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A Review of Medium Access Control (MAC) Protocols in Wireless Body Area Network

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Abstract

In this work, a comparative review of recently developed MAC protocols for Wireless Body Area Network based on QoS parameters was carried out by examining the superframe structure and access schemes of the protocols. Special emphasis was placed on hybrid protocols since they are a combination of both the scheduled based and contention based protocols. The study revealed that most of the protocols discussed have employed a combination of CSMA/CA and TDMA for their hybrid MAC design and that prioritizing the patient's data is a great determinant of how efficient the protocol is. Lastly, it is important to note that parameters such as body postures and implant type significantly affect the QoS parameters.

***Keywords**: Wireless Body Area Network, Medium Access Control, Protocol, Quality of Service, Latency*

1. Introduction

Recently, the use of Wireless Body Area Network in health services delivery is becoming increasingly popular and attractive in health institutions. Wireless Body Area Network (WBAN) consists of low powered wireless sensor nodes which can be placed in or on the body for constant health monitoring [1]. Efficiency is one of the most important factors that are considered when WBAN are to be deployed in such critical situations. Development of Medium Access Control (MAC) protocols in WBAN is most vital because they are responsible for timeslot arrangement, transmission order, conflict detection and priority control [2][25]. The design of MAC protocol involves ensuring adequate Quality of Service (QoS) such as low delay, reliability, latency, high scalability [3] . Also, they should be energy efficient implying that energy wastage should be minimized in the transmission of data. Also, sensor nodes should function using finite energy sources (batteries) and ensure smooth transmission of information in the WBAN [4][27]. All these can be achieved by having minimal collisions of data, over hearing, control packet overhead, over emitting and idle listening [5].

The IEEE 802.15.6 MAC standard was proposed in 2012 for WBAN [6]. The standard provides multiple data rates, node and traffic priority as well as multiple radio interfaces and access methods. It also supports three superframe modes. Beacons are employed to give the length of the superframe. The first mode consists of the Contention Access Phase (CAP), Random Access Phase (RAP), Managed Access Phase (MAP) and the Exclusive Access Phase (EAP) [8]. In the second mode, polling is used to define the transmission time since it is a non-beacon mode. Finally, in the third mode, the coordinator allocates time slots to nodes using slotted ALOHA and Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) [26][8]. However, the IEEE 802.15.6 has a few challenges hence the need for the development of other MAC protocols from the standard. The aim of this work is to examine these derived protocols which should be an improvement on the IEEE 802.15.6 MAC standard in areas such as security, body posture, interference, scalability and latency.

2. Methodology

In this work, a comparative review of recently developed MAC protocols based on the QoS parameters was carried out by examining the superframe structure and access schemes of the protocols and suggestions on ways to improve MAC protocols designed for WBAN was done. MAC protocols can be divided into three categories viz; scheduled based protocol, contention based protocols and hybrid based protocol [7]. Special emphasis was placed on the hybrid protocols being that they are a combination of both the scheduled based and contention based protocols.

2.1 Scheduled Based MAC Protocols vs. Contention based MAC Protocols

A review of scheduled based MAC protocols revealed that they use Time Division Multiple Access (TDMA) to allow multiple transmissions without collision. The transmission time for these protocols is usually divided into slots which can be further ordered into frames; at least one slot is given for a node to send its signal. Multiple nodes can transmit simultaneously without interference in a WBAN by the use of a scheduling algorithm [9]. The algorithm usually finds the shortest possible frame to achieve low packet latency. Scheduled based WBAN allows several users to share the same frequency channel by dividing the signal into different time-slots. It has the advantage of collision-free medium access. It supports low duty cycle operation: a node only switches on its radio during the slot that it is allotted to transmit or receive. The limitations associated with scheduled based protocols systems are the synchronization of the nodes and adaptation to topology changes [1] [3].

