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A Comprehensive Survey of MAC Protocols in Wireless Body Area Networks

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***Abstract*- Wireless Body Area Network (WBAN) has emerged as an advanced technology for e-healthcare where sensors are placed in, on, and around the human body to monitor various physiological signs. To design appropriate protocols in Wireless Body Area Network (WBAN), issues such as reliability, latency and energy consumption need to be considered. The MAC Layer is the most suitable layer to address these issues. To tackle these issues various MAC protocols are designed for WBAN. In this survey paper, we investigated some of them, highlighted their strengths and weaknesses and, compared them on various parameters. Finally numbers of research issues are discussed for future work.**

Keywords— Wireless Body Area Network (WBAN); Reliability; Adaptive; Energy-Efficiency.

I. INTRODUCTION

Due to the rate of growth of the elderly population and limited financial resources current healthcare systems are facing new challenges [1]. To provide economical solutions to the challenges faced by healthcare systems updated medical data of patient should be delivered to the concerned person in real time via the internet.

Recently, with the rapid advancement in wireless technologies, WBAN has emerged as an advanced technology for e-healthcare where a miniaturized and sophisticated sensors are strategically placed in, on, and around the human body to monitor various physiological signs such as heart-rate, temperature, blood pressure, ECG, EEG, etc [2]. A WBAN provides consistent health monitoring of patients under natural physiological states without affecting their routine activities. Smart and affordable health care system can be developed using WBAN which can be used in diagnostic procedure surgical procedure, maintaining chronic conditions and in an emergency situation [3]. An important requirement in designing WBANs is the energy efficiency i.e. developed system should be energy efficient to maximize the network life. But there is tradeoff between reliability, latency and energy consumption and need to be resolved. The MAC Layer is the most suitable layer to address these issues.

II. MAC PROTOCOLS

In WBAN protocols must be designed to achieve minimum delay, maximum throughput, and energy efficiency. The energy efficiency may be achieved by avoiding idle listening, overhearing, collision and control packet overhead. The various MAC protocols for WBANs are mainly divided in to two categories i.e. Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA). The protocols based on Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA), are not suitable for WBAN as they requires complex hardware and high computational demands respectively whereas TDMA based contention-free MAC protocols such as LEACH[4] are unable to satisfy WBAN stringent requirements. In [5] a comparative study of CSMA/CA and TDMA based protocol is given. After investigating various MAC protocols for WBAN such as Heartbeat driven MAC (H-MAC) [6] it has been observed that TDMA is more suitable for static types of network. To achieve minimum delay, maximum throughput, and maximum network life various MAC protocols are designed for WBAN. The following sections give a brief overview of different MAC protocols proposed for WBAN and highlight their strengths and weaknesses.

A. Energy efficient low duty cycle MAC protocol

Stevan Jovica Marinkovic et al. [7] proposed a MAC protocol for WBAN based on TDMA approach which uses single hop communication to maximize network lifetime. Idle listening and communication overhead is reduced by using TDMA strategy which is more suitable for static type of networks with limited number of sensors, generating data at the same data rate.

The main objective of this protocol is to keep the communication time of each sensor as minimum as possible compared to its power down mode (sleep mode). The protocol tries to optimize the duty cycle which is the key parameter for energy consumption. As shown in Fig 1, in each TDMA frame (T_{frame}), sensors are allocated fixed time slots (S1 to Sn) in which they send their sensed data to a Master Node (MN). For reliable communication some extra slots (RS1 to RSk) are reserved for retransmission in case of communication error. Data is aggregated and processed by MN and further transmitted to Master Station (MS) in the remainder of T_{frame}. Guard time (Tg) is inserted between consecutive time slots to prevent transmission overlapping from different sensors due to clock drift.

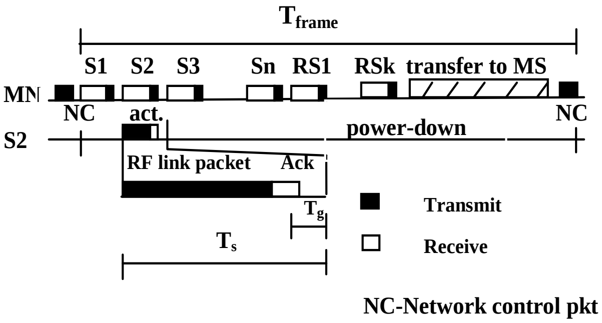

Fig 1: TDMA timing diagram.

