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A prioritized resource allocation algorithm for multiple wireless body area networks

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Abstract This paper presents a prioritized resource allocation algorithm to share the limited communication channel resource among multiple wireless body area networks. The proposed algorithm is designed based on an active superframe interleaving scheme, one of the coexistence mechanisms in the IEEE 802.15.6 standard. It is the first study to consider the resource allocation method among wireless body area networks within a communication range. The traffic source of each wireless body area network is parameterized using the traffic specification, and required service rate for each wireless body area networks can be derived. The prioritized resource allocation algorithm employs this information to allocate the channel resource based on the wireless body area networks' service priority. The simulation results verified that the traffic specification and the wireless body area network service priority based resource allocation are able to increase quality of service satisfaction, particularly for health and medical services.

Keywords Active superframe interleaving · IEEE 802.15.6 · Resource allocation · Wireless body area networks

1 Introduction

Development of wireless communication, miniaturized computing devices, and low power technologies enable to collect biometric information using tiny sensor nodes and provides various human-centric services. This technology is called as wireless body area networks (WBANs). The WBAN has recently attracted the public attention and has been expected to be used in a variety of ubiquitous services, e.g., healthcare and wearable computing [1]. Bluetooth 4.0 [2], IEEE 802.15.4 [3], and IEEE 802.15.6 standard [4] are currently regarded as candidate wireless communication technologies for WBANs. Bluetooth 4.0 and IEEE 802.15.4 designed for covering short communication range can support a few application requirements for WBAN related services, but they cannot satisfy the wide range of WBAN application requirements.

IEEE LAN/MAN standardization committee completed IEEE 802.15.6 standardization for both WBAN PHY and MAC layers in February 2012 [4]. Unlike Bluetooth 4.0 and IEEE 802.15.4, IEEE 802.15.6 is an exclusive standard that is flexibly designed to support various application requirements for WBANs. It provides three physical layer modes such as a narrowband (NB) PHY, an ultra-wideband (UWB) PHY, and a human body communication (HBC) PHY that support various data rates and transmission characteristics. IEEE 802.15.6 has three medium access control layer modes, i.e., beacon mode with superframes, non-beacon mode with superframes, and non-beacon mode without superframes. The developers can decide the operating modes and flexibly compose the access phases according to the application requirements. In addition, the developer can select diverse access modes, coexistence and interference mitigation schemes, and security services. Because of its flexibility, IEEE 802.15.6 is the most

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compatible solution to meet various WBAN application requirements.

WBANs consist of one hub and several sensor nodes around human body, which is called star-topology. The WBAN has links between the hub and the sensor nodes whose maximum communication range is 3 meters. It has various data rate from 10 Kbps to 10 Mbps which is decided by the application requirements. Each sensor node monitors human biometric data periodically or aperiodically and forwards the collected data to the hub. These data can be applicable for ubiquitous applications such as healthcare, wearable computing, sports, entertainment, security, home network, etc.

In general, a person composes one WBAN around his body. As the person moves, the position of WBAN is also shifted. This network mobility causes interference with homogeneous network (e.g., other WBANs) or heterogeneous network (e.g., WLAN, Bluetooth, ZigBee, etc.). This inter-network interference is a rarely considered issue in wireless personal area network (WPAN) domain.

WBAN requires different link reliability, transmission latency, and QoS provision according to data type. For example, data related to medical service demand high link reliability and short transmission latency. On the contrary, data related to non-medical service such as entertainment do not need to guarantee high link reliability and short transmission latency but require high QoS provision. Because the WBAN services are various and change dynamically, it is difficult to satisfy these requirements using conventional wireless technologies.

In the IEEE 802.15.6 standard, three mechanisms are described to reduce this inter-network interference: beacon shifting, channel hopping, and active superframe interleaving. The details of these schemes are described in the Sect. 2. The active superframe interleaving scheme is designed to decrease inter-network interference based on time division multiplexing (TDM). To our best knowledge, the active superframe interleaving scheme has never been studied before and the detailed resource allocation mechanism among different WBANs has not been considered. This motivates us to study this topic.

This paper presents a prioritized resource allocation (PRA) algorithm based on the IEEE 802.15.6 active superframe interleaving scheme. The proposed algorithm adaptively allocates communication channel resource among WBANs according to their service priority. It has two major contributions. Our first contribution is network performance improvement without using various channels like FDM. Based on the network traffic analysis, the proposed scheme has allocated time resource properly and enhanced QoS satisfaction of each network. The second contribution is that the proposed scheme is designed on the basis of the IEEE 802.15.6 standard. It will enhance device compatibility among various devices if they are implemented based on the standard.

