Does the IEEE 802.15.4 MAC Protocol Work Well in Wireless Body Area Networks?

Sabita Nepal, Saurav Dahal, and Seokjoo Shin

***Abstract*—The IEEE 802.15.4 MAC protocol is the standard for Low-rate wireless personal area networks and is widely used in testbeds and simulation for wireless body area networks. Due to effective handling of some features such as low power communication and low data rates, this protocol is widely used for WBAN applications. However, it is not enough to support high data rates applications (>250 Kbps). In this article, feasibility of IEEE 802.15.4 MAC in the areas of Wireless Body Area Network (WBAN) will be studied. By presenting the challenging issues of WBAN and by giving extensive reasoning, it can be concluded that IEEE 802.15.4 MAC can be used in WBAN to some extent but to guarantee near optimum result, still some modifications are required.**

***Index Terms*—IEEE 802.15.4, low-rate WPAN, MAC, WBAN.**

I. Introduction

Wireless Body Area Networks (WBANs) has emerged as a key technology to provide real-time health monitoring of a patient and diagnose many life threatening diseases. For the standardization of WBAN a Task Group called IEEE 802.15.6 is established by IEEE 802. The purpose of this group is to establish a communication standard optimized for short range, wireless communication in or around the human body [1].

WBAN is one of the rapid advancements of wireless communications connecting various sensor nodes within a wireless network. Although WBAN is relative to WPAN, WBAN provides closer interconnection (2-5 meters) with more strict technical requirements such as the high reliability, extreme power efficiency and security, especially the safety for human body. Unfortunately, more protocol details are hidden in current version of IEEE 802.15.6 standard; it is a better way to design a new WBAN system based on IEEE 802.15.4 standard, which is mature protocol and has been applied in many fields.

Due to the low energy consumption, lower cost, and reliable data transmission features, IEEE 802.15.4 provides a solution for low-rate low-power WPAN in the personal operating space (POS) of 10 meters, typically sensor network [2]. IEEE 802.15.4 has attracted plenty of interests both from academia and business, since the release of first version in 2003. IEEE 802.15.4 standard is widely used for WBAN because of its features such as energy efficiency, scalability, and design flexibility. However, it is unable to meet all the stringent network requirements of BAN yet. IEEE 802.15.4 is challenging, especially when the time critical emergency events are to be reported. IEEE 802.15.4 doesn't differentiate the time criticality of the monitored events and hence doesn't provide any preferential access for emergency devices while accessing the shared wireless channel. Hence, different MAC Protocols are designed to maximize throughput, reduce latency, save energy, and ensure fairness, based on IEEE 802.15.4.

In this paper, IEEE 802.15.4 standard is considered as a candidate for low bit rate WBAN applications and present a short review of different modified MAC. The main objective is to answer a question concerning the performance of IEEE 802.15.4 MAC Protocol over a WBAN.

The rest of this paper is organized as follows. Section II briefly describes the IEEE 802.15.4 MAC protocol. Section III describes the challenges of WBAN and State of Art of existing IEEE 802.15.4 MAC Protocols are discussed in Section IV. Finally Section V gives a conclusion of the paper.

II. An Overview of the IEEE 802.15.4 Standard

The IEEE 802.15.4 standard is a low-power standard designed for low data rate Wireless Personal Area Network (WPAN), low power consumption, low hardware cost features [2] and is quite flexible for a wide range of application. Ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life are the main objectives of a Low Rate-WPAN [2]. The standard provides only the physical (PHY) layer and the medium access control (MAC) layer specification. In particular, it defines two PHYs representing three license-free bands that include sixteen channels at 2.4 GHz, 10 channels at 902 to 928 MHz and 1 channel at 868 to 870 MHz with maximum data rates of 250 Kbps, 40 Kbps and 20 Kbps, for each band respectively [3].

There are two different device types in IEEE 802.15.4 network, a full-function device (FFD) and a reduced-function device (RFD). The FFD can work as a personal area network (PAN) coordinator and can talk to FFD or RFD while an RFD can only talk to its FFD and can be implemented using minimum capacity and resources.

