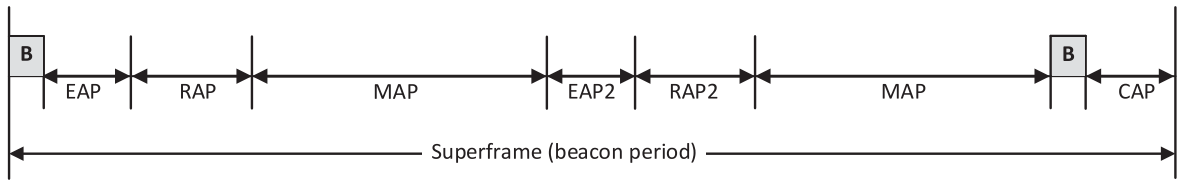


Figure 4. Beacon Mode with Beacon Period Superframe [19]

Table 1. User Priority (UP) Mapping [19]

|  |  |  |  |
| --- | --- | --- | --- |
| **Priority** | **(UP)** | **Traffic Designation** | **Frame Type** |
| Lowest  Highest | 0 | Background (BK) | Data |
| 1 | Best effort (BE) | Data |
| 2 | Excellent effort (EE) | Data |
| 3 | Voice (VO) | Data |
| 4 | Video (VI) | Data |
| 5 | Medical data or network | Data and management |
| 6 | High-priority medical data or network control | Data and management |
| 7 | Emergency or medical implant and even report | Data |

**4. MULTIPLE ACCESS (MA) MECHANISM**

In the MAC protocols of WBAN, the allocation of slots for sensor nodes is facilitated through various Multiple Access (MA) mechanisms. These mechanisms include Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA), Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Slotted Aloha. The MAC layer utilizes these MA techniques to enable efficient channel access for sensor nodes. There are three main categories of MA schemes used in WBAN at the MAC layer: contention-based, schedule-based, and hybrid-based, along with polling/Low-Power Listening (LPL) methods [30], [31]. Table 2 provides a comprehensive comparison of different MA mechanisms. The adoption of MA mechanisms helps in the allocation of channels for heterogeneous data from patients. Various MA techniques have been employed to enhance throughput, optimize channel utilization, nable fast and accurate data transfer, and minimize collisions, delay, re-transmissions, and energy consumption.

**4.1. Contention-Based Slots Allocation (CSMA/CA)**

The CSMA/CA scheme is the most widely used because of its scalability and easy deployment. The First Come, First Served (FCFS) principle supports the slot allocation scheme for body sensor nodes employed by the CSMA/CA scheme [32]. This scheme has no reserved time slots for the channel [33]. Each sensor node listens to the channel to determine whether it is idle before data transmission. If the channel is accessible, the sensor node starts the data transmission. The sensor node will back off and try again if no channel is available. Therefore, the main shortcoming of CSMA/CA is the wastage of energy consumption for protocol overhead and collision avoidance [34]. Despite this, the advantage of contention-based slot allocation includes low delay, low complexity, effective traffic load adaptation, and reliable WBAN data transmission. For WBAN with a low traffic volume and frequent network changes, CSMA/CA is more effective.

**4.2. Schedule-Based Slots Allocation (TDMA/FDMA)**

TDMA and FDMA are schedule-based slot allocations, where a fixed or variable amount of time slots with a specified frame length are allocated to the channel communication of the sensor nodes [35]. Depending on the requirements and data volume, every sensor node can have the allocation for multiple time slots. Collisions can be circumvented, since sensor nodes only transmit during their designated time slots. In this scheme, each sensor node must be synchronised using various control messages to ensure the sensor nodes send their packets in the stipulated time slots. Thus, the main drawback of schedule-based MAC protocols is synchronization issues [36]. TDMA surpasses CSMA/CA in terms of energy efficiency, bandwidth utilization, and throughput [37]. This scheme is well-suited for networks with high periodic traffic volume and infrequent network changes.

**4.3. Hybrid-Based Slots Allocation**

Hybrid-based slot allocation combines schedule-based schemes, such as TDMA, with contention-based techniques like CSMA/CA, resulting in MAC protocols that aim to leverage the advantages of both approaches [11]. However, integrating these two schemes increases the complexity of the hybrid MAC protocols. Moreover, the transition between schedule-based and contention-based schemes requires additional control packets, increasing network traffic and energy consumption. Therefore, while hybrid-based slot allocation offers the potential for improved performance, it comes with the trade-off of increased protocol complexity and higher resource utilization.

