A Study on the Wireless Body Area Network MAC Protocol Using Dynamic Superframe for e-Health IoT

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Abstract. One of the most remarkable applications of the Internet of Things is health monitoring. Wireless body area networks (WBANs) consist of several body sensors implanted in or place on a human body and a coordinator. One of the essential issues of WBANs is the design of Medium Access Control (MAC) protocol to improve system efficiency. In this paper, we modify the IEEE 802.15.4 standard MAC superframe structure and propose an energy-efficient MAC protocol for WBANs in the e-Health Internet of Things (IoT) systems. In this scheme, the time slots are divided into mini-slots. The lengths of the contention access period and the contention free period are both variable. By using this mechanism, the utility of time slots can be considerably increased.

1. Introduction

Wireless body area network (WBAN) is one of the prospective technologies for wearable health monitoring systems, which can detect early abnormal situations and prevent grievous consequences. WBANs consist of multiple structured body sensor nodes, which are implanted in or place on the human body [1]. These nodes can sample, process, and communicate body signs. The continued health data gathering benefits the patients maintaining an optimum condition of chronic diseases or supervising healing of an acute illness [2].

The specification for the Medium Access Control (MAC) layer divides the channel into superframes, which are held at both ends by the beacons. The MAC layer protocols control the channels and time resources of the network and manage the access of network channels. It is an essential part of how the network resources, such as channels and time slots, are used by the nodes. Sensor node batteries of WBANs have lower capacity due to size constraints. They cannot be recharged or replaced conveniently. As a result, in the design of the WBAN MAC protocol, energy consumption and efficiency should be considered. In addition, the body sensors are heterogeneous, which gather and send out different classes of data. These various kinds of data packets have disparate Quality of Service (QoS) and Quality of Experience (QoE) requirements. To improve the system efficiency and QoS, the network protocols should be designed properly. The MAC layer protocols take charge of the access of the network channel. The MAC protocol plays a critical role in energy efficiency, the utility of the network resource, and network performance, such as throughput and transmission rate. The energy efficiency can increase if we improve the time slots utilization, diminish the beacon and data collision, and reduce the idle time. Also, the network QoS like network delay, fairness, jitter, and throughput need to be improved. Diverse applications and various types of data must support a flexible MAC protocol.
In this paper, we modify the IEEE 802.15.4 standard [3] MAC superframe structure and design an energy-efficient MAC protocol for WBANs in medical IoT systems. In this scheme, the time slots are divided into mini-slots. The lengths of the superframe, the contention access period (CAP), and the contention free period (CFP) are all variable. By using this mechanism, the utility of time slots can be considerably increased. The remainder of the paper is structured as follows. Section 2 is the related work. In section 3, the IEEE 802.15.4 MAC protocol is briefly introduced. In section 4, we propose the variable MAC protocol. Section 5 concludes the paper.

2. Related Works
WBAN has acquired increasing interests in both academia and industry. There are several existing MAC protocols for WBAN as a practicable model for future e-Health systems. In the literature [4], Zhang et al. propose a MAC protocol called MEM-MAC for the application of medical emergency monitoring. In this scheme, the length of the active period and the duty-cycle are depended on the condition of application data traffic. Using this mechanism, if the sensors seldom generate data, the duty-cycle will be short, letting the nodes staying in the sleeping mode for a longer time. On the other hand, the body sensor nodes can wake up instantly if an emergency happens. To transmit the emergent data, the body sensor nodes may keep in the active period for a longer time. Thus the duty-cycle gets higher, careless of energy-efficiency. After transmission of emergent data, nodes will turn back to the normal situation. The length of duty-cycle is recalculated and configured shorter. The system turns to energy-saving mode during the sleeping period of sensors. The standard superframe structure is changed to accommodate the application traffic. In the literature [5], Pandit et al. design a MAC protocol called TaMAC for cluster-tree topology, in which several sensors form clusters. The cluster headers (CHs) gather the data from the sensor nodes, which have more energy capacity and computing resources than body sensor nodes. The management algorithm is performed by the cluster headers. It can monitor the application traffic patterns. The duty-cycle can be adapted according to the traffic patterns. During the nodes’ inactive period, if there is any emergency and on-demand requirement, the cluster header will send out the wake-up control frame to the sensor nodes. However, since TaMAC is adapted based on the slotted ALOHA MAC protocol, the probability of collision gets higher if many sensor nodes are attempting to transmit data simultaneously. A higher collision rate will raise the cost of retransmission.

In the literature [6], Javaid et al. and other authors design an adaptive MAC protocol based on the TDMA scheme. Nodes are arranged to different time slots for data transmission. System synchronization is needed for time management to moderate collisions. In this protocol, the gateway allocates the time slots to the cluster headers. The cluster headers arrange the beacon slots to each sensor nodes exclusively. Since the sensor nodes transmit their data in different time slots, the probability of collision can be reduced. However, in this mechanism, to gather information to avoid beacon collision, the system needs a long process to start-up. Moreover, this protocol cannot avoid the beacon collision completely among the cluster headers. In the literature [7], an optimal data transmission protocol considering body shadowing is proposed. In the protocol, the data is sent to the access gateway through the relay nodes. However, there are some limitations to this scheme. It requires that the system duty-cycles should be lower. The relay nodes cannot communicate directly with the parents. In the literature [8], Nepal et al. present an emergency handling mechanism. In this protocol, the active period is used in the case of an emergency. Different time circles are arranged to different cluster headers. However, in this scheme, cluster headers need to wait for several beacon intervals (BIs) for sending another beacon, which lengthens the beacon and data delay. The sensor node may lose time synchronization due to the delay of beacon frames.

