Ann. Telecommun. (2016) 71:441–451
DOI 10.1007/s12243-016-0499-6

Fairness-aware radio resource management for medical interoperability between WBAN and WLAN

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Received: 6 September 2015 / Accepted: 26 February 2016 / Published online: 12 March 2016

Abstract Wireless body area networks (WBANs) in the industrial, scientific, and medical (ISM) bands have been increasingly adopted for various medical applications. Due to the shared nature of the ISM bands, when a WBAN coexists with a wireless local area network (WLAN), performance of WBAN may significantly degrade because of asymmetric attributes between WBAN and WLAN such as transmit power and response time. In this paper, we propose a novel channel access protocol for achieving effective channel sharing in the aspect of efficiency and fairness, which adaptively controls the contention window size of WLAN based on the delay information of WBAN. Our extensive simulation results for real-time electrocardiogram (ECG) monitoring show that the proposed scheme can guarantee the required quality of service of WBAN while insignificant degradation of WLAN performance.

Keywords Medical interoperability · Coexistence · WBAN · WLAN · Electrocardiogram (ECG)

1 Introduction

With the rapid advancement of wireless technologies, the demand for wireless networks has been greatly increased for various medical applications. Consequently, electronic healthcare is coming into the spotlight [1]. However, for successful deployment of wireless technologies in medical applications, we need to resolve key challenges such as coexistence and interoperability, reliability, privacy and security, and many more [2].

In particular, we pay attention to the interoperability in typical medical scenarios with a two-hop network, where a wireless body area network (WBAN) by ZigBee coexists and interoperates with a WLAN by Wi-Fi as shown in Fig. 1. In this medical loop, a central coordination unit (CCU) collects via WBAN vital signals such as temperature, electrocardiography (ECG), blood pressure, and SpO2 from the sensors. Then, the decision support entity in the CCU processes the data for possible generation of alarms. Furthermore, the CCU delivers via WLAN the collected vital signals to caregivers for proper treatments for the patient. The main challenge in this loop is to guarantee the required quality of service (QoS) level of wireless medical applications [3–5].

We focus on efficient coexistence of WBAN and WLAN when both technologies access the channel with carrier sense multiple access with collision avoidance (CSMA/CA). We propose a channel access protocol which can adaptively control the contention window size of WLAN for effective channel sharing for medical environments. The main idea is to mitigate mutual interference by decreasing the channel access attempt of WLAN and give more channel access opportunities to

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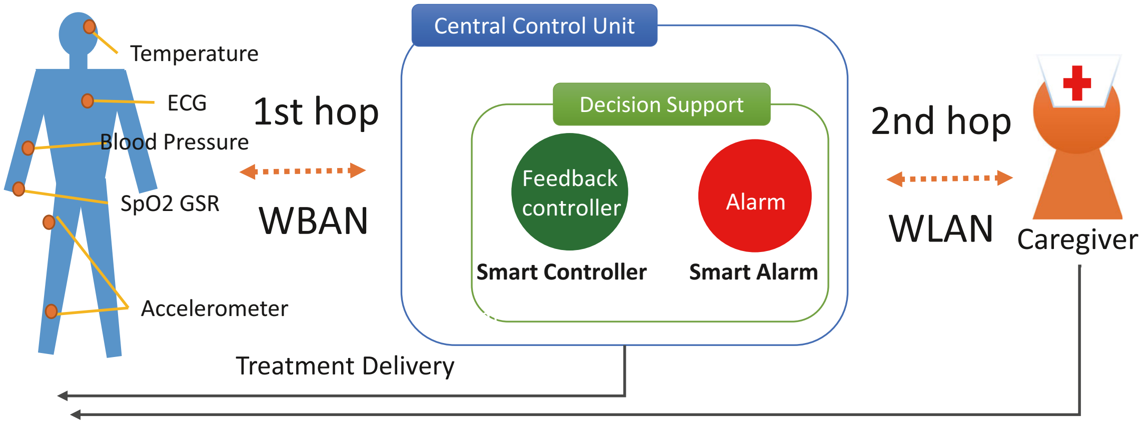


Fig. 1 Two-hop medical networks with WBAN and WLAN

WBAN. More specifically, our main contributions are as follows:

- We identify the severe unfairness issue between WBAN and WLAN in medical environments due to asymmetric attributes such as transmit power and response time.
- We propose an effective channel access scheme for providing the required medical quality of service (QoS) of WBAN.
- By implementing a customized simulator, we validate the proposed scheme under various simulation scenarios.

The coexistence between WBAN and WLAN have been widely studied so far. For example, device to device communication such as the WiFi Direct technology can cause unmanageable performance degradation of ZigBee [6]. When WiFi traffic becomes intensive, ZigBee may adaptively switches to other idle or less frequntly used channels, which is called the frequency planning method [7]. However, this approach is insufficient to resolve massive collisions because it can respond only after some collisions. In addition, it requires substantial delay in detecting interferences and changing to different channels. Therefore, in this paper, we propose an effective channel access algorithm for coexistence between WLAN and WBAN as an alternative solution.

Another method is to use an additional signaler that ZigBee can announce its on-going transmission. In [8], a cooperative busy tone is proposed that enables the coexistence between ZigBee and Wi-Fi. However, this approach requires additional cost for operation and spends more energy with signaler which is not suitable for body sensors with limited battery capacity.

