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Review Article

A Comprehensive Survey of Medium Access Control Protocols for Wireless Body Area Networks

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Wireless body area networks (WBANs) have emerged as a promising technology for health monitoring due to their high utility and important role in improving human health. WBANs consist of a number of small battery-operated biomedical sensor nodes placed on the body or implanted, which are used to monitor and transmit important parameters such as blood pressure, electrocardiogram (ECG), and electroencephalogram (EEG). WBANs have strict requirements on energy efficiency and reliability during data collection and transmission. The most appropriate layer to address these requirements is the MAC layer. Medium access control protocols play an essential role in controlling the operation of radio transceivers and significantly affect the power consumption of the whole network. In this paper, we present a comprehensive survey of the most relevant and recent MAC protocols developed for WBANs. We discuss design requirements of a good MAC protocol for WBANs. We further review the different channel access mechanisms for WBANs. Then, we investigate the existing designed MAC protocols for WBANs with a focus on their features along with their strengths and weaknesses. Finally, we summarize the results of this work and draw conclusions.

1. Introduction

Wireless body area networks (WBANs) have gained much attention in recent years due to the advances in microelectronics, integrated circuits, and wireless communications. A wireless body area network (WBAN) is defined as a subcategory of wireless sensor networks (WSNs) with its own challenges and requirements. It consists of smart, low power, miniaturized, heterogeneous, and autonomous wireless sensor nodes, which are attached to (or implanted into) the body for continuous health monitoring. The communication architecture of WBANs can be classified into three levels as follows [1]: Level 1: intra-WBAN communication, Level 2: inter-WBAN communication, and Level 3: beyond-WBAN communication. Figure 1 shows a 3-level architecture of WBANs for medical and nonmedical applications.

In view of the size limitation of the biosensor nodes and the importance of the life signals transmitted, compared with general wireless sensor networks (WSNs), WBANs have more strict requirements on energy efficiency and reliability during data collection and transmission [2]. Each node in the network is fitted with a limited battery, but it is very difficult to change or recharge batteries. WBANs require an energy-efficient mechanism for long-term patient health monitoring. Thus, energy efficiency is one of the most essential factors of the MAC design.

For the purpose of solving the major challenges confronted by WBANs, in view of the reliable data transmission and energy efficiency requirements, a great number of MAC protocols have been proposed in the literature. This paper is aimed at surveying recent works of power-efficient MAC protocols for WBANs. We investigate the most commonly used MAC protocols in WBANs by highlighting their salient features and emphasizing their strengths and shortcomings.

The major contributions of this research work are summarized as follows:

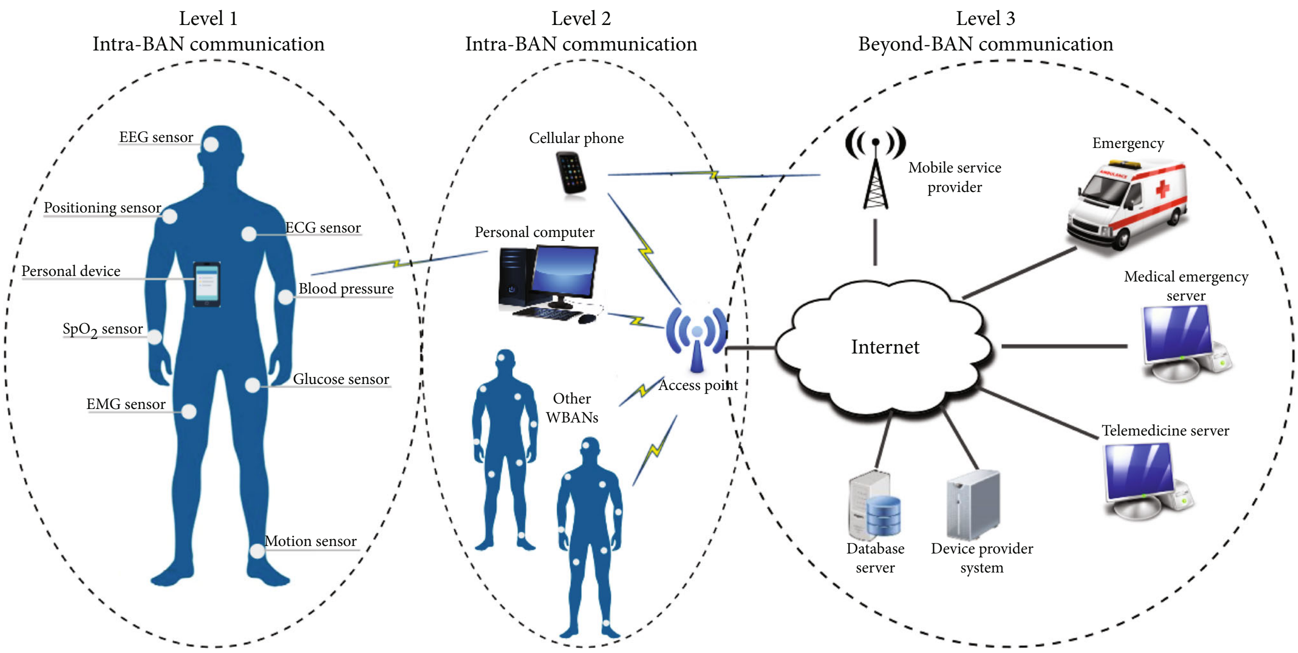

Figure 1: General architecture for wireless body area networks.

(i) We outline the main requirements of a good MAC protocol for WBANs

(ii) We investigate and compare different channel access mechanisms in the context of WBANs

(iii) We analyze the relevant MAC protocols for WBAN with regard to their specific features, advantages, and disadvantages

(iv) The MAC protocols taken into account for survey are S-MAC, T-MAC, DMAC, Ta-MAC, PA-MAC, BMAC, WiseMAC, X-MAC, TAD-MAC, Med-MAC, BodyMAC, IEEE 802.15.4 MAC and Wise-MAC, IEEE 802.15.6 (Baseline-MAC), CA-MAC, TDMA-based directional MAC, TTR-MAC, Z-MAC, HEH-BMAC, CoR-MAC, and A-MAC protocols

(v) Finally, we summarize the results of this study and discuss a number of future research directions and conclusions

The rest of the paper is organized as follows: Section 2 discusses various survey papers in WBAN focusing on MAC protocols. Section 3 discusses the requirements of MAC protocols for WBANs. Section 4 presents principal medium access control approaches. Section 5 reviews the existing MAC protocols designed for WBANs. Section 6 provides a summary of findings. The last section concludes this paper and discusses a number of open research issues.

2. Related Survey Paper

In the literature, there are various surveys on WBANs [3–15]. However, the majority of these surveys have focused on the applications [16, 17], technologies [18–20], standards [21], and design issues [17, 22–24] of WBANs rather than evaluating various research efforts made towards achieving efficient MAC protocols for WBANs, which is the main objective of this survey.

The authors in [25] reported a survey that presents the history of research efforts in MAC protocols for WBANs from 2000 to 2010. In particular, the authors outlined the WBAN requirements that are important for the design of a low power MAC protocol. Then, they studied low power MAC protocols proposed/investigated for a WBAN with emphasis on their strengths and weaknesses. The authors also reviewed different power-efficient mechanisms for a WBAN.

In [26], the authors offered a survey of wireless body area networks. The authors focused on some applications with a special interest in patient monitoring. They discussed the communication in a WBAN and its positioning between the different technologies. The authors also provided an overview of the current research on the physical layer, existing MAC, and network protocols. However, this survey does not provide any investigation of the existing MAC protocols for WBANs.

Hughes et al. [23] presented a survey of energy efficiency of MAC protocols for WBANs. The authors highlighted the features of MAC protocols along with their advantages and limitations in the context of WBASNs. Comparison of low power listening (LPL), scheduled contention, and Time Division Multiple Access (TDMA) is also elaborated. MAC protocols with respect to different approaches and techniques which are used for energy minimization and traffic control mechanisms for collision avoidance are discussed. One of the limitations of this survey is that the number of protocols investigated is quite restricted.

Ullah et al. in [27] reviewed the fundamental mechanisms of WBAN including architecture and topology, wireless implant communication, low power medium access control (MAC), and routing protocols. A comprehensive study of the proposed technologies for WBAN at physical (PHY), MAC, and network layers is presented, and many useful solutions are discussed for each layer. The authors also highlighted numerous WBAN applications. However, they surveyed only a few number of articles related to MAC protocols without giving an in-depth analysis of the feasibility of reported studies.

In [28], Chen et al. analyzed the existing MAC protocols for WBANs with emphasis on energy minimization. However, they investigated only a few number of protocols. The study in [29] reviews some MAC protocols that could be exploited in WBANs and those proposed specifically for the WBAN systems. Also, these MAC protocols were grouped and compared based on short- and long-range communication standards. However, the study did not assess any comparison of the envisaged protocols.

