LETTER *Special Section on Information and Communication Technology for Wellness and Medical Applications*

A Dynamic CFP Allocation and Opportunity Contention-Based WBAN MAC Protocol*

Young-Sun SEO[†], **Dae-Young KIM**[†], *Nonmembers, and* **Jinsung CHO**[† a)], *Member*

SUMMARY WBANs provide communication services in the vicinity of the human body. Since WBANs utilize both MICS frequency band for implant medical applications and ISM frequency band for medical and consumer electronics (CE) applications, MAC protocols in WBAN should be designed considering flexibility between medical and CE applications. In this letter, we identify the requirements of WBAN MAC protocols and propose a WBAN MAC protocol which satisfies the requirements. In order to provide transmission flexibility for various applications, we present the dynamic CFP allocation and opportunity period. Extensive simulation results show that the proposed protocol achieves improved throughput and latency in WBAN environment compared with IEEE 802.15.4.

key words: *wireless body area networks, MAC, hybrid MAC, CFP allocation, contention-based protocol*

1. Introduction

Recent attentions to healthcare and lifecare have provided driving forces behind wireless personal area network (WPAN) studies. A wireless body area network (WBAN), which functions around, on, or in a human body, becomes the next generation of wireless technology for the WPAN [1]. WBAN consists of a coordinator, medical devices, and consumer electronics (CE) devices [2]. It can provides various ubiquitous services.

IEEE constructed IEEE 802.15.6 TG for standardization of WBAN on November, 2007 [1], [2]. The IEEE 802.15.6 allows simultaneously both medical and CE applications. It provides a flexible data rate of 10 kbps to 10 Mbps as well as a very short transmission range of at least 3 m with low power. In addition, the IEEE 802.15.6 considers both MICS (Medical Implant Communications Service) and ISM (Industrial Scientific Medical) as frequency bands.

In general, medical applications have periodic characteristics with a low data rate. On the other hand, CE applications are event-driven in nature with a high data rate such as entertainment video clips. Therefore, WBAN should support both medical and CE devices simultaneously. However, existing MAC protocols (i.e., TDMA or IEEE 802.15.4 MAC), which are being used in a body sensor network, do not satisfy the requirements in the specification of the IEEE 802.15.6.

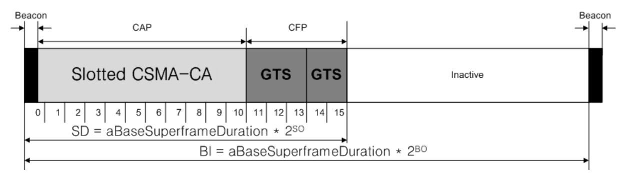

Fig. 1 Superframe structure in IEEE 802.15.4.

TDMA was studied in early stage of WBAN researches, which considered only medical sensor devices [3]. When WBAN consists of various devices with different characteristics, TDMA may not be adequate.

IEEE 802.15.4 [4] uses a superframe structure in a beacon-enabled mode as shown in Fig. 1. The superframe duration (SD) as an Active period is divided into 16 equal-sized time slots. A guaranteed time slot (GTS) is allocated in one or more slots to a device. If lots of GTS slots are allocated, a contention access period (CAP) is decreased. In addition, the GTS of IEEE 802.15.4 allows at most 7 devices. If IEEE 802.15.4 needs more CAP slots, a coordinator may increase a value of SO for the extension of CAP duration. By increasing SO, however, the size of a GTS slot also increases together. Thus, it may lead to unnecessary increase of GTS slots.

To solve the above problems, there exist several studies to enhance GTS [5]. Assuming applications which transmit packets periodically, however, they focus on increasing the number of GTS slots and the bandwidth utilization. If the studies are applied to CE applications which generate sporadic packets in WBAN environments, large transmission latency results from an Inactive period. In addition, there are several proposals submitted to IEEE 802.15.6 TG [2], but they are not finalized yet.

Recently several studies about WBAN MAC have been introduced. For example, Ullah et al. pointed out the problems of beacon-enabled IEEE 802.15.4 and proposed an asynchronous traffic-based wakeup mechanism [6]. Since a lot of works are based on IEEE 802.15.4 for on-body sensor network [7], however, we attempt to modify IEEE 802.15.4 for the purpose of WBAN.

In this letter, we identify the requirements of WBAN MAC protocols considering flexibility between medical and

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†The authors are with the Dept. of Computer Engineering, Kyung Hee University, Korea.
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a) E-mail: chojs@khu.ac.kr, corresponding author.
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CE applications and propose a WBAN MAC protocol which satisfies the requirements.