In addition, WiCop is proposed as a policing framework that can effectively control the temporal white spaces between Wi-Fi transmissions [9]. In particular, two policing schemes are proposed: (i) Fake-PHY-Header and (ii) DSSS Nulling. In the Fake-PHY-Header scheme, a policing node is added to the WBAN. Then, the policing node runs the WiCop framework by properly sending policing signals and controlling the WBAN operations. Then, each WBAN polling period begins with a policing node broadcast in the temporal domain, which is called a Fake-PHY-Header. In the DSSS Nulling scheme, they generate a policing signal to create spaces for WBAN signals. By using these two schemes, WiCop increases WBAN packet delivery rates by up to 40 %.

Most of existing solutions for coexistence between WBAN and WLAN focus on how much performance of WBAN can be improved. Unlike these approaches, we pay attention to fair channel sharing without significant performance degradation of WLAN.

The rest of the paper is organized as follows: In Section 2, we state the major coexistence issues of WBAN and WLAN in medical environments. Then, we provide the system model for interoperation of WBAN and WLAN and present our proposed scheme for resolving the coexistence issues. Section 3 provides the performance of the proposed scheme with medical data of ECG signals. Finally, our conclusion follows in Section 4.

2 Proposed scheme

2.1 Problem statement

The coexistence problem between WBAN and WLAN comes from the fact that both uses the same 2.4 Ghz industrial, scientific, and medical (ISM) band. Furthermore, the maximum transmit power of WBAN (IEEE 802.15.4) is typically as low as 0 dBm while that of WLAN (IEEE 802.11) usually 15 to 20 dBm [10]. For this reason, WLAN can fail to detect WBAN transmission because it does not reach

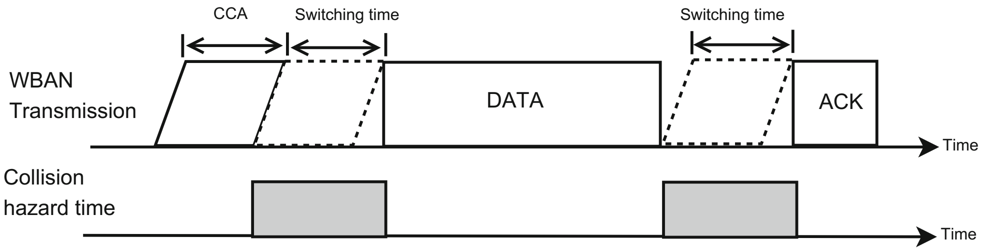


Fig. 2 WLAN preempts WBAN transmission due to shorter response time

to energy detection (ED) threshold level. Consequently, WBAN may have unfair channel share.

In addition, the difference in response time of WLAN and WBAN makes collision hazard time as shown in Fig. 2. Table 1 shows the system parameters in IEEE 802.15.4 and IEEE 802.11g. The MAC layer time slot is only 9 or 20 μ s for WLAN in contrast to 320 μs for WLAN [14]. Since WLAN has a shorter $SlotTime$ duration than WBAN [8], it makes a fast channel access and transmission than WBAN. Accordingly, as shown in Fig. 2, if a WLAN node performs a clear channel assessment (CCA) which is a combination of carrier sensing (CS) and energy detection (ED) to check the channel is busy or not, it would consider the channel as available. Then, it would start data transmission and result in collision with data transmission of WBAN. Also, it may interrupt ACK transmission of WBAN as soon as it detects that the channel is available during the switching time of WBAN. Therefore, there are two collision hazard times in each WBAN transmission, which is a serious problem, especially when WBAN transmits critical data such as medical information.

WBAN and WLAN are unable to exchange the control message each other, since they have different PHY layer properties. Therefore, it is impossible to schedule the transmission considering each other transmission to avoid the collisions. Hence, an effective method for efficient channel share between WBAN and WLAN is required.

2.2 System description

We consider that WBAN adopts IEEE 802.15.4 because it is most widely used in wireless sensor networks (WSNs). In particular, when compared with Bluetooth, IEEE 802.15.4 is more suitable for WBAN because it can have more active devices and give less interference to other devices [11]. The IEEE 802.15.4 standard specifies the physical layer and medium access control (MAC) layer. In the 2.4 GHz ISM band, there are 16 channels with channel spacing of 5 MHz, operating with a raw data rate of 250 kb/s using the offset quadrature phase shift key (O-QPSK) modulation [14]. For random channel access, IEEE 802.15.4 provides slotted CSMA/CA and un-slotted CSMA/CA. In this paper, we only consider the asynchronous mode of un-slotted CSMA/CA medium access protocol which is well known as non-beacon enabled networks. In this mode, each node wakes up and performs its backoff procedure to transmit only if there are data to be sent.

In the un-slotted CSMA/CA, if a WBAN node attempts to transmit data, it first performs the backoff procedure. It chooses a random integer uniformly between 0 and 2^{BE}, where BE is the backoff exponent which has the default minimum value ($macMinBE$) of 3. CCA is performed after the backoff procedure to check if the channel is idle. If the channel is idle, the node transmits data. Otherwise, BE is incremented by one until it reaches to the maximum of backoff exponent ($aMaxBE$), where the default value is set to 5. Then, the backoff procedure repeats again.

In the case of WLAN, it transmits only if it detects the channel idle for the arbitrary inter-frame space (AIFS) period. Otherwise, it waits until the backoff procedure ends. The number of backoff is chosen randomly from the range of contention window. It should be noted that CCA of WBAN is performed only after the backoff procedure. Therefore, WBAN performs CCA only after finishing the backoff procedure unlike the backoff procedure of WLAN, which freezes its backoff timer until the channel becomes idle.

