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ORIGINAL PAPER

RACOON: A Multiuser QoS Design for Mobile Wireless Body Area Networks

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Abstract In this study, Random Contention-based Resource Allocation (RACOON) medium access control (MAC) protocol is proposed to support the quality of service (QoS) for multi-user mobile wireless body area networks (WBANs). Different from existing QoS designs that focus on a single WBAN, a multiuser WBAN QoS should further consider both inter-WBAN interference and inter-WBAN priorities. Similar problems have been studied in both overlapped wireless local area networks (WLANs) and Bluetooth piconets that need QoS supports. However, these solutions are designed for non-medical transmissions that do not consider any priority scheme for medical applications. Most importantly, these studies focus on only static or low mobility networks. Network mobility of WBANs will introduce unnecessary inter-network collisions and energy waste, which are not considered by these solutions. The proposed multiuser-QoS protocol, RACOON, simultaneously satisfies the inter WBAN QoS requirements and overcomes the performance degradation caused by WBAN mobility. Simulation results verify that RACOON provides better latency and energy control, as compared with WBAN QoS protocols without considering the inter-WBAN requirements.

Keywords Wireless body area network · Multiuser quality of services · Mobility · Prioritized scheduling · Interference detection

Introduction

Quality of Service (QoS) for medical applications is an emerging issue for wireless body area networks (WBAN) [1, 2]. To reliably transmit data streams of medical applications (e.g. vital signals or diagnosis audio / video), WBAN QoS is asked to meet more harsh requirements than those of other wireless networks in terms of transmission latency, packet error rate (PER), and energy consumption, as mentioned in [3–9]. Furthermore, WBAN QoS is featured by considering different critical levels of vital signals. For instance, electrocardiograms (ECG) are deemed to have more important information than body temperature to indicate the health status of a person, hence ECG signals are supposed to have higher priority than that of body temperature. Many centralized scheduling technologies of medium access control (MAC) layer have been proposed to support QoS for a single WBAN (single user) [3–9]. In these works, a central processing node (CPN) of a WBAN centrally schedules radio resources of wireless sensor nodes (WSNs) illustrated in Fig. 1. These centralized controls can effectively meet various QoS requirements of vital signals. They also save energy consumptions of WSNs due to their light control loading of WSN in the CPN-centralized controls [9]. Nevertheless, some WBAN scenarios involve co-existence of multiple users, e.g. a hospital waiting room or a crowded subway station. Co-channel and co-location interference happens when WBANs move close to each other. It causes packet collisions and energy waste, which hence impact WBAN QoS. Besides, multiuser scenarios

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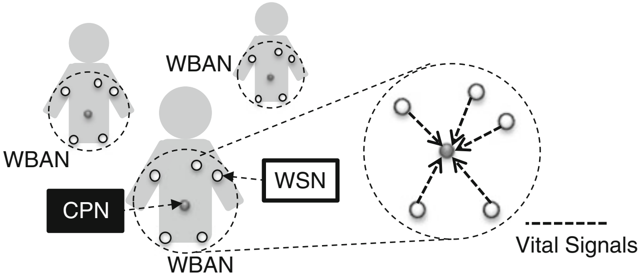


Fig. 1 Wireless body area network

might need extra definitions of critical levels of medical data. The critical levels of vital signals might vary according to not only signal properties (like the ECGs v.s. Body temperature example in a single WBAN QoS) but also user status. For instance, vital signals of an injured person might need higher priority than that of a healthy one. Thus, inter-WBAN priority scheme would be necessary. As a result, a new challenge of multiuser QoS that considers above inter-WBAN issues is introduced. To the best of our knowledge, there is no existing works addressing on solutions of multiuser WBAN QoS so far. Comprehensive studies are still required.

QoS designs for overlapped wireless local area networks (WLANs) or Bluetooth piconets might be the closest problems to multiuser QoS. *Jiang and Howitt* [10] analyze load-balancing between co-channel and co-location (overlapped) WLANs. Access points (APs) properly share bandwidth according to an optimized load-balancing through backhaul (wire-line) communications. On the other hand, for overlapped piconets, the inter-piconet interference is overcome by interconnecting discrete piconets into a scatternet [11–16]. A scatternet (cross piconet) scheduling is thus applied to provide collision free transmissions among overlapped piconets. However, these approaches might not be suitable multiuser QoS solutions for several reasons. First, these approaches are originally designed for non-medical transmissions, which have less strict QoS requirements and lack priority schemes for medical data. Furthermore, the WLAN approach focuses on static or low mobility scenarios. Its backhaul optimization is only suitable for fixed wireless nodes, which is not possible to be applied for mobile WBANs. On the other hand, the scatternet approach introduces extra control/traffic loading and energy consumption of slave nodes (similar to WSNs in WBAN) when they serve as scatternet bridges. However, for many WBAN applications, WSNs are expected to be very low power and have a very long battery-life, e.g. an implanted pacemaker is requested to perform years heart-pacing without battery changes. Thus, neither the QoS solutions for overlapped WLANs nor piconets can be applied directly to multiuser QoS.