At the end of each TDMA frame MN broadcast a Network Control (NC) packet for frame synchronization in alarm conditions or while network is forming. The maximum number of TDMA cycles that can pass before the sensor needs to resynchronize using the NC packet, depends on the slot guard time and the clock accuracy of the sensor.

Salient Features: The protocol avoids collisions by using TDMA scheme. To lower the probability of losing errors, protocol transmits redundant data and sensors are allowed to go in sleep mode for long time to achieve energy efficiency. Low channel utilization is the weakness of the protocol in case of networks having sensors with different sampling rates as sensors with lower sampling rates sends their sampled data after a fixed time interval instead of in every time frame, resulting wastage of time slots allotted to them.

B. Priority-based Adaptive Timeslot Allocation (PTA) Scheme for Wireless Body Area Network

Jin Shuai et al. [8] proposed a priority-based adaptive timeslot allocation (PTA) scheme. In this scheme data traffics are classified into three categories based on priorities of data traffic like medical, non medical and emergency data as shown in table 1. The CAP is divided into three sub-phases accordingly: Phase-1, Phase2 and Phase-3 as shown in Fig 2. Phase-1 can be used in transmitting C1 type of data, Phase-2 can be used in transmitting C1 and C2 type of data and Phase-3 can be used in transmitting all kinds of data. First timeslot of CAP is reserved for phase-1 irrespective of the fact whether C1 exists or not.

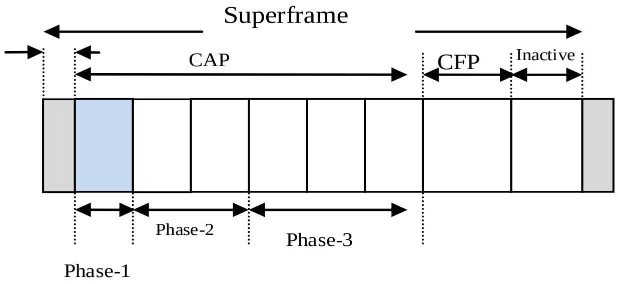

Fig 2: Superframe structure of PTA scheme.

In order to avoid wastage of timeslot utilization, lengths of phase-2 and phase-3 are dynamically changes and calculated by the coordinator depending on the nodes joining or deviating from the network.

Table 1: DATA PRIORITY

Priority	Symbols		Data Type	Example
1	C1		Emergency alarm	Emergency vital signals
2	C2	C21	Continuous medical	EEG/EMG
		C22	Discontinuous medical	Temperature/ blood pressure
3	C3		Continuous non medical	Audio/Video

Under PTA scheme, the slot allocation request for continuous traffic C21 and C3 are sent in Contention Access Period (CAP) and actual traffic are delivered in Contention Free Period (CFP) of next superframe. The emergency data or bursty data are delivered during CAP period through CSMA/CA approach. In this scheme two kinds of sensor nodes are assumed i.e. sensors that transmit C2 type of data and sensors that transmit C3 type of data. In case of alarming conditions any kind of sensors can generate C1 type of data.

Salient Features: The scheme classified the data on priority basis to achieve quality of service (QoS) and is able to cope with dynamically changing network size. To achieve energy efficiency, MAC level acknowledgement is disabled in the scheme.

C. BodyMAC

Gengfa Fang, and Eryk Dutkiewicz [9] proposed a TDMA based MAC protocol. The main aim of this protocol is to reduce packet collisions, radio state switching times, idle listening duration and control packets overhead by dividing the MAC frame into three parts: Beacon, Downlink and Uplink as shown in Fig 3.