The IEEE 802.15.4 provides two types of topologies, star topology, and peer to peer topology. Peer to peer topology is a distributed network without no central coordinator. On

Table 1 IEEE 802.15.4 and IEEE 802.11g system parameters

Parameter	IEEE 802.15.4	IEEE 802.11g (SlotTime = 20 μs)	IEEE 802.11g (SlotTime = 9 μs)
SlotTime	320 μs	20 μs	9 μs
RxTx TurnaroundTime	192 μs	5 μs	5 μs
CCATime	128 μs	15 μs	4 μs

the other hand, star topology enables to configure a system that can transfer data to a CCU. Then the CCU can transmit gathered data which is composed of such as ECG and blood pressure from body sensors to caregivers. Therefore, we adopt a star topology in our system because it is suitable for medical environments.

2.3 Throughput model

In this section, we derive an analytical throughput model to show how WBAN and WLAN throughput are related with the contention window of WLAN. There is a very well-known throughput model for the distributed coordination function (DCF) of IEEE 802.11 [12]. However, the Bianchi's throughput model cannot be directly applied to our case because the transmission failure results from interference from other network instead of collision in the same network. The purpose of deriving an analytic throughput model is to evaluate the effect of several parameters and to resolve the unfairness problem between WLAN and WBAN. A throughput model depends on the transmission coverage, transmission rate, number of nodes, and contention window size. Assume that there are N_{wlan} WLAN senders within the transmission coverage of WLAN and N_{wban} WBAN senders coexist with the WLAN nodes. We define CW_{wlan} and CW_{wban} as the contention window size of the WLAN and WBAN senders, respectively.

We make several assumptions for our scenarios. First, WLAN and WBAN senders always have sending data and compete for channel access. The transmission round is defined as the time interval between two consecutive packet transmissions. Second, the WLAN senders can detect the WBANs packet transmission with a probability of P_d, while the WBAN senders can completely detect the WLANs packet transmission. Third, when both WLAN and WBAN initially start to transmission, their nodes select their own random backoff counters, b_{wlan} and b_{wban}, respectively.

We define $p_{bo,wlan}$ and $p_{bo,wban}$ as the backoff probability of the WLAN and WBAN sender as follows:

$$p_{bo,wlan} \triangleq Pr\{b_{wlan} = k_{wlan}\} = \frac{1}{CW_{wlan}},\quad 0 \le k \le CW_{wlan} \tag{1}$$

$$p_{bo,wban} \triangleq Pr\{b_{wban} = k_{wban}\} = \frac{1}{CW_{wban}},\quad 0 \le k \le CW_{wban} \tag{2}$$

Let us define $t_{bo,wlan}$ and $t_{bo,wban}$ as the minimum backoff time among N_{wlan} WLAN senders and N_{wban} WBAN senders.

- CASE 1: $t_{bo,wlan} < t_{bo,wban}$ (channel occupation by WLAN)
- CASE 2: $t_{bo,wlan} \ge t_{bo,wban}$ (channel access attempt by WBAN before WLAN)

First, we focus on CASE 1 where WLAN sender starts to transmit at the $(t_{bo,wlan}+1)$th time slot. The probability that a WLAN sender accesses the channel without intra system collision and inter system interference after $t_{bo,wlan} = k_1$ backoff time, $p_a^1(k_1)$ is represented as

$$p_a^1(k_1) = N_{wlan}\, p_{bo,wlan} \left(1-(k_{wlan}+1)\, p_{bo,wlan}\right)^{N_{wlan}-1} \left(1-(k_{wlan}+1)\, p_{bo,wban}\frac{t_{s,wlan}}{t_{s,wban}}\right)^{N_{wban}}, \tag{3}$$

where $t_{s,wlan}$ and $t_{s,wban}$ is the slot time of WLAN and WBAN. The average throughput of WLAN is

$$TH_{wlan}^1 = \sum_{i=1}^{CW_m-1} P_a^1(k_1)(1-ber_1)^L \times \frac{L}{k_1 t_{s,wlan} + L/R_{wlan} + t_{oh,wlan}}, \tag{4}$$

where CW_m is the minimum value of CW_{wlan} and CW_{wban}. L is the packet size in bits. R_{wlan} is the transmission rate of the WLAN nodes from 6 to 54 Mb/s. The bit error rate (BER) can be obtained with a path-loss model and a geometric model specifying the locations of nodes and the assumption of additive white Gaussian noise channel in [13]. In addition, $t_{s,wlan}$ is the slot time and $t_{oh,wlan}$ is the overhead time. In this case, WBAN defers the channel access, and thus its throughput is zero.

In CASE 2, the WBAN sender makes the channel access attempt before the WLAN sender attempts to channel access. In this case, we should distinguish the case where the WBAN sender detects WLANs transmission from the case where the WBAN sender does not detect WLANs transmission. Define two cases; $TH_{wban,1}^2$ is the WBAN throughput when the WBAN detects WLANs transmission, and $TH_{wban,2}^2$ is the WBAN throughput when WBAN does not detect WLANs transmission. Accordingly, we can summarize the throughput of the WBAN in CASE 2 as follows:

$$TH_{wban}^2 = p_d TH_{wban,1}^2 + (1-p_d)TH_{wban,2}^2, \tag{5}$$

where the WBAN throughput without interference by WLAN can be obtain by the same equation with Eq. 4. Now we derive the the throughput of WLAN in CASE 2 TH_{wlan}^2 and WBAN $TH_{wban,2}^2$. The channel access probability of WLAN and WBAN senders when $t_{bo,wlan} = k_1$ and $t_{bo,wban} = k_2$ can be represented as

$$p_a^2(k_1,k_2) = N_{wlan}\, p_{bo,wlan}(1-(k_1+1)p_{bo,wlan})^{N_{wlan}-1} N_{wban}\, p_{bo,wban}\frac{t_{s,wlan}}{t_{s,wban}}(1-(k_2+1)p_{bo,wban}\frac{t_{s,wlan}}{t_{s,wban}})^{N_{wban}-1}. \tag{6}$$