**4.4. Polling/Low-Power Listening (LPL)**

In the polling/LPL access mechanism, sensor nodes periodically wake up to monitor the channel's activity without actively receiving data packets. When the channel is found to be empty, the sensor nodes enter a sleeping mode to conserve energy. However, if the channel is active, the sensor nodes keep their transceivers in active mode to receive incoming data packets. By employing polling techniques, overhearing can be minimized, and synchronization requirements are reduced. Nevertheless, one drawback of the polling approach is the increased energy consumption during the transmission and reception of long preambles, which can impact overall energy efficiency.

Table 2. Comparison of Different Access Mechanisms

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Access Mechanism** | **Reliability Support** | **Energy Efficiency** | **Synchronization** | **Transmission Efficiency** | **Delay** |
| Contention-based | Good | High | - | Low | Variable |
| Scheduling-based | Good | Low | Necessary | High | Fixed |
| Polling-based | Good | Moderate | Necessary | High | Fixed |
| Hybrid-based | Good | High | - | Variable-fixed | Variable-fixed |

**5. DYNAMIC MANAGEMENT MAC PROTOCOLS**

MAC protocols should prevent packet collisions, idle listening, and overhearing to maximise the reliability and lifespan of WBAN [38]. WBAN consist of heterogeneous nodes with various traffic demands. Priorities, data rates, and traffic patterns vary between WBAN applications. After identifying the traffic pattern, the coordinator should assign radio resources to a node, and the nodes should wake up or enter the sleep mode depending on the transmission cycle. By considering the traffic flow and priority, the coordinator must dynamically determine the access phase and the number of time slots in the superframe. Superframe length, back-off boundaries, bit rate, the number of time slots, and time slot duration are target parameters that can be dynamically changed using the traffic pattern. This section reviews the MAC protocols related to dynamic parameter management.

The authors in [39] proposed an All Dynamic-MAC (AD-MAC) protocol that optimised the superframe with dynamic priority control, a dynamic time-slot allocation mechanism, and a dynamic length allocation mechanism for different access periods to achieve reliable data transmission with low energy consumption and delay. The proposed MAC protocol used a hybrid superframe structure designed based on the IEEE 802.15.6 standard, which consisted of CAP and CFP phases. In the CAP, the nodes contended for time slot allocation using CSMA/CA to complete the data transmission. In CFP, the TDMA access scheme was utilized. The duration of each access phase was adaptively adjusted based on network traffic and data type. Since AD-MAC can dynamically modify the length of two access periods, it can effectively reduce the energy consumed for re-transmission by high-rate sensor nodes due to transmission collision.

The IEEE 802.15.6 standard-based Adaptive-MAC protocol (A-MAC) with a modified superframe structure was introduced in [40], which performed dynamic time-slot allocation according to traffic volume change, producing better traffic adaptation and high energy efficiency. To effectively reduce collisions when the data channel is accessed, the data service was classified into three categories based on the type of service. The superframe structure has four phases: beacon phase, CAP, CFP, and inactive phase. The CAP was further broken into three sub-phases, with each sub-phase duration being dynamically changed by the priority of the data. Figure 5 illustrates the proposed superframe structure of A-MAC. All nodes in the CAP phase competed for the same access channel using CSMA/CA. CAP and CFP lengths were dynamically adjusted according to the number of nodes that produced priority data. The outcomes showed that the A-MAC protocol can reduce network delay and energy consumption and enhance network adaptability.