Beacon is used for synchronization and description of the MAC frame structure. The Downlink part is reserved for the transmission from the gateway to the nodes. The Uplink part has two subparts: Contention Access Period (CAP) and Contention Free Period (CFP). In CAP, the node contends for transmission of MAC control packets and gets their guaranteed time slot in CFP. The duration of Downlink, CAP and CFP are adaptive and conFigd by the gateway based on the current traffic.

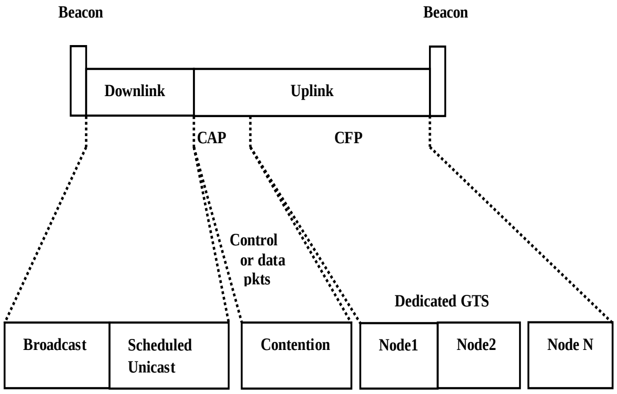

Fig 3: BodyMAC Frame Structure.

By using above frame structure, energy of a node can be saved by reducing the frequency of switching between the transmitting and receiving state of its radio. Energy can be saved further by allocating guaranteed time slots (GTS) in CFP to improved successful packet transmission rate and hence reduce retransmission of data. To reduce idle listening duration, an energy efficient sleep mode is proposed to turn off node's radio during Beacon, Uplink and Downlink periods.

Since the nodes and the gateway have their own clocks, it is difficult for nodes to synchronize themselves with the gateway when they wake up after a long period of sleep. So a re-synchronization process is followed.

BodyMAC also supports time critical event reporting by a node during its sleep mode. An event report packet can be sent by a node either in CAP or GTS if the node has been allocated GTS in the current frame. The different types of data communications such as periodic data and time critical event reporting are dealt using three different bandwidth allocation mechanisms: Burst Bandwidth, Periodic Bandwidth and Adjust Bandwidth. These dynamic bandwidth allocation mechanisms improve bandwidth allocation flexibility of BodyMAC.

Salient Features: In the scheme bandwidth allocation is flexible, adaptive and energy efficient. BodyMAC offers better performance in terms of the end-to-end delay and energy saving compared to the IEEE 802.15.4 MAC. The CAP in Uplink part is based on CSMA/CA which consumes high energy due to Clear Channel Assessment (CCA) and collision issues and it is difficult for the nodes to be precisely synchronized to the gateway.

D. Energy efficient medium access protocol

Omeni, O.C. et al. [10] proposed a new MAC protocol based on master-slave architecture where master node coordinates with all its slaves. The traffic is managed centrally by master node to avoid idle listening and overhearing. The network access is clear channel assessment avoidance with time division multiplexing (CCA/TDMA) to avoid idle listening and collision. The basic operations of the MAC protocol are based on three main communication processes:

Link establishment process: The master node establishes the link with slave nodes by sending a beacon packet and slave node sends acknowledgement to the master after getting the beacon. At the end of the link establishment process, the slave has a unique address, configuration information and sleep time.

Wakeup Service: During the wake time the slave sends its data to master node and master node tells to the slave about its new sleep time thus setting its next wakeup time slot.

Alarm: Whenever a slave node detects an alarming condition, it immediately informs it to the master node without waiting for its next wake-up time slot.

The protocol proposed a novel concept of wakeup fallback time (WFT) which is used to avoid continuous time slot collisions and ensures that time-slot overlaps are managed. Every slave node communicates with the master node in its allocated time-slot. If it fails to communicates with the master node, it goes back to sleep with a sleep time set by the WFT.

After WFT, it wakes up and searches the master node again. To enable the system to better cope with fluctuating traffic, the master node may dynamically allocate time-slots to its slave nodes. To reduce the possibility of collision, idle listening and power consumption, the clear channel assessment avoidance with time division multiplexing (CCA/TDMA) is used to access the network.