We consider two WLAN and WBANs backoff time are independent. When there exists interference to the WLAN and WBAN by the WBAN and WLAN, respectively, then the throughput are represented as

$$TH^2_{wlan} = \sum_{k_{wban}=0}^{CW_m-1} \sum_{k_{wlan}=k_{wban}}^{CW_m-1} p_a^2(k_1, k_2)(1-per_1)\frac{L}{n_{t,1}t_{s,wlan}}, \tag{7}$$

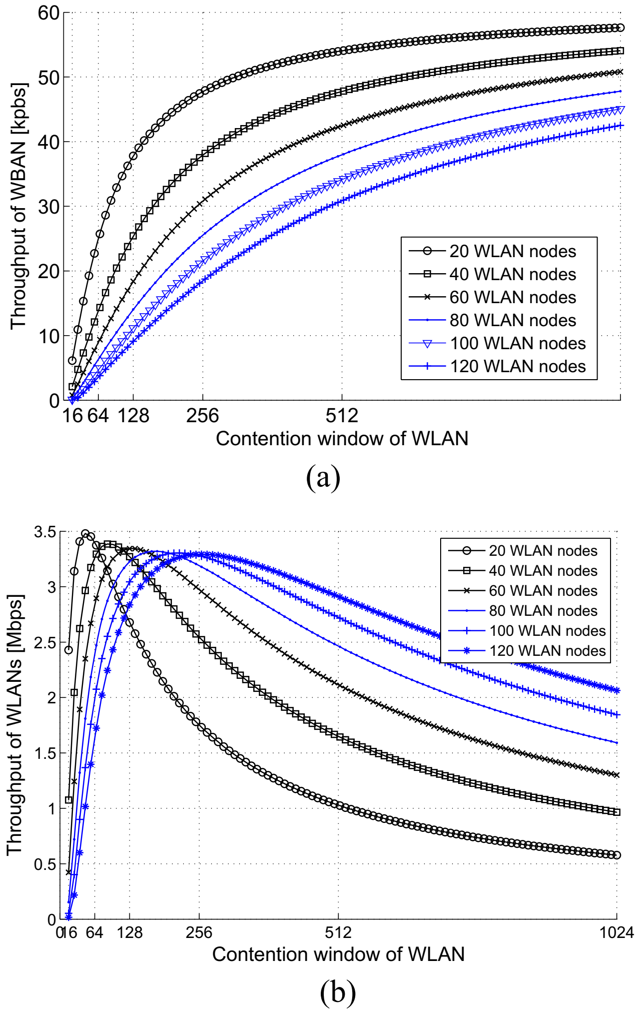
$$TH^2_{wban,2} = \sum_{k_{wban}=0}^{CW_m-1} \sum_{k_{wlan}=k_{wban}}^{CW_m-1} p_a^2(k_1, k_2)(1-per_2)\frac{L}{n_{t,2}t_{s,wban}}. \tag{8}$$

The packet error rate (PER) of WLAN and WBAN, per_1 and per_2 can be obtained in [16]. To obtained per_1 and per_2 values, we need to calculate the number of time slots with inter-system interference during both WLAN and WBAN send packet. In addition, we need to calculate how many time slots occupied by the WLAN and WBAN senders without interference. The $n_{t,1}$ and $n_{t,2}$ gives the number of time slots elapsed from the start of transmission round to the end of WLAN and WBAN packet transmission. By using all these equations, we can obtain the final WLAN and WBAN throughput as

$$\begin{aligned} WLAN : TH_{wlan} &= TH^1_{wlan} + TH^2_{wlan} \\ WBAN : TH_{wban} &= p_d TH^2_{wban,1} + (1-p_d)TH^2_{wban,2}. \end{aligned} \tag{9}$$

By using the derived throughput model, we investigate the effect of the contention window. we consider the simple geometry model, where distance between the transmitter and receiver of the WLAN is 100 m and that of the WBAN is 10 m and distance between WLAN and WMAN transmitters is 300 m. Here, we set the number of WBAN nodes as 20, and CW_{wban} is set to 7 and CW_{wlan} changes from 16 to 1024. Figure 3a shows that the throughput of WBAN increases as CW_{wlan} increases. On the other hand, WLAN throughput also increases initially as CW_{wlan} increases as shown in Fig. 3b, which results from the decreased probability of transmission failure due to collision among WLAN nodes. The throughput of WLAN decreases after the maximum of the throughput.