In this study, proposed Random Contention-based Resource Allocation (RACOON), which is extended from our previous work [17], provides a multiuser QoS scheme for mobile WBANs. RACOON is featured by:

- *Simple inter-WBAN resource allocation*, which simplifies the control overhead of inter-WBAN QoS control. Resource allocation between WBANs is decided through random-value comparisons between WBANs. In RACOON, only one broadcasting packet that carries random values will be required to complete every inter-WBAN resource contention.
- *Iterative inter/intra-WBAN QoS control*, which supports a dynamic QoS adjustment in mobile WBAN scenarios. The adjustment will consider both critical-level differences among (i) adjacent WBANs and (ii) Vital signals.
- *Hierarchy CPN/WSN resource allocation*, which utilizes the asymmetric CPN/WSN structure and thus decrease control loadings and energy consumptions of WSNs. In the hierarchy CPN/WSN resource allocation, CPN is in charge of both inter/intra resource scheduling. WSN only wakes up while it is polled by its associated CPN.
- *Probing base inter-WBAN interference detection*, which detects potential inter-WBAN interferences before actual collisions happen in both downlink (CPN to WSN) and uplink (WSN to CPN) transmissions. The interference detection avoids packet collisions and energy waste caused by WBAN mobility and hence extends battery life of WSNs.

The rest of this paper is organized as follows: "WBAN quality of services (QoS)" section introduces requirements of WBAN QoS. "Random contention-based resource allocation (RACOON)" section reveals the proposed RACOON multiuser QoS protocol. "Computer simulation" section presents the experimental results and "Conclusion" section concludes this paper.

WBAN quality of services (QoS)

Requirements of WBAN QoS

WBAN QoS controls that simultaneously support both intra and inter WBAN QoS are studied in this work. A WBAN consists of a single central processing node (CPN) and several wireless sensor nodes (WSNs). These WSNs collect various medical data (including vital signals from human body and diagnosis audio/video) and forward them to the CPN, which is depicted in Fig. 1. Intra WBAN QoS controls should make sure these medical data are timely transmitted by following their delay-bound and delay-variation requirements [18]. However, when total bandwidth requirements of a WBAN overflow its capacity, transmissions should be scheduled in an order from the highest-priority data to that has the lowest priority, which guarantees the QoS level of high priority data. Such priority settings are usually designed by medical experts according to their clinical experiences. For example, a heart failure could introduce much instant life risk than an abnormal body-temperature. Hence, ECG signals directly reflecting heart activity should have higher priority than that of temperature records. This kind of priority is called as intrinsic data priority. Furthermore, if abnormal vital signals are detected, the priorities of these signals should be dynamically increased to be higher than those of normal signals. Such priority is called as emergent data priority. Therefore, intra WBAN QoS controls should meet various latency requirements of difference medical data and follow proper intrinsic and emergent data priorities simultaneously.

On the other hand, for inter-WBAN QoS designs, proper user priority should be further provided. In scenarios of multiple overlapped WBANs, WBANs need to share radio resource with each other. Once the overall capacity is not sufficient to support all transmission bandwidth of WBANs, radio resources should be allocated to WBANs that has higher user priority. Such priority should also be defined by medical experts. Usually, priority settings follow an order from the highest to the lowest life-critical WBAN users. High user-priority WBANs should be allowed to transmit all necessary medical data; low user-priority WBANs should transmit only partial medical data to maintain normal health monitoring. As a result, WBAN QoS controls should simultaneously satisfies (i) intrinsic data priority (ii) emergent data priority and (iii) user priority for both intra and inter WBAN QoS.

Aside from transmission qualities above, a WBAN QoS control should try to lower energy consumption of WSNs as well [1, 18, 19]. In a WBAN, a CPN will most likely be embedded in personal devices such as cellular phones or PDAs with larger and rechargeable batteries. In contrast, WSNs are expected to be light weight (small battery) and even un-rechargeable for certain implantable applications. Thus, WSNs are expected to keep their energy consumptions as low as possible.

Performance metrics

To qualify a QoS control for WBAN, following performance metrics will be evaluated.

- Transmission Latency: transmission latency affects smoothness of real-time display of vital signals. A transmission latency of a medical packet is calculated from the time of a packet is generated in a WSN to the time of the packet is successively received by a CPN. To ensure a vital signal is timely displayed, every packet of the signal should be received before its delay bound expires.
- Joule per bit of WSN: energy consumption of a WSN affects its battery life. To evaluate energy consumptions of WSNs with various traffic loading, an energy measurement is normalized by its transmission bandwidth with the unit, Joule per bit. An energy measurement of a WSN will count all its packet transmissions (successful/unsuccessful packet transmissions from WSN to CPN) and receptions (successful/unsuccessful polling message receptions from CPN to WSN).
- User capacity: user capacity affects the density of coexistence WBAN users, which is important for dense WBAN scenarios. User capacity is defined as the maximum number of coexistence WBANs that satisfy desired WBAN QoS requirements.

Related works

Significant contributions toward high quality WBAN QoS designs have been made in recent years [3–8, 20, 21]. These works adopt different framing, scheduling, and novel hardware techniques to optimize emergency transmission, packet latency, and power consumption of a single user WBAN. *Huasong* [5] creates a framing-structure-turning procedure to simultaneously improve throughput, queuing delay, and energy consumption of IEEE 802.15.4, a candidate protocol for WBAN. *Yoon* [3] further modifies the framing structure of 802.15.4 to remarkably reduce the packet delay of emergency alarm. He further introduces a preemptive scheduling to guarantee the transmission priorities of various medical data. There are also scheduling techniques utilizing TDMA-overhead-reduction [20], adaptive duty cycle [21], prioritized retransmission [6], delayed retransmission [4], fuzzy-logic controls [8], and wake-up radio [21] to enhance WBAN QoS. *Su and Zhang* further combine scheduling with realistic battery charging/discharging effect to significantly prolong battery life of WBAN sensors. More complete introductions and comparisons of existing WBAN QoS solutions are summarized by *Ullah* [19]. Different from above single WBAN solutions, proposed RACOON protocol puts more focus on multi-user WBAN QoS solution, which will be introduced in following sections.

