Adaptive Priority-based Medium Access Control Protocol for IEEE 802.15.6 Wireless Body Sensor Networks

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Concern about energy-efficient medium access control (MAC) protocols for wearable devices is increasing owing to support for healthcare services using wireless body sensor networks (WBSNs). The most popular energy-efficient MAC protocol for WBSNs is the IEEE 802.15.6 standard, which adopts carrier sensing multiple access with collision avoidance (CSMA/CA). The CSMA/CA mechanism of the IEEE 802.15.6 standard allows differentiated channel access by assigning a different size of contention window to the nodes, each of which has a different priority. However, the existing CSMA/CA of IEEE 802.15.6 still cannot guarantee successful data transmission in error-prone channels and congested network environments, which leads to wasted energy owing to data retransmission. In this paper, we propose an adaptive priority-based MAC (AP-MAC) protocol for IEEE 802.15.6 WBSNs, which utilizes transmission opportunities suitable for WBSNs. For this, data types are classified with predefined priorities with each data type having a different opportunity to access the channel. In addition, the priority of each classification is updated adaptively according to the update metrics channel state and congestion level. Simulation results show the enhanced performance of the AP-MAC protocol compared with that of the IEEE 802.15.6 standard.

1. Introduction

With the spread of wearable devices such as the Samsung Galaxy Gear, interest in the provision of healthcare services through wireless body sensor networks (WBSNs) is increasing. Healthcare services using WBSNs collect sensor measurements of a person's biosignal, such as blood glucose level or electrocardiogram, and transmit the data.[1] Unlike a conventional communication service, healthcare service data should be transmitted within a certain timeframe because receiving the data after this is meaningless in most healthcare service contexts. That is, there is growing demand for a communication scheme that guarantees data delivery within a predefined timeframe with low power and low cost.[2]

As defined in the IEEE 802.15.6 standard, WBSNs aim to provide short-distance communication in or around a human body. In particular, IEEE 802.15.6 defines the user priority (UP) mapping for the quality of service (QoS). Similarly, the IEEE 802.15.4 standard for wireless personal area networks (WPANs) focuses on the power and cost of increased inactive nodes and infrequent data transmission. However, it cannot efficiently support the QoS such as the delay constraint requirement due to the absence of a UP scheme.

A lot of research based on analytic models for the performance evaluation of the IEEE 802.15.6 standard has been conducted to support the QoS requirement.[3,4] Ameen *et al.* introduced an energy-efficient medium access control (MAC) protocol with the aim of improving the energy consumption of WBSNs using a low-cost wake-up radio (WUR) to increase the sleep period of the node.[5] However, their method had a drawback in that it could not support existing WBSN terminals because an additional wake-up module was needed. Kim *et al.* proposed a priority-based channel access scheme to reduce the collision probability in an IEEE 802.15.6 network.[6] The key idea was the division of the contention access phase (CAP) into subphases according to the delay requirements for four categories. Unfortunately, it was still difficult to satisfy the QoS requirement and low energy consumption when errors occurred and the network load was severely congested. Furthermore, a WUR has been proposed for some MAC protocols, but this had a drawback in that it invoked increases in node cost and size.[7,8]

In this paper, we propose an adaptive priority-based MAC (AP-MAC) protocol that utilizes transmission opportunities suitable for IEEE 802.15.6 WBSNs. For this, data types are classified with predefined priorities where each data type has a different opportunity to access the channel. Furthermore, the priority of each classification is updated adaptively according to the update metrics channel state and congestion level. Simulation results show the enhanced performance of the AP-MAC protocol compared with that of the IEEE 802.15.6 standard.

The rest of the paper is organized as follows. In Sect. 2, we present the existing IEEE 802.15.6 standard, and Sect. 3 contains a description of the proposed AP-MAC method. In Sect. 4, we present simulation results and demonstrate that the AP-MAC protocol outperformed the existing IEEE 802.15.6 standard. Finally, conclusions are reported in Sect. 5.

