A Survey on IEEE 802.15.4 MAC Protocols for Body Sensor Networks

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***Abstract*—IEEE 802.15.4 is the Body Sensor Networks (BSNs) de facto standard that defines the requirements of these networks' implementations, protocols, and architecture. In orchestrate sensor node connection, the MAC protocol is required in the wireless medium of communication. While IEEE 802.15.4 MAC is characterized by a collection of robustness that has led to its popularity in different BSNs, many limitations play a significant part in deteriorating its performance. Also, the IEEE 802.15.4 based networks are commonly implemented in the proximity of other wireless networks operating in the same ISM band from a realistic point of view. This implementation ensures the MAC layer for IEEE 802.15.4 should be enabled for other networks to cope with interference. These factors have inspired efforts to improved MAC protocols of BSNs for IEEE 802.15.4. In this paper, we highlight the advantages and disadvantages of approaches to optimizing the IEEE 802.15.4 of MAC protocols and we discuss two methods that are used in our proposed work.**

Keywords—Body Sensor Networks, IEEE 802.15.4, MAC, Backoff, Duty-Cycle

I. INTRODUCTION

The body sensor networks (BSN) and body area networks as described in IEEE 802.15 are the communication standard intended for low-power devices operating on or in the human body and functioning for the benefits of the user [1]. A BSNs is a separate and distinct form of sensor network consisting of several sensor nodes that are typically referred to as implantable medical devices (IMDs). These sensors calculate various physiological signals from the body of a person. Zimmerman first implemented a BSNs in 1996 as a precise procedure for a personal area network [2], [3]. BSNs and their implementations can enhance the quality of life of the user. It can be characterized majorly concerning their use in the non-medical and medical field [4], [5].

The non-Medical field is not only confined to the medical area, as this field just has significant and life-saving implementation results. Applications of the BSNs are vast and can be implemented in various areas other than medical like military, sports, and other entertainment activities. In medical field, there is a need for consistent monitoring and observation of the biological signals generated from human body. The medics can observe, analyze and diagnose by tracking the health record of the patient via the help of node sensors attached to or inside the human body These nodes attached to the patient's clothes and accessories like a vest, shirt, wrist wearable, sunglasses, and belts, etc.

The de facto set of requirements recommended for running BSNs is the IEEE 802.15.4 criterion. Together with the many performance criteria of these applications, the wide range of applications motivated by the advent of BSNs have prompted the research community to concentrate on developing IEEE 802.15.4 of MAC protocol to minimize its shortcomings. Motivated by different goals, several research teams have been working for more than a decade on maximizing the benefits of The IEEE 802.15.4. Researcher's goals primarily include reducing power usage, improving throughput/channel use, improving reliability/packet distribution ratio/reliability, decreasing collision risk, and minimizing end-to-end delays.

In this paper, we provide simplified coverage of different approaches available and explain two of them used in our study. The remainder of the paper is organized as follows: Section II describes BSN architecture. Section III describes the IEEE 802.15.4 of MAC protocol. Section VI provides approaches to optimize the IEEE 802.15.4 MAC protocol. Finally, Section V concludes this.

II. BSN ARCHITECTURE

The body sensor network architecture with various nodes used as sensors in medical science for monitoring a patient's health is shown below in Fig. 1. Multiple tiers of BSN is illustrated in Fig. 1 [6], [7]. The personal server collects data generated and transmitted by the different sensors and devices such as blood pressure sensors, ECG, and EMG sensors. However, sending data to the medics for analysis is accomplished through another network setting.

The data sending may use commonly available networks such as wireless local area networks. If the range is not a problem, then other communicative technologies like Bluetooth or NFC may also be used. The biomedical data is transmitted remotely to the medics for further testing, analysis and diagnosis. These sensors can also work as emergency lifesavers by sending the data in real-time to seek medical assistance on time.