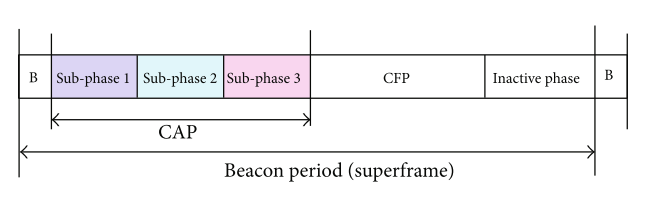


Figure 5. Superframe Structure of A-MAC

A novel approach for dynamic superframe adjustment based on IEEE 802.15.6 (EAP 1, EAP 2, and RAP) called the Drop Packet Estimation technique (PDE) was employed in [41]. The proposed method modified the duty cycle based on packet drops to lower the usage of communication channels. By exploiting the dynamic time-slot allocation in the superframe structure, this method aimed to avoid the wastage of communication channels if no emergency traffic exists. Every node estimated the time between the packets being created and discarded to determine how long it would take to complete a task. The sender predicted the number of dropped packets and determined the time acquired based on the packet drop estimation. The packet reception rate increased by 10% by increasing the EAP phase time according to the emergency traffic.

The work in [42] proposed a dynamic superframe structure-based MAC protocol and priority-based dedicated slot allocation for each sensor device. In the proposed work, EAP and MAP lengths were dynamically adjusted based on data gathered from the hub’s sensors during the beacon phase. The dedicated slots for all emergency nodes in the EAP used TDMA. The sensor nodes in the RAP use the CSMA/CA scheme to transfer data of all types of traffic. Numerous Listening Windows (LWs) were dynamically introduced into the MAP to allocate the slots for all sensing devices. Each sensor device’s slots were allocated during the EAP and MAP phases based on their priority value. Figure 6 depicts the superframe structure of the proposed MAC protocol. The CRITIC mathematical model was used to determine the priority value for each sensor device based on various sensor parameters, such as UP, packet creation rate, buffer occupancy status, data transmission rate, and packet size.

A dynamic slot allocation scheme using non-overlapping contention windows was presented in [43] to improve the utilisation of the IEEE 802.15.6 superframe. First, a Non-Overlapping Backoff Algorithm (NOBA) was introduced to prevent inter-priority collisions caused by a backoff. The outcomes of this scheme were contrasted with those of the Prioritised Fibonacci Backoff (PFB) and the Binary Exponential Backoff (BEB) schemes. The NOBA reduced access delay, individual throughputs, and overall throughput. Second, Dynamic Slot Allocation (DSA) was implemented to prevent wastage caused by the fixed slot size. It distributed the dynamic slots and phases in a superframe based on the amount of traffic. The third approach was the DSA-NOBA scheme, which combined the NOBA and the DSA. Individual throughput, sum throughput, latency, energy, superframe time, and superframe efficiency were performance indicators compared with the standard IEEE 802.15.6 superframe (with the BEB) and Dynamic Phase Allocation (DPA) systems.

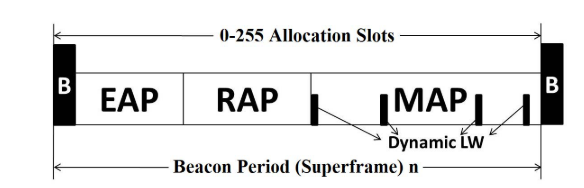


Figure 6. Proposed MAC Superframe Structure

In [44], a group-based MAC (G-MAC) protocol was proposed, which addressed the dynamic adjustment of the IEEE 802.15.6 superframe structure according to high-priority traffic, with node-based buffering controlling the remaining traffic. The modified superframe structure comprised the EAP, MAP, RAP, and CAP. The EAP was used to carry emergency traffic (UP=7), and the MAP is used to transmit dependent traffic (4<UP<6) buffered via a relay node. The RAP was accessed by emergency traffic, relaying nodes, and independent traffic (0<UP<3), while all traffic accessed the CAP. The EAP and MAP phases were TDMA-based, whereas the RAP and CAP were CSMA/CA-based.

By modifying the allocated slots for the EAP and RAP phases of the IEEE 802.15.6 superframe structure dynamically, a dynamic EAP-based MAC protocol was proposed in [45]. The proposed approach required satisfying the sensor nodes’ transmission needs and made use of packet prioritisation to lessen resource rivalry during the RAP phase. The total time needed for all the packets the EAP sensor node had scheduled to send during the beacon period was used to calculate how long the EAP would last. On the other hand, the length of the RAP was calculated by dividing the remaining time by the length of each EAP phase that came before it. The proposed MAC accessed the channel via a polling technique.