Unlike Scheduled based protocols, protocols involving Contention based MAC show that they do not rely on fixed time slots for transmission of data. Instead, nodes struggle with other nodes to send information. The nodes do not require synchronization of information and they can get into or leave the network without any hindrance. These protocols adapt quickly to changes in the network topology or traffic characteristic of the channel [1]. The protocols are simple, flexible, and robust [3]. The contention-based protocols result in high collision rates and increased energy costs due to idle listening and overhearing. The protocols also suffer from fairness issues because some nodes may not be able to obtain steady access to the channel [24]. The main advantage of the contention protocols over scheduled protocol is that its resources can be assigned on request. Since the topologies are changing frequently, the protocols are more flexible and peer-to-peer communications are directly maintained [1]

2.2 Hybrid MAC Protocols

Some Medium Access Protocols (MAC) do not fit into either the contention-based protocols or the scheduled based protocols but instead have features of both categories of protocols. This type of protocol is proposed to combine the important feature of the two already mentioned protocol [3]. Hybrid Protocols can reduce the number of collisions by relying on features present in periodic contention-free medium access protocols while taking. advantage of the flexibility and low complexity of contention-based protocols [6]. Hybrid MAC protocols show better and efficient features for real-time applications but they have challenges that need to be solved especially in the sensor networks where there is a need to find out the suitable solution for real-time communication and energy efficiency.

There are many possible variants of hybrid MAC protocols. In this section, we critically analyze each of them.

1. Medical Emergency Based (MEB)-MAC [10]: Medical Emergency Body MAC (MEB-MAC) is made to improve the quality of Emergency Time (ET), which is usually less frequent. The Exclusive Access Phase (EAP) is removed and short frames are used for ET, which improves the overall throughput. It is said that both Random Access Period (RAP1) and RAP2 cannot be used for ET because a loss or collision is probable. The coordinator introduces several listening windows on the Managed Access Period (MAP) to solve for ET. The emergency devices can transmit information in listening windows without notifying the coordinator using TDMA. It can assure reliability and improves access time. The duration of access phases is dynamic and it is defined by the application requirements. The traffic is classified based on strictness and a backoff timer is assigned. The coordinator stores information of all the ET requests in the MAP and multiple slots are introduced in listening windows based on their appearance in the MAP to accommodate ET traffic needs. One set back of MEB-MAC protocol is that it has a high energy

consumption which reduces the lifetime of sensors. This is mainly due to the removal of EAP and the dynamic access period in the MAC.

2. Poll Based (P)-MAC [11]: In a P-MAC protocol, the coordinator transmits beacons at the beginning of a superframe to define its transmission time. It further defines uplink (UL) and downlink (DL) intervals. The superframe starts with a preamble for synchronization followed by DL and UL sub- fields. The DL sub-field determines the time of existence of the physical layer in the DL subframe, which can be unicast or broadcast. The UL contains the data of each node and defines the transmission possibility of each node. It is further subdivided into two parts; TDMA and CSMA. The TDMA mode is divided into two parts; Time Slot Reserved for ET (TSRE) and Time Slot Reserved for Normal traffic (TSRN) to cater to both the Emergency Traffic and Normal Traffic demands. The CSMA mode is divided into Contention Access Phase (CAP) which is further subdivided into two control channels, Uplink Control for Emergency traffic (UCE) and Uplink Control of Normal traffic (UCN). The ET can use both the UCE and UCN while the normal traffic can only use UCN. For better performance, new inter-frame gaps are introduced. The ET has to wait for Emergency IFS (EIFS) and the normal traffic has to wait for Normal IFS (NIFS) to transmit at UCN. The protocol facilitates sleep mode to improve energy efficiency. The basic idea of sleep mode is to preserve network energy by strongly coupling the sleeping schedule of all the nodes. sleep request is sent by a node at the start of a frame in the CAP and the coordinator confirms it by sending an acknowledgement (ACK) frame. Initially, the node sleeps for T intervals, it wakes up and checks if there is no data to transmit, it sleeps again for T/2 intervals and the cycle continues. The main issue with this protocol is that structure of the superframe is very complex.