IEEE 802.15.4 LR-WPAN may operate either in star topology or peer-to-peer topology. The communication is established between devices and a single central controller, called the PAN coordinator in star topology. The peer-to-peer topology also has a PAN coordinator; however, it differentiates from star topology such that any device may communicate with any other device as long as they are in

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range of one another.

A. IEEE 802.15.4 MAC Layer

The MAC sub-layer is the second layer specified in the standard. It mainly provides two services, data and management service, both accessible through different interfaces. The MAC layer protocol supports two operational modes as shown in Fig. 1 [2].

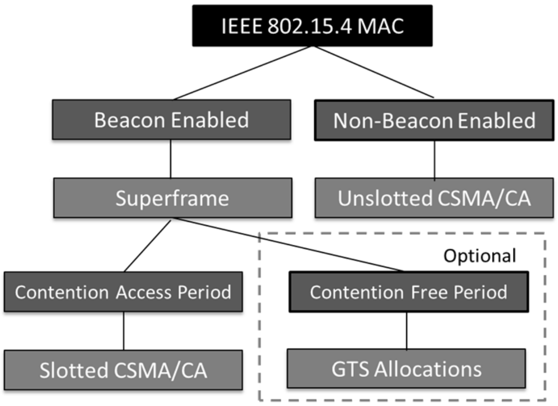

Fig. 1. IEEE 802.15.4 operational modes.

The non-beacon-enabled mode: During this mode, there exist neither beacons nor superframe and medium is accessed by an unslotted CSMA/CA mechanism.

The beacon-enabled mode: In this mode, beacons are periodically sent by the PAN coordinator for synchronization and association control of the nodes associated with it, and to identify the PAN. A superframe is always initiated by the beacon frame that defines a time interval during which frames are exchanged between different nodes in the PAN. Medium access is basically ruled by the slotted CSMA/CA. However, the beacon-enabled mode also enables the allocation of contention free time slots, called Guaranteed Time Slots (GTSs) for the nodes requiring guaranteed bandwidth.

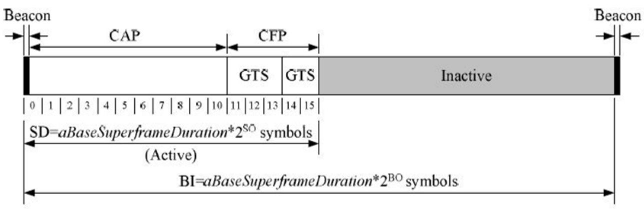

Fig. 2. IEEE 802.15.4 superframe structure.

In beacon-enabled mode, each coordinator defines a superframe structure as shown in Fig. 2 based on:

- *Beacon Interval (BI)*, which defines the time between two consecutive beacon frames;
- *Superframe Duration (SD)*, which defines the active portion in the BI, and is divided into 16 equally-sized time slots, during which frame transmissions are allowed.

Optionally, an inactive period is defined if BI > SD. During the inactive period (if exists), all nodes may enter into a sleep mode to save energy. BI and SD are determined by two parameters, the Beacon Order (BO) and the Superframe Order (SO), respectively, as follows:

$$BI = aBaseSuperframeDuration * 2^{BO}$$

$$SD = aBaseSuperframeDuration * 2^{SO}$$
$$Inactive\ Period = BI - SD$$

where, $0 \leq SO \leq BO \leq 14$, and

$$aBaseSuperframeDuration = 960\ symbols$$

GTSs are allocated as per request by PAN Coordinator if there are available resources. It allocates up to 7 of them which may contain one or more time slots either in transmit or receive direction. The allocation of the GTS cannot reduce the length of the CAP to less than aMinCAPLength (440 Symbols). Note that a device to which a GTS has been allocated can also transmit during the CAP. During the inactive period, each device may enter into a low-power mode to save energy.