In [46], an Improved Packet Scheduling Mechanism (IPSM) algorithm for the Dynamic Allocation of Slots to the Node (DASN) was introduced. The DASN was proposed to avoid congestion, improve energy efficiency, and prolong the life of the network, as less energy consumption leads to longer life of the battery on which network sensing devices work. The IPSM scheduled the packets to prevent collisions to reduce network congestion at the data link layer. Additionally, the IPSM employed a scheduling procedure for the nodes that perceived data, while transferring it over a specific period. Before transmitting the frame, the IPSM scheduled and gave the remaining nodes information during the open slots, saving them from waiting for the subsequent timeframe.

[47] proposes a novel enhanced-TDMA MAC protocol based on the IEEE 802.15.4 standard, which dynamically assigned time slots for body sensor nodes. The key limitations of a static TDMA were its lower channel utilisation rate under numerous traffic loads, inability to lower packet loss rates, and delay in the occurrence of packet collisions. This study offered a unique Enhanced Packet Scheduling Algorithm (EPSA) for scheduling the data packets to reduce energy consumption and increase overall throughput to minimise these issues. The EPSA performed a scheduling process for sensor nodes that sensed data and were ready for a specific timeframe. Some sensor nodes may occasionally have data to transmit but still not receive a time slot in a frame even if they sensed the data and received a specific time slot in that frame. Another scenario involved the sending of empty time slots. This technique allocated time slots before transmitting the frame. It made vacant slots available to other waiting nodes or ready nodes with critical information to avoid such problems and enhance channel utilisation.

A Traffic-Aware MAC (TA-MAC) protocol based on IEEE 802.15.4 was proposed in [48], in which time slots were dynamically allocated on the basis of traffic priority, providing the required QoS. The TA-MAC protocol prioritised sensor nodes by using a priority-aware CSMA/CA in the CAP. For each traffic priority level, the CAP was split into sub-phases: ET-CAP, ODT-CAP, NT-CAP, and NMT-CAP. The coordinator determined the length of each sub-phase based on the number of priority nodes on that sub-phase using equations (1), (2), and (3) to prevent wasting time-slot utilisation.

(1)

(2)

(3)

The authors in [49] presented a Priority Adaptive-MAC (PA-MAC) protocol based on the modifications of the IEEE 802.15.4 superframe structure. The PA-MAC divided the superframe into two access phases: CAP and CFP. In the CAP phase, traffic was prioritised using a priority-guaranteed CSMA/CA mechanism and was divided dynamically into four sub-phases based on the number of nodes in each traffic category, with each category having a different priority. Based on the traffic priority, the proposed MAC assigned the time slots dynamically. The main drawback of the PA-MAC was performance degradation caused by the lack of guaranteed time slots (GTS), particularly for heavy and high-traffic loads.

The work in [50] proposed a Traffic-Adaptive Priority-MAC (TAP-MAC) protocol using a modified IEEE 802.15.4 superframe structure. This work addressed the issue raised by [49] by decreasing contention in the CAP period and providing a fair chance for low-priority traffic. Otherwise, the probability of collisions in the data transmission would increase. In the PA-MAC, all traffic priorities contended in the CAP period, which led to collisions and retransmissions.

Energy Consumption Traffic Prioritisation-MAC (ECTP-MAC) protocol was proposed in [51] to guarantee energy consumption and delay reduction based on the priority of data traffic. The data traffic was prioritised and divided into normal data (ND), periodic data (PD), and emergency data (ED). The ECTP-MAC improved the IEEE 802.15.4 superframe structure and data prioritisation. The CSMA/CA channel access scheme was used to transfer the ND. Furthermore, the TDMA channel access scheme was used for PD transmission. Additionally, the coordinator used an additional phase and the superframe’s inactive phase to effectively transfer data to convey ED.

In [52], a Prioritised Data-MAC (PD-MAC) protocol for WBAN applications was developed. It was designed to enhance the IEEE 802.15.4 superframe structure. The modified superframe structure comprised a beacon, CFP, CAP, and inactive period. The TDMA channel access mechanism was used for data transmission in CFP slots allocated for high- and medium-priority traffic loads. The CSMA/CA mechanism was used in CAP slots, which were distributed for medium- and low-priority traffic. The starvation index slots were introduced in the modified superframe to improve the packet drop and retransmission processes.