Compared with the surveys in the literature, we aim to provide a comprehensive study of well-known MAC protocols developed for WBANs and compare features of the various channel access mechanisms. Compared to other related surveys, the present survey considers a large number of MAC protocols and provides a thorough analysis of the feasibility of the reported studies.

3. Requirements of MAC Protocols for WBANs

As comprehensively discussed in [25], the most important requirements of a good MAC protocol are energy efficiency, scalability, latency, reliability, throughput, interference mitigation, and priority traffic in a WBAN system. In this section, each requirement is reviewed in detail.

Energy Efficiency: energy efficiency is one of the most important goals to be achieved in WBANs. Sensor nodes are battery-operated with limited computational and communication capabilities. Replacement or recharging of batteries is not possible. Energy dissipation should be reduced as much as possible to achieve uninterrupted long-time patient monitoring.

Scalability: as the number of nodes varies according to patient monitoring requirements, used protocols have to be able to easily reconfigure a WBAN by either adding or removing nodes without affecting the operation of the WBAN.

Interference Mitigation: as the WBAN nodes are mobile, the channel condition is constantly changing. The channel condition deteriorates significantly in areas densely populated with other WBAN users. The MAC scheme should be resilient to multiple network interferences.

Latency and Reliability: latency and reliability are two highly important factors in health monitoring applications. High reliability and low latency of data transmission ensure that emergency data is successfully sent and is immediately accessible to healthcare providers. Reliability directly affects the quality of patient monitoring. It can be life-saving in many cases and in a worst-case event; it can be catastrophic when a life-threatening incident has not been observed or detected.

Throughput: throughput refers to the amount of transmitted data through the channel during a specific time. Like latency, the throughput depends on the application.

Priority Traffic: WBAN data traffic is classified into three categories [27]. They are normal traffic which is the data traffic in a normal situation; this kind of traffic is generated at regular intervals; on-demand traffic which is introduced by the coordinator to acquire certain information, mostly for the purpose of diagnostic recommendations; and emergency traffic is irregular traffic, which may occur anytime responding to some critical and unpredictable medical events. Emergency traffic is totally unpredictable. A WBAN MAC protocol should be able to support on-demand traffic and provide a method for emergency data to be transmitted reliably with minimum latency.

4. Classification of MAC Protocols

The MAC protocols developed for WBANs are classified into four categories based on channel access mechanism [30, 31]; contention-free, contention-based, low power listening (LPL) or polling, and hybrid combining TDMA and carrier-sense multiple access (CSMA) mechanisms.

4.1. Contention-Free MAC Protocols (TDMA). TDMA is a contention-free channel access mechanism where the channel is divided into fixed or variable time slots with a fixed frame length that is assigned to nodes for communication. A single node can have multiple time slots depending upon requirements and data volume. Nodes can only transmit during their given time slot; hence, collision is avoided. Each node must be synchronized using different control packets to ensure that nodes send their packets in the assigned time slot.

Synchronization is the major issue in TDMA-based MAC protocols. TDMA is a suitable option for a limited number of sensor nodes in WBANs with a fixed data rate. Assigning time slots to sensor nodes with different data rates, nonperiodic data, and scalability is the key issue in implementing TDMA in WBANs.

4.2. Contention-Based MAC Protocols (CSMA/CA). In this class of MAC protocols, there is no reservation of the channel. Before transmission of data packets, each node will initially listen to the channel and check if it is idle or not then start transmission. If the channel is free, the node starts transmission of data packets. However, if the channel is detected busy, the node will back off and tries again after a period of time.

The major advantages of contention-based mechanisms are low delay, good adaptation to fluctuations in traffic load, low complexity, and reliable transmission of packets in small size networks like a WBAN [32]. However, additional energy consumption for collision avoidance and protocol overhead are major drawbacks of CSMA/CA.

4.3. Low Power Listening MAC Protocols. In the low power listening mechanism, nodes wake up periodically to check the activity of the channel without receiving data. If the channel is detected idle, the nodes go into a sleeping mode;

Table 1: Comparison of LPL, schedule contention, and TDMA mechanisms [23, 25].

LPL	CSMA/CA	TDMA
Does not listen for full contention period; as a result, it is less expensive	Listen for full contention period	Low duty cycle
Asynchronous	Synchronous	Synchronous-fine-grained time synchronization
Poor performance when traffic rates change (optimized for known periodic traffic)	With the increase in traffic, performance is improved	Throughput and number of active nodes are limited
Scalable and adaptive to traffic load and low delay	Better delay performance due to sleep schedules	Better end-to-end reliability, smaller delays, high reliability
Flexible, high throughput, tolerable latency, and low power consumption	High transmission latency, loosely synchronized, low throughput	Good for energy efficiency, prolonged network's lifetime, load balancing

otherwise, they keep the transceiver in an active mode to receive data packets. This is also known as "channel polling." Once the idle interval ends, all nodes wake up to listen to the long preamble transmitted by the network coordinator. The preamble contains the address of the polled node.

Low power listening mechanisms avoid idle listening and overhearing. Synchronization is not required here. The main drawback of the LPL mechanism is that the transmission and reception of a long preamble increase energy consumption significantly.

4.4. Hybrid MAC Protocols (TDMA and CSMA/CA). Other approaches define hybrid mechanisms that switch between different protocol categories depending, in most cases, on the traffic load. The hybrid-based MAC protocols are the protocols that combine contention-free and contention-based access mechanisms.

Numerous MAC protocols have been proposed to combine the features of TDMA and CSMA protocols [33] with the aim of including the benefits from both of them. In this class of MAC protocols, active/sleep duty cycles are applied by dividing time into frames during which a node spends a part of the time for communication and sleep for the resting time to reduce the energy dissipation caused by idle listening.

The hybrid MAC mechanism is used to adapt to the transmission of different priority levels of traffic as well as allow the sensor to retransmit data packets. The combination of the two mechanisms increases the complexity of the hybrid protocols. The transition between the contention-based and contention-free mechanism requires more control packets. The transmission of those packets will increase the network traffic and consume additional energy. Table 1 represents a comparison of the three main classes of channel access mechanisms.

5. Existing MAC Protocols for WBANs

The following sections present a brief overview of different MAC protocols designed for WBANs and emphasize their strengths and weaknesses.

5.1. Contention-Based MAC Protocols.

S-MAC: Sensor MAC: S-MAC [34] was proposed for wireless sensor networks. It is derived from IEEE 802.11. S-MAC is a contention-based MAC protocol using a periodic listen and sleep mechanism. A time frame in S-MAC is split into an active and a sleep cycle. The listen and sleep time in the S-MAC are fixed intervals. Only for an active cycle, the node can communicate with other nodes and send some control packets such as SYNC, RTS (Request to Send), CTS (Clear to Send), and ACK (acknowledgment). The rest of the time, the node is sleeping. The main goal of the S-MAC protocol is to decrease energy consumption and to provide good scalability and collision avoidance. To achieve the design goal, S-MAC consists of three principal components: periodic listen and sleep, collision and overhearing avoidance, and message passing.

In S-MAC, the energy dissipation caused by idle listening is reduced by periodic sleep-listen schedules. However, overhearing and collision may cause high latency and low throughput. Since the periodic sleeping scheme is unchanged, S-MAC is not able to work efficiently under variable traffic load.

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T-MAC: Timeout MAC: T-MAC [35] is an improvement on S-MAC by introducing adaptive duty cycles that can adapt to network traffic loads and avoid useless wakeups. The idea of T-MAC is to send all messages in bursts of variable length and to sleep between bursts for more energy saving. Figure 2 illustrates the sleep and wake-up cycles in S-MAC and T-MAC. T-MAC introduces an active timeout mechanism that reduces the amount of energy wasted on idle listening by dynamically adjusting the active period according to network traffic loads. However, due to the mechanism of dynamic duty length adjustment, T-MAC can suffer from the early-sleep problem. This is simply because when some node fails to detect other nodes' activity in Time Activity (TA) length time, these nodes will go to sleep. T-MAC minimizes the delay and gives better results under variable traffic load. However, it suffers from sleeping problems.

DMAC: Data Gathering MAC: DMAC [36] is an energy-efficient and low latency MAC protocol proposed for tree-based data gathering in wireless sensor networks. This

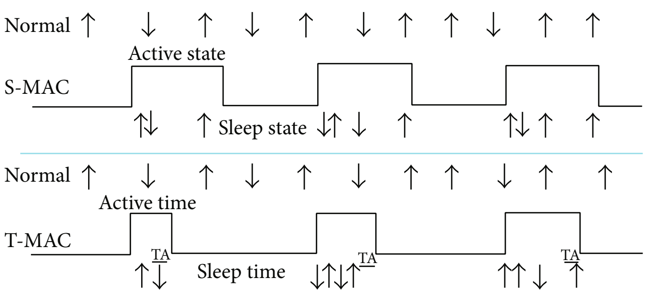

Figure 2: Sleep and wake-up cycles in S-MAC and T-MAC.

protocol is developed to solve the data forwarding interruption problem (DFI) present in implicit adaptive duty cycle techniques and enables continuous packet forwarding by giving the sleep schedule of a node an offset that depends upon its depth on the tree. DMAC also adapts the duty cycles according to the traffic load in the network. To enable continuous data forwarding on a multihop path, DMAC staggers the schedule of the nodes on the multihop path and allows the nodes to wake up sequentially like a chain reaction. Figure 3 presents the DMAC data gathering tree. DMAC achieves very good latency compared to other sleep/listen period assignment protocols [36]. The principal problem of this protocol is packet collision which occurs because many nodes in the tree could share the same schedule and DMAC employs restricted collision avoidance methods.