The architecture of communicating sensors with a local server, and then local servers to the remote locations made up a BSN and can be categorized into three different parts. The first tier is intra-BSN communication, known as Tier-1. The second tier (Tier-2) is called inter-BSN communication and the third tier (Tier-3) is beyond-BSN communication. These tiers are discussed in subsections A, B and C. Nodes and communicative network architecture are shown in Fig. 1.

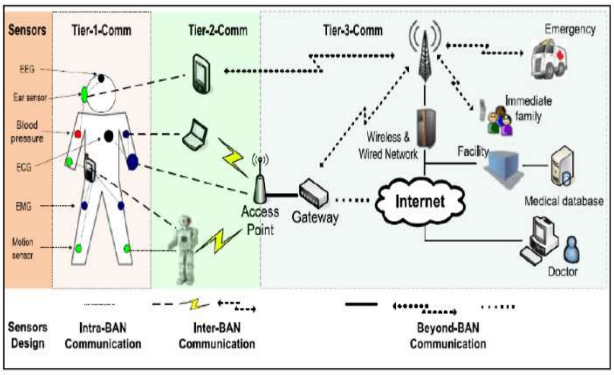

Fig. 1. BSN architecture based on Three-tier for a communications system [8].

A. Tier-1: Intra-BSN Communication

The intra-BSN communication connects between two indistinct types of nodes, BSN nodes, and the master node also called the coordinator node. Moreover, this communication is among the nodes of the body sensor networks. BSN nodes are small with significantly lower power depletion with a very less range of communication. This communication is in direct contact with the human body and it might necessitate differently and dependence of data rate on the nature of the sensor and its features, it has a range of almost from 1 to 5 meters. The Personal Server (PS) or on-site sink located in Tier-1 receives data transmitted from the sensors attached to the body. Here, the Tier-1 communication process is completed, now this data is sent to the remote location. To do this, the processed data and collected data are transmitted to an arrival point in Tier-2.

B. Tier-1: Intra-BSN Communication

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C. Tier-2: Inter-BSN Communication

Now when the data is received in the Tier-2, at this stage communication takes place among personal based server or sink and other network starts. That other network depends upon the architecture of Tier-2 communication. In case WLAN is used the data from the PS is transmitted to the gateway or access point which is part of Tier-2 communication and is technically and dynamically placed in the environment to cope with the emergency situation. This tier has the purpose of working as the communication agent between BSN and other networks through a cellular network or the Internet.

D. Tier-3: Beyond-BSN Communication

The remote location of medics where the data is to be sent from the Tier-1 through Tier-2 architecture and devices may be far enough to use the dedicated connection. Thus the use of a metropolitan area network (MAN) is used. Different available devices can be used to bridge the attachment between Tier-2 and Tier-3 architecture, and then it can be transmitted to the medical server at a distant location using the Internet. Though beyond-BSN communication represents the specific application used on the medical server; a database is the most crucial part of the medical environment. This database is essential because it holds and records the history of the particular patient and their profile. Using these architectures with the help of records in the database, the doctors and the patient can be aware of the latest health conditions and warned through SMS or the Internet.

III. OVERVIEW OF THE IEEE 802.15.4 MAC PROTOCOL

The IEEE 802.15.4 standard defines the PHY layer and the Low Rate-Wireless Personal Area Network (LR-WPAN) MAC sub-layer specifications [9]. The standard operates in any of the two modes depending on the form of the CSMACA mechanism used [9], [10]. The default will run in a non-beacon mode, if un-slotted, the CSMA-CA is used. When using the slotted CSMA-CA, the standard will operate in beacon mode.

In this article, our focus is on the latter mode. In this mode, to coordinate communication over the wireless medium, a superframe structure has been used. The superframe is delimited through beacons that are regularly sent to synchronize the nodes by the Personal Area Network (PAN) coordinator. The superframe duration (SD) and beacon interval (BI) are used to describe the superframe fully. The time among two consecutive beacons is referred to by BI and consists of an active section and an optional inactive section.