Random contention-based resource allocation (RACOON)

The proposed Random Contention-based Resource Allocation (RACOON) is a bandwidth control system embedded in medium access control (MAC) layer for multi-WBAN QoS, which consists of two major designs: a CPN-based resource allocation and a random contention-based inter-CPN negotiation.

CPN-based resource allocation

The CPN-based resource allocation of RACOON is designed to minimize energy consumptions of WSNs and early detect inter-WBAN interference to avoid unnecessary packet collisions. The proposed CPN-based protocol has a two-step resource allocation scheme, which is illustrated in Fig. 2. There are two distinct channels for inter and intra-WBAN communication, respectively. The inter-WBAN channel is used to exchange the resource negotiation messages between WBANs. Only CPNs can access the inter-WBAN channel. On the other hand, the intra-WBAN channel is used to transmit polling messages from CPN to WSN and data packets from WSN to CPN. The superframe is divided into fixed number of slots. Each slot is subdivided into a short polling slot and a data slot, which are illustrated in Fig. 2. WSN receive not only transmission schedule from polling messages but also framing structure information including the start of a superframe and number of slots in it. When multiple WBANs overlap with each other, a CPN first negotiates WBAN resources with adjacent CPNs through the inter-WBAN channel. The detailed procedure of inter-CPN negotiation will be introduced in "Random contention-based inter-CPN negotiation" section. The CPN then assigns reserved resources to its WSNs by polling messages through the intra-WBAN channel. As a result, the WSNs wake up only when (1) receiving polling messages from the associated CPN in polling slots and (2) transmitting vital signals to that CPN if they are polled, hence energy consumptions of the WSNs can be reduced.

In the proposed CPN-based resource allocation, WSNs do not need to perform any interference detection. Instead, a probing-based interference detection, which utilizes a coverage difference between CPN and WSNs, is used and illustrated in Fig. 3. A CPN has a larger transmission range than that of WSNs, which allow the CPN to detect potential interferences to its uplink (WSN to CPN) and downlink (CPN to WSN) transmissions. The detection is realized by periodic "probing" from the CPN to its adjacent CPNs. These probing messages are exactly the inter-CPN negotiation messages and the CPN is probed when it receives negotiation messages from other CPNs. Therefore, the interference detection and inter-WBAN negotiation are finished at the same time. Figure 3 illustrates the proper range settings of a CPN and a WSN. For example, in an uplink (WSN to CPN) transmission with WSN' as the source of interference (Soi), which is shown as case (a) in Fig. 3, CPN (CPN') and WSN (WSN') have the transmission ranges R_{CPN} and R_{WSN}, respectively. For simplicity, the range of possible WSN position is assumed as a cylinder and shadowing effects of human body are ignored. CPN is located at the center of cylinder and WSNs are located within the cylinder. In case (a), a data packet is transmitted from WSN to CPN. In the mean time, WSN' is transmitting data as well. To avoid a data collision happens at CPN, the distance from the interference edge of WSN' (Soi) to CPN (Rx), that is, $D_{Esoi2Rx} = \left|\overrightarrow{W'C}\right| - R_{WSN}$ should be positive. Because the location of WSN' is confined by the cylinder, the minimum $\left|\overrightarrow{W'C}\right|$ lies on the $\overrightarrow{C'C}$ connection. For this reason, the minimum R_{CPN} that makes $\left|\overrightarrow{W'C}\right| - R_{WSN}$ positive should be larger than $R_{WSN} + \frac{d}{2}$, where d is the diameter of the cylinder. CPN thus can detect the neighbor WBAN from radio activities of CPN' before the interference of case (a) happens. Results of other combination of possible transmission directions and sources of interference are also presented in Fig. 3. By considering all cases, R_{CPN} should be at least larger than $R_{WSN} + d$ to ensure collision free transmissions.

Random contention-based inter-CPN negotiation

The inter-CPN negotiation of RACOON is an iterative bandwidth control scheme adjusted by two parameters: Bandwidth Requirement and User Priority Index. These two parameters are calculated by each CPN according to the status of it associated WSNs. From Fig. 4, each WBAN iteratively contends wireless resources to achieve a predefined bandwidth target. Besides, to reflect the emergency level (user priority index) of WBAN, two trends of