2. IEEE 802.15.6 Overview

The IEEE 802.15.6 standard defines eight UPs classified on the basis of traffic characteristic with each one having a different pair of minimum (CW_{min}) and maximum (CW_{max}) contention windows, as shown in Table 1. That is, IEEE 802.15.6 originally provides channel access priority as traffic designation.

In IEEE 802.15.6, the beacon period (superframe period) is divided by the coordinator of the WBSNs. A superframe has exclusive access phases (EAPs), random access phases (RAPs), Type I/II access phases, and CAP, as shown in Fig. 1. All phases except for RAP1 can have zero period. EAP periods can only be accessed to transmit the UP7 traffic (emergency or medical event reporting), while RAP and CAP periods can be utilized by all UP traffic. Furthermore, to enhance channel utilization, EAP1 and RAP1 can be merged as EAP1, and in the same way, EAP2 and RAP2 can be combined as EAP2. Following this, Type I/II access phases are used

Table 1
UP of IEEE 802.15.6.

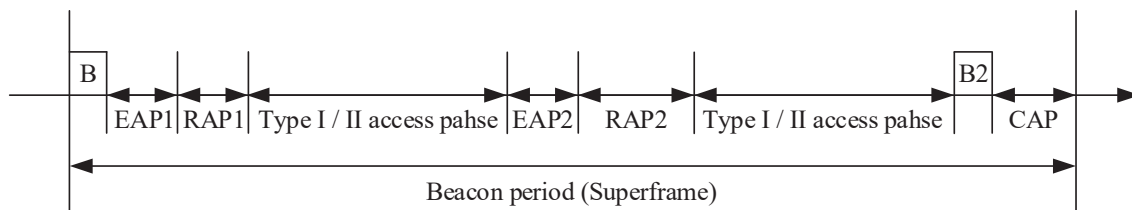| UP	Traffic designation	CW_{min}	CW_{max}
0	Background (BK)	16	64
1	Best effort (BE)	16	32
2	Excellent effort (EE)	8	32
3	Controlled load (CL)	8	16
4	Video (VI)	4	16
5	Voice (VO)	4	8
6	Media data or network control	2	8
7	Emergency or medical event report	1	4

Fig. 1.　IEEE 802.15.6 access phases in a superframe.

by the coordinator for the polling scheme and the remainder are used for CAP—carrier sensing multiple access with collision avoidance (CSMA/CA). In particular, we focus on CAP, which is difficult to control because of the contention of multiple nodes. A detailed procedure of the channel access mechanism of IEEE 802.15.6 can be found in the standard.[9]

3.　Design of AP-MAC

To support healthcare applications that monitor human body signals such as electrocardiogram (ECG) and electromyography (EMG) signals with wearable devices, WBSNs should support reliable data transmission. Here, reliable data transmission means not only data transmission without any error but also data reception within a time constraint in an energy efficient manner. However, since a wearable device attached to the body changes its position frequently according to the movements of the wearer, data transmission error frequently occurs as a result of changes in channel state (e.g., path loss and interference level). In other words, there is a limitation on providing reliable and energy-efficient data transmission using conventional IEEE 802.15.6. This is because it uses the fixed UPs in the WBSN environment where the network topology of the transmitter/receiver is frequently changed. Figure 2 depicts an example of a WBSN and network topology changes with human movement.

In this paper, we propose the AP-MAC protocol that adaptively changes the UPs according to channel state and network congestion level (interference level). The AP-MAC eliminates unnecessary transmissions caused by poor channel conditions owing to the movement of transmitters or receivers. The AP-MAC protocol determines the channel state based on previous successful acknowledgment (ACK) reception history. The transmitter records successful ACK reception history for each receiver in a channel state table, which is updated per
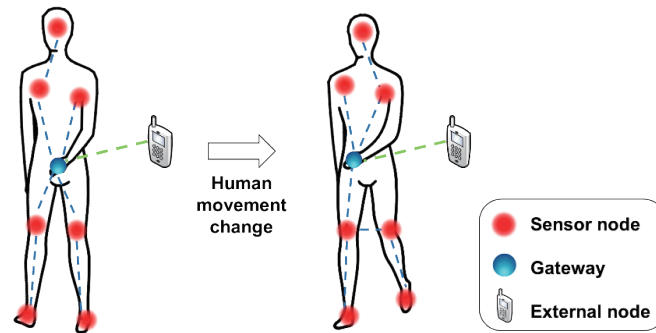
Fig. 2.   (Color online) Example of WBSN.