To evaluate the performance with respect to CW_{wlan}, we conduct simulation with the setting in Section 3.1. In the simulation scenario, 10 WBAN nodes periodically generate packets and coexist with 10 WLAN nodes. Figure 4 shows the number of successful packets of WLAN and Fig. 5 shows the results of WBAN. Increasing the contention window size of the interferer (CW_{wlan}) gives more channel access opportunity to the victim (WBAN), and the number



(a)

(b)

Fig. 3 Analytic results: **a** WBAN throughput with respect to CW of WLAN, **b** WLAN throughput with respect to CW of WLAN

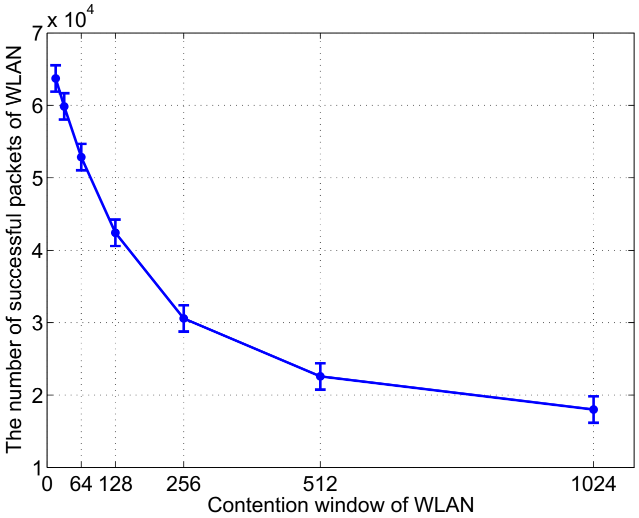


Fig. 4 Effect of the contention window of WLAN on the the number of successful packets of WLAN

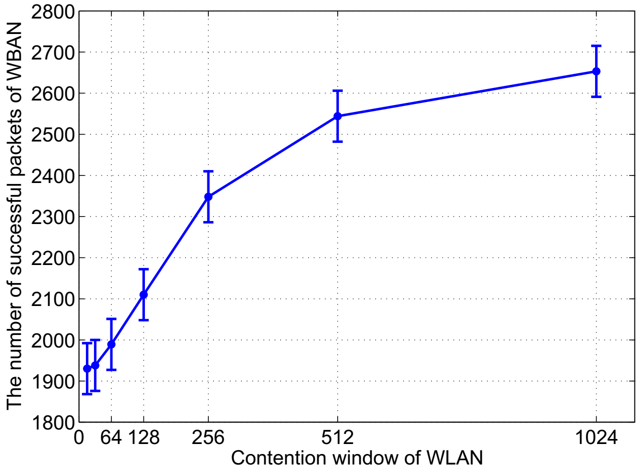


Fig. 5 Effect of the contention window of WLAN on the the number of successful packets of WBAN

of successful packets of WLAN is decreased as contention window of WLAN increases. Therefore, the number of successful packets of WBAN is increased because WBAN nodes can finish their transmission during WLAN's back-off procedure. Consequently, we can adjust the fairness between WBAN and WLAN by controlling the contention window size of WLAN.

2.4 Proposed scheme for effective channel share between WBAN and WLAN

In this section, we propose an efficient channel share protocol that adaptively controls the contention window size of WLAN for effective channel sharing between WBAN and WLAN. The main idea is to mitigate interference by decreasing the channel access attempt of WLAN and give more channel access opportunities to WBAN.

The system architecture for our proposed algorithm is shown in Fig. 6. The coordinator contains a CCU of WBAN and a WLAN node. The role of WBAN CCU is to collect sensed data from sensor nodes and that of the WLAN node is for long range transmission as already explained in Fig. 1. In general, WBAN and WLAN are unable to exchange control messages because of the different physical layers. However, we can use a signal path between WBAN and WLAN in our system architecture using the coordinator as shown in Fig. 6.

First, an access point (AP) of WLAN sends a message after measuring the aggregate throughput TH_{wlan} and managing the number of nodes N_{wlan}. Also, the coordinator of WBAN measures the aggregate throughput TH_{wban} and recognizes the number of relevant nodes N_{wban} in every monitoring interval. Then, the coordinator calculates the total throughput η_{eff} as

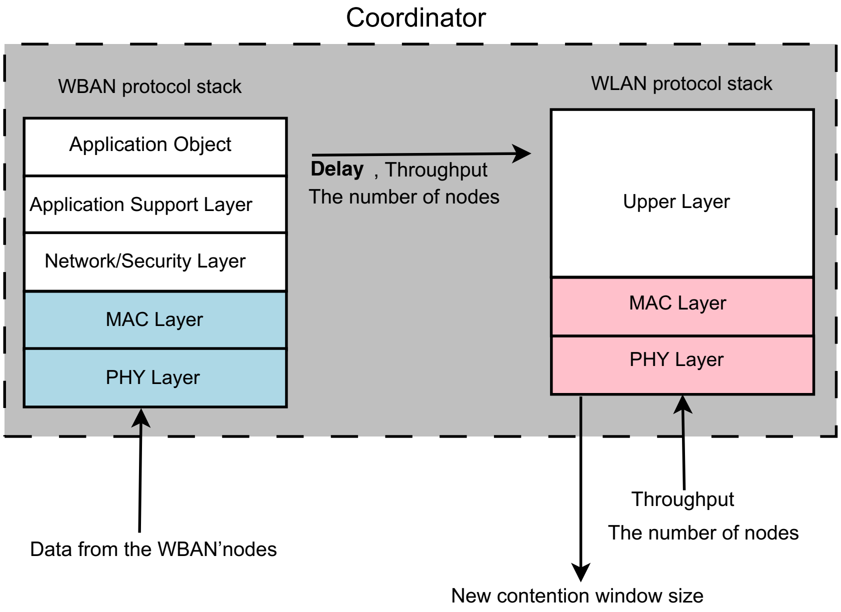
$$\eta_{eff} = TH_{wlan} + TH_{wban}. \tag{10}$$