3. Overview of IEEE 802.15.4 Standard MAC Protocol
In the IEEE 802.15.4 standard, there are two modes of MAC protocol: the beacon-enabled and the non-beacon-enabled mode. It cannot provide the time synchronization service due to no beacon frame. It also has a higher power consumption than the beacon-enabled mode. For this reason, we will study the beacon-enabled mode.
In the beacon-enabled mode, the coordinators send beacon frames to the nodes which are associated with it periodically to maintain synchronization. The superframe structure is shown in figure 1. The active period of the superframe is composed of 16 time slots. It has three portions: the beacon frame, the contention free period (CFP), and the contention access period (CAP). During the inactive period, the sensor nodes and coordinator turn into a low-energy sleep mode.

\[ BI = a_{\text{BaseSuperframeDuration}} * 2^{BO} \quad (0 \leq BO \leq 14) \]
\[ SD = a_{\text{BaseSuperframeDuration}} * 2^{SO} \quad (0 \leq SO \leq BO \leq 14) \]
\[ a_{\text{BaseSuperframeDuration}} = a_{\text{BaseSlotDuration}} \times a_{\text{NumSuperframeSlots}} \]

4. MAC protocol based on mini-slot and variable superframe

In this section, we consider the wireless body area networks MAC protocol design problem and propose a mechanism based on mini-slot and variable superframe. This protocol can improve the utilization efficiency of time slots, reduce the probability of data collision, and enhance network performance. This method adopts the beacon-enabled mode to realize synchronization. It is based on the aforementioned IEEE 802.15.4 standard MAC protocol. Time is divided into equal interval periods, called superframe, which is defined by beacon frame sent by WBAN coordinator. As shown in figure 2, the superframe includes the active period and inactive period. Coordinators send beacon frames in the beacon period. Sensor nodes transmit and receive data in the active period, and switch to low-power mode in the inactive period for saving energy. The GTSs are allocated to sensor nodes to send critical data. In the CAP, carrier sense multiple access with collision avoidance (CSMA/CA) protocol is used to access the channel.

To improve the utility of time slots, each time slot is divided into several mini-slots. The number of mini-slot in one slot depends on different applications. Time slots are used to transmit data frames with a heavy load, while mini-slots are used to transmit control frames and light load data frames. To adapt to different application scenarios, the number of time slots in the CFP and the CAP is also variable, which can be dynamically adjusted according to the service conditions. When a sensor node has requirements for real-time services, it will send a GTS request to the coordinator during the CAP of the superframe.
current superframe. After receiving the GTS request, the coordinator sends back an optional acknowledgment frame and then checks whether there are GTS resources available for allocation in the current superframe. If the resources are sufficient, the coordinator will allocate the time slots or mini-slots to the sensor node according to the service priority and the data frame length. The coordinator puts the GTS allocation information into the beacon frame of the next superframe and informs the sensor node by broadcasting. After the GTS request successes, the node stays waiting until it receives the beacon frame containing the GTS allocation information. The sensor nodes begin to transmit data in the allocated GTS in the superframe.

The length of the CFP is variable, which depends on the GTS request of the sensor nodes in the previous superframe. If there is no GTS request in the previous superframe, the length of the CFP is 0. In addition, it takes a certain time for the MAC sublayer to process the data received from the physical layer. Therefore, there should be an appropriate time interval between two frames, whose length depends on the length of the previous transmission frame. The interval time between frames must be considered in using CSMA/CA protocol to transmit data in CAP.

5. Conclusions and Future Work
In recent years, the applications of WBANs have developed rapidly. The design of the MAC protocol of WBAN is an important challenge due to the limited battery capacity of body sensor nodes. We modify the IEEE 802.15.4 standard MAC superframe structure, and design a MAC protocol for WBANs. The performance evaluation based on model analysis and testbed experiments will proceed in future work.

Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grant No. 61901099 and the Natural Science Foundation of Hebei Province under Grant No. F2020501037.

References
[1] Zhang H, Li J, Wen B, Xun Y, and Liu J 2018 Connecting intelligent things in smart hospitals using NB-IoT. *IEEE Internet Things Journal* vol. 5, no. 3, pp. 1550–1560
[2] Khan R A, Pathan A S K 2018 The state-of-the-art wireless body area sensor networks: a survey. *International Journal of Distributed Sensor Networks*, vol. 14, no. 4, pp. 1-23
[3] IEEE-TG15.4 2006 Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs), IEEE standard for Information Technology.
[4] Zhang C, Wang Y, Liang Y, et al. 2016 An energy-efficient MAC protocol for medical emergency monitoring body sensor networks. *Sensors* vol. 16, no. 385, pp. 2–19
[5] Pandit S, Sarkar K, Razzaque M A, et al. 2015 An energy-efficient multiconstrained QoS aware MAC protocol for body sensor networks. *Multimedia Tools and Applications* vol. 74, no. 14, pp. 5353–5374
[6] Javaid N, Ahmad A, Rahim A, et al. 2014 Adaptive medium access control protocol for wireless body area networks. *International Journal of Distributed Sensor Networks* vol. 10, no. 3, pp. 156–160
[7] Argyriou A, Breva A C, and Aoun M 2015 Optimizing data forwarding from body area networks in the presence of body shadowing with dual wireless technology nodes. *IEEE Transactions on Mobile Computing* vol. 14, no. 3, pp. 632–645
[8] Nepal S, Pudasaini A, Pyun J, Hwang S, Lee C G, and Shin S 2016 A new MAC protocol for emergency handling in wireless body area networks. *Proc. IEEE Ubiquitous and Future Networks (ICUFN)*, pp. 588–590