The coordinator insides a low-power mode maintains its power resources during the duration latter. However, the active cycle fits the SD and split into 16 time slots. The active portion comprises the contention access period (CAP) and the optional contention-free period (CFP).

Two attributes define the configuration of the superframe, namely the macSuperframeOrder (SO) and the macBeaconOrder (BO). The BO determines the duration span during which the coordinator should communicate using the beacon frames. The SO specifies the active component length plus the frame of the beacon. The configuration of the superframe of the beacon- activated mode is shown in Fig. 2 [10].

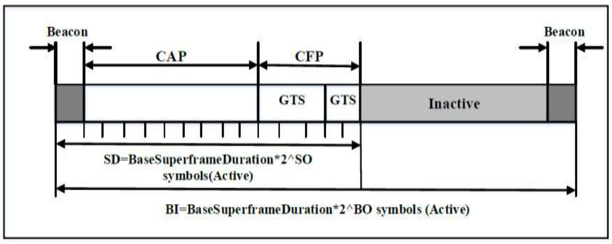

Fig. 2. Superframe structure [10].

BO’s value is correlated with the beacon interval (BI) as follows:

$$BI = aBaseSuperframeDuration * 2^{BO} \text{ symbols} \qquad (1)$$

$$0 \leq BO \leq 14$$

In which the number of symbols is aBaseSuperframeDuration, and a superframe whenever the SO is set to zero. The value of macSuperframeOrder is ignored if BO is set to 15, and beacon frames will not be sent except on request. The SO specifies the length of the active portion plus the beacon frame. The SO value is attached to the length of the superframe duration (SD), as follows:

$$SD = aBaseSuperframeDuration * 2SO \text{ symbols} \qquad (2)$$

$$0 \leq SO \leq BO \leq 14$$

The slotted CSMA-CA framework [11], [12], [13] is used by nodes during the CAP to attempt for media access. The slotted CSMA-CA uses the Binary Exponential Backoff (BEB) algorithm as a way of reducing the likelihood of collisions over the wireless channel. The Binary Exponential Backoff acts on three parameters as follows, the number of backoff stages (NB), the Contention Window (CW), and the Backoff Exponent (BE), which are initialized before any transmission attempt. These parameters are initialized with zero, two, and macMinBE, respectively.

After that, for a random period chosen from the [0, 2^{BE} – 1] range, the node backs off. The node carries out two Clear Channel Tests (2CCA) until the back-off time expires. The number of CCAs is regulated through the parameter CW, in as much as the CW is not zero, CCAs are carried out. CW is reset to two if each CCA indicates that the medium is busy.

Before starting a transmission, the CCAs are required to verify if the wireless medium is free of any operation. Transmission of packets begins only if during the two CCAs the medium is found to be clear (as long as that the residual time slots in the current limit are adequate to transmit the packet and its ACK. Anything else, the node has to delay the transmission of the packet to the next superframe).

However, suppose one of the CCAs indicates that the medium is busy. In that case, the BE value increases by one (up to the limit of macMaxBE) and the node backs off again (i.e., NB increases by one and can reach the limit of macMaxCSMABackoffs). Once a packet is successfully transmitted, the receiver node sends back an ACK packet. If the ACK packet is not received, the node attempts to retransmit the packet (up to a limit of macMaxFrameRetries attempts). The full BEB procedure is re-applied for each retry.

If the macMaxFrameRetries file is crossed, it will reject the packet. AUnitBackoffPeriod is the primary time unit used by CSMA-CA. Fig. 3 shows the flow chart for the slotted CSMA-CA process.

The contention-free period (CFP) is applied to support QoS specifications (low latency, number of Guaranteed Time Slots (GTSs) for particular data bandwidths) by the coordinator. A set of Guaranteed Time Slots (GTSs) that the coordinator dedicates to such nodes upon their request constitute the CFP. In the active portion of the superframe, GTSs begin immediately following the end CAP. Seven is the highest amount of GTSs a coordinator can delegate. During its GTS, a node having an allocated GTS has complete access to the channel. The nodes operation at GTS should finish before the start of the next GTS or the end of the CFP.

