Energy-Efficient MAC Protocols for Wireless Body Area Networks: A Survey

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Abstract: In this paper, we provide a comprehensive survey of key energy-efficient medium access control (MAC) protocols for wireless body area networks (WBANs). At the outset, we outline the crucial attributes for a good MAC for WBAN. Several sources that contribute to the energy inefficiency for WBAN are identified, and features of the various MAC protocols qualitatively compared. Then, we further investigate some representative TDMA based energy-efficient MAC protocols for WBAN by emphasizing their strengths and weaknesses. Finally, we conclude with a number of open research issues with regard to WBAN MAC layer.

Key words- Medium Access Control (MAC), Wireless Body Area Networks (WBANs), Energy-Efficiency

I. INTRODUCTION

An important requirement in wireless body area networks (WBANs) is the energy efficiency of the system. A medium access control (MAC) layer is the most suitable level to address the energy efficiency [1]-[4]. This layer is used to coordinate node access to the shared wireless medium. The MAC is the core of communication protocol stack which provides the basis for achieving Quality of Service (QoS) in any wireless networks. A versatile MAC should support diverse applications and different types of data such as continuous, periodic, burst and non-periodic data along with high level QoS. MAC plays a major determining factor in improving overall network performance. The fundamental task in MAC protocol is to avoid collisions and to prevent simultaneous transmissions while preserving maximum throughput, minimum latency, communication reliability and maximum energy efficiency. It is important to note that while designing MAC protocols one should keep in mind that nodes are prone to failures, constrained capabilities and restricted energy resources.

In this paper, we have provided a survey of recent energy-efficient medium access control (MAC) protocols for wireless body area networks (WBANs) and compare features of the various approaches pursued. Various MAC protocols with different objectives have been proposed for WBANs. More specifically, in this paper we focus on TDMA based energy-efficient MAC protocol devised for WBAN. At first, we outline the properties that are crucial for the design of MAC layer protocols. Several sources that contribute to the energy inefficiency are identified and qualitative comparisons of other MAC protocols are summarized. Then, we investigate some representative TDMA based MAC protocols devised for WBAN by emphasizing their strengths and weaknesses. Moreover, comparisons with other MAC protocols in the context of WBAN are tabulated in detail. As a conclusion, we put forward a number of open research issues with regard to WBAN MAC layer.

The main contribution of this paper is summarized as follows:

- We have made a substantial effort to analyze the various energy-efficient MAC protocols for WBAN with regard to their specific features, advantages and disadvantages.
- We outline the characteristic properties of a good MAC for WBAN and identify the potential source of energy waste that influences the energy efficiency at medium access communication.
- Finally, we put forward a number of future research directions and conclusions for the researchers with regard to open research issues that have not been studied thoroughly.

The rest of the paper is organized as follows. In Section II, we outline the crucial attributes of a good MAC and identify the factors that influence the energy efficiency. The categorization of possible communication patterns is also outlined. In Section III, we investigate various energy-efficient MAC protocols proposed for WBAN. A number of open research issues are discussed in Section IV. Section V concludes the paper.

II. CHARACTERISTICS OF MAC & SOURCE OF ENERGY WASTE IN WBAN

2.1 Attributes of a good MAC

Several attributes need to be considered for the design of an energy-efficient MAC protocol for a WBAN. The prime attribute is energy efficiency. WBAN devices, being operated by a battery require stringent restriction on the use of energy resources. To achieve this goal, design of energy-aware communication protocol is required. Energy-efficiency can be increased by minimizing the energy wastes identified below. However, WBANs are intended to support life saving critical applications. Hence reliability, safety and security are considered important metrics besides energy efficiency. The QoS is also an important factor of a good MAC protocol. Other parameters of importance include scalability, adaptability to changes in network topology, throughput, jitter, latency and bandwidth utilization. Throughput, jitter and latency requirements depend on the nature of the application. In case of medical applications, latency should be less than 125ms for QoS packet, whereas in case of consumer electronics (CE) applications, jitter and latency should be less than 50ms and 250ms, respectively [5]. In summary, the attributes of a good MAC in WBAN include energy-efficiency, reliability, heterogeneous traffic, safety and security in addition to QoS [6].