Also, we set an objective function for adjusting the contention window of the WLAN as follows:

$$\mathscr{F}(CW_{wlan}) = w\frac{\eta_{eff}}{C_{\max}} + (1-w)\mu_{\text{fair}}, \tag{11}$$

which is a linear function of normalized efficiency $\eta_{eff}/C_{\max}$ and the jain's fair index μ_{fair}, both of which are less than one [15]. The $C_{\max}$ is the ideal maximum capacity calculated under the assumption that there are no collision and interference. Therefore, it is considered that it

Fig. 6 Architecture and information exchange of the proposed scheme



has the maximum transmission rate $R_{\max}$ and the minimum contention window $C_{\min}$, i.e.,

$$C_{\max} = \frac{L}{t_{oh} + ((CW_{\min} - 1)/2)t_s + L/R_{\max}}. \tag{12}$$

In the meantime, w $(0 \leq w \leq 1)$ is a weight factor, which can be controlled according to the importance of efficiency or fairness in the channel sharing.

Also, μ_{fair} in Eq. 11 is calculated as

$$\mu_{fair} = \frac{\left(\frac{TH_{wlan}}{N_{wlan}} + \frac{TH_{wban}}{N_{wban}}\right)^2}{2\left\{\left(\frac{TH_{wlan}}{N_{wlan}}\right)^2 + \left(\frac{TH_{wban}}{N_{wban}}\right)^2\right\}}. \tag{13}$$

Here, we further introduce weighted fairness, i.e., TH_{wban} is replaced with $K \cdot TH_{wban}$ where K is an arbitrary value to balance between TH_{wban} and TH_{wlan}, since TH_{wban} is much smaller than TH_{wlan}.

The overall problem can be formulated as an optimization problem as follows [16]:

$$\begin{aligned} \max_{CW_{wlan}} \quad & \mathscr{F}(CW_{wlan}) \\ \text{subject to} \quad & CW_{wlan} \in \Omega, \end{aligned} \tag{14}$$

where $\Omega = \{CW_{wlan} | CW_{\min} \leq CW_{wlan} \leq CW_{\max}\}$, $CW_{\min}$ and $CW_{\max}$ are the minimum and maximum values of the contention window, respectively, and the optimal value of CW_{wlan} can be obtained as

$$CW^*_{wlan} = \arg \max_{CW_{wlan} \in \Omega} \mathscr{F}(CW_{wlan}). \tag{15}$$

Figure 7 shows an simulation results of $\mathscr{F}(CW_{wlan})$, which is conducted from simulation setting in Section 3.1. CW_{wban} is set to 7. $\mathscr{F}(CW_{wlan})$ is a *unimodal* and *concave* function with respect to CW_{wlan} so that there exists a unique optimal value that maximizes $\mathscr{F}$.

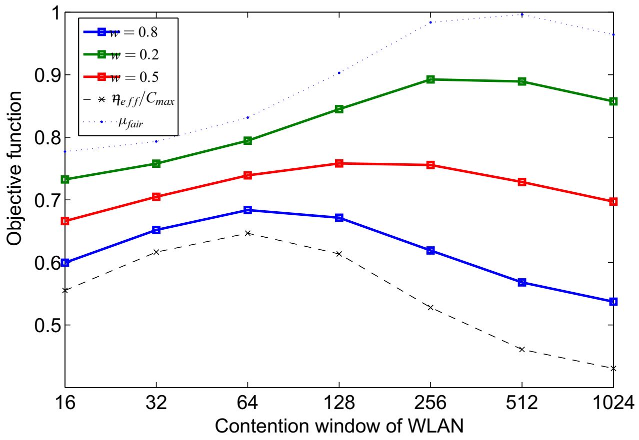


Fig. 7 Objective function (weighted sum of μ_{fair} and $\eta_{eff}/C_{\max}$ versus CW_{wlan}

Table 2 Parameters used in the simulations

Parameter	WLAN	WBAN
Transmission power	50 mW	1 mW
Minimum receiver sensitivity	–80 dBm	–85 dBm
Coverage	50 m	5 m
Arrival rate	Poisson $(\mu = 200\mu s)$	CBR (4 kbps)
Channel access	CSMA/CA	Un-slotted CSMA/CA
Data	General	ECG
Weighted fairness (K)	1000	
Distance between the centers of WLAN and WBAN	10 m	
Path-loss exponent	3	
Shadowing	6	

Since wireless channels have dynamic characteristics, it is important to adaptively control the contention window of WLAN. So, the weight factor is controlled according to the average delay of WBAN nodes in our algorithm. If the current average delay of WBAN's nodes is smaller than the delay requirement required by the application, the weight factor will be increased to give more transmission opportunity to WLAN. On the contrary, if the average delay of WBAN exceeds the delay requirement, the weight factor will be decreased for fairness.

To control the weight factor, the WBAN coordinator measures the delay of WBAN's nodes T_d as

$$T_d = T_{\text{backoff}} + T_{\text{packet}} + T_{\text{overhead}}, \tag{16}$$

where T_{backoff} is backoff time, T_{packet} is packet transmission time, and T_{overhead} is the time for inter-frame space (IFS), ACK and turnaround time for switching the antenna to transmit from receive. The average delay of WBAN is given as

$$T_{average} = \frac{\sum_{i=1}^{N} T_d}{N}, \tag{17}$$

where N is the number of WBAN nodes. Then, finally, the coordinator estimates the objective function in Eq. 11 and uses the golden section search algorithm to find the optimal contention window size of WLAN in every update interval of T_{ae}, which is a simple algorithm for finding the local optimum of a one-dimensional unimodal-function in a closed interval without requiring the derivative of function [17].