3. Modified Frame Structure (MFS) -MAC [12]: The main aim of this MAC is to lessen energy consumption which is proportional to several nodes in WBAN. It has four phases; in the first phase, nodes send a beacon to the Coordinator, then the coordinator synchronizes with the nodes in the second phase. In the third phase, a channel schedule is created between the coordinator and nodes. Actual transmission is achieved in the fourth phase. The structure of a superframe of MFS-MAC joins Type I and Type II phases and moves it to the end of the superframe to keep polling minimum. Secondly, Exclusive Access Phase (EAP2) and Random Access Phase (RAP2) come right after the Exclusive Access Phase (EAP1) and Radom Access Phase (RAP1). If transmission occurs only in EAP1, the node can go to sleep after the transmission to save energy. The nodes provide the transmission information to the coordinator so it can synchronize all the nodes. The benefit of this process is that the coordinator only wakes up when there exists a node with information to send. When all the nodes complete transmissions, the coordinator can go to sleep and waits for the next synchronization. This protocol is mainly designed from an energy consumption perspective. Therefore, the throughput given by this is relatively low.

4. All Dynamic (AD) -MAC [13]: In this protocol, a superframe is divided into three parts, a beacon followed by the Contention Access Period (CAP) and Contention Free Period (CFP) with a total of 32 slots [13]. This lowers the complexity of the superframe. The duration of both phases is adjusted based on the rate and data type. The nodes are ranked and they can get slots with high probability in CFP. The Coordinator sends a beacon for synchronization, power management and to set the length of CAP, CFP, and individual slot. The CSMA/CA mode is used in CAP while the TDMA mode is used in CFP. The coordinator gives slots to the nodes based on their priority. The nodes with no data to send can go to the sleep state to save energy. Three priority levels are defined in this protocol from 0 to 2 depending on severity (from maximum to minimum). A priority level 0 is given to the node with a high rate and emergency nature, level '1' is also for ET while level '2' is used for normal traffic [13]. The nodes with the highest priorities will have a small range of CW. Finally, the number of slots can be assigned to nodes depending on the priority level. A drawback of this protocol is that the packet loss probability is high and this will

lead to low throughput in the presence of high traffic or a large number of nodes and this is because the range of the contention window is small.

5. Adaptive CSMA/CA (A-CSMA/CA) [14]: This protocol combines the polling and carrier sensing of A-CSMA/CA. The coordinator uses a random backoff counter depending on the Contention Window (CW) size and then it makes CCA avoid Intra-WBAN collisions. The MAC frame is made up of three parts, a beacon, `an uplink, and a downlink. A beacon is used for synchronization and it defines the time of each field and the frame. Other nodes use beacons to repair their network allocation vector (NAV) that indicates how long the medium is busy [14]. The uplink part is composed of the Contention Access Period (CAP) and Contention Free Period (CFP). In the CAP, nodes contend for chance using slotted CSMA/CA while the coordinator manages slots in CFP. Adaptive CSMA/CA (A-CSMA/CA) first analyzes the interference level and adjusts the frame length. It uses the Additive Increase, Multiplicative Decrease (AIMD) to determine the interference in their buffer then they can also contend for more than one slot on CFP. A limited sensing protocol is also defined to reduce energy consumption. The basic idea of this is to sense channel intermittently rather than continuously.

6. Jacob MAC [15]: In Jacob MAC, a combination of CSMA/CA and polling is used where some nodes use contention access and other nodes use polling. The Exclusive Access Phase (EAP) is combined with the Random Access Phase (RAP) in a superframe, hence it is made from RAP & Managed Access Phase (MAP) portions. The RAP uses CSMA/CA while polling is used in the MAP portion. The user's priority level is set between 0-7 from lowest to highest and ranges of the CW are defined accordingly. For polling, two control packets: EPOLL and EPOLLFINISH are used. A node sends packets once it receives an EPOLL packet from the coordinator and it sends EPOLLFINISH when it completes sending data. The nodes that are not sending information can sleep to save energy. The coordinator regulates the sleep time of a node and puts its value in the EPOLL packet [15]. The node then gets this information and behaves accordingly. The different ratios of RAP and polling result in a tradeoff between different QoS parameters by using different ratios of RAP and polling.