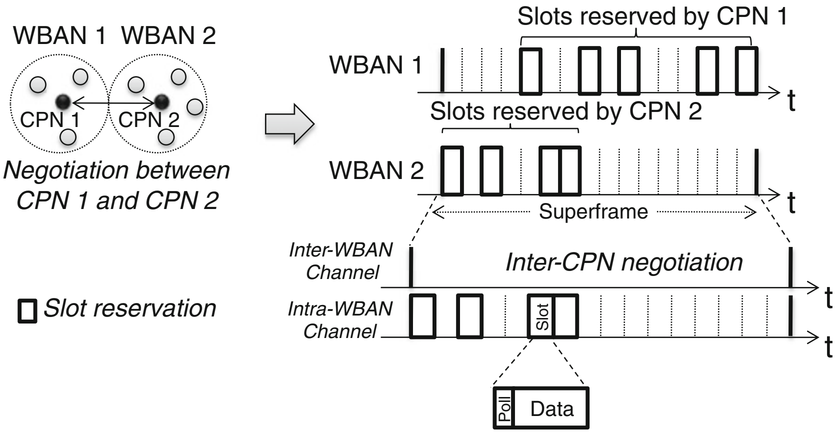
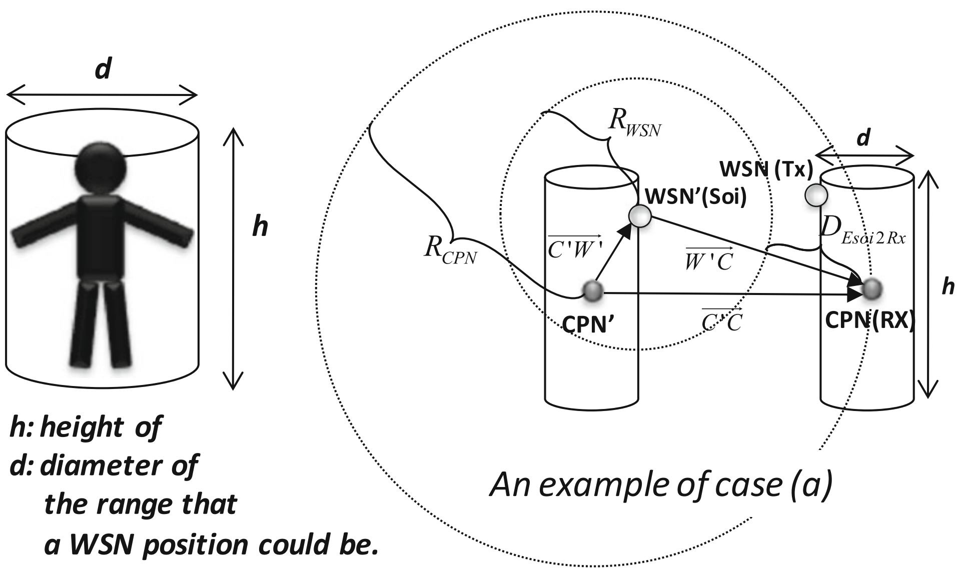


Fig. 2 CPN-based resource allocation of RACOON

Fig. 3 Probing-based interference detection



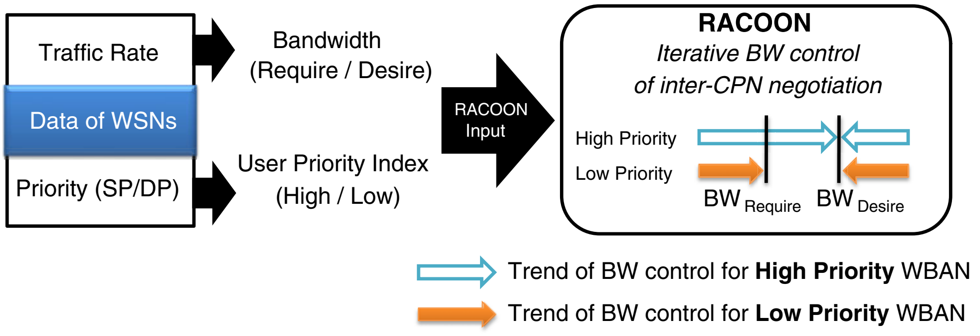
Tx→Rx		Soi	$D_{Esoi2Rx}$	Condition that CPN detects interf. from Soi with Cylinder Model
(a)	WSN→CPN (Uplink)	WSN'	$\lvert\overrightarrow{W'C}\rvert - R_{WSN}$	$R_{CPN} > R_{WSN} + d/2$
(b)		CPN'	$\lvert\overrightarrow{C'C}\rvert - R_{CPN}$	N/A $*R_{CPN} = \lvert\overrightarrow{C'C}\rvert$
(c)	CPN→WSN (Downlink)	WSN'	$\lvert\overrightarrow{W'W}\rvert - R_{WSN}$	$R_{CPN} > R_{WSN} + d$
(d)		CPN'	$\lvert\overrightarrow{C'W}\rvert - R_{CPN}$	$R_{CPN} > R_{WSN} + d/2$

bandwidth control scheme are provided for high and low priority WBANs, respectively. High priority WBANs aggressively contend resources to achieve a high bandwidth target, BW_{Desire}. Bandwidth requirements of a low priority WBANs are relaxed to be in between BW_{Desire} and a lower target BW_{Require}. Thus, when high and low priority WBANs contend to each other, high priority WBANs are expected to achieve better bandwidth targets than those of low priority WBANs can achieve.

The calculation of the bandwidth target, BW_{Desire}, BW_{Require}, and User Priority Index depends on proposed priority system for WSN. Each WSN has two kinds of priority indexes: static priority (SP) and dynamic priority (DP). Both SP and DP are set to either 0 (low) or 1 (high) depending on its intrinsic and emergent data priorities mentioned in "WBAN quality of services (QoS)" section. SP represents the importance of monitored signal. DP denotes the emergency level when a value of a monitored signal is out of its normal range.