The authors in [53] developed an Energy-Efficient Traffic Prioritisation-MAC (EETP-MAC) protocol, which modified the IEEE 802.15.4 superframe structure to provide efficient traffic prioritisation. To avoid channel interference from high latency, this protocol contained sufficient slots with broader bandwidth and guard bands. Several categories were used to categorise the data traffic, which were non-constrained data, delay-constrained data, reliability-constrained data, and critical data. The transmission of crucial and reliability-focused packets during the CFP period occurred in their designated slots during dynamic time slot allocation and was free from contention. As a result, delivering an alarm signal to the specific slot of an emergency beacon ensured the accuracy of the crucial data.

**6. MAC PERFORMANCE EVALUATION**

Several simulators and emulators are utilized in WBAN research to evaluate proposed MAC protocols. These simulation tools include Objective Modular Network Testbed in C++ (OMNeT++), Castalia, MiXiM, Network Simulator 2 (NS-2), Network Simulator 3 (NS-3), and MATLAB.

OMNeT++ is the most frequently used discrete-event simulator for creating network simulators. It features a modular object-oriented framework and a module-based architecture that simplifies its utilization in network simulator proposals. MiXiM [54] and Castalia [55] are two frameworks built on top of OMNeT++ for network simulation. MiXiM is suitable for modeling mobile and fixed wireless networks, such as WSN and WBAN, as it offers complete models for radio wave propagation, interference estimation, radio transceiver power consumption, and wireless MAC protocols. However, MiXiM does not include the implementation of the WBAN standard. On the other hand, Castalia is specifically designed for low-power device networks and provides a radio model for low-power communication and an advanced channel model for simulating WBAN based on empirically measured information for the human body as the propagation medium. Castalia also includes a partial implementation of the MAC layer of the IEEE 802.15.6 standard, making it the most recognized simulator for WBAN [3] [39], [56], [57], [58], [59].

NS-2 is a non-commercial and open-source discrete-event network simulator written in C++ and commonly used to simulate both wired and wireless networks. Some researchers have employed NS-2 to simulate and evaluate routing algorithms for WBAN. Although the MAC layer implementation of the IEEE 802.15.4 standard in NS-2 has been reported in [48], [60], [61], the implementation of the MAC layer of the IEEE 802.15.6 standard in NS-2 has yet to be published. NS-3, released in 2006, is another non-commercial and open-source discrete-event network simulator written in C++ and Python [62]. It is considered the next generation of NS-2 and has been used in several studies to construct models simulating accurate WBAN settings. For example, works such as [63], [64], [65] propose NS-3 implementations of the IEEE 802.15.6 standard.

MATLAB, a powerful simulation tool, is employed in various WBAN-related research works, such as [2], [44], [66]. However, MATLAB does not support simulation of all network layers. It provides a platform for model implementation, simulation, and behavior analysis. While different simulators have their strengths and applications, performing comparative evaluations with real scenarios is crucial for WBAN. In this regard, the Castalia simulator stands out due to its superior features and accurate models, making it the preferred choice for WBAN simulations.

**7. WBAN** **RESEARCH CHALLENGES**

WBAN encounter numerous challenges that can impede their performance. Ensuring a smooth operation in WBAN applications requires addressing significant challenges in the design of the MAC protocols. In this section, we outline some of the challenges highlighted in extant literature.

**7.1. Heterogeneous Data**

WBAN data is inherently heterogeneous, as it involves multiple sensor nodes monitoring diverse vital information within the network. As a result, there are variations in data rate, frequency, and computing power among the nodes. Certain applications necessitate RT data, while periodic data measurements suffice for others. Therefore, it is crucial for the MAC protocols to incorporate a dynamic resource allocation technique. Traditional MAC protocols that allocate fixed slots are inadequate for meeting the demands of heterogeneous and dynamic traffic in WBAN. To address this challenge, a dynamic superframe structure can be employed, which effectively handles the diverse traffic by considering user priorities. This approach prevents inefficient utilization of the superframe time and ensures that the MAC protocols caters to the specific requirements of each traffic category in WBAN.