The rest of this paper is organized as follows. Section II briefly describes related works. Section 3 introduces token bucket TSPEC. Section 4 presents the prioritized resource allocation algorithm. Section 5 describes the experimental results and the performance evaluation, and Sect. 6 draws the conclusion.

2 Related works

Sometimes, the WBAN is required to share limited communication channel resource with other WBANs in a case where they are in a range of each other and use the identical communication channel. Sharing the channel resource among nodes has been studied a lot in the wireless communication research area [5, 6]. In WBANs, sharing the channel resource (i.e., interference mitigation or coexistence) solutions can be classified as follows: time division, frequency division, code division, standard modification, standard adaptation, and hybrid solutions. The detailed solution can be referred in [5]. This paper has been focused on IEEE 802.15.6 standard adaptation solution, so non-standard based mechanisms have not been considered.

The IEEE 802.15.6 standard introduces three schemes to share a limited channel resource among WBANs. The first one is a beacon shifting scheme. The beacon shifting scheme randomly shifts beacon transmission period that results in avoiding repeated beacon collision. The IEEE 802.15.6 beacon shifting based algorithm already has been studied [15]. Secondly, channel hopping is a technology for WBAN altering communication channels periodically. The channel hopping is frequency division multiplexing (FDM) solution that uses separated frequency. The channel hopping is widely used scheme by Bluetooth [2] under the name of frequency hopping. It enables the WBAN to use various communication channels, which decreases the probability of using the same channel with other WBANs. B. Cao et al. [16] has been proposed to use this channel hopping mechanism for avoiding the inter-network interference. However, the FDM based coexistence scheme has some limitations [15] such as channel modification overhead, waste of the limited frequency, etc. Above two schemes are useful when WBAN mobility is active.

The third proposed scheme is an active superframe interleaving scheme. This scheme adjusts active superframe of each WBAN as in Fig. 1. It enables to share a channel resource among WBANs. In case of WBAN allowing active superframe interleaving, a hub (called hub 1) transmits a beacon or B2 frame with superframe interleaving field being 1. If the other WBANs' hub (called hub 2) receives hub 1's the beacon or B2 frame, it can try to

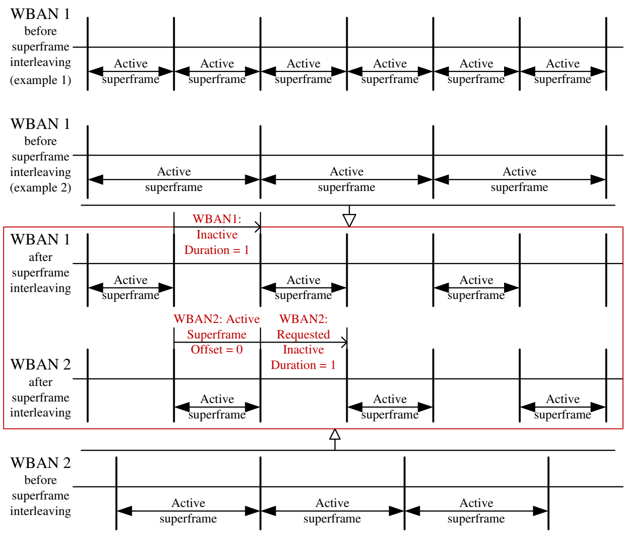

Fig. 1 IEEE 802.15.6 active superframe interleaving illustration [3]

share its channel resource by sending an active superframe interleaving request frame. In a case where the hub 1 receives the active superframe interleaving request frame, it decides to share the channel resource or not by referring the requested frame information. If the hub 1 decides to allow channel resource sharing, it transmits an active superframe interleaving response frame to the hub 2 and the channel resource can be shared successfully. More detailed superframe interleaving scheme can be found in the IEEE 802.15.6 standard [4].

The active superframe interleaving scheme is useful for an environment where WBAN has low mobility and should share channel resource for a long time. The IEEE 802.15.6 standard does not currently provide a specific way how to allocate the channel resource for the active superframe interleaving scheme. Therefore, the active superframe interleaving scheme requires a proper channel resource allocation method to guarantee each WBAN's performance requirement.