2.2 Potential Source of Energy Waste

As widely addressed in the literatures, several sources contribute to the energy inefficiency include collisions, idle listening, overhearing, over-emitting, control packet overhead and traffic fluctuations. Collisions contribute a major source of energy inefficiency. Collisions occur when two or more sensor nodes attempt to transmit data packets simultaneously. Idle listening incurs when a node listens to an idle channel to receive possible traffic. Overhearing occurs when one receives a packet that is destined to other nodes. Overemitting is caused by the prolonged transmission of a message when the destination node is not ready to receive. Control packet overhead means that the minimal number of control packets should be used for data transmission. Sending, receiving and listening for control packets consume energy. Since control packets do not directly convey data, they reduce the effective throughput. However in WBAN, idle listening, collisions and overhearing can be considerably reduced by using master-slave architecture with Time Division Multiple Access (TDMA)/ Clear Channel Assessment (CCA) link scheme. This scheme can significantly reduce the likelihood of collisions and idle listening leading to significant power savings. Flexible duty cycle and power-efficient techniques are required to minimize the packet collisions, overhearing, idle listening and control packet overhead issues.

2.3 Communication Patterns

To realize communications between devices in the WBAN, techniques from the Wireless Sensor Networks (WSNs) and ad hoc networks could be adapted. In order to have a clear understanding, two important communication patterns in a WBAN i.e., intra-body communication and extra-body communication should be considered. The intra-body communication controls the information handling between the sensors or actuators and the sink. The extra-body communication ensures the communication between the sink and an external network. The combination of intra and extra-body communication can be seen as enabler for ubiquitous healthcare service provisioning.

III. PROPOSED MAC LAYER PROTOCOLS

In this section, a wide range of MAC protocols are described by stating the essential behavior of the protocols, wherever possible. The main schemes of MAC protocols for WBANs are grouped into contention-based or random access, and contention free or scheduled-based protocols.

Contention-based MAC such as Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) protocols nodes competes for the channel to transmit data. Nodes have to perform Clear Channel Assessment (CCA) before transmission of data. If the channel is busy, the node defers its transmission till it becomes idle. CSMA based MAC protocols such as S-MAC [7], T-MAC [8], B-MAC [9], P-MAC [10], D-MAC [11] and WiseMAC [12] are known to be not energy-efficient for WBANs. CSMA/CA is not a reliable protocol for WBAN due to its collision issues and unreliable CCA.

Time Division Multiple Access (TDMA) mechanism on the other hand, is an attractive solution for WBAN applications because of its energy-efficiency. TDMA is a schedule-based multiple access technique where transmission of packets are managed in the form of time frames and time slot. A time slot can be seen as a dedicated transmission resource used to carry data with minimum or no overhead. In a TDMA, the channels are divided into fixed/variable time slots which are assigned to a particular sensor node to transmit during its slot period. Since slots are pre-allocated to individual nodes at initialization, they are collision-free. TDMA based contention-free MAC protocols such as

PACT [13], LEACH [14], FLAMA [15] and HEED [16] are known to be energy-efficient MAC protocols. However, they have some limitations to satisfy the stringent requirements of WBAN. Other MAC protocols such as Preamble-based TDMA [17], Heartbeat Driven MAC (H-MAC) [18], Reservation-based Dynamic TDMA (DTDMA) [19], Distributed Queuing Body Area Network (DQBAN) [20], Battery-aware TDMA [21], Scalable and Robust MAC [22] and [23] have also been investigated for WBAN in recent literature. Other scheduled MAC like Code Division Multiple Access (CDMA) and Frequency Division Multiple Access (FDMA) protocols are not suitable in the context of body sensor networks (BSNs), since the sensors are often constrained in terms of limited frequency bands and computation capability. Essentially, all of above mentioned schemes/mechanisms are designed to enable a trade-off amongst the important performance metrics.