Ta-MAC: Traffic-Adaptive MAC: the traffic-adaptive MAC (Ta-MAC) [37] protocol is proposed for WBANs to improve energy efficiency by exploiting the traffic information (traffic patterns) of the nodes.

Ta-MAC introduced two channel access mechanisms: a traffic-based wake-up mechanism used to accommodate normal traffic and a wake-up radio mechanism used to accommodate emergency/on-demand traffic.

In this protocol, the channel is bounded by superframe structures as shown in Figure 4. The superframe consists of three parts: a beacon, a Configurable Contention Access Period (CCAP), and a contention-free period (CFP). The beacon part is used for synchronization and resource allocation. The CCAP period is used for short data transmission. The CFP period contains a series of Guaranteed Time Slots (GTS), which are used for data transmission.

In the traffic-based wake-up mechanism, the operation of each node is based on the traffic patterns. The initial traffic patterns are predefined by the coordinator. The traffic patterns of all nodes are organized into a table named traffic-based wake-up table. Since the nodes are assigned predefined traffic patterns, they wake up once they have data to send or receive; otherwise, they stay in the sleep mode. This mechanism avoids additional power consumption incurred by idle listening and overhearing and minimizes the delay. In the wake-up radio mechanism, the nodes (for emergency traffic) or the coordinator (for on-demand traffic) sends wake-up radio signals to each other. This mechanism is also used to update the traffic-based wake-up table.

As in the Ta-MAC protocol, the traffic patterns are predefined by the coordinator, in a static topology. Therefore, it does not work efficiently in a dynamic topology where

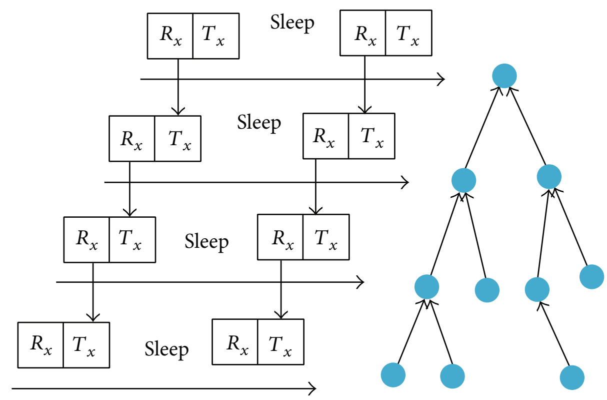

Figure 3: Data gathering tree in DMAC.

the traffic patterns are changed frequently. This protocol accommodates communication of normal, on-demand, and emergency traffic. But it is not suitable for dynamic topologies.

PA-MAC: Priority-Based Adaptive MAC: PA-MAC [38] is a priority-based adaptive MAC protocol developed for WBANs to provide energy efficiency and QoS for different applications of WBANs by disseminating the contention complexity. PA-MAC uses the beacon channel (BC) for the reception and transmission of the beacon frames and data channel (DC) for the remaining communication. PA-MAC prioritizes the data traffic by using a priority-guaranteed carrier-sense multiple access with collision avoidance (CSMA/CA) procedure in the contention access period (CAP). The superframe structure of PA-MAC is depicted in Figure 5.

To support various QoS requirements, PA-MAC classifies the data traffic into four categories: emergency, on-demand, normal, and non-medical. It gives the highest priority to emergency traffic and least priority to non-medical traffic. The CAP period is divided into four subperiods dynamically, according to the number of nodes in each traffic category. The PA-MAC assigns time slots dynamically according to the traffic priority. In PA-MAC, multiple channels are used to decrease access delay in medical networks with the coexistent networks.

PA-MAC shows good performance regarding delay, PDR, and energy. However, it does not provide any mechanism to handle emergency alarm during CFP and IP periods of beacon interval which decreases PDR when traffic load is high due to limited GTS slots.

5.2. LPL-Based MAC Protocols.

BMAC: Berkeley MAC: the Berkeley MAC protocol was introduced in 2004 [39] for low power wireless sensor networks. This protocol uses an adaptive preamble sampling technique to decrease the duty cycle and minimize idle listening. BMAC employs clear channel assessment (CCA) and packet backoffs for channel arbitration, link layer acknowledgments for reliability, and low power listening (LPL) for low power communication. It employs an enhanced filtering method to increase the reliability of channel assessment. In

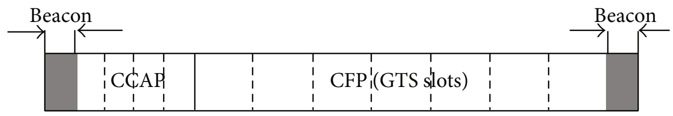

Figure 4: Ta-MAC superframe structure.

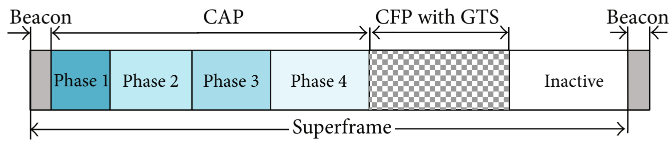

Figure 5: Superframe structure of PA-MAC.

the BMAC protocol, the nodes will also periodically sense the channel in a fixed interval (using the LPL mechanism) to check the channel. If the channel is found busy, the nodes will remain awake for the time needed to receive the incoming packets. After reception, the node goes back to sleep. If no packet is received, a timeout forces the node back to sleep.

BMAC has several advantages compared to S-MAC: simplicity, good packet delivery rate, high throughput, and low power consumption. The major disadvantage of BMAC is that the long preamble creates a large overhead and increases power consumption.

WiseMAC: Wireless Sensor MAC: WiseMAC is a MAC protocol developed for wireless sensor networks [40]. This protocol minimizes the power consumed when listening to an idle medium by using a nonpersistent CSMA and preamble sampling technique. The novel idea presented by WiseMAC is to minimize the length of the wake-up preamble, using the knowledge of the sampling schedule of the transmitter node's direct neighbors. WiseMac consists in sampling the medium regularly to check for activity. Sampling the medium can be defined as listening to the channel for a short period. Each node in the network samples the medium with the same fixed period. If the channel is found busy, the node continues to listen until it receives a data frame or until the channel becomes idle again. The wake-up preamble is added in front of every data frame to make sure that the receiver will be awake when the packet arrives.

Figure 6 shows preamble minimization in WiseMAC. WiseMAC is scalable and adaptive to different traffic conditions; it is a mobility support protocol. The major drawback of this protocol is that the long wake-up preamble causes a throughput limitation and a large power consumption overhead in transmission and reception.

X-MAC: the X-MAC protocol [41] is an improvement on the concepts of BMAC. It employs a strobed preamble approach by transmitting a series of short preamble packets, each containing the address (ID) of the target node, as shown in Figure 7.

When a node wakes up and receives a short preamble packet, it looks at the target node ID that is included in the packet. If the node is not the intended receiver, the node returns to sleep immediately and continues its duty cycling as if the medium had been idle. If the node is the intended receiver, it remains awake for the subsequent data packet. As seen in the figure, a node can quickly go back to sleep, thus avoiding the overhearing problem. This short strobed preamble approach reduces the time and energy wasted waiting for the entire preamble to complete. Figure 7 shows a comparison between low power listening and X-MAC.

X-MAC protocol is energy-efficient and has low latency. The technique of avoiding overhearing by embedding the target receiver node ID makes multicasting and broadcasting difficult.

TAD-MAC: Traffic-Aware Dynamic MAC: TAD-MAC is an energy-efficient Traffic-Aware Dynamic MAC protocol [42], which may be considered an addition in the class of preamble sampling MAC protocols proposed to deal with all types of variable traffic that can occur in WBANs. The TAD-MAC protocol targets both invasive and noninvasive body area networks by considering a hybrid network topology which includes star network for in-body and mesh network for on-body WBAN. In TAD-MAC, each node has a traffic status register bank (TSR-bank) which contains the traffic status according to the data received from all the neighbor nodes. The TSR-Bank is used to continuously update the WUInt of the receiver node with respect to the transmit node data transmission rate. The dynamic adaptation of TAD-MAC results in ultralow energy consumption incurred by idle listening, overhearing, collisions, and unnecessary wake-up beacon transmission. The communication of on-demand and emergency traffic is not considered.