IV. APPROACHES TO OPTIMIZE BEACON-ENABLED IEEE 802.15.4 MAC PROTOCOLS

To enhance the 802.15.4 MAC protocol, we can classify the key proposed approaches into eight different categories as follows: parameter tuning-based, QoS-based, duty cycle-based, priority-based, IEEE 802.11-based, hidden node resolution-based, backoff-based and cross layer-based [14]. Table 1 highlights the advantages and drawbacks of the various optimization methods dealing with the IEEE 802.15.4 slotted CSMA/CA

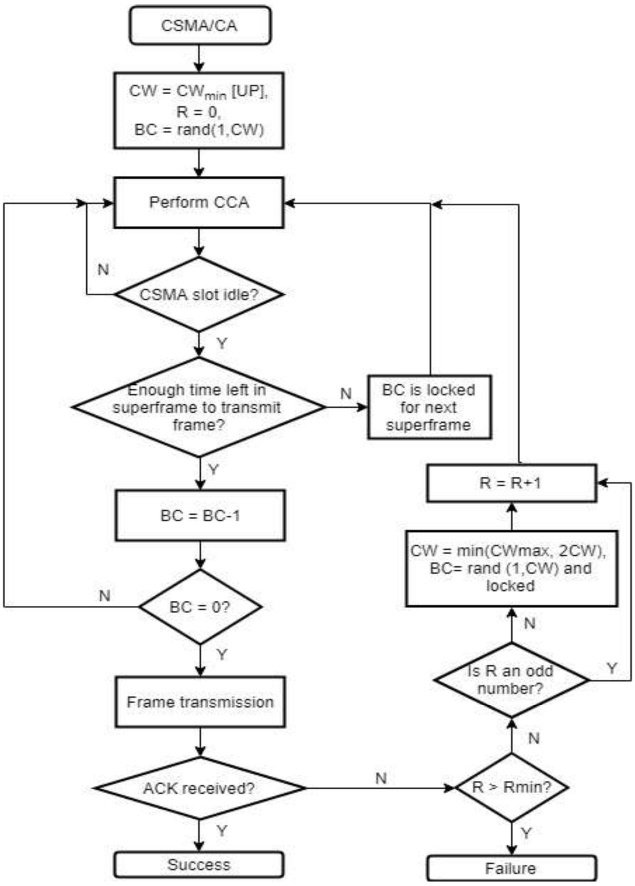

Fig. 3. CSMA-CA mechanism [14], [11].

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The current IEEE 802.15.4 MAC optimization literature can be classified into different methods, and two of them are used in our proposed approach in this paper. Duty cycle-based approach discusses channel access control during the superframe's active and inactive times, intending to make productive use of power. By controlling the service cycle duration, the benefit of this approach is to maximize the network lifespan. While backoff-based approach recommends that minimum modification should be made to the standard so that appropriate benefits can be achieved from the strengths of the standard.

The advantages of this approach include making the 802.15.4 MAC more dynamic and adaptive, network scalability support, and few performance trade-offs between reliability, and latency, similarly between delay and energy consumption.