III. Challenges in WBAN

This section highlights the main design challenges of WBANs. Due to their special properties such as size, data rate, reliability, security, QoS requirements, transmission range etc., they require special design adjustment to meet their particular needs. The most essential function of WBAN is to efficiently deliver reported information from a certain application. Effective communication is described as reliable, secure, fast, fault-tolerant, scalable, interference-immune, and low power data communication.

Wireless body area networks have diverse functions and demand strict network requirements, which make it different from other WPANs applications. There are lots of issues which still need to address, and still many problems require better solution. There are many factors which need to be considered while implementing WPAN based BAN application systems [4], [5]. Some of them are listed as follows:

A. Heterogeneous Traffic

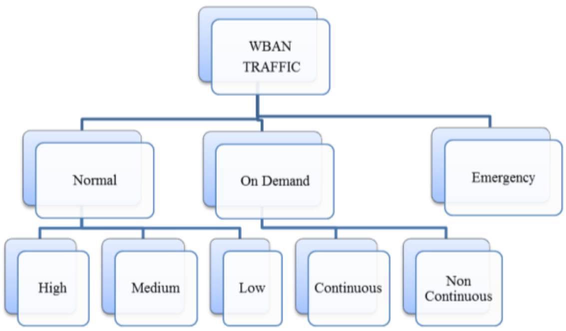

Fig. 3. Classification of traffics.

Wireless body sensor networks (WBSN) and wireless body area networks (WBAN) have been widely applied in ubiquitous healthcare systems that are capable of monitoring human body dynamic health conditions and transmit sensor data in real-time and reliable manner. In WBSN and WBAN, sensor nodes have different bandwidth requirements, therefore heterogeneous traffic is created. The entire WBAN traffic is categorized into three groups: Normal, On-demand, and Emergency traffic as shown in Fig. 3 [6]. WBAN should handle all these diverse traffics. As WBAN is related to human health, efficient and quick response to emergency as well as on demand traffic is needed.

B. Interoperability

Depending on the application types, the sensors in WBAN application can be wearable on the body surface and also can be implanted inside the body. These sensors hence can operate on different frequency bands and PHY layers. So, the sensors must be interoperable at multiple frequency bands and support multiple physical layers (PHYs).

C. Latency

Wireless body area network contains emergency data which can be life critical, if is not responded quickly. The delay requirement for medical data is no greater than 125ms. So, latency is a one of the important factor which needs to be considered in WBAN.

D. Scalability

Scalability of the network refers to capability of the network to add or remove at least one or more nodes without any overheads. Random access MACs like contention based CSMA/CA MACs provides good scalability than the rigid TDMA based MACs. Similarly, scalability can also be referred to handling of different heterogeneous traffics and variable data rates. The WBAN MAC must be scalable for both the periodic and non-periodic data. Most of the time physiological information from nodes is normal but often in case of emergency the data are non-periodic and bursty in nature [7].

E. Energy Efficiency

Sensor nodes in WBAN are powered by batteries. Once nodes are implanted inside the body, batteries should be durable for a longer period since they cannot be easily replaced. Hence, energy conservation is an important attribute. The main sources of energy depletion are the activities of radio such as idle collision, idle listening, over hearing, control packet overheads, frequent nodes synchronization etc.

F. Security and Privacy

WBAN has provided to help in real-time health monitoring of a patient and diagnose many life threats diseases. So, the data collected from a BAN application system or during their transmission outside of wireless BAN must be highly secured and maintain the highest degree of privacy protection. The alteration in data could lead to serious problems. The sensors devotedly employed for a person only should generate the data for that patient. The data transmission over the networks should be secured and accurate. It requires a high system level and device level security [8].

G. Quality of Service (QoS)

QoS is another attribute to be considered while designing MAC. MAC level QoS includes the communication range, throughput, and reliability, delay variations etc. Since the WBAN nodes are either implanted inside the human body or worn on human body, the nodes must support the simultaneous operations.