Salient Features: **T**he collisions due to common time slots resulting from alarm conditions or other interference is reduced. Maximum number of slaves that can join to the cluster is 8 and only one slave node can join to the network at a time, which causes large setup time for the network.

E. Priority-guaranteed MAC (PG-MAC) protocol

Yan Zhang [11] proposed a protocol which separated the control channels from data channels to support collision free data transmission of both medical applications and high data rate consumer electronic (CE) applications. The control channels uses the CAP period and data channels uses Guaranteed Time Slots in CFP period of superframe structure which is bounded by beacons. The active part of frame structure is divided into five parts as shown in Fig 4. Beacon is used for downlink synchronization. The control channels AC1 and AC2 are used for uplink control of emergency medical traffic and CE traffic respectively whereas the data channels TSRP and TSRB are reserved for periodic traffic and busty traffic respectively.

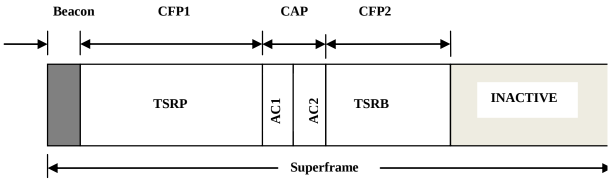

Fig 4: Superframe structure of priority-guaranteed MAC.

Randomized slotted ALOHA is used as random access mechanism on the control channels to improve the resource efficiency.

Since the dedicated control channel is split into two sub channels AC1 and AC2, the access contention of higher priority medical traffic is isolated from much busier CE traffic. In this protocol control channels are reserved on regular basis whereas two data channels are reserved on demand resulting frame structure of high scalability and leads to maximize power efficiency of the master node.

Salient Features: The protocol demonstrates significant improvements on throughput and energy efficiency. The access latency and power consumption for the emergency traffic is also minimized.

F. MedMAC Protocol

N. F. Timmons et al. [12] proposed a MedMAC protocol which incorporates adaptable TDMA mechanism and an optional adaptable contention period. The TDMA mechanism uses variable slot sizes for heterogeneous applications whereas the contention period is used to accommodate emergency traffic, low grade applications and network initialization procedures. The MedMAC uses a multi-superframe structure as shown in Fig 5, which further consists of various dynamic and programmable superframes bounded by beacons to support all classes of data required for BAN applications.

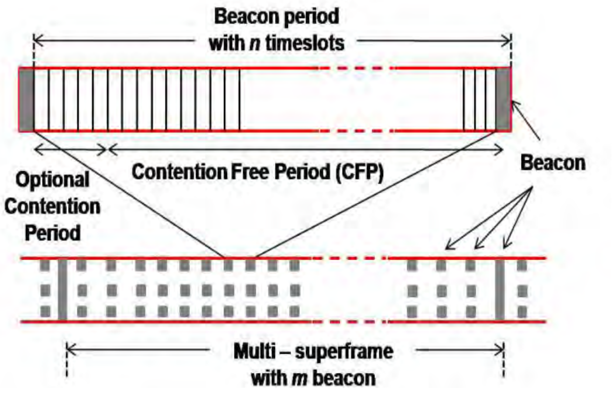

Fig 5: Multi-superframe structure.

The protocol uses a novel synchronization mechanism where a node can sleep through a number of beacon broadcasts to save power. The node receiver is activated to listen only the beacons bounding of the muti-superframe. A combination of timestamp scavenging and an Adaptive Guard Band Algorithm (AGBA) is used for maintaining synchronization of devices. The timestamp from the coordinator is used at the start of the muti-superframe to synchronization all nodes in the network. If an application requires very low throughput AGBA algorithm is invoked to calculate the default guard band (GB) for each node in the worst cases. The Drift Adjustment Factor (DAF) is used to minimize bandwidth wastage by calculating the relative drift between the default GB and the actual drift (AD) and an adjustment is made to the default GB accordingly.

Salient Features: The MedMAC protocol attempts to provide flexibility and scalability with ultra low power consumption and also supports emergency traffic. It uses Guaranteed Time Slots to avoid collision and wastage of bandwidth is avoided by using DAF. The synchronization overhead is mitigated by using a combination of timestamp scavenging and AGBA. The protocol focuses only on low data rate medical applications.