BW_{Require} is defined as the minimum resource that a WBAN requires to transmit its emergency data, that is, $BW_{\mathrm{Require}} = \sum_i BW_i, (\forall i \in W) \cap (DP_i = 1)$, where W is

Fig. 4 Random contention-based Inter-CPN negotiation of RACOON



the set of WSNs in a WBAN; DP_i is the dynamic priority of WSN_i. On the other hand, BW_{Desire} is defined as the bandwidth that a WBAN needs to transmit both emergency and non-emergency data, that is, $BW_{Desire} = \sum_i BW_i$, $\forall i \in W$. As for the User Priority Index, it is decided by comparing the ratio of the number of emergency WSNs over all WSNs with a pre-defined threshold of User Priority Index, which are $\frac{|E|}{|W|}, E = \{\forall i \subset W \cap DP_i = 1\}$ and UPI_{th} respectively. When $\frac{|E|}{|W|} > UPI_{th}$, it is a high priority WBAN, otherwise, it is a low priority WBAN. Usually, UPI_{th} is a personal configuration and is expected to be defined by medical experts by considering syndromes and associated sensors of a WBAN user.

In RACOON, with the inputs of BW_{Desire}, $BW_{\mathrm{Re}quire}$, and User Priority Index, each CPN generates a weighted random value to contend resources with its neighbor CPNs. The scheme of weighted random value is inspired by Neighborhood-aware Contention Resolution (NCR) algorithm [22], which provides collision free scheduling. The skill of NCR is a random value comparison scheme. Each wireless node first generates a random value. The wireless node that has the largest random value wins the transmission slot. As for the weighted random value contention in our case, it can be realized by a pseudo contention. A CPN first generates its N_{rnd} uniform random values and picks the largest one for a slot contention. The average probability P_i that CPN i can obtain a slot is proportional to the number of random values, N_{rnd_i}, used in the pseudo contention. That is

$$P_i = \frac{N_{rnd_i}}{\sum_{j, j \in N(i) \cup i} N_{rnd_j}} \tag{1}$$

where $N(i)$ is the set of neighbors of CPN i. With this skill, each CPN iteratively controls its N_{rnd} to achieve their bandwidth targets according to the control flow illustrated in Fig. 5. At the start of each contention iteration, the available bandwidth BW_{Avb}, which is defined as the bandwidth that a WBAN has in its previous iteration, is compared with its two bandwidth targets, BW_{Desire} and $BW_{\mathrm{Re}quire}$. Then a three-case decision is decided basing on that:

$$\text{Case } 1: \ BW_{Avb} < BW_{\mathrm{Re}quire}$$

$$\text{Case } 2: BW_{\mathrm{Re}quire} \leq BW_{Avb} \leq BW_{Desire}$$

$$\text{Case } 3: BW_{Desire} < BW_{Avb}$$

The value of N_{rnd} will be changed based on the priority setting of a WBAN. As shown in Fig. 5, high-priority WBANs are designed to increase their N_{rnd} more aggressively than those of low-priority WBANs. Thus, the high priority WBANs are more possible to achieve their bandwidth requirements than the low priority WBANs. In the proposed design, an iteration of contention is performed in a superframe. A CPN first generates random values for all slots according to N_{rnd} respectively and broadcasts only one negotiation message carrying these values through the inter-WBAN channel to its adjacent CPNs. Thus, contentions can be performed by value comparisons between CPNs. To avoid collisions between negotiation-messages, these messages are broadcasted at random time slots within a superframe.

After a CPN finish an inter-WBAN resource contention, it performs an intra-WBAN scheduling to allocate its reserved transmission slots to its WSNs. A multi-queue scheduler is adopted to schedule resource by following order from the WSN that has the highest value of SP + DP to that has the lowest value, which is depicted in Fig. 6. A data in a queue is scheduled only when there is no data in other queues that has higher SP + DP value.

Computer simulation

Benchmarking WBAN QoS protocol

BodyQoS [9] is a MAC layer scheduling scheme chosen to benchmark the proposed WBAN QoS protocol. BodyQoS is a CPN-centralized single-WBAN-QoS control that is capable of overcoming performance impacts from co-channel interference. The design strategy of BodyQoS is to increase transmission opportunities of a WSN when it suffers a bad channel condition. The transmission opportunity is inversely proportional to its available bandwidth, hence a vital signal can be timely transmitted without extra delay. The bandwidth control of BodyQoS can be expressed as:

$$\frac{TxOpportunities(t)}{TxOpportunities_{ideal}} = \frac{BW_{ideal}}{BW_{Avb}(t-1)}$$

$$BW_{Avb}(t-1) = \alpha \cdot BW_{Measured}(t-1) + (1-\alpha) \cdot BW_{Avb}(t-2) \tag{2}$$

where BW_{ideal} is the ideal bandwidth with perfect channel; $BW_{Avb}$is calculated by a moving average of previous measured bandwidth $BW_{Measured}$. To fairly compare the BodyQoS with the proposed RACOON protocol, bandwidth measurement of the BodyQoS is performed every superframe. Besides, to avoid unpredictable interference, transmission opportunities are randomly scheduled within every superframe.[1]

Experimental settings

A MATLAB simulation platform is built to evaluate the proposed RACOON protocol. Detail settings of topology,

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[1] The original interference-avoidance scheme of BodyQoS is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. A random scheduling is used to simulate the random backoff skill of CSMA/CA.