H. Co-existence and Interference Mitigation

Multiple WBAN applications may exist in a confined area like a hospital room. In that condition, there can be a high chance of interference between the wireless networks in a user standing next to each other or even the possibility of colliding signal within user itself. In order to prevent from data collision due to interference, these networks must co-exist without any interference between them. And, the wireless link should also increase the coexistence of sensor node devices with distinct network devices available in the environment.

Besides these, there are other challenges like node size, date rates, throughput etc. In order to design an appropriate MAC protocol, all above attributes need to be considered.

IV. State of Art of Existing IEEE 802.15.4 MAC Protocol

Over the past decades, a number of MAC protocols have been researched and proposed based on IEEE 802.15.4, such that it can fulfill the requirement of WBAN. Among these proposed protocols, the majority are focused on QoS provisions [9]-[18]. Very few studies deal with the subject of emergency handling [13]-[15] for WBAN. Some of them have focused on saving energy [19]-[23].

As WBAN technology gains worldwide interests, considerable research efforts are dedicated to propose new MAC protocols based on 802.15.4 in order to satisfy the stringent requirements of WBAN. In [9], the authors presented a priority guaranteed MAC protocol, where the data and the control channels are split to support collision-free high data rate communication. Application specific control channels are adopted to provide priority guarantee to the life-critical medical applications from much busier CE traffic. Improvements on throughput and energy efficiency are achieved from this MAC protocol.

Eui-Jik *et al*. [11] have proposed a mechanism for IEEE 802.15.4 to provide traffic differentiation scheme based on the contention window (CW) size and Backoff Exponent (BE). In this scheme, higher-priority-class nodes have the lower CW and BE values than others. CW effect more on the saturation throughput while BE is affected more by the average delay of every device. So, tuning of the throughput could be performed by varying backoff exponent while the better throughput could be performed by adjusting contention window size.

Kwak and Ullah have proposed a traffic-adaptive MAC for handling emergency and on-demand traffic, in which a table is maintained to store the traffic patterns of the nodes [12]. It also consists of configurable contention access period (CCAP) but rest of the superframe parts resembles the conventional IEEE 802.15.4 MAC. This superframe helps to solve the idle listening and overhearing problems by exploiting the traffic information of the nodes.

B. Kim *et al*. [13] focus on the emergency handling schemes for WBANs. They proposed a superframe structure with Mixed Period (MP) and Extended Period (EP). In MP, CAP slot called the contention time slot (CTS) is inserted in front of GTS for immediate transmission of emergency data, while EP consists of an extending request period (ERP), a re-allocated CFP, and an additional CAP. EP guarantees transmissions of failed slot in MP at reallocated CFP. MP and EP can handle emergency data with low latency.

C. Lee, H. S. Lee and S. Choi have proposed an enhanced MAC protocol of IEEE 802.15.4 for health-monitoring application with an enhanced superframe structure containing polling period (PP) and an emergency slot (ES) for emergency handling [14]. ES is a quite short period where data transmission is described by success or fail. The protocol contains a long CFP and inactive period follows the CFP.

J. S. Ranjit, S. Pudasaini and S. Shin have also proposed an emergency-handling MAC protocol for health-monitoring application using ERP period and Emergency beacon. This superframe handles the emergency traffic by minimizing the delay by sending the data in the same superframe instead of next superframe [15].

LDTA-MAC [16] protocol improves some of the shortcomings of IEEE 802.15.4. The guaranteed time slots (GTSs) are not fixed, allocated dynamically based on traffic load. And also on successful GTS request, data packets are transmitted in the current superframe.

PNP-MAC [17] protocol is based on IEEE 802.15.4 superframe structure. It can flexibly handle applications with diverse requirements through fast, preemptive slot allocation, nonpreemptive transmission, and superframe adjustments. This MAC inherits the best breeds of contention-based and contention-free medium access techniques, hence supports various types of traffics: continuous streaming, periodic data, time-critical emergency alarm, as well as non-periodic data. It supports QoS in accordance with priority of traffics.