2. Requirements of WBAN MAC Protocols

As mentioned in Sect. 1, WBANs operate in the vicinity of the human body with various devices which have different characteristics (i.e., medical or CE). Therefore WBAN MAC protocols should provide flexibility between various devices or applications. Including support for the flexibility, WBAN MAC protocols should satisfy the following requirements [8], [9].

- **power consumption**: The energy efficiency is a major issue in WBAN because WBAN devices are implanted or portable and based on battery power.
- **duty cycle**: The duty cycles of WBAN should be scalable. Medical devices demand low duty cycle (e.g.,<1% or <10%). On the other hand, CE devices do not demand strict duty cycles (e.g., low, medium or high).
- **latency**: For emergency, QoS, and real-time services, the low latency is demanded. (≤ 125 ms, medical applications; ≤ 250 ms, CE applications)
- **scalability**: The network size should be scalable up to 256 devices. The data rate should be also scalable from 10 kbps to 10 Mbps.
- **periodic and non-periodic**: Most of medical applications tend to be periodic in nature. Packet generation intervals may vary from 1 ms to 1000 s. On the other hand, CE applications occasionally transmit packets which are generated with sporadic and bursty traffic in general.

In summary, although the energy efficiency is the most significant requirement, in WBAN, the flexibility of latency, QoS support, and scalability for various applications is another challenging issue.

3. The Proposed WBAN MAC Protocol

Since providing the flexibility for various applications is the main goal, as we identified in Sect. 2, we focus on the following ideas: First, the number of slots for applications using CFP should be sufficient, so that the number of tries to obtain a channel even when contention is present can be reduced. In IEEE 802.15.4 as shown in Fig. 1, one or more GTS slots may be allocated to a device. Once GTS slots are allocated to a device, the device exclusively occupy the slots every superframe whether it sends data or not. Thus, if the device has a long period, bandwidth wastage is inevitable. In addition, since IEEE 802.15.4 permits only at most 7 devices for GTS, devices which are not allocated GTS have alternative but to use CAP. WBANs employ a star topology typically and thus a coordinator may manage lots of devices which require GTS. To support a large number of devices with GTS, we propose a **dynamic CFP allocation**. The proposed scheme dynamically allocates CFP slots in demand-driven manner, so that it can provide the flexibility while reducing bandwidth wastes. In addition, it allows more CFP allocations than IEEE 802.15.4.

Second, we exploit the **Opportunity period** in Inactive period for the flexible ranges of the latency. In IEEE 802.15.4, the Inactive period is determined by BO and SO in a beacon and all the devices sleep in the period. If CAP is insufficient due to increased temporary traffics, IEEE 802.15.4 expands CAP by increasing SO in a beacon. However, when SO increases, the size of a CFP slot also exponentially increases. To support sporadic traffics of CE applications flexibly, the Opportunity period is proposed.

Figure 2 depicts the proposed superframe structure. As compared with the superframe of IEEE 802.15.4 in Fig. 1, the CFP allocation period is added and the duration of CFP is variable due to our dynamic CFP allocation. Since the Active period (CAP + CFP) is fixed in each superframe, the duration of CAP is also variable but the minimum region of CAP is guaranteed through our Maginot line mechanism. The Inactive period of IEEE 802.15.4 can be switched into the Opportunity period in our protocol. The following subsections will give the detailed description.

3.1 Dynamic CFP Allocation

For dynamic CFP allocation, we should provide a mech-

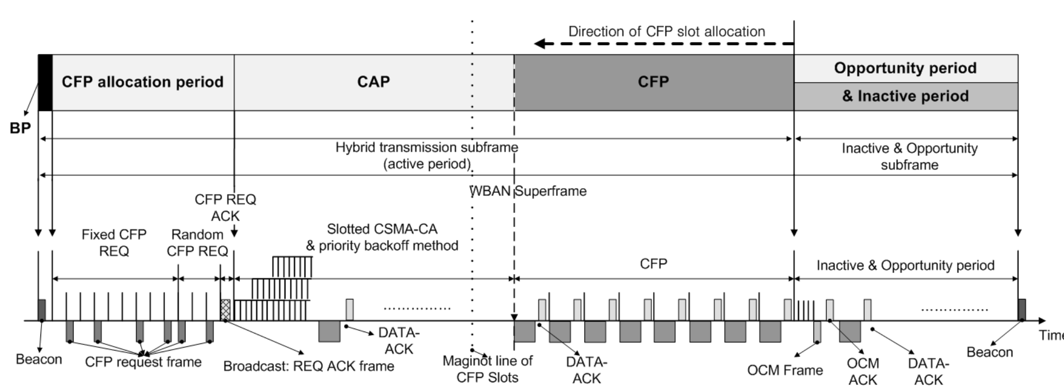


Fig. 2 Proposed superframe structure.