predefined time—generally coherent time. If the receiver has successful ACK receiving history, AP-MAC follows the existing UP policy, if not, AP-MAC determines that the current channel condition is in a bad state owing to network topology changes. Under these circumstances, AP-MAC follows the new UP policy to prevent unnecessary data transmission. The new UP policy is derived as

$$
\text{New UPs policy} = \begin{cases} \text{backoff decrement freezing,} & \text{UP}_0 - \text{UP}_2 \\ \dfrac{CW_{min,i}}{\alpha}, \ \dfrac{CW_{max,i}}{\alpha}, & \text{UP}_3 - \text{UP}_6 \\ \text{equal to previous policy,} & \text{UP}_7 \end{cases}
\tag{1}
$$

$$
\alpha = 1 - ef,
\tag{2}
$$

where *ef* is a user-defined energy factor ranging from 0 to 1 that controls whether or not to transmit low-priority data after considering both the restriction of energy consumption and channel condition. For example, as *ef* approaches 1, alpha approaches 0, so UP$_3$ to UP$_6$ have a larger *CW*. In other words, access to channels in bad channel states by UP$_3$ to UP$_6$ is limited to reduce unnecessary energy consumption, and AP-MAC freezes the backoff decrement procedure for non-delay-sensitive data such as background, best effort, and excellent effort for bad channel states. In the case of delay-sensitive data such as controlled load, video, voice, and media data or network control, AP-MAC modifies the contention window size as *ef* for bad channel states. Only the transmission of emergency or medical event report data follows the previous policy.

We present an analytical model for the IEEE 802.15.6 CSMA/CA mechanism. First, we assume a finite number of contending nodes, n_i, in UP classes $i = \{0, 1, 2, ..., 7\}$, and each n_i has a packet available for transmission. Let b_i be the probability that the channel is sensed as busy for priority class i. Hence, an error-prone channel has a frame error rate (FER) determined as

$$
P_F = 1 - (1 - P_b)^{d_l + ack_l},
\tag{3}
$$

where P_b is the bit error rate (BER), d_l is the data frame bit length, and ack_l is the ACK frame bit length.

The average energy consumption is calculated as how long the device stays in an active state, such as during a backoff procedure, channel sensing, transmission, or retransmission. Thus, the total energy consumption per device is given by

$$\bar{E}_l = E[B_i] + E[CS_i] + E[T_i], \tag{4}$$

where $E[B_i]$ is the average energy consumption by a backoff procedure, $E[CS_i]$ is the average energy consumption by a carrier sensing procedure, and $E[T_i]$ is the average energy consumption for successful transmission after m attempts. In addition, we can describe

$$E[B_i] = P_{idle} \times T_{average\_backoff}, \tag{5}$$

$$E[CS_i] = P_{rx} \times T_{average\_busy}, \tag{6}$$

$$E[T_i] = (1 - P_F^{m+1})\{P_{tx} \times T_{data} + P_{rx} \times (T_{ack} + 2SIFS)\}, \tag{7}$$

where $T_{average\_backoff}$ and $T_{average\_busy}$ are the average backoff time and average channel busy time, respectively, which have previously been derived in detail.[10–12]

4.   Performance Evaluation

We compared energy consumption between AP-MAC and IEEE 802.15.6. For simplicity, we considered that the total number of nodes varied from 8 to 32 and each priority class had the same number of nodes (Table 2 depicts the evaluation parameters). Results were obtained for $BER = 10^{-3}$ (bad channel conditions) and $BER = 10^{-6}$ (good channel conditions).