Authors proposed an OCDP-MAC [18] protocol for contention-based medical and CE applications. To support bursty CE data and emergency medical data, the proposed WBAN MAC protocol provides a temporary switching method between the Inactive period and the Opportunity period through OCDP (opportunistic contention decision period), and 4-mode opportunity period.

In [19], authors proposed a battery-aware TDMA based MAC protocol with cross-layer design to maximize network life. This protocol takes the following parameters into account for medium access: electrochemical properties of battery, time varying wireless fading channel, and packet queuing characteristics.

In [20], authors proposed a new MAC protocol based upon centrally controlled wakeup and sleep mechanisms to maximize energy efficiency. Some upper layer functionalities are incorporated to reduce power dissipation due to overhead. This protocol is based upon basic assumption of sensor nodes with a star topology where a central node (master node) coordinates with on-body/implanted sensor nodes (Slave nodes).

In [21], authors proposed a Body MAC, which is a TDMA-based MAC protocol where they define uplink and downlink subframes to facilitate sleep mode with emphasize on energy minimization. Different data communication models are accommodated using bandwidth management procedures which are efficient and flexible to improve network stability and transmission of control packets.

In [22], authors proposed Medical Medium Access Control (MedMAC) protocol for WBANs to improve channel access mechanism and reduce energy dissipation. This protocol include: contention free channel access over a variable number of TDMA channels; energy efficient and dynamically adjustable time slots; a novel adaptive and low-overhead TDMA synchronization mechanism; optimized energy efficiency by dynamically adjusting the QoS requirements using ongoing traffic analysis; and optional contention period used for low grade data, emergency operation, and network initialization procedures.

In [23], authors proposed Reservation-based Dynamic TDMA Protocol (DTDMA) for medical body area networks (MBAN). This protocol provides more dependability in terms of low packet dropping rate and less the power consumption especially for an end device of a MBAN.

Table I shows the overall comparison of existing IEEE MAC protocols. The comparisons of these protocols have been done using the various headings like Topology, Application, Access Mechanism, Traffics, Superframe, Priority Handling and Performance Measures. Topology defines the formation of the nodes in which this MAC can be applied. Application gives the environment which the MAC supports. The procedure to handle different types of data is given by Access Mechanism. The types of data supported by various MACs are tabulated under Traffics. Superframe gives the structure of MAC while methods to handle different kind of priority are given by Priority Handling. Under Performance Measures, Energy Saving, Throughput and Delay are listed for different MACs.

V. Conclusion

This article presents the detail review and comparison of the existing IEEE 802.15.4 standard MAC protocol to answer whether the IEEE 802.15.4 MAC Protocol Work Well in Wireless Body Area Networks or not. By presenting the several challenges of WBAN, in section III, and revealing their underlying mechanisms, we can conclude that IEEE 802.15.4 MAC can be used in the areas of WBAN according to the requirement of the WBAN. In the entire stated MAC, it is seen that, all of the MACs are not able to handle the diverse traffics of WBAN such as emergency traffic, CE traffic etc. More efficient MAC protocol need to be developed in order to reduce the delay, increase the throughput and handle different types of traffic. The existing MAC protocol has only focused on the emergency traffic handling and QOS. There is still lack of energy efficient MAC. To handle the emergency traffic, most of the MACs are designed to use the inactive period, which increases the power consumption of the node.

Each MAC has its own characteristics. Some are designed for priority handling, some are designed to provide QoS, and others are designed for emergency efficiency and so on. Requirements of all aspects usually cannot be satisfied simultaneously.

Due to diverse application requirement and hardware constrains, no one protocol is being accepted as a standard. A new protocol needs to be developed to achieve requirements of WBANs like energy efficiency, scalability, fairness, reduced implementation complexity, support for diverse application, reduced synchronization overhead, and QoS. Although one particular MAC cannot fulfill all the requirements of WBAN, there are various MACs which can fulfill different requirements. Thus, it can be concluded that, the IEEE 802.15.4 MAC is feasible in WBAN as long as it can fulfill the requirement of WBAN.