The pseudo code for the overall algorithm is given in Algorithm 1.

Algorithm 1 Find optimal value of CW_{wlan}

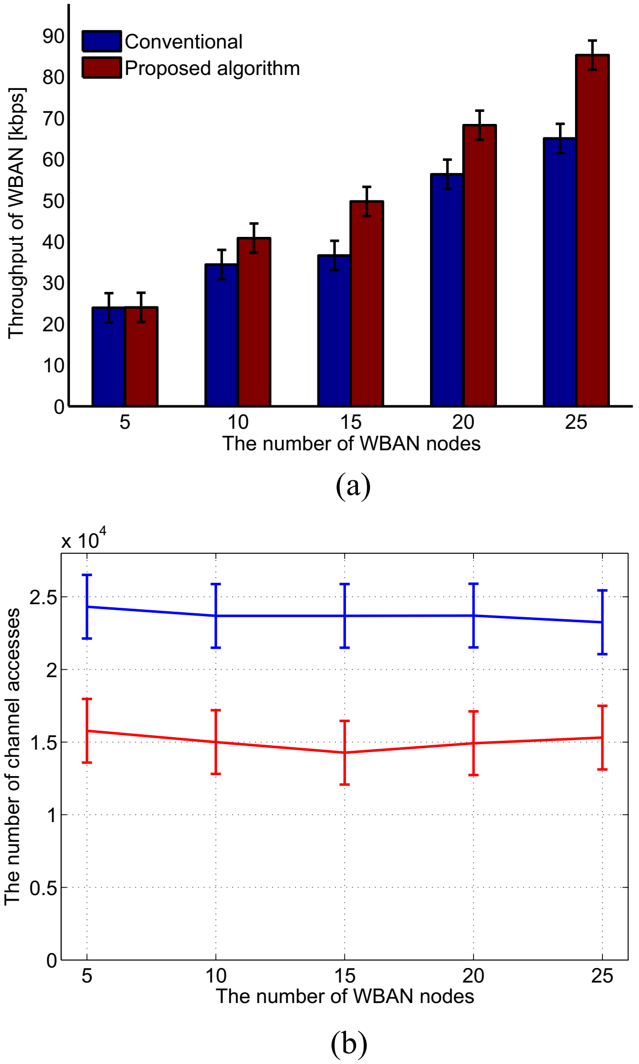
```
$cw_{int} = CWmin + \rho * (CW_{max} - CW_{min})$   ▷ initial intermediate point
$cw\_bound1 = CW_{min}, cw\_bound2 = CW_{max}$   ▷ initial two bound of search space
$cw_{opt} = cw_{int} + \rho * (cw\_bound2 - cw_{int})$   ▷ initial two bound of search space
for every update interval $T_{ae}$ do
    if $T_{average} > T_{req}$ then   ▷ fairness-centric
        $w$ - 0.1
    else if $T_{average} \leq T_{req}$ then   ▷ efficiency-centric
        $w$ + 0.1
    end if
    $Obj_{cur} = \mathscr{F}(CW_{wlan})$   ▷ calculate objective function
    if $Obj_{cur} > Obj_{prv}$ then
        $cw\_bound1 \leftarrow cw_{int}$
        $cw_{int} \leftarrow cw_{opt}$
        $Obj_{prv} \leftarrow Obj_{cur}$
    else if $Obj_{cur} \leq Obj_{prv}$ then
        $cw\_bound2 \leftarrow cw\_bound1$
        $cw\_bound1 \leftarrow cw_{opt}$
    end if
    $cw_{opt} = cw_{int} + \rho * (cw\_bound2 - cw_{int})$   ▷ set $CW_{wlan}$ as $cw_{opt}$
end for
```

The initial intermediate point is set to $cw_{int} = CW_{\min} + \rho * (CW_{\max} - CW_{\min})$ within the narrower search space of $[min(cw\_bound1, cw\_bound2), max(cw\_bound1, cw\_bound2]$ to be converged to the optimal contention window of WLAN. Then, Obj_{cur} is calculated from the objective function and Obj_{prv} is its previous value. At every update interval T_{ae}, the value from the objective function at the point of cw_{opt} is evaluated, and the coordinator sends a control message to the WLAN AP. Finally, the AP broadcasts a new contention window size of WLAN via a control message, and the other WLAN's nodes set the their contention window size as cw_{opt}.

3 Performance evaluation

3.1 Simulation setup

We conduct simulation to validate the performance of the proposed scheme. We develop a customized simulator which includes the CSMA/CA mechanism both in WBAN and WLAN. Our simulator closely follows IEEE 802.15.4 and IEEE 802.11g protocol specifications, where the slot time is set to 9 μs. The parameters and their values used in the simulation are listed in Table 2. The WBAN transmission range is set to 5 m which is suitable for personal healthcare devices. That of WLAN is set to 50 m. We analyze the case where the packets of WLAN arrive according to a Poisson process for general applications, and WBAN traffic is ECG monitoring application generating packets at a constant rate at every 200 ms. We observe the performance in 10 million time slots and the objective function is calculated 20 times. Node placement is chosen randomly in each coverage and simulation results are averaged over ten simulation runs. The initial value of the weight factor is set to 0.5. First, the WBAN coordinator calculates the average transmission delay of WBAN T_d, which is measured every five hundred thousand slots. The weight factor is updated using



(a)

(b)