7. CFTIM [16]: This work focuses on interference mitigation in WBAN. The CFTIM protocol uses a combined distributed carrier sensing technique with the combination of CSMA/CA and TDMA in relay-assisted Intra-WBAN. All the non-interfering nodes use CSMA for coordination, Flexible TDMA (FTDMA) is used for high interfering sources and the coordinator. The frame is divided into two major sections. The first is used by the coordinator to broadcast messages to the nodes and the second is used for transmitting the information to the coordinator. The second portion is also divided into two portions, CSMA/CA, and TDMA. nodes begin with CSMA/CA after the reception of a beacon from the coordinator. The coordinator then divides the nodes into two types, high interfering (IS) and non-interfering (TS). The TS uses contention access and decides the best relay to convey the information. A relay first checks the ID of the node from the slots list, if it finds the ID it sends information at defined slots, if this is not done then it allocates a random slot. A node that is a member of IS checks the ID in the list and transmits accordingly. If no ID exists in the list, an IS node selects a random slot. If the transmission fails an IS node can continue trying till a slot is found. The coordinator then uses the information of all the nodes and makes a new node list to start a fresh round.

8. Traffic Aware Dynamic (TAD) MAC [17]: TAD MAC functions using an adaptive algorithm and this allows nodes to adjust their sleep and wakeup patterns based on traffic behavior during transmission. This protocol has two stages. In the first, all nodes sending wait for a beacon from the coordinator containing ID and transmission schedule. After this stage, the steady phase begins where the coordinator implements its wakeup interval so that idle listening is reduced. A mechanism called Additive Increase Multiplicative Decrease (AIMD) uses the history of the Contention Window (CW) size to update the frame size [17]. If the present contention window is

greater than the past average contention window, then it is expected that the coordinator is facing more interference. The coordinator then decreases its frame size to give an extra opportunity to Emergency Traffic (ET) with the minimum collision. Regarding the beacon, the nodes define their sleep and wakeup times. The challenge with this protocol is that it requires a thorough search to compute the wakeup intervals for the convergence [17].

9. Body Area Network (BAN) MAC [18] – This MAC is based on the cross-layer design approach. It allows centralized and distributed coordination in the case of multiple co-located networks. The BANMAC features both centralized and fully distributed coordination mechanisms. It uses the services of a global coordinator whenever available and easily changes to a fully distributed mode once the network deviates from the range of the coordinator. It is a collision-free MAC protocol; however, the data transmission is scheduled. This protocol can forecast if the node is on a mobile limb and if it is, then this MAC predicts the center Opportune Transmission Window when the transmission of the mobile node is likely high [18]. BANMAC is flexible concerning applications of defined scheduling policy.

10. Human Activity Based (HAC) MAC [19]: The HACMAC protocol is used to improve the reliability of communication when various human activities interrupt Radio Frequency (RF) spectrum without compromising energy efficiency. The nodes are classified into priority and non-priority nodes. The superframe is divided into three parts: EAP, RAP, and MAP. In both EAP and RAP, the nodes send ET based on contention. In a MAP, the coordinator chooses to use any of the following CSMA/CA, slotted ALOHA, or TDMA for nodes to send medical data. A beacon is sent at the start of each transmission to coordinate the process. HAC-MAC uses Received Signal Strength Information (RSSI) and Packet Delivery Ratio (PDR) to foresee the changes possible in human activities to improve reliability and energy efficiency. This protocol uses three main arrangements; qualitative time-slot allocation, m-period interleaving, and adaptive relay establishment.

11. Hybrid (Hy) MAC [20]: This protocol is used to solve the issue of an energy shortage, which affects the lifetime of the sensor nodes, the designed MAC layer protocol is to enhance the energy efficiency and also extend the lifetime of body sensor nodes in wireless body area networks. The protocol utilizes a hybrid scheme by taking the advantages of carrier-sense multiple access with collision avoidance scheme and time division multiple access schemes as well as the state division of the Body Sensor Network. It also allocates the main transmission overhead at the personal station side and designs an awaiting order state for sensor nodes to improve energy efficiency. Then finally to save both energy and extend the lifetime of the Network, most of the transmission overhead is put in the personal station.