Figure 3 shows a comparison of the energy consumption of AP-MAC and the IEEE 802.15.6 standard for $BER = 10^{-3}$. AP-MAC prevented unnecessary energy consumption due to transmission failure (channel error and collisions). When the number of nodes in the network was small, it can be seen that AP-MAC outperformed IEEE 802.15.6 in terms of energy consumption in the cases where transmission failure was dominated by channel error. Moreover, when the number of nodes in the network was large and transmission failure occurred because of collisions, the AP-MAC performance was still superior to the IEEE 802.15.6 standard.

Table 2
Evaluation parameters.

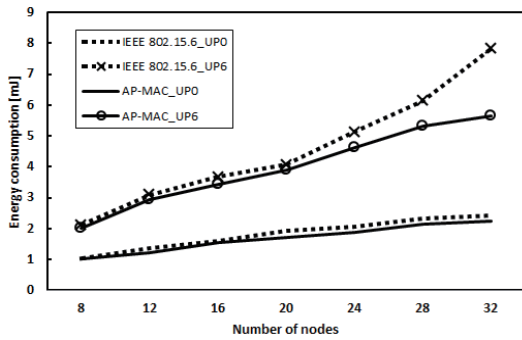| P_{tx}	27 mW	P_{rx}	1.8 mW	P_{idle}	5 μW
SIFS	75 μs	Data	150 bytes	ACK	193 bits

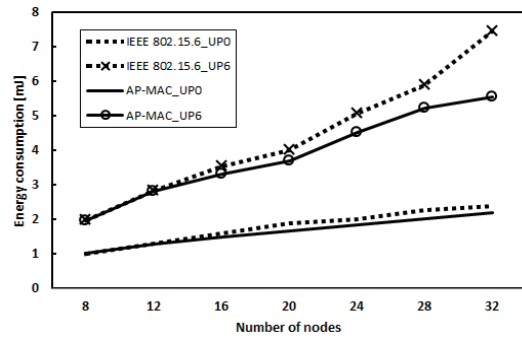Fig. 3. Energy consumption comparison for $BER = 10^{-3}$.

Fig. 4. Energy consumption comparison for $BER = 10^{-6}$.

Table 3
Average energy consumption by *ef* for $BER = 10^{-3}$ with 24 nodes.

		AP-MAC		IEEE 802.15.6	
		UP0 (mJ)	UP6 (mJ)	UP0 (mJ)	UP6 (mJ)
	0.9	1.28	4.88		
ef	0.5	1.28	4.27	1.33	5.12
	0.1	1.27	5.07		

Figure 4 shows a comparison of the energy consumption of AP-MAC and the IEEE 802.15.6 standard for $BER = 10^{-6}$, and it can be seen that AP-MAC still outperformed the IEEE 802.15.6 standard. When the number of nodes in the network was small, the performances of the two schemes were similar. However, when the number of nodes increased, there was a difference in energy consumption between the two schemes because transmission error was dominated by collisions. In other words, even when the channel state was good, it was confirmed that AP-MAC still had improved performance compared with IEEE 802.15.6 in terms of energy consumption.

Finally, we evaluated the average energy consumption compared with *ef*, the results of which are reported in Table 3. Since AP-MAC freezes the backoff decrement counter regardless of *ef* for UP0 and reduces the channel access probability of UP6, the average energy consumption was increased by the backoff procedure. However, AP-MAC does not permit meaningless transmission, so it was confirmed that it had low energy consumption compared with IEEE 802.15.6. Furthermore, since the average energy consumption by backoff and transmission procedures increased or decreased according to *ef*, its value should be selected by considering both channel conditions and target energy consumption.

5. Conclusions

In this paper, we present the energy-efficient AP-MAC protocol for WBSNs. The AP-MAC modifies the existing UP policy considering the channel environment [channel error and network density (collisions)] to reduce retransmission, which causes unnecessary energy consumption. From the results of a performance evaluation, it was confirmed that the energy

consumption performance of AP-MAC was better than that of IEEE 802.15.6 as the channel state deteriorated and the number of nodes increased.

Acknowledgments

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