anism for devices to request CFP slots to the coordinator. This request can be also contention-free or contention-access similar to data transmission. Therefore our CFP allocation period consists of two types of subperiod. In the Fixed CFP REQ, there exist small request slots, so called mini-slots, mapped to each device (i.e., one-to-one mapping between mini-slot and device). Since the number of mini-slots is limited, however, a device which is not allocated the mini-slot selects a mini-slot randomly in Random CFP REQ subperiod and send its request. If a collision occurs in the mini-slot, the devices retry in the next superframe. In addition, CFP slots can be allocated without requests through the beacon (BP) like IEEE 802.15.4.

In summary, there exist three types of CFP allocation: in BP, Fixed CFP REQ, and Random CFP REQ. The allocation in BP has no overhead because there is no request message. The overhead in Random CFP REQ is the largest because of collision possibility. The policy of CFP-slot allocation method can be expressed like: As a device sends data more frequently, the device should be provided a CFP-slot allocation method which has smaller overhead.

In our dynamic CFP allocation, devices which request CFP slots are distinguished into 3 groups as follows:

- *Group 1*: Devices such that $T_p = 1$.
- *Group 2*: Devices such that $1 < T_p < \alpha$.
- *Group 3*: Devices such that $T_p \geq \alpha$.

T_p is the transmission period of the device and the unit is a superframe. For example, if $T_p = 5$, the device sends data every 5 superframes. When a device registers to the coordinator, T_p is delivered together. Since devices in *Group 1* transmit data every superframe, CFP slots for *Group 1* devices are allocated in BP. Devices in *Group 2* and *Group 3* are allocated CFP slots dynamically in CFP allocation period. Similar to IEEE 802.15.4, the maximum number of devices in *Group 1* is 7 and thus the 8th device in *Group 1* belongs to *Group 2*. Since the number of mini-slots in Fixed CFP REQ subperiod is limited, the number of devices in *Group 2* is controlled with the parameter α. In other words, the coordinator reduces the value of α when the number of devices in *Group 2* exceed its upper limit.

After the coordinator collects CFP request frames during Fixed CFP REQ and Random CFP REQ subperiods, it analyzes the requests and broadcasts the result (REQ ACK) to allocate CFP slots for *Group 2* or *Group 3* devices in CFP REQ ACK period. While allocating CFP slots, the coordinator allocates them to reverse direction from the end point of Active period. Since the Active period consists of CAP and CFP, however, it is necessary to guarantee the minimum region of CAP similar to IEEE 802.15.4. Our allocation of CFP slots to reverse direction from the end point of Active period are available until **Maginot line** as depicted in Fig. 2.

The dynamic CFP allocation period in the proposed protocol is required to deliver overhead messages such as CFP request and REQ ACK frames. However, there are a lot of wastes of GTS slots statically allocated in IEEE 802.15.4 if the transmission period is larger than a superframe (i.e., the slots are reserved but not used.). In spite of the overhead, it is proved in Sect. 4 that the throughput of the proposed protocol outperforms that of IEEE 802.15.4 in WBAN environments which have various medical and CE devices.

3.2 Opportunity Period

In WBAN environments as mentioned earlier, CE devices may generate sporadic and burst data. In order to support large amount of sporadic data and to reduce the transmission latency, we propose the Opportunity period in Inactive period. A coordinator waits control frames (Opportunity Contention Message, OCM) from devices at the initial stage of Inactive period. If the coordinator receives OCMs, it notifies devices to switch the Inactive period into the Opportunity period by broadcasting OCM ACK. In short, instead of changing BO and SO values which configure each period of superframe as in IEEE 802.15.4, the proposed WBAN MAC protocol provides flexible transmissions through the temporary switching method between the Inactive period and the Opportunity period. Since CE devices mainly use the Opportunity period, medical devices can sleep at the initial stage of Inactive period immediately.