G. Energy-Efficient Multi-hop Transmission in Body Area Networks

HyungTae Kwon [13] proposed energy-efficient dynamic body-MAC in which slot reservation periods are allocated dynamically to heterogeneous sensor nodes based on the traffic generated by them. The sensors implanted in-body sends their data to the coordinator via multi-hop and the coordinator constructs an energy-efficient Minimum Spanning Tree (MST) for the implanted BAN on the basis of each node’s battery status and the distance from the coordinator. The MST contains information about the time slots allocate to each node. Since the nodes consume power due to transmission of medical data, the MST is reconstructed periodically and dynamically.

The node in the network periodically (say after k Beacon Intervals) sends its energy status along with data to the coordinator during its allocated time slot in CFP. Based upon this information the coordinator reconstructs the MST and broadcast the information about MST in the next Beacon. If during these k beacon intervals, the energy of the node falls below a certain threshold, the node sends a TC_Request (Topology Control Request) message along with energy status to the coordinator. On receiving the TC_Request, the coordinator rebuilds the MST. Each node aggregates the data from its children and forwards that data along with its own data to its parent. Based on the traffic information, the coordinator determines the size of the time slots for each node dynamically and allocates time slots to each node in MST by modifying the superframe structure supported by the IEEE 802.15.4 standard.

Salient Features: The scheme enhances channel utilization by dynamic time slot allocation and dynamic construction of MST increases the lifetime of medical sensors. Scalability is an issue in the protocol.

H. BATMAC

Maman M. [14] proposed BAN Adaptive TDMA MAC (BATMAC) protocol which detects the shadowing effect and adjusts its communication protocols and IEEE 802.15.4 superframe parameters accordingly. The protocol uses an adaptable and flexible TDMA and beacon-enabled MAC with relaying enhancement to mitigate shadowing effects. One or more relays are chosen to maintain the connectivity of the network. The relays are beneficial in two different ways. The first one is the decrease of the transmission power which allows us to save energy. The second impact is about the interference generated in the environment as high power transmission pollutes the other surrounding communications and jeopardize BAN coexistence.

A centralized time slot allocation mechanism is used which avoids idle listening and overhearing resulting in low power consumption. The protocol uses the SuperFrame (SF) format as in IEEE 802.15.4 and has features proposed by the IEEE 802.15.6. The BATMAC SuperFrame consists of 6 periods as shown in Fig 6.

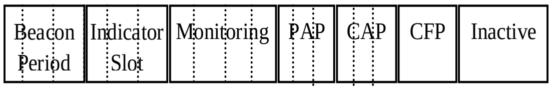

Fig 6: BATMAC Superframe structure.

The devices get themselves synchronized and update their knowledge about the BAN by receiving beacon from their parents in the Beacon Period (BP) and send the direct notification to their parents about the reliability of the link which leads to automatic relay scheduling in the Indicator Period. The Monitoring Period consists of number of guaranteed time slots (GTS) which is dedicated to the data transmission by the devices to the coordinator. The devices contend to get access for life critical and emergency traffic in Priority Access Period (PAP). The Contention Access Period (CAP) is mainly used for uplink GTS requests or other management packets using a slotted Aloha or CSMA/CA approach whereas the Contention Free Period (CFP) is an optional period used for the exchange of other data than monitoring data and to achieve energy efficiency coordinator and devices goes in to sleep mode in inactive Period.

Salient Features: The protocol is energy-efficient and adaptive in nature. The protocol introduces relay nodes to mitigate the shadowing effects and in order to minimize the energy consumption, it chooses the originator of the first beacon correctly received as the best parent (coordinator or relay) and further Transmit Control Power (TCP) is used based on receiver feedback to improve the energy consumption jointly with the relaying mechanism. The protocol uses redundancy in the form of retransmission or relayed packets is introduced to minimize the Packet Error Rate (PER) and due to multi-hop communication it causes high latency.