3 Token bucket TSPEC

This section presents token bucket TSPEC that is used to analyze the required resource for each WBAN. The token bucket TSPEC (Traffic Specification) [7–9] is a standard of parameters to characterize the behavior of network traffic source. Based on token bucket TSPEC, a range of service rates can be derived to guarantee network QoS. The token bucket TSPEC represents the characteristics of traffic source using the theoretical fluid twin token bucket model [10]. The fluid twin token bucket model is to describe the behavior of a network traffic stream as shown in Fig. 2.

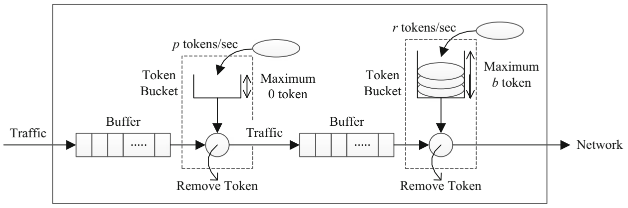

Fig. 2 Fluid twin token bucket model

Tokens are continually stacked up in the token bucket with a fixed rate, p or r. If there are packets to be transferred, the tokens decrease as many as the number of packets, and the packets are delivered to the network. In a case where the token bucket does not have any token, the packets can wait or be dropped in the buffer. The rate of token stack for the first token bucket, p, means a peak rate of traffic flow. The rate of token stack for the second token bucket, r, indicates a mean rate of traffic flow. The maximum depth of the second token bucket, b, represents allowable burst traffic. Therefore, the fluid twin token bucket model of Fig. 2 has a traffic stream with characteristics of {r, b, p}.

Figure 3 shows service rate to transfer the traffic stream according to the TSPEC. The bold line indicates arrival curve of a traffic stream. This arrival curve follows the fluid twin token bucket model with traffic characteristics of {r, b, p}. The diagonal line is a selected service rate at which the traffic stream is transferred. After the cross point between the bold line and the diagonal line, the provided traffic stream is fully serviced. The slack term, S, is a gap between maximum allowed delay, d_{max}, and queuing delay bound, d_q, of selected service rate. In other words, it means a margin to satisfy required delay bound. Thus, the longer slack term is, the higher QoS provision can be. The vertical

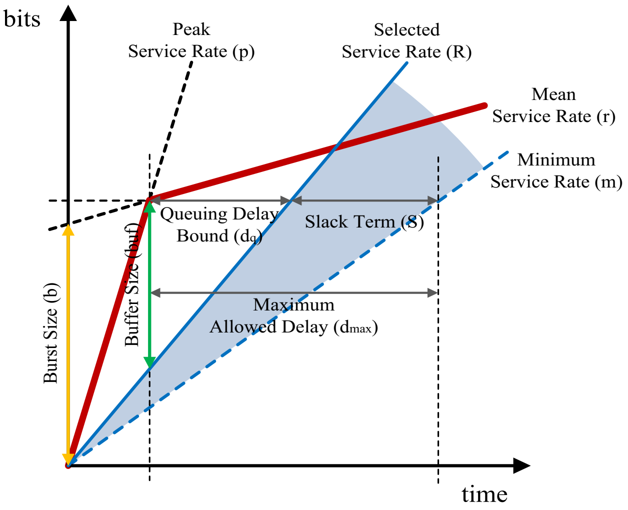

Fig. 3 Service rate to transfer the traffic stream according to the TSPEC

line between the bold line and the diagonal line indicates minimum buffer size to avoid buffer overflow for the selected service rate. By means of the distance formula, the minimum buffer size can be derived by:

$$buf = \frac{p - R}{p - r} \cdot b \tag{1}$$

The queuing delay bound, d_q, is the maximum delay length between packet arrival curve and selected service rate, that is to say required time to transport all packets in the buffer. This queuing delay bound, d_q, is given by:

$$d_q = \frac{buf}{R} = \frac{p - R}{p - r} \cdot \frac{b}{R} \tag{2}$$

From above equation, selected service rate, R, can be derived as follows:

$$R = \frac{p}{1 + d_q \cdot \frac{p-r}{b}} \tag{3}$$

The selected service rate, R, is to guarantee queuing delay bound, d_q, for a traffic stream with characteristics of {r, b, p}. Thus, if the application provides d_q and {r, b, p}, the proper selected service rate is predictable between minimum service rate, m, and peak service rate, p. The maximum allowed delay, d_{max}, can be derived by adding queuing delay bound, d_q, and slack term, S, as follows:

$$d_{\max} = d_q + S = \frac{p - R}{p - r} \cdot \frac{b}{R} + S \tag{4}$$

From the above equations, the selected service rate satisfying specific delay and requiring buffer size can be derived.