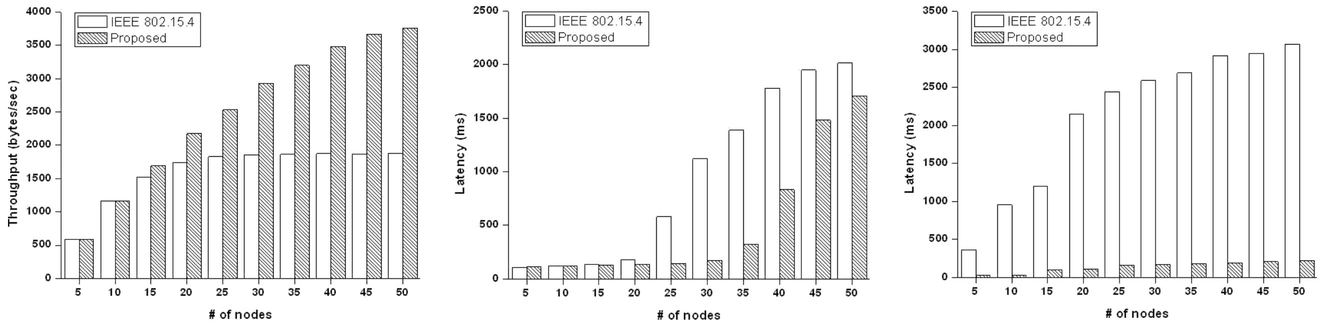
When we exploit the Opportunity period, it has a few overheads. A coordinator and devices cannot immediately sleep in the Inactive period because of OCM and OCM ACK. In addition, there exists additional energy consumption to transmit OCM and OCM ACK messages. However, the overheads are inevitable to provide flexible transmissions in WBAN and can be neglected in case of the coordinator and CE devices which have relatively large capacity of battery power compared with medical devices.

4. Performance Evaluation

We first describe our simulation model to compare the performance of the proposed WBAN MAC protocol with that of IEEE 802.15.4. As for the PHY model, we assume ISM band, O-QPSK modulation, 2,000 kcps chip rate, and 250 kbps data rate [4]. In addition, both the proposed and IEEE 802.15.4 MAC protocols use the superframe structure, and BO and SO determine the superframe length and the active period, respectively. In order to satisfy the latency requirement in Sect. 2, we set BO=4 (245.76 ms of superframe) and SO=3 (122.88 ms of active period).

Next, the traffic model is as follows: There exist 5 to 50 medical devices of which the period is 100 ms (20%), 400 ms (20%), 800 ms (20%), 1 s (20%), and 10 s (20%). The initial value of α is set 10. They send a packet of 40 bytes every period. One CE device sends a message of 5000 bytes sporadically. The message is split into MAC-layer packets of 127 bytes which is the maximum size of IEEE 802.15.4 [4]. The above simulation model has been implemented in our simulator using C++.

Figures 3(a) and 3(b) show the throughput and the latency, respectively, when there exist only medical devices.



(a) Throughput comparison (medical devices)

(b) Latency comparison (medical devices)

(c) Latency comparison (CE device)

Fig. 3 Simulation results.

The IEEE 802.15.4 MAC protocol allocates CFP slots to at most 7 devices statically and thus devices which are not allocated CFP slots should compete to use CAP. Furthermore, there exist bandwidth wastes when devices which are allocated CFP slots do not transmit data. As shown in Fig. 3(a), the throughput of IEEE 802.15.4 does not increase when there are more than 25 medical devices. Since the proposed protocol allocates CFP slots dynamically to devices which transmit data in the superframe, however, the throughput of our protocol increases even when there are more than 25 medical devices. As we can expect, both protocols exhibit the similar performance in terms of the throughput when there are less than 10 medical devices.

In terms of the latency, the proposed protocol also outperforms IEEE 802.15.4 as shown in Fig. 3(b). If devices which are not allocated CFP slots do not acquire CAP slots, in IEEE 802.15.4, they should retry in the next superframe. In our protocol, however, relatively large numbers of devices can be allocated CFP slots and thus the average transmission latency of the proposed protocol is smaller than that of IEEE 802.15.4 as depicted in Fig. 3(b). As the number of medical devices is larger, we can find from Figs. 3(a) and 3(b) that the proposed protocol is superior to IEEE 802.15.4 through the dynamic CFP allocation.

Figure 3(c) shows the latency when a CE device is added. In IEEE 802.15.4, the CE device should contend medical devices which are not allocated CFP slots. However, it can use the Opportunity period in our protocol, so that the latency can be reduced dramatically. We can conclude that the proposed protocol can be used flexibly in a variety of WBAN applications while providing high throughput and low latency.

5. Conclusion

In this letter, we have identified the requirements of WBAN MAC protocols and proposed a WBAN MAC protocol which satisfies the requirements. Since our proposed protocol employs the dynamic CFP allocation and opportunity period, it can be used flexibly in various WBAN devices and applications which require from small to large duty cycle, latency, and scalability. We have validated the flexibility through extensive simulations.

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