**7.2. Quality of Service (QoS)**

To achieve differentiated QoS, optimization of various MAC parameters is essential. The coordinator should be able to selectively allocate radio resources to each sensor node based on their data priorities, thereby providing high-priority data with differential QoS [67]. For instance, emergency or critical data can be better supported by allocating more dedicated time slots to the nodes handling such crucial information. Using a fixed channel allocation approach may lead to performance degradation or resource waste, particularly because the on-body communication link experiences significant fluctuations [68]. To address this, differentiated QoS can be facilitated by improving the CSMA/CA-based channel contention mechanism. One approach is to dynamically determine the back-off bounds, which increases the probability of channel access for high-priority traffic, thereby ensuring a more efficient and responsive MAC protocols for WBAN.

**7.3. Energy consumption**

Energy consumption is a critical challenge in WBAN due to their severe resource constraints. These networks consist of battery-powered sensor nodes with limited processing and communication capacities, and the nodes typically cannot have their batteries changed or recharged. Therefore, it is essential to minimize energy dissipation to enable continuous and long-term patient monitoring. The energy efficiency in WBAN can vary depending on the communication standards employed. Among these standards, IEEE 802.15.6 demonstrates a better successful packet transmission rate compared to IEEE 802.15.4, despite consuming more energy. In IEEE 802.15.6, the higher energy consumption can be attributed to the carrier detecting the channel and subsequently reducing the back-off counter based on the sensed channel conditions. Efforts to address energy consumption in WBAN are crucial to ensure the longevity of battery life and to optimize the network's overall performance.

**7.4. Reliability**

Reliability is the utmost importance in WBAN as it directly impacts patient health monitoring. Ensuring a highly reliable network is essential to maintain the effectiveness of end-to-end communication and the quality of links within the network. Reliability can be evaluated by assessing factors such as fault tolerance, QoS, and security in network communication. By addressing these aspects, a reliable WBAN can be established, meeting the requirements for a dependable network that satisfies user expectations and ensures the well-being of patients [69].

**7.5. Interference**

Interference poses a significant challenge in WBAN and demands careful consideration. The transmission of medical data can suffer from delays or incompleteness caused by inter-WBAN interference, particularly in adjacent WBAN. The IEEE 802.15.6 standard addresses this issue by specifying that when multiple WBAN are co-located, the network should operate effectively within a transmission range of up to 3 meters [19] to mitigate inter-WBAN interference. Within a single WBAN, strategies such as coordinating or combining various channel access techniques [11] can effectively reduce intra-WBAN interference, enhancing the overall network performance and reliability.

**7.5. Body Movements**

Unpredictable body movements and posture changes pose a significant challenge for MAC protocols in WBAN as they can disrupt network performance [70]. However, cooperative communication through relay nodes offers a promising solution to manage outages caused by these changes. By leveraging relay nodes, traffic can be intelligently diverted to less congested routes, thereby improving Packet Delivery Rate (PDR) and overall network reliability [11]. This approach ensures that the impact of unpredictable body movements and posture changes on network performance is minimized, leading to more robust and stable communication in WBAN.

**8. CONCLUSION AND FUTURE DIRECTION**

This study analyzes various MAC protocols proposed for WBAN applications, highlighting their features, advantages, and disadvantages. The inherent characteristics of WBAN, including system architecture, network topology, and multiple types of sensor nodes, were discussed to provide a comprehensive understanding. Efficient traffic prioritization in MAC protocols for WBAN hinges on two critical criteria: the design of the superframe structure and the selection of suitable MA schemes. The latest IEEE 802.15.6 standard for WBAN offers an energy-saving approach, providing low-power and reliable communication compared to IEEE 802.15.4, which consumes more energy and utilizes higher bandwidth. The Castalia framework emerged as the most specific simulator for simulating WBAN MAC protocols. It offers advanced channel and radio models, which are crucial for accurate simulations based on empirical data from the human body as the communication medium. Future MAC protocols for WBAN must address adaptive traffic loads and perform dynamic time slot allocation based on traffic priority. Energy-saving MAC protocols are essential to ensure efficient and reliable data transmission while using limited wireless channel resources in WBAN. Moreover, when dealing with heavy traffic loads, MAC protocols need to strike a balance between PDR, energy consumption, and minimal delay. Meeting QoS requirements without performance degradation is also crucial for WBAN applications. Hence, addressing these challenges will be a vital focus for future work in developing novel MAC protocols to enhance WBAN channel access control and reliable link-level communication, ultimately advancing the field of WBAN.

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