4 A prioritized resource allocation algorithm

To share the limited channel resource among multiple WBANs, efficient channel resource allocation method is necessary. Because required channel resource is different according to WBANs' service requirements, each hub should identify the required channel resource of every node in WBANs first and requests the active superframe interleaving to another WBAN. In the IEEE 802.15.6 standard, the WBAN requesting the active superframe interleaving should allow it if the channel resource is sufficient. Otherwise, the WBAN can deny the active superframe interleaving request. This simple resource allocation solution is inefficient scheme in terms of channel resource usage.

This paper proposes a prioritized resource allocation (PRA) algorithm for efficient and reasonable channel resource allocation. Each WBAN determines required channel resource using the fluid twin TSPEC model. The WBAN attempting the active superframe interleaving (called slave WBAN) delivers minimum service rate, m, peak service rate, p, and maximum allowed delay, d_{max}, using active superframe interleaving request frame (as in Fig. 4). The values, m, p, and d_{max}, can be determined using the active superframe interleaving request frame fields.

$$d_{max} = Requested\ Inactive\ Duration \tag{5}$$

$$p = \frac{Requested\ Beacon\ Period\ Length + Requested\ Active\ Superframe\ offset}{Requested\ Beacon\ Period\ Length + Requested\ Inctive\ Duration} \tag{6}$$

$$m = \frac{Requested\ Beacon\ Period\ Length}{Requested\ Beacon\ Period\ Length + Requested\ Inctive\ Duration} \tag{7}$$

The WBAN received the active superframe interleaving request frame (called master WBAN) determines an appropriate selected service rate, R, and slack term, S, using m, p, and d_{max}. R can be given by:

$$R = \frac{m \cdot p \cdot d_{\max}}{p \cdot d_{\max} + S \cdot m - S \cdot p} \quad where\ S = d_{\max} \cdot P(S) \tag{8}$$

(8) is derived by (3) where S is determined by a proportion of d_{max} as described in Table 1. $P(S)$ indicates the proportion to decide the length of slack term. Detailed procedure to derive (8) can be referred in "Appendix" section.

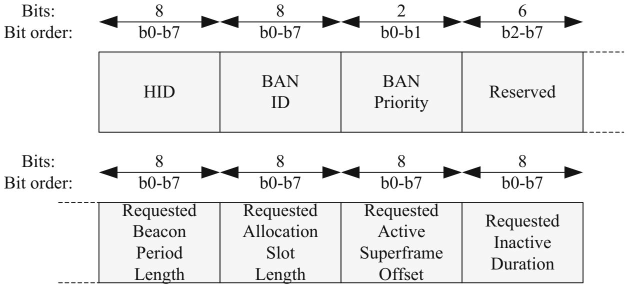

Fig. 4 Data format for the active superframe interleaving request frame [4]

Table 1 Priority based slack term

Priority	WBAN services	Proportion for slack term, $P(S)$ (%)
0	Non-medical services	25
1	Mixed-medical and non-medical services	50
2	General health services	75
3	Highest priority medical services	100

Table 1 is the slack term proportion in d_{max} according to WBAN service priorities. The four service priorities are presented in the IEEE 802.15.6 standard. As the WBAN service priority increases, the proportion for slack term grows. For example, in case of the highest priority medical services, the selected service rate is identical with the peak service rate. Thus, WBANs with high priority can obtain more channel resource that increases WBANs' QoS satisfaction. If the selected service rate is decided, the master WBAN transmits the active superframe response frame to the slave WBAN requesting the active superframe interleaving.

As the WBANs sharing the same channel resource increase, available channel resource decreases. Thus, the prioritized resource allocation algorithm proposes to reduce the slack term gradually according the priority of WBANs. As shown in Fig. 5, the proportion for the slack term of non-medical service is reduced from 25 to 0 % when the total channel usage rate is over 20 %. The slack term of the other services also decrease to 0 % as the channel usage rate exceeds 40, 60, and 80 %. Thus, in case of the channel usage rate over 80 %, all WBANs' selected service rate, R, become minimum service rate, m.

In a case where the channel usage rate exceeds 100 % due to the active superframe interleaving request from new WBAN, the priorities of new WBAN and WBANs already sharing the channel resource are compared. If the new WBAN has the lowest service priority among the WBANs, the active superframe interleaving request is denied. Otherwise, the active superframe interleaving of WBAN providing the lowest service priority is canceled.