Table I presents a detailed comparisons with other MAC protocols in the context of WBAN. In the following sub-section, we briefly investigate various TDMA based MAC protocols for WBAN towards energy-efficiency.

TABLE I. QUALITATIVE COMPARISION OF MAC PROTOCOLS IN THE CONTEXT OF WBAN

Protocols	MAC Approach / Basic Operation	Time Synchronization Needed	Advantages	Disadvantages	Comments
S-MAC [7]	CSMA / Scheduling	No	Simplicity, high latency, time synchronization overhead may be prevented due to sleep schedules	Low throughput, overhearing and collision may cause if the packet is not destined to listening node	Good for normal traffic applications
T-MAC [8]	CSMA / Scheduling	No	Packets are sent in burst, better delay, gives better result under variable load	Suffers from sleeping problems	Adaptability to changes in traffic condition is good
B-MAC [9]	CSMA / Scheduling	No	Simplicity, good packet delivery rate, high throughput, low overhead	Overhearing problem is not solved, long preamble increases the power consumption	Good for normal-traffic applications
P-MAC [10]	CSMA / Listening	No	High throughput	Adaptation to changes might be slow	Good for delay-sensitive applications
D-MAC [11]	CSMA / Scheduling	No	Good delay performance, energy-efficient	Collision avoidance are not utilized, leading to collisions	Good for low delay applications
WiseMAC [12]	np-CSMA / Listening	No	Mobility support, scalable and adaptive to traffic load	Decentralized sleep-listen scheduling results in different sleep and wake-up times	Good for normal-traffic applications
PACT [13]	TDMA / Passive clustering	No	Low overhead, prolonged network lifetime	High traffic overhead and idle listening, lacks support for dynamic network	Good for low delay applications
LEACH [14]	TDMA / Clustering	Yes	Distributed protocol, requiring no control information from the base station	Extra overhead for dynamic clustering	WBAN coordinator can act as a cluster-head
FLAMA [15]	TDMA / Scheduling	Yes	Low delay, better end-to-end reliability, significant energy savings	Lack of support for multiple channels, requires time synchronization	Good for normal-traffic applications
HEED [16]	TDMA / Clustering	Yes	Low overhead, Scalable prolonged network lifetime	Cannot guarantee optimal set of cluster heads	WBAN coordinator can act as a cluster-head

3.1 Energy Efficient Medium Access Protocol

The authors in [24] proposed a MAC protocol for single-hop communication in order to reduce energy consumption by centrally controlled wakeup/sleep time. The central nodes act as a master while the other nodes are slaves. Each slave node is assigned a slot by the central node. Slave nodes are the nodes which acquire sensor data readings and transmit to a master node for processing. The basic operation of the MAC protocol is based on three communication processes: link establishment process, wakeup service process and alarm process. The protocol introduces a concept of wakeup fallback time (WFT) to mitigate continuous time-slot collisions. If a slave wakes up and fails to communicate with the master, it goes back to sleep with a sleep time set by the WFT.

Computation details on the power and duty cycle analysis of three important applications like blood glucose monitoring, body temperature sensing and ECG streaming have been reported. It can be concluded that the measured power for a body sensing application depends on sleep time as well as number of retransmissions. As sleep time increases, the duty cycle decreases after several retransmissions. Hence, average power consumption is dependent on duty cycle value. This protocol exploits the centrally assigned wakeup/sleep time and shows significant energy reductions as compared to other network MAC protocols such as IEEE 802.11, Bluetooth and Zigbee. One key difference from other related works is that RF power requirement is significantly lower.