12. Contention Over Reservation (CoR) MAC [21]: The purpose of this protocol is to merge the advantages of contention and time slot reservations. One of the aims of the CoR-MAC is that it used dual reservation. Time slots are first reserved for each node, but in case there is a vacant slot then the other nodes can access them. This implies that this protocol provides the benefits of efficient channel utilization and reduced delay. In this MAC traffic is categorized into three priority levels namely urgent, time-critical and non-time-critical. This MAC has the following stages; beacon stage, contention access stage, and contention-free stage. In the beacon stage, the coordinator node broadcasts information for the aim of harmonizing the network by giving time slots to each node. Urgent data can be sent during both the contention access period and the contention-free period while the time-critical traffic is transmitted during Contention Access Period or reserved slot in Contention Free Period but non-time-critical data is transmitted during Contention Access Period or Contention Free Period only if the high priority data is not being sent. CoR-MAC provides instant channel access for urgent data, but it also enhances channel utilization by ensuring the transmission of non-urgent data in case the channel is idle.

13. Energy Consumption Traffic Prioritization MAC protocol [22]: The main aim of this protocol is energy management and reducing energy consumption and delay, and packet drop, as well as controlling and regulating the overhead and backoff periods to improve the network lifetime and efficiency. This protocol is designed in four sections: In the first section, the patient's data traffic is identified and prioritized, in the next section the superframe structure is Improved and the data priorities are optimized, the next section involves a reduction in energy consumption and delay using radio wake up mechanisms and controlling the node modes. The fourth and final section is for checking the node modes. The state diagram and the asymmetric hidden Markov method are exploited to model the limited capacity of the buffers [22]. This MAC is prioritized based on data traffic, in which data are transmitted based on priority as normal data, periodic data, and emergency data. To transmit normal data, the CSMS/CA mechanism is used to send data based on the TDMA time slot. Also, to transmit the emergency data the central coordinator performs data transfer by using an extra phase, and the inactive phase of the superframe is proficiently used. Finally, this ECTP-MAC showed improvement in energy consumption and delay as well as improved performance and lifetime of the sensors.

14. EE-DQRA [23] - This protocol utilizes the idea of distributed queuing for the enhanced radio channel. The main idea behind this protocol is that it has a collision resolution queue and a data transmission queue. The sensors in or on the body are controlled by the collision resolution queue and data traffic management is managed by the data transmission queue. Four integers are needed to implement this protocol, within these four integers, two depend mainly on the body sensors and define the position in each queue while the other two integers are distributed by all body sensors. The superframe structure of this protocol is composed of four different parts: contention reservation window (CRW), contention feedback window (CFW), data transmission window (DTW), and data feedback window (DFW) [24]. The EE-DQRA system comprises an enable transmission interval (ETI) module, a collision resolution queuing (CRQ) module, and a data transmission queuing (DTQ) module. This protocol allows body sensors to minimize energy consumption per bit, it also shows a great performance by improving the probability of successful transmission by avoiding collision in transmission in the data transmission queue module and at the same time keeping the control packet overhead smaller in the collision resolution queue.

Table 1 shows the comparison of various hybrid MAC protocols.

Table I: Comparison of Hybrid MAC Protocols

S/N	Name	Year	Protocol type	Standard	Body Posture	QoS	Energy Harvesting	Hybrid Type	Sensor position
1	MEB-Mac	2012	Hybrid	IEEE 802.15.6	Yes	T, L	No	CSMA/CA + TDMA	In/On Body
2	P-MAC	2013	Hybrid	IEEE 802.15.4	No	S, T	No	CSMA/CA + TDMA	On Body
3	MFS- MAC	2014	Hybrid	IEEE 802.15.6	No	E	No	CSMA/CA + TDMA	On Body
4	AD- MAC	2015	Hybrid	IEEE 802.15.6	No	L	No	CSMA/CA + TDMA	On Body
5	A-CSMA/CA	2015	Hybrid	IEEE 802.15.6	No	T	No	Polling + CSMA/CA	On Body
6	Jacob MAC	2015	Hybrid	IEEE 802.15.7	No	E	No	Polling + CSMA/CA	In/On Body
7	CFTIM	2016	Hybrid	IEEE 802.15.6	Yes	T	No	CSMA/CA + FTDMA	In/ On Body
8	TAD MAC	2016	Hybrid	IEEE 802.15.6	Yes	L	No	TDMA + CSMA/CA	On Body
9	BAN MAC	2016	Hybrid	IEEE 802.15.6	No	E	No	CSMA/CA + TDMA	In/ On Body
10	HAC MAC	2016	Hybrid	IEEE 802.15.6	Yes	T, L	No	TDMA+ CSMA/CA +	In/ On Body