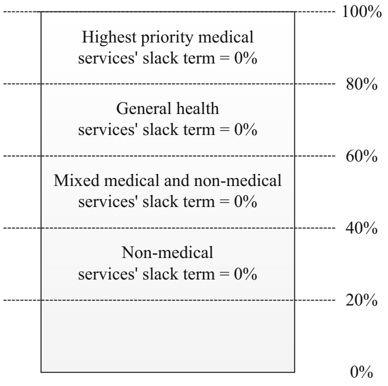

Fig. 5 The usage rate of channel resource

5 Performance evaluation

In this section, the performance of the prioritized resource allocation (PRA) algorithm has been evaluated based on the IEEE 802.15.6 standard. This is the first work to study WBAN resource allocation for the IEEE 802.15.6 active superframe interleaving scheme. First, experiments without the IEEE 802.15.6 active superframe interleaving according to WBANs allocated slot length has been performed. After that, the PRA algorithm and other two methods have been compared: non-active superframe interleaving and the IEEE 802.15.6 superframe interleaving including the fair resource allocation (FRA) scheme. The FRA scheme impartially assigns the limited channel resource to the WBANs in order to satisfy their QoS requirements. Thus, all WBANs within a communication range have the same length of the channel resource. At the last, the performance of the PRA algorithm has been evaluated depending on WBAN's service priorities and proved QoS satisfaction.

5.1 Simulation environment

The performance evaluation has been conducted by OMNeT++ [11] simulator implementing IEEE 802.15.6 features in NICTA's Castalia model [12]. The basic parameters are set based on 2.4 GHz narrowband PHY and MAC in the IEEE 802.15.6 standard. A simulation lasts 10 h and is repeated 5 times using different random seed. Every device for the simulation transmits a packet with -25 dBm output power. Data rate is configured as 1024 Kbps and total packet size is 70 bytes including 30 bytes application payload. If the packet cannot be delivered successfully, it will be retransmitted in three times. MAC has a capability to store 100 packets in its buffer. Beacon period consists of 256 slots. A slot length is 1 ms, so the hub broadcasts a beacon packet every 256 ms. The allocated slot employs random access procedure that employs carrier sense multiple access with collision avoidance (CSMA/CA) [13]. The simulation assumes 10 persons who respectively compose the WBAN just stay in same position or move freely in a 25 × 25 meters chamber. For the mobility scenario, each person walks to random direction at a various speed (1.8–4.3 km/h). If the persons reach the direction, they stay there during 10 s and moves to another random direction again. Every node in the WBANs collects data and delivers it to the hub. The nodes use diverse sampling rates from the minimum sampling rate (1–10 ms) to the maximum sampling rate (10–100 ms), so the minimum service rate, *m*, and the peak service rate, *p*, are different to the WBANs.

5.2 Simulation results

Sharing the same channel resource among WBANs is possible to cause a lot of interference that decreases packet success rate. In order to investigate the interference effect, IEEE 802.15.6 with non-active superframe interleaving scheme was evaluated first according to the allocated slot length. The simulation result is derived based on the average value for a subject WBAN in 5 repeated simulations.

Figure 6 indicates packet success rate for non-active superframe interleaving scheme. Every WBAN has a fixed allocated slot length as shown in x-axis values. As the allocated slot length becomes longer, the packet success rate also grows because a chance to transmit or retransmit packets increases. In case of non-mobility, 10 WBANs are within a communication range and uses the same channel resource simultaneously regardless of the other WBANs' transmission. It causes a lot of interference that result in packet failures. In the mobility case, each WBAN randomly moves in the confined area, so the WBAN is possible to be out of other WBANs' transmission range. It gives more chance to transmit packets without interference as the allocated slot length increases. Therefore, the packet success rate in the mobility case becomes higher than the non-mobility case.