5.3. TDMA-Based MAC Protocols.

MedMAC: Medical MAC: the medical medium access control (MedMAC) [43] protocol was proposed for energy-efficient and adaptable channel access in wireless body area networks. MedMac is an adaptive TDMA-based MAC protocol.

MedMAC incorporates a multisuperframe structure as shown in Figure 8; the main unit of the structure is a dynamic and programmable superframe bounded by a beacon frame sent at regular intervals by the coordinator. The beacon period consists of an optional contention period and a contention-free period made up of time slots. The contention-free period and the contention period make up a total number of time slots varying from 2 to 256. The durations of the superframe and the time slots are programmable

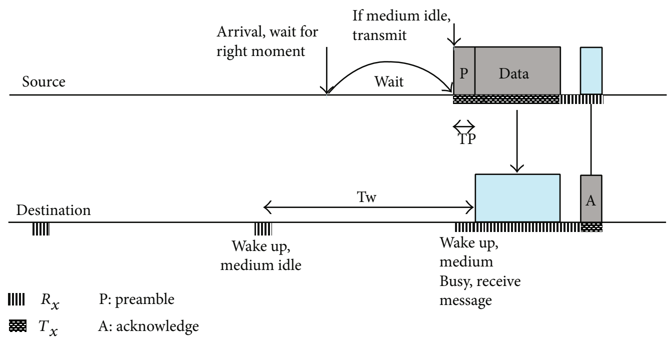

Figure 6: WiseMAC.

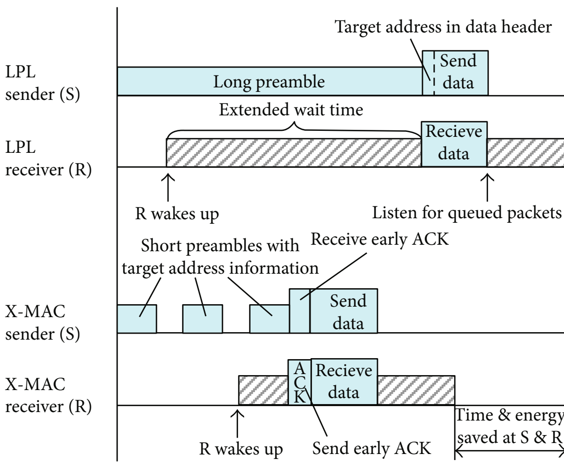

Figure 7: Comparison of the timeliness between LPL's extended preamble and X-MAC's short preamble approach [41].

and dependent on the application requirements including sleep/power saving demands.

The MedMAC protocol integrates a novel synchronization mechanism (AGBA) where a node can sleep through a number of beacon periods without losing synchronization with the coordinator. Collision of data packets is avoided using a Guaranteed Time Slot (GTS) for each sensor node. Synchronization between the coordinator and the other nodes can be maintained by the combination of timestamp scavenging and an Adaptive Guard Band Algorithm (AGBA). AGBA allows the node to sleep through many beacon broadcasts by introducing a guard band (GB) for each time slot to track the actual drift. The Drift Adjustment Factor (DAF) is used to avoid the waste of bandwidth. At the start of the multisuperframe, all the nodes are brought into synchronization by use of a timestamp. At this point, the algorithm AGBA is used to calculate the GB for each node.

In this protocol, the energy consumption due to collision is reduced by introducing Guaranteed Time Slot (GTS). Each device has exclusive use of a channel for a fixed time slot; therefore, synchronization overhead is also reduced. This protocol works efficiently for low data rate applications but does not support high data rate applications.

BodyMAC: BodyMAC is an energy-efficient TDMA-based MAC protocol [44] developed for WBANs. The primary design goal of the BodyMAC protocol is to be energy-efficient and flexible in terms of bandwidth allocation and supporting a sleep mode to fulfill the requirements of dynamic applications in wireless body area networks. The MAC frame in BodyMAC has three parts: beacon, downlink, and uplink as shown in Figure 9. Beacon is dedicated for MAC layer synchronization and a description of the MAC frame structure. It also contains network information that necessitates being broadcast to nodes periodically. The downlink part is used for the transmission from the gateway to the nodes. It can be either unicast data for a specific node or broadcast data for all nodes in the network. The uplink part is divided into two subparts: Contention Access Part (CAP) and Contention-Free Part (CFP). The CAP part 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 duration of downlink and uplink is adaptively configured by the gateway on the basis of the current traffic characteristics.

BodyMAC protocol outperforms the IEEE 802.15.4 MAC protocol in terms of end-to-end delay, flexible bandwidth allocation, and energy saving [44]. However, clear channel assessment (CCA) and packet collision in CAP result in high energy consumption.

IEEE 802.15.4 MAC: IEEE 802.15.4 is a standard designed for low data rate applications [45]. The IEEE 802.15.4 MAC protocol is the most commonly used MAC in wireless sensor networks. It can operate in two different modes: nonbeacon mode and beacon mode.

In a beacon-enabled mode, the coordinator periodically sends beacon frames for device synchronization and association control. The channel is limited by a superframe structure as illustrated in Figure 10.

The superframe may have an active and an inactive period. The active period is composed of three components: a beacon, a contention access period (CAP), and a contention-free period (CFP). The coordinator communicates with nodes during the active period and sleeps during the inactive period to conserve energy. The CFP is optional and contains a maximum of seven Guaranteed Time Slots (GTS) in each superframe. GTS are assigned by the coordinator in the CFP period to support time-critical data applications. In this mode, a slotted CSMA/CA mechanism is used in the CAP period for data transmission.

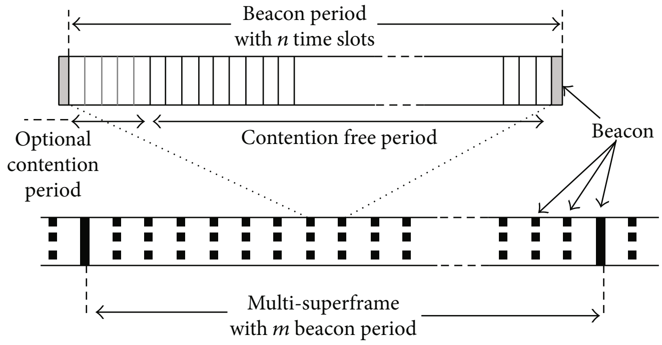

Figure 8: Multisuperframe structure for the MedMAC protocol.

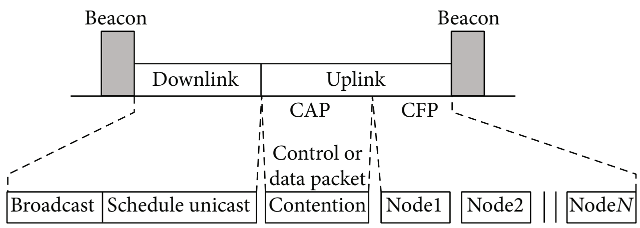

Figure 9: BodyMAC superframe structure.

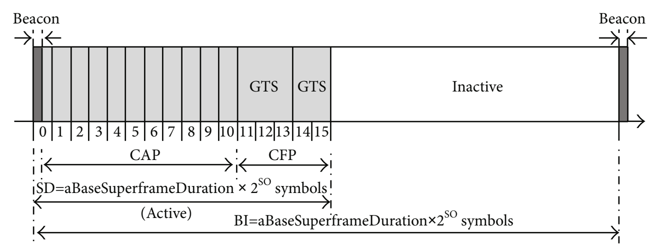

Figure 10: IEEE 802.15.4 superframe structure.

In the non-beacon-enabled mode, there is no superframe defined, and no slot synchronization is available, no GTS can be reserved, and only random access is adopted for medium sharing. The unslotted CSMA/CA mechanism is used for data transmission. This mechanism does not provide any time guarantee to deliver data frames [45].

The main reasons for selecting IEEE 802.15.4 for WBANs are low power communication and support of low data rate WBAN applications [25]. However, the IEEE 802.15.4 MAC protocol is not suitable for variable traffic since only the limited number of GTS is supported.

IEEE 802.15.6 (Baseline-MAC): the 802.15.6 standard was proposed to support WBAN requirements like low power, low complexity, and reliable communication. The MAC protocol proposed by the [46] standard splits the channel into superframe structures of the same length. The superframe is bounded by a beacon period of equal length. Each beacon period contains a number of allocation slots used for data transmission. The hub selects the boundaries of the beacon period and the slot allocation and sends a beacon frame in each beacon period except in inactive superframes. The IEEE 802.15.6 standard operates in one of the following modes.

(1) Beacon Mode with Beacon Period Superframe Boundaries. In this mode, the hub sends a beacon frame in every beacon period except in inactive superframes. The superframe structure is composed of the following phase beacon, Exclusive Access Phase (EAP1, EAP2), Random Access Phase (RAP1, RAP2), managed access phase (MAP), Beacon 2, and a contention access phase (CAP), as illustrated in Figure 11. In CAPs, RAPs, and EAPs, nodes contend for resource allocation using slotted Aloha access procedure or CSMA/CA. EAP1 and EAP2 are reserved for high priority traffic such as reporting emergency events, while CAP, RAP1, and RAP2 are reserved for regular traffic. Type I/II phases are used for bilink, downlink, uplink, and delay bilink allocation intervals. The coordinator can disable any of these periods by setting the duration length to zero, depending on the application requirements [47]. The main disadvantage of this mechanism is not considered specific allocation intervals for critical data.