TABLE III. ADVANTAGES AND DISADVANTAGES OF IEEE 802.15.4 MAC OPTIMIZATION APPROACHES

Class of Parameter Approaches	***Advantages***	***Disadvantages***
Parameter Tuning-based	No explicit change to IEEE 802.15.4.4 is needed.	• Application Specific • Output limited by MAC parameter theoretical range.
Hidden Terminal Resolution-based	• A substantial decrease in collisions. • Eliminating needless retransmission of packets. • Better use of energy resources.	The overhead of the PAN coordinator to enforce an effective node grouping strategy to prevent transmission overlaps.
Backoff-based	• Making the 802.15.4 MAC more dynamic and adaptive. • Network scalability support. • Adjust to various topologies. • No hardware upgrade may be needed.	• May introduce major changes to the standard. • Adaptive processing comes at the cost of additional processing tasks at each sensor node.
Cross Layer-based	Optimized performance by including various layers' perspectives.	• Increments in latency. • Control overhead to facilitate inter-level contact.
802.11-based	Proven technology reuse	Built without special power conservation measures.
QoS-based	• Improve IEEE 802.15.4's GTS feature. • Better time-sensitive application support.	To solve complicated optimization problems, place extra tasks on PAN coordinators.
Duty Cycle-based	• Exploit the features of IEEE 802.15.4 with minimal modifications. • Discover more ways to save power using the standard's original configuration.	Burden the coordinator of the PAN with a processing and analysis overhead.
Priority-based	Support QoS parameters during the CAP	Extra power consumption is followed by overhead of classifying nodes and traffic

A. Duty Cycle Based Approaches

The solution for the overhearing and idle listening issue is given as the duty cycle mechanism which is thought to be an efficient solution. It usually does well in random-access networks, mainly where periodic schemes are in locations such as wake-up time and sleeping time. The duty cycle mechanisms provide low-power listening without using any external device or hardware. The mechanisms discussed are very efficient and attract attention at locations where data traffic and the position of the nearest node are changing with observance to time [16], [17].

The mechanisms based on the complete synchronization given by the beacon mode are responsible for the efficient use of energy sources. Shortage of dynamic adaptive capabilities, unauthorized channel access in saturated environments, and more extended periods of back-off could be observed in the event of channel access failure, and all these problems are experienced by the IEEE 802.15.4 standard. These challenges generate low BSN efficiency, whereas these BSN applications require a limited delay, defined throughput, reliability and efficient use of energy at a given time.

However, some studies emphasize optimizing the efficiency of the slotted mode concerning end-to-end delay and the energy expended when changing the duty cycle. In order to make the use of power-efficient and reliable, channel access control during the cycles of operation and inactivity of the superframe is addressed by these approaches. By controlling the duty cycle duration, this approach increases the network lifetime.

The MAC layer state index refers to the details used for the queuing delay and the Duty Cycle Adoption (DCA) [18] uses the occupancy of the buffers at the MAC. Changing the length of the active time is the reason behind using the queuing delay and buffer occupancy information in the MAC status index (MSID). The frame structure's reserved MAC control field is used to send the buffer status and queuing information using the node and algorithm. In this case, the active time of the superframe can be modified using data extracted by the coordinator. The queue occupation, which is inserted into all frames during the active time, is computed by DCA.

In DSAA [19], the author suggested changing the service cycle based on two factors: the occupancy rate of the Superframe Order and the collision rate. The coordinator computes the occupancy and collision rate at the end of each active portion of the superframe. Then, the occupancy rate is compared to the threshold for superframe occupancy. Next, the collision rate is compared with the threshold of the collision. Finally, in the next superframe, the coordinator changed the SuperFrame Order length.

In addition , the author proposed the Adaptive Duty Cycle Algorithm (ADCA) [20] to address the problems and challenges of beacon-based energy consumption that enables wireless sensor networks. The coordinator node collects the network information, which includes the status of the queue on the nodes and their idle time. Using this protocol, network traffic estimation is improved as a trend prediction capability and it also changes the network's duty cycle. Also, the coordinator node is selected and predicted by the next superframe order.

Another protocol in [17] has proposed the usage of MAC tuning parameters and service cycle-based tuning to form a Tele-medicine Protocol. This protocol is appropriate for patient monitoring applications that have minimal delay and adequate reliability. The computing and functional methods on which this protocol is built and based are the delay reliability factor, channel access, network traffic estimation and collision probabilities.

However, considering the energy-saving benefits of the duty-cycle protocols, certain limitations have been placed in the sense of the provision of a consolidated collection of QoS. Next to the superframe, all previous studies boost superframe order and all information is determined by the coordinator. Those methods can result in high collision rates, and the excess of the allocation of coordinator slots is not captured with the utmost optimal knowledge.