								ALOHA	
11	CoR MAC	2016	Hybrid	IEEE 802.15.6 and 15.4	No	L	No	TDMA + CSMA/CA	On Body
12	Hy MAC	2018	Hybrid	IEEE 802.15.6	No	E, L	No	CSMA/CA + TDMA	On Body
13	ECTP- MAC	2019	Hybrid	IEEE 802.15.4	No	L, E	No	CSMA/CA + TDMA	In/ On Body
14	EEDQR	2020	Hybrid	IEEE 802.15.6	Yes	E	No	TDMA + CSMA/CA	In/ On Body

KEY: T-Throughput, E- Efficiency, L- Latency, S- Scalability

3. Discussion and Findings

In WBAN, it was observed that data transferred over communication channels can be classified into critical data, delay sensitive data and ordinary data. For health related applications of WBAN, the inclusion of TDMA approach in any hybrid design is high recommended since it is suitable for emergency data because without carrying out contention, the emergency-based sensor will usually transmit alert signal to body controller for slot allocation immediately in the hybrid MAC design. Body Posture has a major impact on hybrid MAC protocols because variation can hinder transmission of data thereby necessitating the need for retransmission of such data. This retransmission is bad for energy consumption of WBAN. Traffic behavior in WBAN can improve the connectivity and scalability of the network. This is due to the fact that management of Emergency Time (ET) is important in WBAN and Contention Window (CW) is usually used to distinguish between emergency time and normal time as seen in the TADMAC and ECTP protocols. Protocols such as the AD MAC, HACMAC, used the IEEE 802.15.6 defined CW size while others like A-CSMA/CA and EEDQR, the CW used custom defined window sizes and this helped improve on the efficiency of the protocol.

It is important to note that latency differs for the various traffic type in WBAN. This is a major QoS feature and with the evolution of MAC protocols in the network this feature has improved. Looking closely at EE-DQRA MAC latency is minimized when compared to the IEEE802.15.4 due to the overhead minimization and queueing utilization used in the EE-DQRA MAC. In CoR-MAC a dual reservation scheme is used for emergency data this therefore reduces the latency considerably when compared to protocols such as the HyMAC because the dual reservation scheme allows a time slot to be used even if it is owned by another.

Table 1 showed that most of the hybrid protocols discussed employed the CSMA/CA, these protocols sustain collisions which implies that retransmission of information will be done. In order to reduce retransmission, contention window ranges can be changed or an Automatic Repeat Request scheme employed as revealed in A-CSMA/CA. Adoption of the concept of data aggregation which involves gathering data coming from different nodes, and minimizing the number of transmissions can be done in order to improve the performance of the protocol in WBAN. Lastly, sensors in WBAN report on a static schedule, however in case of emergency it is required that information be transmitted on a regular basis and this process requires more energy. Although low duty cycle sleeping mode is used in extending the lifetime of sensors, further improvement can be attained by engaging adequate energy harvesting technique.

5. Conclusion

Medium Access Control (MAC) protocols are very important in WBAN design as they are vital in the transfer of information between sensors. Hence, a qualitative review of recently developed MAC protocols for WBAN has been the crux of this work. It involved examining the superframe structure and access schemes of the protocols. The protocols dealt with are mainly the hybrid MAC protocols. The study revealed that most of the protocols discussed have employed a combination of CSMA/CA and TDMA for their hybrid MAC design and that prioritizing the patient's data determines the efficiency of the protocol. Finally, it is important to note that parameters such as body postures and implant type significantly affect the QoS parameters.

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