Advantages – The concept of WFT has been introduced in the presence of link failures to mitigate time-slot collision which enables every sensor slave node to maintain a guaranteed time slot (GTS) even if the slave node fails to communicate with the master or vice-versa. As the traffic is managed centrally, idle listening and over-hearing can be avoided in this protocol.

Disadvantages – The maximum number of slaves connected to a master in one cluster is limited to 8, which restricts the inclusion of other slave nodes. In all the three processes of basic operation, communication should be initiated by the master. Moreover, only one slave node can join the network at a time.

3.2 MedMAC Protocol

The medical medium access control (MedMAC) protocol [25] is an adaptive TDMA based MAC protocol. For this, the star network configuration of IEEE 802.15.4 standard at 2.4GHz was considered for a WBAN. The MedMAC incorporates a novel synchronization mechanism where a node can sleep through a number of beacon periods. The beacon period consists of a contention free period (CFP) and optional contention access period (CAP) which are made up of 2-256 timeslots as shown in Figure 1. The duration of the multi-super frame is defined by synchronization mechanism.

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 timeslots to track the actual drift. The Drift Adjustment Factor (DAF) minimizes the bandwidth waste. At the start of multi-superframe, 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. Each node has a dedicated time slot which means no collision occurrences. Calculations of default GB for subsequent beacon of multi-superframe and slot start times (SST) for each slot was also computed. Power efficiency of MedMAC is compared with IEEE 802.15.4 of medical applications such as respiration, temperature and pulse monitor using OPNET simulations.

At lower rate applications (Class 0) such as health/fitness monitoring simulation demonstrated similar performance for MedMAC and IEEE 802.15.4. The extra power consumption in this low data rate is possibly due to the overhead in the IEEE 802.15.4 specification. At medium data rate medical applications such as EEG (Class 1), MedMAC consumes lesser power (<10%) than required by IEEE 802.15.4 MAC. Simulation results showed that the IEEE 802.15.4 model consistently suffered node failures. Hence, it can be concluded that MedMAC outperforms IEEE 802.15.4 in terms of power efficiency in low and medium data rate applications.

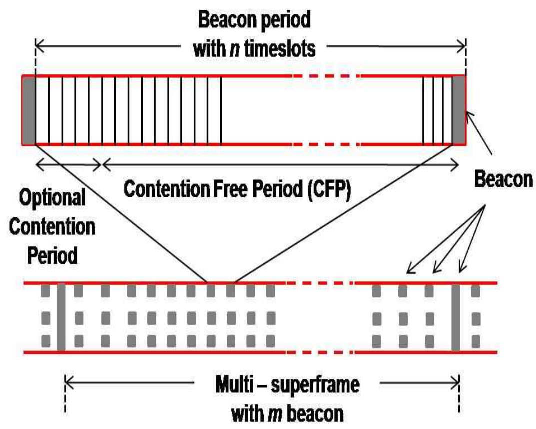

Figure 1. Super frame structure of MedMAC protocol [25]

Advantages – The energy efficiency simulation results reveal that MedMAC shows better performance than IEEE 802.5.4 for Class 0 and Class 1 of medical devices. The energy waste caused by collisions is reduced by making use of a GTS. Besides, each device will have exclusive use of the channel for a fixed timeslot which mitigates the synchronization overhead.

Disadvantages – The protocol focuses only on low data rate medical applications. However the data rates of on-body and in-body nodes of WBAN are sometimes high.

3.3 Energy-Efficient Low Duty Cycle MAC Protocol

The authors in [26] propose a low duty cycle TDMA-based MAC protocol, developed for a single-hop communication to support streaming of physiological signal data. The protocol exploited the fixed network structure of WBAN to implement an effective TDMA strategy. The network topology is hierarchical with a number of sensor nodes, a Master Node (MN) that coordinates the synchronization and transmission to sensor nodes and a Monitoring Station (MS) that gathers the data from the MN's for further analysis. Figure 2 shows the TDMA timing diagram of the protocol. Time slots are allocated to *n* different nodes which are separated by a guard time (T_g). Insertion of T_g prevents transmission overlaps and reduces bandwidth waste. The communication between MN and MS can be established in two aspects: when MN with one transceiver and when MN with two transceivers.