(2) Nonbeacon Mode with Superframe Boundaries. In this mode, the hub operates only during the managed access phase (MAP) as shown in Figure 12.

(3) Nonbeacon Mode without Superframe Boundaries. In this mode, there are no superframe boundaries. The hub provides only unscheduled type II polling allocation, which means that each node has to determine its own time schedule independently as depicted in Figure 13.

5.4. Hybrid MAC Protocols.

CA-MAC: Context-Aware MAC: CA-MAC [48] is a Context-Aware MAC protocol proposed to overcome the challenges resulting from time-varying traffic and channel conditions in WBANs by using a hybrid of contention-based and TDMA-based mechanisms.

CA-MAC designs a new hybrid contention/TDMA MAC frame structure, which is shown in Figure 14, to accomplish channel awareness and traffic awareness. It is composed of three parts: beacon, contention, and TDMA. The beacon and the whole frame have a fixed length, but the contention part and the TDMA part have a variable length depending on the wireless channel status. In CA-MAC, the master node dynamically modifies the structure of the MAC frame based on both channel status and traffic request.

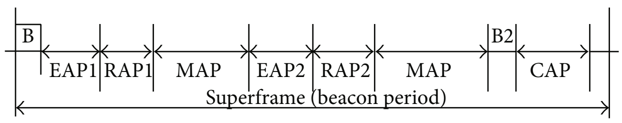

Figure 11: Beacon mode with beacon period superframe boundaries.

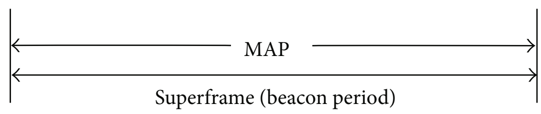

Figure 12: Nonbeacon mode with superframe boundaries.

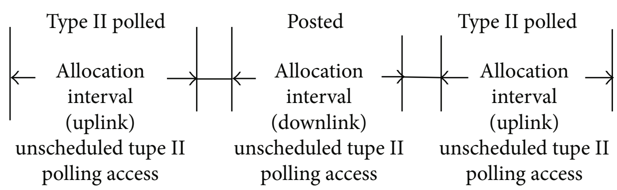

Figure 13: Nonbeacon mode without superframe boundaries.

In CA-MAC, a centrally controlled TDMA-based mechanism is used to address the problems of collision, idle listening, and overhearing because the sensor nodes transmit data only in their dedicated slots. In a beacon slot, the 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 have 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.

The CA-MAC protocol performs better than traditional MAC because of the higher packet delivery ratio and throughput, less control overhead, and low synchronization overhead using optional synchronization. However, the error correction mechanism is to be implemented for a successful delivery of data, and emergency data is not considered.

TDMA-Based Directional MAC: the TDMA-based directional MAC protocol was proposed for WBANs [49]. It employs TDMA and multibeam antenna concept simultaneously to provide spatial division multiple access (SDMA). In this approach, the human body is divided into four sectors keeping the body area network coordinator (BAN_C) as its center as shown in Figure 15. Each sector has its own transceivers that are capable of simultaneous transmission, and directionality is used only on BAN_C. The use of multibeam directional antennas makes each sector independent of others and is also advantageous from the standpoints of spatial reuse, extended range, and energy saving.

All types of WBAN traffic are considered: normal traffic, on-demand traffic, and urgent traffic. For 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 sectors. For urgent traffic, if there is urgent data in the reserved time slot of a node, the node will send the data to the main BAN_C; otherwise, the node will send data to the 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 be in either sleep mode or transmitting mode. Data transmission will then take place.

The TDMA-based direction MAC protocol has several advantages from spatial reuse, extended range, and energy saving thanks to multibeam antennas, and the three types of WBAN traffic are considered. The main disadvantage of this protocol is that neither analysis nor simulation result is given.

TTR-MAC: Token-Based Two-Round Reservation MAC: in [50], a novel Token-based Two-Round Reservation MAC (TTR-MAC) protocol has been employed based on IEEE 802.15.6 for health monitoring in WBANs. TTR-MAC categorizes the data into periodic data and burst data. It adopts two-round reservations to guarantee the data transmissions for the two data types to reduce energy consumption and overhead caused by control frames. Moreover, this protocol attributes suitable numbers of allocation time slots to nodes in different data arrival rates. The hub utilizes a token to attribute additional allocation intervals for burst data according to the user priority of nodes and the criticality of burst data.

The superframe structure of TTR-MAC is presented in Figure 16. It consists of a beacon period followed by the first-round reservation period (FRRP) and the second-round reservation period (SRRP) and ends with the sleep period (SP). The FRRP is used to send the periodic data and raise the second-round reservation if burst data occurs. The SRRP is reserved for the transmission of burst data. All devices, including nodes and hub, enter the sleep mode to save energy when there are no data transmissions.

Authors showed that the TTR-MAC protocol can achieve high energy efficiency and longer lifetime compared with IEEE 802.15.6 and other one-round reservation MAC (OR MAC) [50].

Z-MAC: Zebra-MAC: Zebra-MAC [51] is a hybrid MAC protocol developed for wireless sensor networks. It combines the advantages of TDMA and CSMA. Z-MAC is a traffic-adaptive protocol; it behaves like CSMA under low contention and like TDMA under high contention to achieve high channel utilization and less collision.

Z-MAC consists of two main phases which are a setup phase and a communication phase. The overhead of the Z-MAC protocol is the setup phase, which is done at the beginning. In the setup phase, the nodes are assigned the time slots for the data transmission. The nodes use the assigned time slots for the transmission of the detected data in a particular period of time known as a frame. A node is designated the "owner" of a time slot if it wins access to the transmission medium; otherwise, the node is named the "nonowner." The nonowners of the time slot have a lower priority to transmit the data when compared to that of owners of the time slot. The priority is set using the contention window size. If at a particular point of time, the owners do not transmit the data, then the nonowners of the time slot may transmit the data by using the time slot that is left unused by the owner of the time slot.

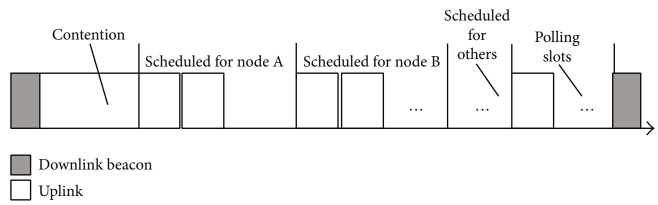

Figure 14: Superframe structure of CA-MAC.

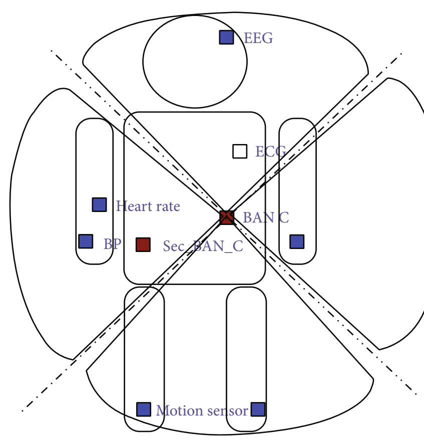

Figure 15: Overview of WBAN with multibeam directional antenna [49].

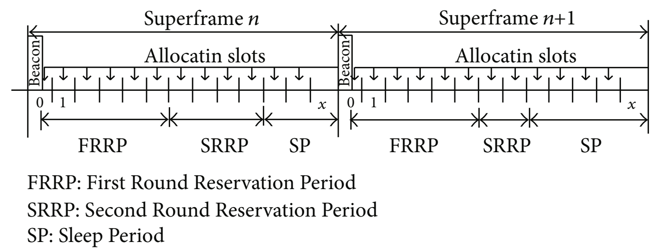

Figure 16: Superframe structure of TTR-MAC.

The main feature of Z-MAC is that its performance is robust to time-varying channel conditions, synchronization errors, and slot assignment failures. In the worst case, its performances are similar to that of CSMA. Z-MAC finds better efficiency during high contention levels, possesses high throughput under low contention, and provides better channel utilization at variable loads. A major drawback is it does not compromise energy inefficiency during low contention levels.

HEH-BMAC: Human Energy Harvesting: the Human Energy Harvesting Medium Access Control Protocol (HEH-BMAC) is proposed in [52] as a hybrid polling MAC suitable for WBANs powered by human energy harvesting. The HEH-BMAC combines two different medium access methods, namely, (i) contention-free ID-polling and (ii) probabilistic contention (PC), to provide energy-aware and priority-based scheduling.