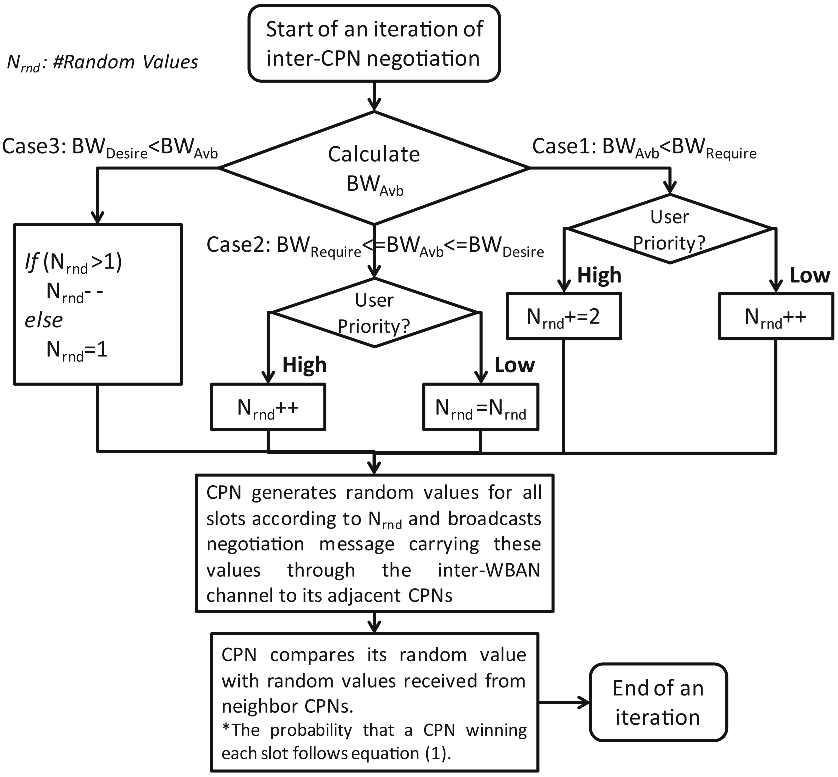

Fig. 5 Bandwidth control flow of inter-CPN negotiation in RACOON

PHY radio, MAC framing, and traffic loads, are listed in Table 1. Besides, to simulate WBAN mobility, the location change of WBANs follows the Gauss-Markov mobility model [23]. We use [23] to simulate the smooth movement path of a human, while avoiding the sudden stops and sharp turns that happen in the random walk mobility model [24]. The Gauss-Markov mobility model has a tuning factor α to control the randomness of WBAN movement. α is set as 0.5 in this study (α=0 and α=1 direct to a Brownian motion and linear movement respectively).

Experimental results

Packet latency of different vital signals in Fig. 7 illustrate how intra and inter WBAN priorities are realized in RACOON. For either high or low priority, latency of vital signals are ranked in order of SP + DP. Signal with higher SD + DP value should have lower latency. Note that SP and DP reflect the intrinsic and emergent data priorities, respectively. Furthermore, due to that the high-priority WBAN contends resources more aggressively than the low-priority WBAN does, same signal with same priority setting in the high-priority WBAN has shorter latency than that in the low-priority WBAN. This meets the QoS requirements of the user priority.

The latency comparison between RACOON and Body-QoS [9] in mobile WBAN scenarios is shown in Fig. 8. RACOON has much lower packet latency than BodyQoS has when WBANs move at either 2 m/s or 6 m/s. The reason is that RACOON makes WBANs cooperatively share the radio resource when they overlap to each other. On the contrary, BodyQoS does not consider interference

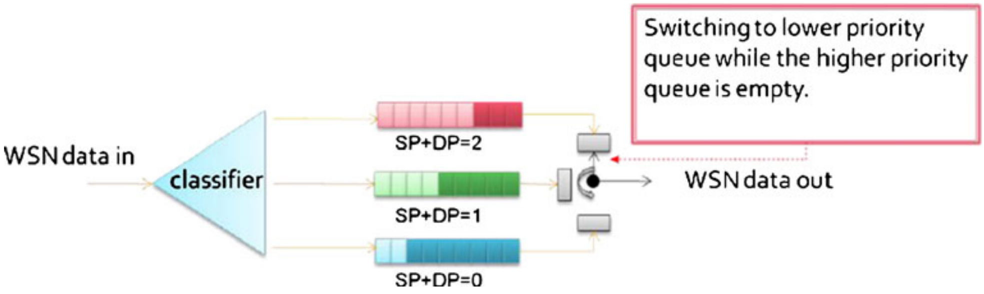

Fig. 6 Multi-queue scheduler of intra-WBAN scheduling

Table 1 Experimental settings

Item	Value
Framing structure	10 slots per superframe / each slot is 50 ms long
Packet size	240bytes
Transmission rate	48 kbps
RX Power	27.3 mW
TX Power	31.2 mW
Topology	1 to 10 WBANs randomly deployed in a 6×6 m^2 square. When number of WBANs is more than one, the ratio between high and low priority WBANs is 1:1.
Transmission range	Distance between CPN and WSN: 0.5 m. Referring to the range settings of probing-base interference detection in section “Random Contention-Based Resource Allocation (RACOON)”, CPN: 3 m / WSN: 2 m.

Data Type	Data Rate	Data Priority (SP, DP)	Delay Bound
ECG ch1	4 kbps	1, 1	1 s
ECG ch2	4 kbps	1, 1	1 s
SpO2	3 kbps	1, 0	1 s
Blood pressure	3 kbps	0, 1	10 s
Temperature	2 kbps	0, 0	10 s
Heart rate	2 kbps	0, 0	10 s

interactions between WBANs, which makes improper decisions of bandwidth control and thus induces high transmission delay. In the original ideas of BodyQoS, interference is assumed to be generated by regular co-channel communications or path-loss due to limb movements. These sources of interference have “passive” interference patterns, which means it does not increase or decrease its interference level following the bandwidth control of BodyQoS. Therefore, BodyQoS reasonably increases transmission opportunities to overcome bad channel conditions. However, in multi-WBAN scenarios, the increasing transmission opportunities cause serious inter-WBAN interference. It than increases the transmission opportunities again and causes more serious interference, which enters a vicious circle. Collision measurements with RACOON and BodyQoS in Fig. 9 echo this observation.