TABLE I: COMPARISON OF EXISTING MACS

Related MACs	Topology	Application	Access Mechanism	Traffics	Superframe	Priority Handling	Performance Measures		
							Energy Saving	Throughput	Delay
Priority Guaranteed MAC [9]	Star	Medical + Nonmedical	Randomized Slotted ALOHA	Periodic + Bursty	Beacon+TSRP+AC1+AC2 +TSRB+ Inactive	Dedicated Control and data channels for both applications	Efficient	Good	Low
Priority-based service differentiation MAC [11]	star	Medical + Nonmedical	Prioritize CSMA/CA based on contention window and backoff exponent	Prioritize Traffic	Beacon +CAP + CFP + Inactive Period	Different priority classes by differentiating contention window and backoff exponent size	Not stated	good	Low
TaMAC [12]	Star	Not stated	Slotted ALOHA	Periodic+ On-demand Emergency	Beacon + CCAP +CFP(GTS)	Radio Wakeup for emergency/on-demand traffic	Efficient	Not stated	Low
Emergency Handling MAC[13]		Medical + Nonmedical	Contention Based CSMA/CA	Emergency + CE	CAP+MP(CTS+GTS)+Inactive Period/EP	Mixed Period and Extended Period for emergency handling	Consumes more energy	Not stated	Low
Enhanced MAC [14]	Not stated	Medical + Nonmedical	Contention Based CSMA/CA	Periodic+ Emergency	primary beacon (PB)+ polling period (PP)+ emergency slot (ES)+CAP +secondary beacon (SB)+ contention free period (CFP)+Inactive Period	Emergency data are transmitted through ES period	Not Stated	Not Stated	Low
Emergency Reporting MAC [15]	Star	Medical	Contention Based CSMA/CA	Regular normal signs(RNS) + Occasional Emergency Signs(OES)	Beacon +CFP+ERP+ (EB+ETB) Inactive period	Emergency Reporting Period (ERP) is used for emergency traffic	Not stated	Not stated	Low
LDTA-MAC [16]	Star	Medical	Contention Based CSMA/CA	GTS traffic	Beacon + CAP + CFP + notification frame + extended CFP + Inactive Period	GTSs are dynamically allocated.	Consumes less energy	High	Low
PNP-MAC [17]	Star	Medical + Nonmedical	Hybrid based CSMA/CA and TDMA	Continuous streaming + periodic+ time-critical emergency alarm+ non-periodic data	Advertisement+ CAP+ beacon+ DTS+ETS+ inactive period/ECAP	ETS is reserved for urgent delivery of unpredictable emergency data	Not stated	Not stated	Low
OCDP-MAC [18]	Mesh	Medical + Nonmedical	Contention Based CSMA/CA	Bursty CE data + Emergency data	Beacon + CAP + GTS + OCDP + Inactive Period/4-mode opportunity period.	OCDP determines to use Inactive period for emergency	Not stated	Not stated	Low
Battery-aware TDMA MAC [19]	Not stated	Medical	TDMA	Not stated	Beacon+ active time slot+ Inactive period	Not stated	Efficient	Good	Not stated
BodyMAC [21]	Star	Medical	CSMA/CA	On-demand + Normal traffic	Beacon+ Downlink+ Uplink (CAP+CFP)	No emergency handling	Efficient	Not Stated	Low
MedMAC [22]	Star	Medical + CE Applications	Slotted ALOHA	Class 0 Class 1 Class 2 and Emergency	Beacon + Optional Contention Period+ Contention free period	TDMA slots can be overridden for emergency data transmission	Efficient	High	Not stated
DTDMA [23]	Not stated	Not stated	Dynamic TDMA	Normal	Beacon + CFP + CAP + Inactive Period	Not stated	Not Stated	Not Stated	Not Stated

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