The use of contention-free ID-polling access is previsioned for nodes with predictable energy sources or nodes with high priority (ID-BNs). And the use of contention-based PC access is previsioned for nodes with unpredictable energy sources or nodes with normal priority (PC-BNs). THE ID/PC modes are dynamically adjusted based on the energy levels of the nodes.

Each node in the HEH-BMAC has a unique ID for data security, data control, and medical application. The communication process in the ID-polling mode consists of three steps: (i) the BNC sends a polling packet containing the ID of the BN to be polled, (ii) the polled BN responds with a data packet transmission, and (iii) the BNC sends an acknowledgment (ACK) packet that confirms the successful reception of the data packet. The PC access mode deals effectively with contentions, achieving high throughput and maintaining fairness for single-hop networks. Besides, this mode offers the advantage of adapting to the changes in the energy harvesting rates, node failures, or additions/removals of nodes. Simulation results in [52] show that the proposed protocol is adaptable to changes in different parameters such as energy harvesting rates, packet interarrival times, and network size. The main problem of this protocol is that the mode of operation leads to high delay.

CoR-MAC: Contention over Reservation MAC: the CoR-MAC protocol [53] is a hybrid priority-based MAC protocol developed for time-critical services in wireless body area networks.

In the CoR-MAC protocol, traffic is divided into three priority levels in descending order of urgency: urgent, time-critical, and non-time-critical data. To accommodate all three traffic types and reduce the transmission delay of emergency data, the CoR-MAC employs a superframe structure consisting of the beacon, CFP, and CAP, as shown in Figure 17. The three traffic types are transmitted as follows: The beacon phase is the time in which only the coordinator is allowed to transmit a beacon frame, and it is used for network synchronization and advertising information, such as time slot allocation. Urgent data can be sent during either the CFP or CAP. The time-critical data can be sent during CAP or the reserved time slot in CFP, as long as urgent data are not being transmitted. Non-time-critical data can be sent during either CFP or CAP, as long as urgent, time-critical, or other non-time-critical data are not being transmitted.

The simulation results demonstrate that the CoR-MAC protocol is very effective and provides significantly shorter delay by providing opportunistic transmission chances. CoR-MAC shows an approximate 50%-85% improvement performance in the delay of urgent and time-critical data. However, the average delay of noncritical data increases by the increasing number of nodes and does not provide any

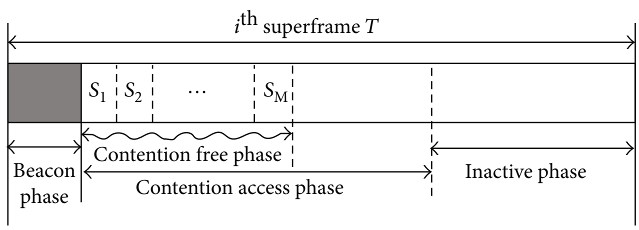

Figure 17: Contention over reservation (CoR-MAC) superframe structure.

mechanism for emergency data transmission during the inactive period.

A-MAC: Adaptive MAC: A-MAC [54] is an adaptive MAC protocol based on IEEE 802.15.6 for WBANs. This protocol sets the data into three priorities based on the type of service. To simplify control difficulty and reduce the control information overhead, the A-MAC protocol improves the superframe structure of IEEE 802.15.6 and reorganizes into four phases, namely, beacon phase (B), contention access phase (CAP), noncontention access phase (CFP), and inactive phase, as shown in Figure 18.

The length of the contention access phase and the noncontention access phase is adjusted according to the proportion of nodes that generate each priority data. The CAP phase is further divided into three subphases, and the length of each subphase is dynamically adjusted according to the data priority. In the contention access phase, all nodes compete for access channels according to the channel access policy. The random data that competes successfully transmits data directly, and the periodic data that competes successfully transmits data in the allocated time slots of the noncontention access phase.

The simulation results show that in terms of throughput, power consumption, and the network time delay, the network performance using the A-MAC protocol is better than the network performance using IEEE 802.15.6 MAC and CA-MAC protocols.

The protocol adjusts the superframe structure based on the IEEE 802.15.6 MAC protocol, divides the service type into different priorities, and performs dynamic time slot allocation according to the traffic volume change, thereby reducing network delay, reducing network energy consumption, and improving the network adaptability.

6. Summary of Findings

In this section, we recapitulate the key features of the investigated protocols and discuss the ability of each protocol to support WBAN applications.

A large number of MAC protocols for WBANs have been designed and published by researchers. The primary issue focused on, relating to MAC protocols, has been energy efficiency. Each protocol strikes a better balance between energy consumption and transmission delay, all pretending to be more efficient than the typical S-MAC protocol. But they are evaluated with different workloads, simulation environments, and hardware platforms, making it hard to assess the true benefits of the individual MAC protocols. A comparison of the aforementioned MAC protocols is given in Table 2.

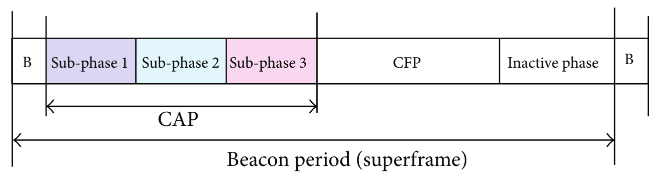

Figure 18: A-MAC superframe structure.

LPL, CSMA, and TDMA are three principal approaches adopted for the energy saving mechanisms in MAC protocols for WBANs. However, each of them has some advantages and drawbacks.

CSMA-based MAC protocols provide promising results such as low delay, reliable transmission of packets in small size networks like a WBAN, and a simple implementation procedure in small dynamic networks. However, additional energy consumption for collision detection or collision avoidance and protocol overhead is a major shortcoming of CSMA. TDMA-based MAC protocols are contention-free; nodes transmit data in predefined time slots to avoid packet collision. For small networks with low mobility and a limited number of sensor nodes and periodic data generation, TDMA is the best approach for medium access control. However, strict synchronization requirement, non-adaptability, and scalability are the key issues in implementing TDMA in WBANs. It is envisaged that if synchronization and dynamic slot assignment of TDMA could be traded off, TDMA could be considered a potential solution for wireless body area networks.

LPL-based MAC protocols avoid idle listening and overhearing. Synchronization is not required here. Based on hardware complexity and listening of a long preamble, LPL techniques are not well suited for WBANs.

The hybrid MAC protocols integrating the two kinds of mechanisms are better in energy efficiency than a MAC using a single mechanism. However, hybrid MAC protocols are usually complex in transition mechanisms between contention-based and TDMA-based; in addition, these protocols are usually complex in implementation.

S-MAC is developed to minimize energy consumption by periodically switching between active and sleep states, thereby making compromises between energy and latency based on traffic conditions. S-MAC provides significant energy improvements over 802.11. However, the duty cycle is required to be synchronized to a specific traffic load. T-MAC improves the design of S-MAC by dynamically adjusting the active period based on network traffic loads. T-MAC improves the energy and gives better results under variable traffic load. However, it suffers from sleeping problems. DMAC was developed to solve the data forwarding interruption problem (DFI) present in implicit adaptive duty cycle techniques. DMAC also adopts an adaptive duty cycle. DMAC achieves very good latency compared to other duty cycle protocols. However, it suffers from packet collisions. The previously discussed protocols with the above limitations seem inappropriate for WBANs.

Table 2: Comparison of MAC protocols in the context of WBANs.

Protocols	Mechanism	Energy efficiency	Latency	Throughput	Priority traffic	Advantages	Limitations	Adaptability to WBANs
S-MAC (2002)	Contention-based	Moderate	High	Low	No	The energy dissipation caused by idle listening is reduced by periodic sleep-listen schedules	Overhearing and collision may cause high latency and low throughput	Good for normal traffic applications
T-MAC (2003)	Contention-based	Good	High	Low	No	Delay minimized and gives better result under variable traffic load	Suffers from sleeping problems	Good adaptability to changes in traffic condition
DMAC (2004)	Contention-based	Good	Low	Moderate	No	Good delay performance, energy-efficient	Collision avoidance not utilized leading to collision	Good for low delay applications
Ta-MAC (2010)	Contention-based	Good	Low	Moderate	Yes	Low delay and energy consumption	Not suitable for dynamic topologies	Good for normal traffic and low power applications
PA-MAC (2016)	Contention-based	Good	Low	High	Yes	Provide better performance regarding the delay, PDR, and energy	Does not handle emergency traffic in CFP and IP periods which decrease PDR when traffic load is high due to limited GTS slots	Good for emergency medical traffic
WiseMAC (2004)	LPL	Moderate	High	Moderate	No	Mobility support; adaptive and scalable to different traffic conditions	Suffers from a long preamble and has no mechanism to adapt to changing traffic patterns	Useful for normal traffic conditions and not suitable for low duty cycle nodes
BMAC (2004)	LPL	Moderate	Low	High	No	Simplicity, good packet delivery rate, high throughput, and low power consumption	The major disadvantage is that the long preamble creates large overhead and increases the power consumption	Good for high traffic applications
X-MAC (2006)	LPL	Better	Low	Good	No	More energy-efficient, overhearing problem reduced and lower latency operation	The technique of avoiding overhearing by embedding the target receiver node ID makes multicasting and broadcasting difficult	Good for monitoring with dynamic traffic loads
TAD-MAC (2012)	LPL	Best	Low	High	No	The energy consumption due to idle listening, overhearing, collisions, and unnecessary wake-up beacon transmission is reduced	Do not consider on-demand and emergency traffic	Good for variable traffic and application dynamics
MedMAC (2009)	TDMA	Good	Low	Low	Yes	Energy consumption due to collision is avoided	Do not support high data rate applications	Efficient for low data rate application
BodyMAC (2009)	TDMA	Good	Low	High	No	Adaptive to uplink and downlink good packet delivery rate; energy-efficient sleep mode	Overhearing problem is not solved, long preamble increases the power consumption	Suitable for normal traffic conditions and not good for high traffic applications
TTR-MAC (2016)	TDMA	High	Low	High	No	High energy efficiency and longer lifetime compared with IEEE 802.15.6 and other one-round reservation MAC (OR MAC)	No priority-based reservation technique has been considered	Suitable for periodic and burst data

Table 2: Continued.