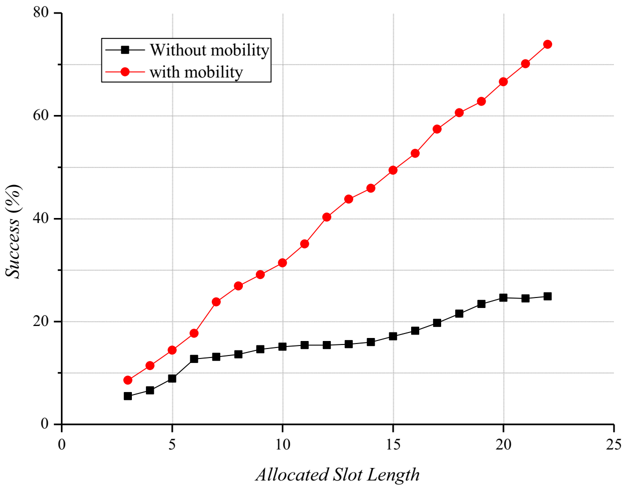

Fig. 6 Packet success rate of non-superframe interleaving

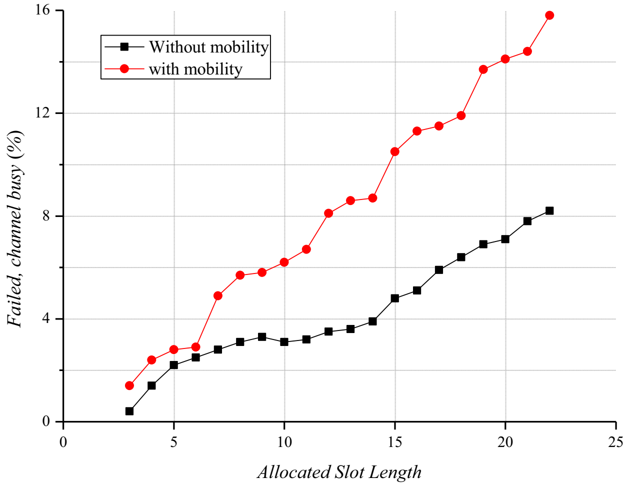

Fig. 7 Packet failure rate of non-superframe interleaving due to channel busy

The packets can be failed due to two reasons. The first reason is channel busy due to interference. As shown in Fig. 7, the packet failure due to channel busy increases according to the growth of allocated slot length. In order to avoid the channel busy, the WBANs perform carrier sensing before transmitting packets in the allocated slots. However, the channel busy still occurs in a case where the back-off counters of WBANs are left equally. The channel busy especially happens more in the mobility case because the WBAN can be frequently in and out of the other WBANs' transmission range. In that case, the CSMA/CA has lower rate avoiding interference than non-mobility case [14].

Another reason is buffer overflow. WBANs contend to transmit packets each other using the CSMA/CA, so some

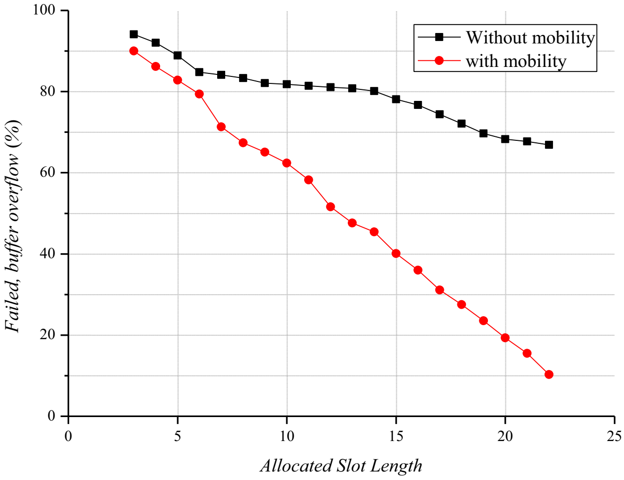

Fig. 8 Packet failure rate of non-superframe interleaving due to buffer overflow

of them may wait continuously like a deadlock state. It leads to stack the packets up in the buffer. If the stacked packets in the buffer exceed the defined buffer size, the buffer overflow occurs. As in Fig. 8, the buffer overflow occurs much more in non-mobility case. It is because the probability of sensing carrier is even higher in the non-mobility case than the mobility case. The long allocated slot length gives more chance to transmit packet for WBANs. Hence, the buffer overflow rate is reduced as the allocated slot length decreases.