The collision measurements also show that collision of WBAN with RACOON is less sensitive to the number of co-existence WBANs, as compared with BodyQoS. Interference between WBANs is overcome by RACOON’s cooperative

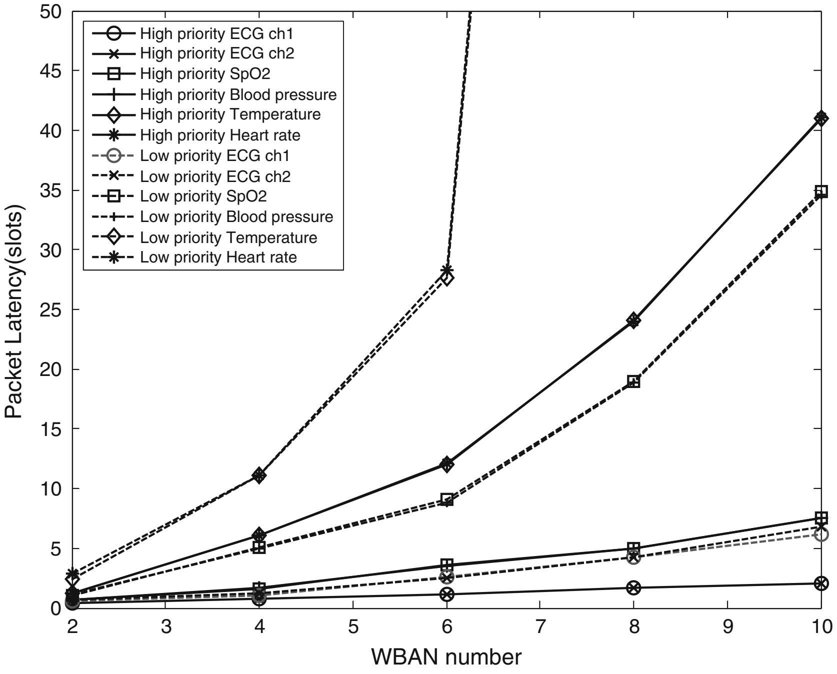

Fig. 7 Packet latency of vital signals in high and low priority WBANs

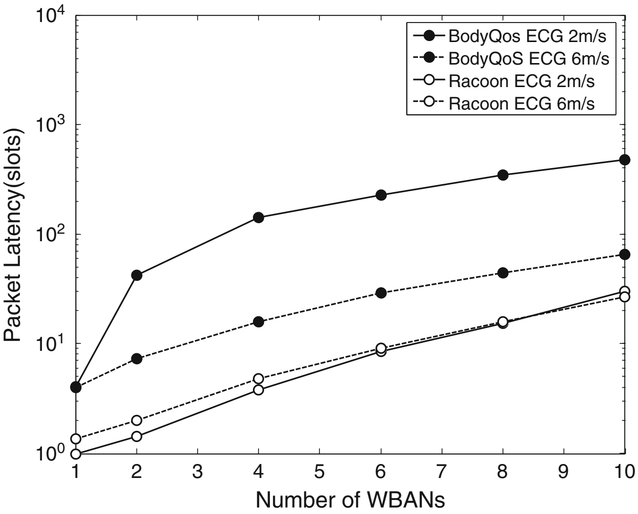

Fig. 8 Packet Latency with RACOON and BodyQoS

inter-WBAN resource sharing scheme and proposed probing-based interference detection. Collisions of RACOON are created by out-of-date scheduling. A WBAN moves and encounters other un-negotiated WBANs with out-of-date inter-WBAN scheduling and thus packet collisions happen. However, besides of collisions created by WBAN mobility, BodyQoS creates extra collision by its problem of the inter-WBAN-interference enhancement. This problem gets worse when number of co-existence WBANs increases and hence introduces more collisions. The difference reasons of collisions of RACOON and BodyQoS are also reflected in their energy consumptions, which is depicted in Fig. 10. Note that the energy consumption is normalized to transmission throughput. The energy consumption considers both TX and RX according to the definition in performance metrics, "Performance metrics" section.