Protocols	Mechanism	Energy efficiency	Latency	Throughput	Priority traffic	Advantages	Limitations	Adaptability to WBANs
TDMA-based directional MAC (2010)	TDMA	Good	Low	—	Yes	Differentiates between normal and urgent traffic using two network coordinators, spatial reuse, extended range, and energy saving thanks to multibeam antennas	Unclear performance improvement (neither analysis nor simulation result is given)	Prioritized service for different nodes according to their application requirements
Z-MAC (2008)	Hybrid	Best	Low	High	No	Possesses high throughput under low contention	Introduces additional overhead to detect abandoned slot	Good for high traffic applications
CA-MAC (2011)	Hybrid	Good	Low	High	Yes	Higher packet delivery ratio and throughput, less control overhead, collision avoidance, low synchronization overhead using optional synchronization	Does not respond to emergency immediately; slow adaptation to changes	Good for variable traffic due to dynamic schedule-based and polling-based slot allocation
HEH-MAC (2013)	Hybrid	Better	High	Better	No	Better in energy efficiency and throughput	Mode of operation leads to high delay	It can be applied dynamically in realistic networks, since it is adaptive to the topology changes, allowing the insertion/removal of wireless sensor nodes
CoR-MAC (2016)	Hybrid	High	Low	High	Yes	Guarantees immediate channel access for urgent data and improved the channel utilization through ensuring transmission of nonurgent data in case the channel is idle	Average delay of noncritical data increases by the increasing number of nodes and does not provide any mechanism for emergency data transmission during inactive period	Good for time-critical applications
A-MAC (2019)	Hybrid	High	Low	High	Yes	Low network delay, low energy consumption, and good network adaptability	The mobility of nodes is not considered	Good for WBAN applications with variable traffic

Low power listening-based MAC protocols such as BMAC, WiseMAC, and X-MAC adapt the duty cycle by using the preamble element of a packet to ensure nodes only wake up when absolutely necessary. The use of the LPL mechanism avoids idle listening and overhearing. However, it is not an optimal solution for in-body and on-body sensor node communication due to strict power capabilities.

The medical MAC (MedMAC) protocol was proposed for WBANs to improve power efficiency and channel access. The MedMAC protocol is intended to improve the performance of the IEEE 802.15.4 MAC protocol for very low data rate WBANs by getting energy efficiency using a novel synchronization mechanism. This protocol works efficiently for low data rate applications, but it does not support high data rate applications.

The BodyMAC protocol was developed for WBANs. The primary design goal of BodyMAC is to be energy-efficient and flexible in terms of bandwidth allocation and supporting a sleep mode to fulfill the requirements of dynamic applications in wireless body area networks. Simulation results show superior performance compared to 802.15.4.

The Context-Aware MAC (CA-MAC) protocol was proposed to overcome challenges resulting from time-varying traffic and channel conditions in WBAN. Simulation of CA-MAC showed a packet loss rate of 50% lower than comparable MAC protocols with a reasonable tradeoff between reliability and efficiency.

7. Conclusion

In this paper, a comprehensive review of different MAC protocols proposed for WBANs has been presented emphasizing their strengths and shortcomings. In addition, several channel access mechanisms such as schedule contention, low power listening, TDMA, and hybrid mechanisms are discussed and compared in the context of WBANs. It has been noted that MAC protocols based on schedule contention and LPL are unable to accommodate on-demand and emergency traffic. On the other hand, TDMA is an important channel access approach for WBANs. A large part of the existing MAC protocols for WBANs are based on the TDMA technique. However, existing TDMA-based protocols exhibit several limitations including dynamic slot assignment, synchronization overhead, and poor adaptation in dynamic environments. Hybrid MAC protocols are developed on the basis that the combination of prominent features of the above protocols can overcome the limitations of an individual protocol at the cost of a complex MAC design and high traffic overhead.

Almost all mechanisms have some design restrictions. Hence, efforts are still needed to design and develop protocols that are able to assure energy efficiency and reduce implementation complexities. Other design objectives include reliable communication, minimum delay, high bandwidth utilization, fairness at the MAC layer, mobility support, and reduced synchronization overhead. Furthermore, the protocols should also have the capabilities to accommodate normal, on-demand, and emergency traffic.

It is expected that this review can be used as a guideline towards the design of a new energy-efficient MAC protocol that provides appropriate channel access control and reliable link-level communication for WBANs.

Data Availability

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Acknowledgments

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References

[1] S. Bhandari and S. Moh, "A priority-based adaptive MAC protocol for wireless body area networks," *Sensors*, vol. 16, no. 3, p. 401, 2016.

[2] Y. Zhou, *Energy efficient wireless body area network design in health monitoring scenarios*, T, University of British Columbia, 2017.

[3] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: a survey," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 115–121, 2006.

[4] A. S. Gopalan and J.-T. Park, "Energy-efficient MAC protocols for wireless body area networks: a survey," in *International Congress on Ultra Modern Telecommunications and Control Systems*, vol. 8, pp. 739–744, Moscow, Russia, 2010.

[5] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient collision-free medium access control for wireless sensor networks," in *Proceedings of the first international conference on Embedded networked sensor systems - SenSys '03. Association for Computing Machinery*, pp. 181–192, New York, NY, USA, 2003.

[6] F. Xia and A. Rahim, "MAC protocols," in *MAC Protocols for Cyber-Physical Systems*, SpringerBriefs in Computer Science, Springer, Berlin, Heidelberg, 2015.

[7] M. Jo, L. Han, N. D. Tan, and H. P. In, "A survey: energy exhausting attacks in MAC protocols in WBANs," *Telecommunication Systems*, vol. 58, no. 2, pp. 153–164, 2015.

[8] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 3, pp. 1658–1686, 2014.

[9] J. Y. Khan, M. R. Yuce, G. Bulger, and B. Harding, "Wireless body area network (WBAN) design techniques and performance evaluation," *Journal of Medical Systems*, vol. 36, no. 3, pp. 1441–1457, 2012.

[10] K. Thotahewa, J. M. Redouté, and M. Yuce, "Medium access control (MAC) protocols for ultra-wideband (UWB)-based wireless body area networks (WBAN)," in *Ultra-Wideband and 60 GHz Communications for Biomedical Applications*, M. Yuce, Ed., Springer, Boston, MA, 2014.

[11] S. Hayat, N. Javaid, Z. A. Khan, A. Shareef, A. Mahmood, and S. H. Bouk, "Energy efficient MAC protocols," in *2012 IEEE*

14th International Conference on High Performance Computing and Communication & 2012 IEEE 9th International Conference on Embedded Software and Systems, pp. 1185–1192, Liverpool, UK, 2012.

[12] A. Rahim, N. Javaid, M. Aslam, Z. Rahman, U. Qasim, and Z. A. Khan, "A comprehensive survey of MAC protocols for wireless body area networks," in *2012 Seventh International Conference on Broadband, Wireless Computing, Communication and Applications*, pp. 434–439, Victoria, BC, Canada, 2012.

[13] F. Masud, A. H. Abdullah, G. Abdul-Salaam, and F. Ullah, "Traffic adaptive MAC protocols in wireless body area networks," *Wireless Communications and Mobile Computing*, vol. 2017, 14 pages, 2017.

[14] K. Hasan, K. Biswas, K. Ahmed, N. S. Nafi, and M. S. Islam, "A comprehensive review of wireless body area network," *Journal of Network and Computer Applications, Volume*, vol. 143, pp. 178–198, 2019.

[15] D. D. Olatinwo, A. M. Abu-Mahfouz, and G. P. Hancke, "Towards achieving efficient MAC protocols for WBAN-enabled IoT technology: a review," *EURASIP Journal on Wireless Communications and Networking*, vol. 2021, no. 1, 2021.