Figure 9 illustrates a proportion of received packets according to different three schemes. In the Fig. 9, 15 slots indicate non-active superframe interleaving scheme with 15 allocated slot lengths. It is the identical result with Figs. 6, 7 and 8. The fair resource allocation (FRA) scheme employs active superframe interleaving to share the limited channel resource among the WBANs. Accordingly, the WBANs can independently use their channel resource without any interference. It brings to reduce most of the channel busy that causes the packet failure. However, some buffer overflow still occurs. As the number of WBANs sharing the channel resource increases, each WBAN suffers from lack of available channel resource for the packet transmission. It drops packet success rate to all WBANs equally. The packet failure rate due to the buffer overflow is 9 % for the non-mobility case and 1.5 % for the mobility case, respectively. Every WBAN indicates almost similar as the previous result. The prioritized resource allocation (PRA) algorithm also operates on the active superframe interleaving scheme. The outcome of Fig. 9 is when the WBAN provides high priority medical service. As the WBAN service priority becomes higher, the WBAN can hold more channel resource compared with the other WBANs having a lower priority. In other words, the PRA algorithm offers more QoS provision to the WBAN with a higher priority at the expense of the other WBANs' QoS provision. It is important to guarantee QoS satisfaction to medical related service. To satisfy this requirement, this biased channel allocation is necessary.

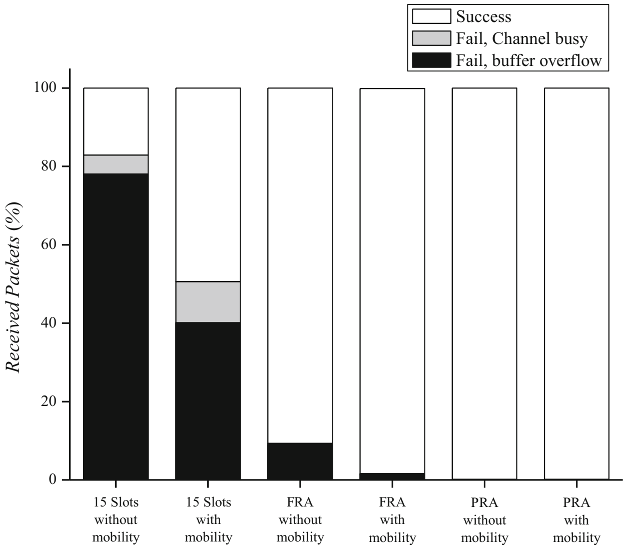

Fig. 9 A proportion of received packets according to different three schemes

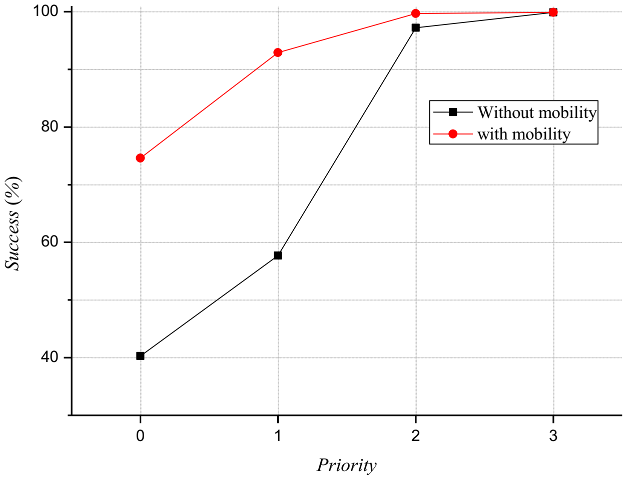

Fig. 10 Packet success rate of the PRA algorithm

In contrast to the FRA scheme, the PRA algorithm has different packet success rate according to its priority. Figure 10 represents the packet success rate of the subject WBAN. Only the subject WBAN has changed its priority from 0 to 3 by maintaining its surrounding environments such as other WBANs' priorities and sampling rate. In this case, the packet success rate increases as the priority becomes higher. Particularly, the WBAN with priority 3 shows almost perfect packet success rate. If the channel resource is not enough to use every WBAN, the PRA algorithm cannot guarantee the QoS satisfaction for low priority WBAN. Instead, it can provide QoS provision to the WBAN with high priority.

The reason for the packet failure is mostly buffer overflow in the PRA algorithm. The WBAN with low priority should reduce to use the channel resource in a case where the channel resource is occupied by other WBANs. In this case, the low priority WBAN can satisfy minimum service rate or cannot use the channel resource. Hence, as many WBANs occupy the same channel resource, the low priority WBAN has less chance to transmit packets that causes the buffer overflow.