I. TAD-MAC

Alam [15] presented a novel traffic aware dynamic MAC (TAD-MAC) protocol that targets both invasive and noninvasive body area networks. The model uses star topology for in-body and mesh network for on-body WBANS. The

TAD-MAC allows the sensor nodes to adapt the wake-up interval dynamically according to variations in the traffic depending on different physiological data emanating from the monitoring patient.

Table 2: Comparison of MAC protocols

MAC Protocol	Approach	Performance Comparison	Time Synchroni-zation	Duty Cycling	Energy Efficiency Mechanism
Stevan Jovica Marinkovi´c [7]	TDMA	Low duty cycle and low power protocols described in [10] [16]	Yes	Yes	TDMA, Concept of Guard time (Tg)
Jin Shuai [8]	TDMA, CSMA/CA	IEEE 802.15.4 MAC	No	No	Avoiding idle listening and overhearing
Gengfa Fang [9] BodyMAC	TDMA, CSMA/CA	IEEE 802.15.4 MAC	Yes	Yes	TDMA, Bandwidth mechanism
Omeni [10]	TDMA	Zigbee, Bluetooth and IEEE 802.11	No	Yes	CCA Algorithm based on standard listen-before-transmit (LBT), Wakeup Fallback Time (WFT)
Yan Zhang [11]	TDMA, Randomized Slotted ALOHA	IEEE 802.15.4 MAC	Yes	Yes	TDMA, Asynchronous wakeup trigger mode
Timmons, N.F. [12] MedMAC	Adaptive TDMA	IEEE 802.15.4 MAC	Yes	No	TDMA, Adaptive guard band algorithm (AGBA), Drift adjustment factor (DAF)
HyungTae Kwon [13]	Adaptive TDMA	IEEE 802.15.4 MAC, Distance-based MST	Yes	No	TDMA, Multi-hop Transmission
Maman M. [14] BATMAC	Adaptive TDMA	IEEE 802.15.6 Standard	No	No	TDMA, Relay Election Strategy, avoiding idle listening and overhearing
Alam [15] TADMAC	CSMA/CA	BMAC, XMAC, RICER, WiseMAC	No	Yes	Adaptive Wake-up interval

The working of the protocol is divided into two phases: evolution phase and steady state phase. During the evolution phase each transmits node waits for the beacon signal from the coordinating node. The coordinating node transmits beacon which contains specific node ID and therefore other intending transmit nodes continue to wait for the next beacon if the next wake-up time is very close, otherwise they can go to sleep mode and wake-up just before the next wake up beacon. The next wake-up time is embedded in the beacon frame that all transmit nodes receive, but only the specified node will respond with the data.

The second phase starts after convergence which indicates that the coordinator (receiving node) node has adopted its wake-up interval schedule based on the statistics of the traffic it receives from each individual transmitting node. This schedule results minimum idle listening. To keep this information each receiving node maintains a traffic status register (TSR) bank. Each register corresponds to a node and is updated on the reception of data in response to the wake-up beacon sent by the receiving node. The adaptive wake- up interval algorithm is designed to converge towards a steady state value of wake-up interval based on the TSR. TSR is used to evaluate the next wake-up interval and helps to reduce the unnecessary wake-up beacons or preamble transmissions. The protocol can be applied to both transmitter initiated and receiver initiated MAC protocols of preamble sampling category for various applications.

Salient Features: TAD-MAC is adaptive and adjustable to variations in traffic which results in reduced energy consumption by reducing idle listening and collisions. The proposed protocol is well suited for normal data traffic only and do not consider the behavior of emergency and on demand traffic.

III. CONCLUSION AND FUTURE WORK

The various MAC protocols discussed in this paper are compared in table 2 on various parameters. Most of the MAC protocols proposed by researchers for WBAN primarily focuses on reliability, latency and energy consumption. A lot of works still need to be done in other layers. For example none of the works has been carried out so far on cross layer optimization. The Data link layer, network layer and cross layer optimization is a promising research area that needs to be addressed more extensively in the future. The TDMA based MAC protocols are contention free and provides collision-free medium access but not adaptive, flexible and scalable, and, need a good synchronization

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