B. *Backoff-Based Approaches*

These approaches concentrate on improving the performance of IEEE 802.15.4 MAC by designing new back-off algorithms that can more effectively control medium access nodes. Many of these approaches manage to make the method of back-off more adaptive and dynamic [21], [22], [15].

Slotted CSMA / CA output is largely regulated by four parameters: macMaxBE, macMinBE, CW and Maximum Backoff Number (macMaxCSMAbackoffs). IEEE 802.15.4 showed a fixed number of backoffs where the real value of macMaxBE = 5 and macMinBE= 3. Variations in these values can influence the implementation of the network. Reducing the values for macMaxBE and macMinBE would decrease the waiting time of the node. On the other hand, where a node attempts to enter the channel with less waiting time, throughput would increase.

The authors in [23], suggested an efficient back-off algorithm to decrease collisions and enhance energy efficiency. In conjunction with the likelihood of a collision, it updates the contention window size and uses temporary backoff and the next temporary backoff during the actual backoff duration. The likelihood of a collision, however, does not accurately represent the degree of contention for channel access.

The authors in [24], suggested dynamic backoff scheduling based on fuzzy logic for low data rate applications in WBAN according to the input parameters such as node data rate and history of previous tests carried out to back off resolution in the IEEE 802.15.4 MAC sublayer make access equal for channel access and make it possible for sensor nodes in heterogeneous networks to zanalyze the isolated data rate values and their channel access success rate during previous tests. Owing to the contention-based process, this scheme is not ideal for high data rate WBAN nodes.

The authors in [25] proposed a Backoff Counter Reservation (BCR) scheme in BCR and the coordinator forecasts the next MAC payload backoff value for each transmission. Therefore, the coordinator knows each sensor's next back-off period and controls the transmission of data since it avoids delays and collisions between the sensor nodes. Subsequently, when the data frame does not arrive at the expected transmission slot, the coordinator assigns a GTS to every sensor node in the next superframe. The coordinator node must check to send an acknowledgement packet to the sensor node any time after receiving the future backoff value.

In ABM method [26], the author suggested an adaptive contention window MAC protocol to provide better performance under a heavy load. To represent the contact status and wireless channel use, this protocol selects from the background of the collision. A vast collision represents greater competition in the wireless channel and based on this situation, a large contention window is required. The authors claimed to extend the access time to get rid of the competition. However, when the traffic load is dense, this exponential rise in speed may potentially lead to avoidable delays. This protocol could also lead to a heavy traffic load that causes latency.

However, the methods mentioned above chiefly focused on adjust the backoff approach some of them Adaptive CW selection algorithms are most commonly used in (CSMA/CA) to improve throughput and fairness and to reduce the delay and the collision probability. At the same time, a standard set of QoS parameter optimization is essential for BSN medical applications. Besides, decision information is obtained from the node.

V. CONCLUSION

BSN is still a relatively young technology that influences the development and advancement in healthcare applications that to contributes to advances the future of health applications. In this paper, we briefly explain several implementations of BSN in the field of non-Medical and Medical to monitors and observe the biological signals from the human body. The medics can identify, detect, and diagnose the human body by tracking the sensor nodes that are connected to their bodies. Also, we deliberated on the network architecture with many nodes that are working as sensors in medical science to investigates patient health. And we conducted a deep-rooted review on the set of necessities suggested for processing BSNs as the IEEE 802.15.4 standard. The research community is focusing on enhancing the IEEE 802.15.4 MAC and tries to mitigate its shortcomings. To minimizes these issues, many beacon-enabled optimization approaches have been developed together with MAC protocol parameter tuning-based, duty cycle-based, cross layer-based, QoS-based, backoff-based, and priority-based. But there is still a need for an efficient technique to overcome these rising issues related to the IEEE 802.15.4 MAC protocol.

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