The FRA scheme allocates the limited channel resource to all WBANs equally. As seen in Fig. 11, average length of the allocated slot length per superframe is equal regardless of the WBAN service priorities. The PRA algorithm allocates more channel resource to the WBANs which have higher priority. Unlike the FRA scheme, it

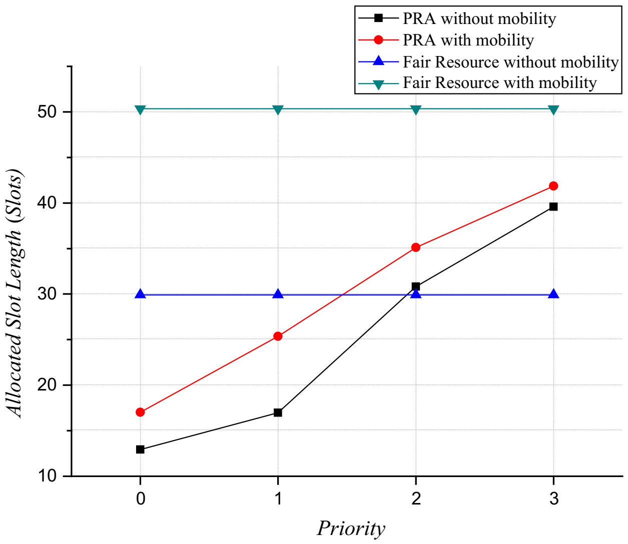

Fig. 11 Average slot length per superframe for the FRA scheme and the PRA algorithm

shows a growing shape as the priority increases. Thus, the PRA algorithm can guarantee more QoS satisfaction to the WBAN with higher priority in a case where the channel resource is insufficient for every WBAN. For the mobility case, the WBAN with the FRA scheme uses around 50 slots per superframe. That result is much higher than the PRA algorithm regardless of WBAN's priorities. This is because the FRA scheme wastes the limited channel resource a lot even if the WBANs do not require such a long channel resource. This redundant resource allocation results in low energy efficiency and channel resource shortage. For non-mobility scenario, the channel resource is always insufficient to provide QoS satisfaction for the entire WBANs. In this case, the FRA scheme identically allocates around 30 slots to all WBANs. The WBAN for the PRA algorithm obtains less QoS provision than the FRA scheme for the priority 0 and 1. However, the WBAN using the PRA algorithm satisfy more QoS provision for the priority 2 and 3. The QoS satisfaction is a very critical issue for healthcare service, especially for medical service. Therefore, the PRA algorithm is the suitable solution to provide healthcare service using the WBAN.

6 Conclusion

In this paper, the PRA algorithm based on IEEE 802.15.6 active superframe interleaving scheme was proposed. The IEEE 802.15.6 active superframe interleaving scheme is presented to share the limited channel resource among many WBANs. In the simulation results, as the number of WBANs using the same channel resource within the communication range increases, the WBANs experience much interference that results in low packet success rate. Therefore, to share the channel resource, the active superframe interleaving scheme is an essential technology, especially for non-mobility environment. By this time, the researches which allocate the channel resource based on the IEEE 802.15.6 active superframe interleaving scheme have not been performed yet. This paper presents efficient channel resource allocating algorithm that provides QoS satisfaction based on WBAN's service characteristics. If the channel resource is fairly allocated to all WBANs, it is excellent from the network resource fairness point of view. However, this fair resource allocation method cannot provide differentiated QoS satisfaction according to diverse WBAN services. The PRA algorithm adaptively allocates the channel resource based on the WBAN's service priorities, so it guarantees more QoS satisfaction to the high priority service. This means the PRA algorithm is an appropriate solution to serve various WBAN services and a practical solution because it is designed based on the IEEE 802.15.6 standard.

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Appendix

This section presents derivation process for (8). The minimum service rate, m, can be obtained from (3) as follows:

$$m = \frac{p}{1 + d_{\max} \cdot \frac{p-r}{b}} \rightarrow \frac{p-r}{b} = \frac{p-m}{m \cdot d_{\max}} \tag{9}$$

From (9), the selected service rate, R, can be derived by:

$$\begin{aligned} R &= \frac{p}{1 + d_q \cdot \frac{p-r}{b}} = \frac{p}{1 + (d_{\max} - S) \cdot \frac{p-m}{m \cdot d_{\max}}} \\ &= \frac{p}{\frac{p}{m} + \frac{S \cdot m - S \cdot p}{m \cdot d_{\max}}} = \frac{m \cdot p \cdot d_{\max}}{p \cdot d_{\max} + S \cdot m - S \cdot p} \end{aligned} \tag{10}$$

(10) is an m, p, d_{max}, and S based formula. Therefore, the selected service rate can be obtained from the active superframe interleaving request frame.

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