Duty cycle is the main parameter for energy consumption comparison of the different MAC protocols, since it is minimally dependent on the transceiver used. The protocol compares its performance with those of two cases; the low duty cycle and low power protocols described in [24] and [27], respectively. Comparison with [24] is based on the duty cycle for the sampling data rate of 2500bit/s. The power consumption versus data generation interval with the duty cycle values are represented in terms of two data rates of 19.2 and 250Kbit/s. The protocol greatly reduces power consumption for streaming data compared to [27].

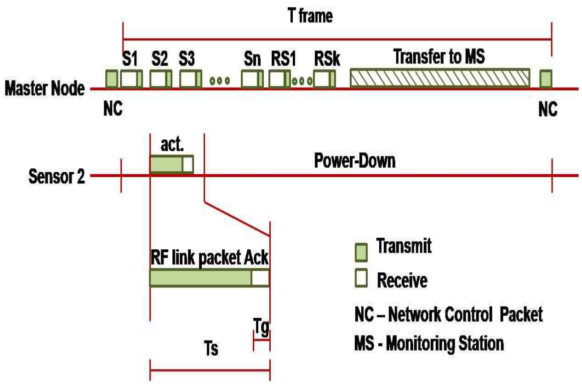

Figure 2. TDMA timing diagram [26]

Advantages – It is shown that the protocol is energy-efficient for sending short bursts of data. The protocol overcomes the collisions by using the effective TDMA strategy. This enables collision on the lowest level possible. The protocol can be used in a real time electroencephalogram (EEG) monitoring scenario and the scheme results in reliable data transfer which is crucial especially in medical applications.

Disadvantages – Due to the static network topology adapted in the TDMA strategy, the protocol may not respond well when the topology is dynamic.

3.4 BodyMAC

Fang and Dutkiewicz in [28] propose energy efficient TDMA-based MAC protocol for WBAN. In this protocol, packet collision, idle listening and control packet overhead have been reduced by allocating three bandwidth management schemes: Burst Bandwidth, Periodic Bandwidth and Adjust Bandwidth in order to improve energy efficiency. An efficient sleep node is introduced to turn off a node's radio, especially for the nodes supporting low duty cycle applications. The MAC frame in BodyMAC protocol has three parts: Beacon, downlink and uplink sub frames. The beacon serves the purpose MAC layer synchronization. The downlink frame is used for transmission from gateway to node, which can accommodate on-demand traffic. The uplink frame consists of two sub-parts: Contention Access Part (*CAP*) and Contention Free Part (*CFP*).

One of the criteria of WBAN MAC design is the inclusion to support time critical event reporting. Sleep mode has to support time critical events that may come at any time. An event report packet can be sent either in CAP or GTS. The simulation results reveal that the BodyMAC protocol shows better performance than IEEE 802.15.4 in terms of end-to-end delay and energy saving.

Advantages – Since nodes and gateway are synchronized in time, nodes can enter into sleep mode and wake up only when they have data to send to the gateway. The slot allocation in CFP is collision free, which improves packet transmission and hence saves energy.

Disadvantages – The protocol uses CSMA/CA in the uplink frame of CAP period, which is not reliable scheme due to its unreliable CCA and collision issues.

All the above discussed MAC protocols have their own pros and cons in the context of real WBAN systems. As a common ground, most of the existing MAC protocols for WBAN in the literature assume star topology using master/slave communication. However, majority of the MAC devised for WBAN is based on TDMA.

In Table II, we give a comparison of the investigated TDMA-based energy-efficient MAC protocols. The column heading "Time Synchronization Needed" indicates whether the protocol assumes that the time synchronization is achieved externally.