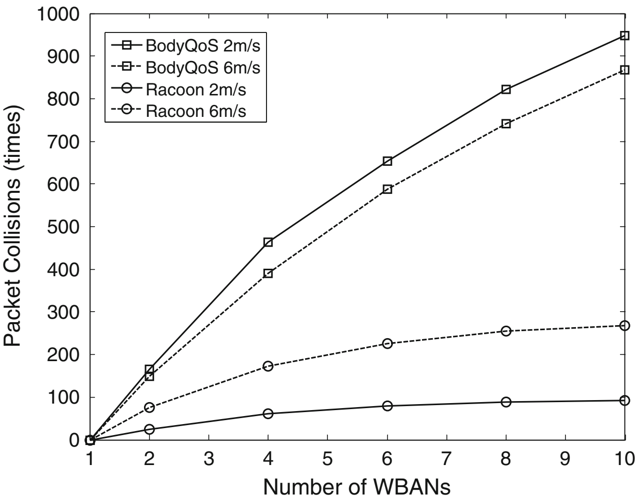

Fig. 9 Packet collisions with RACOON and BodyQoS controls

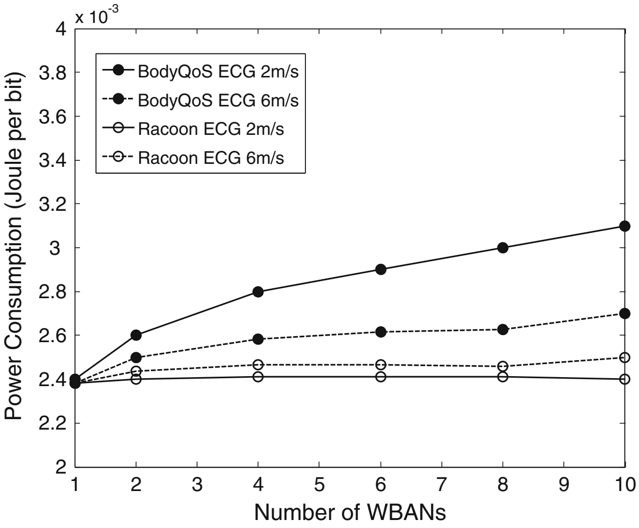

Fig. 10 Energy consumption of WSN with RACOON and BodyQos

There is an interesting result in Figs. 8, 9, and 10. While mobility of WBAN user is increased, BodyQoS and proposed RACOON have opposite reactions. For BodyQoS, the latency, collision, and energy consumption of a WBAN are decreased. On the contrary, for RACOON, those of a WBAN are increased, which are shown in Figs. 8, 9, and 10. The reason comes from the different anti-interference strategies of them. As for BodyQoS, a WBAN increases its transmission opportunities when it suffers inter-WBAN interference. If a collision history of a WBAN is separated into collision and non-collision, it will form an iterative collision / non-collision / collision / non-collision … pattern. Thus, for BodyQoS, a WBAN first senses collision and tries to increase its TX times. When the TX times are increased and the WBAN moves into a non-collision area, the latency, collision, and energy consump-

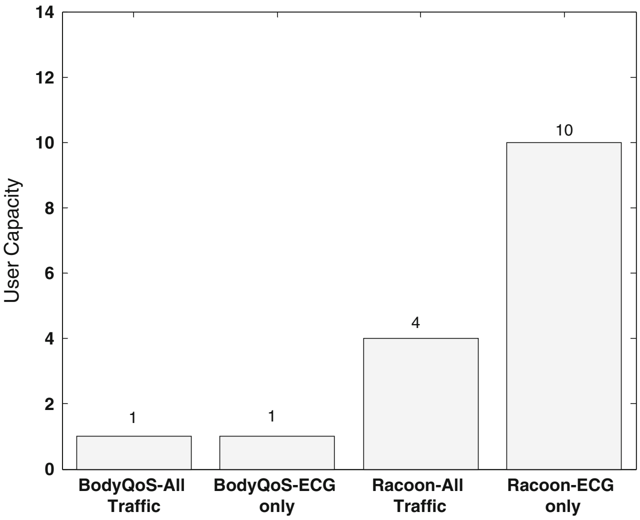

Fig. 11 User Capacity with RACOON and BodyQoS

tion of a WBAN are decreased. And then this WBAN starts to decrease the TX times because it senses no interference in the non-collision area. While the TX times are decreased and the WBAN happens to move into a collision area, some collisions are avoided. As a result, for BodyQoS, mobility helps a WBAN to decrease its latency, collision, and energy consumption. RACOON has an opposite strategy in TX-times control. For RACOON, a WBAN tries to decrease its TX times (through inter-WBAN resource negotiation) to resolve inter-WBAN collision and increase the TX times when there is no collision. RACOON thus has an opposite collision result during the iterative collision / non-collision pattern. As a result, RACOON introduces more collision to a WBAN when its mobility is increased. Although mobility helps the performance of BodyQoS and decreases that of RACOON's, RACOON still guarantee a WBAN to have lower latency, collision rate, and energy consumption than what BodyQoS does due to RACOON's cooperative inter-WBAN resource allocation.

User capacity is calculated by counting number of co-existence WBANs that provide delay-bound-satisfied transmissions of corresponding vital signals, which is illustrated in Fig. 11. The proposed QoS protocol, RACOON, provides up to four co-existence WBANs that guarantee delay-bound requirements of all traffics. Its user capacity can be increased to ten co-existence WBANs when only the delay-bound of ECG traffics are satisfied. On the contrary, BodyQoS can support only single WBAN QoS due to its problem of inter-WBAN-interference enhancement.

Conclusion

This work proposes Random Contention-based Resource Allocation (RACOON) protocol to provide multiuser QoS for wireless body area networks (WBANs). By considering QoS requirements of practical medical applications, the inter-WBAN scheduling should have QoS controls that simultaneously consider three different priorities: (i) intrinsic data priority, (ii) emergent data priority, and (iii) user priority. The proposed RACOON protocol uses a dynamic weighted-random-value-comparison scheme to meet these priority requirements. Furthermore, RACOON utilizes a centralized control and a probing-based inter-WBAN interference detection to simplify QoS controls of wireless sensor nodes (WSNs), which decreases unnecessary energy waste of WSN. Simulation results shows that RACOON has better QoS performance in terms of transmission latency, energy consumption, and user capacity, as compared with other WBAN QoS controls that do not consider inter-WBAN interference and priority.

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