[16] D. D. Olatinwo, A. M. Abu-Mahfouz, and G. P. Hancke, "A hybrid multi-class MAC protocol for IoT-enabled WBAN systems," *IEEE Sensors Journal*, vol. 21, no. 5, pp. 6761–6774, 2021.

[17] D. M. Barakah and M. Ammad-uddin, "A survey of challenges and applications of wireless body area network (WBAN) and role of a virtual doctor server in existing architecture," in *2012 Third International Conference on Intelligent Systems Modelling and Simulation*, pp. 214–219, Kota Kinabalu, Malaysia, 2012.

[18] C. Li, B. Zhang, X. Yuan, S. Ullah, and A. V. Vasilakos, "MC-MAC: a multi-channel based MAC scheme for interference mitigation in WBANs," *Wireless Networks*, vol. 24, no. 3, pp. 719–733, 2018.

[19] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "Wireless body area network (WBAN): a survey on reliability, fault tolerance, and technologies coexistence," *ACM Computing Surveys*, vol. 50, no. 1, pp. 1–38, 2017.

[20] M. S. Hajar, M. O. Al-Kadri, and H. K. Kalutarage, "A survey on wireless body area networks: architecture, security challenges and research opportunities," *Computers & Security*, vol. 104, article 102211, 2021.

[21] O. D. Incel, "A survey on multi-channel communication in wireless sensor networks," *Computer Networks*, vol. 55, no. 13, pp. 3081–3099, 2011.

[22] B. Zhang, C. Li, Z. Liu, X. Yuan, and L. Yang, "On energy-delay efficiency for WBAN: a multi-channel scheme," in *015 IEEE/CIC International Conference on Communications in China (ICCC)*, pp. 1–5, Shenzhen, China, 2015.

[23] L. Hughes, X. Wang, and T. Chen, "A review of protocol implementations and energy efficient cross-layer design for wireless body area networks," *Sensors*, vol. 12, no. 11, pp. 14730–14773, 2012.

[24] K. G. Dangi and S. P. Panda, "Challenges in wireless body area network-a survey," in *2014 International Conference on Reliability Optimization and Information Technology (ICROIT)*, pp. 204–207, Faridabad, India, 2014.

[25] S. Ullah, B. Shen, S. M. Riazul Islam, P. Khan, S. Saleem, and K. Sup Kwak, "A study of MAC protocols for WBANs," *Sensors*, vol. 10, no. 1, pp. 128–145, 2010.

[26] P. Huang, L. Xiao, S. Soltani, M. W. Mutka, and N. Xi, "The evolution of MAC protocols in wireless sensor networks: a survey," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 101–120, 2013.

[27] S. Ullah, H. Higgins, B. Braem et al., "A comprehensive survey of wireless body area networks," *Journal of Medical Systems*, vol. 36, no. 3, pp. 1065–1094, 2012.

[28] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, and V. C. Leung, "Body area networks: a survey," *Mobile Networks and Applications*, vol. 16, no. 2, pp. 171–193, 2011.

[29] B. Latré, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *Wireless Networks*, vol. 17, no. 1, pp. 1–18, 2011.

[30] K. Joice Olempia, C. Pandeeswaran, and P. Natarajan, "A survey on energy efficient contention based and hybrid MAC protocols for wireless sensor networks," *Indian Journal of Science and Technology*, vol. 9, 2016.

[31] B. Yahya and J. Ben-Othman, "Towards a classification of energy aware MAC protocols for wireless sensor networks," *Wireless Communications and Mobile Computing*, vol. 9, no. 12, 1607 pages, 2009.

[32] C. Buratti, A. Conti, D. Dardari, and R. Verdone, "An overview on wireless sensor networks technology and evolution," *Sensors*, vol. 9, no. 9, pp. 6869–6896, 2009.

[33] A. Saboor, R. Ahmad, W. Ahmed, A. K. Kiani, Y. L. Moullec, and M. M. Alam, "On research challenges in hybrid medium-access control protocols for IEEE 802.15.6 WBANs," *IEEE Sensors Journal*, vol. 19, no. 19, pp. 8543–8555, 2019.

[34] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proceedings. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, pp. 1567–1576, New York, NY, USA, 2002.

[35] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the first international conference on Embedded networked sensor systems - SenSys '03*, pp. 171–180, New York, NY, USA, 2003.

[36] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "An adaptive energy-efficient andlow-latency MAC for data gathering in wireless sensor networks," in *18th International Parallel and Distributed Processing Symposium, 2004. Proceedings*, Los Angles, USA, 2004.

[37] K. S. Kwak and S. Ullah, "A traffic-adaptive MAC protocol for WBAN," in *2010 IEEE Globecom Workshops*, pp. 1286–1289, Miami, FL, 2010.

[38] S. González-Valenzuela, X. Liang, H. Cao, M. Chen, and V. C. M. Leung, "Body area networks," in *Autonomous Sensor Networks*, D. Filippini, Ed., vol. 13 of Springer Series on Chemical Sensors and Biosensors (Methods and Applications), Springer, Berlin, Heidelberg, 2012.

[39] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems - SenSys '04*, NewYork, NY, USA, 2004.

[40] A. El-Hoiydi and J.-D. Decotignie, "WiseMAC: an ultra low power MAC protocol for the downlink of infrastructure wireless sensor networks," in *Proceedings. ISCC 2004. Ninth International Symposium on Computers And Communications (IEEE Cat. No.04TH8769)*, vol. 1, pp. 244–251, Alexandria, Egypt, 2004.

[41] M. Buettner, G. V. Yee, E. Anderson, and R. Han, “X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks,” in *Proceedings of the 4th international conference on Embedded networked sensor systems*, pp. 307–320, New York, NY, USA, 2006.

[42] M. M. Alam, O. Berder, D. Menard, and O. Sentieys, “TAD-MAC: traffic-aware dynamic MAC protocol for wireless body area sensor networks,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, no. 1, pp. 109–119, 2012.

[43] N. F. Timmons and W. G. Scanlon, “An adaptive energy efficient MAC protocol for the medical body area network,” in *2009 1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology*, pp. 587–593, Aalborg, Denmark, 2009.

[44] G. Fang and E. Dutkiewicz, “BodyMAC: energy efficient TDMA-based MAC protocol for wireless body area networks,” *2009 9th International Symposium on Communications and Information Technology*, 2009, pp. 1455–1459, Icheon, Korea (South), 2009.

[45] C. Li, H.-B. Li, and R. Kohno, “Performance evaluation of IEEE 802.15.4 for wireless body area network (WBAN),” in *2009 IEEE International Conference on Communications Workshops*, pp. 1–5, Dresden, Germany, 2009.

[46] “IEEE standard for local and metropolitan area networks - part 15.6: wireless body area networks,” in *IEEE Std 802.15.6-2012*, pp. 1–271, 2012.

[47] S. Ullah, M. Mohaisen, and M. A. Alnuem, “A review of IEEE 802.15.6 MAC, PHY, and security specifications,” *International Journal of Distributed Sensor Networks*, vol. 9, no. 4, 2013.

[48] B. Liu, Z. Yan, and C. W. Chen, “CA-MAC: a hybrid context-aware MAC protocol for wireless body area networks,” in *2011 IEEE 13th International Conference on e-Health Networking, Applications and Services*, pp. 213–216, Columbia, MO, USA, 2011.

[49] A. Hussain, Md, N. Alam, S. Ullah, N. Ullah, and K. Kwak, “TDMA based directional MAC for WBAN,” in *INC2010: 6th International Conference on Networked Computing*, pp. 1–5, Gyeongju, 2010.

[50] X. Yuan, C. Li, L. Yang, W. Yue, B. Zhang, and S. Ullah, “A token-based dynamic scheduled MAC protocol for health monitoring,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2016, no. 1, 2016.

[51] I. Rhee, A. Warrier, M. Aia, J. Min, and M. L. Sichitiu, “Z-MAC: a hybrid MAC for wireless sensor networks,” *IEEE/ACM Transactions on Networking*, vol. 16, pp. 511–524, 2008.

[52] E. Ibarra, A. Antonopoulos, E. Kartsakli, and C. Verikoukis, “Energy harvesting aware hybrid MAC protocol for WBANs,” in *IEEE 15th International Conference on e-Health Networking, Applications and Services (Healthcom 2013)*, pp. 120–124, Lisbon, Portugal, 2013.

[53] J. Yu, L. Park, J. Park, S. Cho, and C. Keum, “CoR-MAC: contention over reservation MAC protocol for time-critical services in wireless body area sensor networks,” *Sensors*, vol. 16, no. 5, p. 656, 2016.

[54] D. Yuan, G. Zheng, H. Ma, J. Shang, and J. Li, “An adaptive MAC protocol based on IEEE802.15.6 for wireless body area networks,” *Wireless Communications and Mobile Computing*, vol. 2019, Article ID 3681631, 9 pages, 2019.