IV. OPEN RESEARCH ISSUES

Most of the work primarily focuses on the energy efficiency/power consumption. However, still a lot of work has to be done in other areas such as data link layer, network layer and cross layer design. None of the works has been carried out so far on cross layer optimization. One should consider the mobility of the nodes in human body to develop a WBAN specific MAC protocol. Network layer should take into account the integration of thermal-aware routing together with energy efficient QoS-mechanisms. Cross layer design is a way to improve efficiency by combining two or more layers from the protocol stack. The more layers contributing to the system performance, the more efficient the system can be. Therefore, data link layer, network layer and cross layer optimization are another promising research area that needs to be addressed more extensively in the future. Other interesting open research issues are MAC transparency, interoperability, mobility support, security and so on.

TABLE II. COMPARISON OF INVESTIGATED TDMA-BASED MAC PROTOCOLS

Protocols	Performance Comparison	Time Synchronization Needed	Reasons for Energy-Efficiency	Comments
Omeni [24]	Zigbee, Bluetooth and IEEE 802.11	No	Centrally controlled wakeup/sleep time reduce energy consumption	Good for important applications like ECG streaming, blood glucose monitoring
MedMAC [25]	IEEE 802.15.4 MAC	No	Maximized energy efficiency through dynamical adjustments for QoS requirements	Good for low rate (Class 0) and medium data rate (Class 1) medical applications
Marinkovic [26]	Protocols described in [24] and [27]	Yes	Long sleep times for sensors ensures reduced power consumption	Good for sending short bursts of data
BodyMAC [28]	IEEE 802.15.4 MAC	Yes	Flexible bandwidth allocation improves node energy efficiency	Good for periodic data sensing and event reporting

CDMA offers a collision-free medium, but its computational requirement is a major obstacle for the lower energy-consumption objective.

FDMA although offers a collision-free access to the medium, requires complex hardware circuitry to communicate with different channels.

CSMA schemes have promising throughout potential and low delay capability. However it, incurs significant protocol overhead. CSMA require additional collision avoidance or collision detection methods. CSMA/CA is scalable with no time synchronization constraint. CSMA/CA shows good adaptation to topology changes, consumes low bandwidth utilization and more power. The main advantages of CSMA/CA include simplicity of its implementation, lower delay and reliable transmission of packets in small size networks like a WBAN.

TDMA-based protocols require a good synchronization scheme. TDMA schemes are contention free but are not adaptive, flexible and scalable. It is found that TDMA is more suitable for non-dynamic type of networks with a limited number of sensors generating data at a fixed rate. It is envisaged that if synchronization and dynamic slot assignment of TDMA could be traded off, TDMA could be considered as a potential solution for WBAN. Future sophisticated WBAN MAC protocols would be based on TDMA scheme with additional features to support that compliments its benefits.

The research on WBANs MAC protocol is still in its developing stage and a lot of open research issues are to be resolved. The diversity of applications of WBAN requires different selection of MAC protocols. However, improvements to an existing protocol are often required to meet the desired application needs and mitigate its inherited drawbacks. Although there are few efficient MAC layer protocols devised for WBAN, there is no implementation accepted as a standard. One of the reasons for this is that, the choice of MAC protocol in general is hardware and application dependent. Another reason may be due to the fact that lack of standardization of the layers. A particular choice of MAC would depend on the specific circumstances of deployment scenarios and applications.

V. CONCLUSIONS

In this paper, we have presented a survey on energy-efficient MAC protocols for WBAN. The requirements of a good MAC protocol for WBAN have been identified, and various approaches of WBAN MAC protocols are comparatively analyzed. At this point of stage, a unified hybrid and cooperative MAC is required to satisfy WBANs requirements such as guaranteed QoS, multiple physical layer support and adaptability to traffic variations, etc. It is believed that this paper will inspire researchers to develop novel and energy-efficient MAC protocols for WBANs.

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