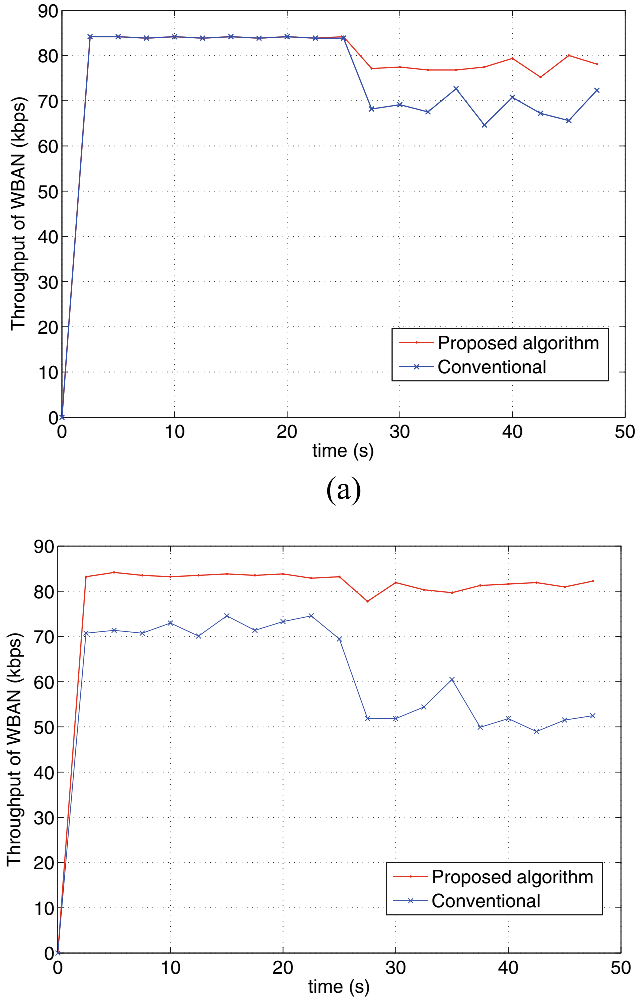
Fig. 8 The performance of the proposed algorithm when there are 10 WLAN nodes: **a** Throughput of WBAN with respect to the number of WBAN nodes, **b** the number of channel access of WLAN with respect to the number of WBAN nodes

T_{average} compared with the delay requirement T_{req}. To better react to the weight factor, we use an upper and a lower bound T_{low} and T_{up} as

$$T_{\text{up}} = T_{\text{req}} + \alpha, \tag{18}$$

$$T_{\text{low}} = T_{\text{req}} - \alpha. \tag{19}$$

Here, T_{req} is set to 50 ms and α is set to 10 ms. T_{req} and α can be set by considering the application's requirement and network topologies. For example, if the T_{average} is larger than T_{up}, then the weight factor is deceased by 0.1 to get fairness in the network. On the other hand, if T_{average} is less than T_{up}, then the weight factor will be increased to obtain efficiency in the network.



(a)

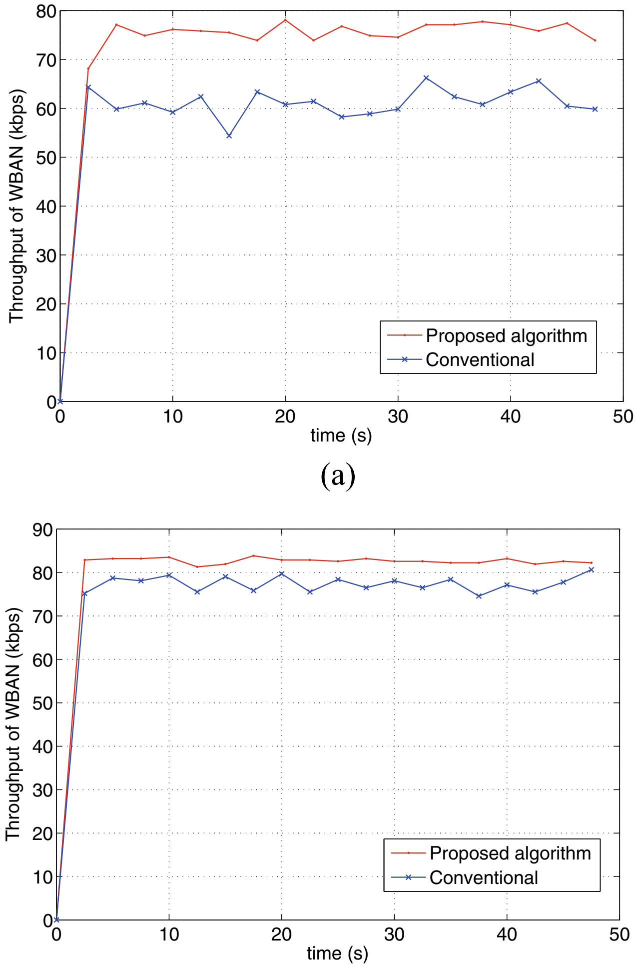
(b)

Fig. 9 The adjustability of the proposed algorithm when 20 WBAN nodes exist: **a** Add 5 WLAN nodes at 25 s when there are no WLAN node initially. **b** Add 5 WLAN nodes at 25 s when there are 5 WLAN nodes initially

3.2 Performance evaluation

To validate the performance of our proposed algorithm, first we change the number of WBAN nodes from 5 to 25 while the number of WLAN nodes is fixed to 10. From Fig. 8a, our proposed scheme gives better WBAN throughput than the conventional algorithm. The number of successfully transmitted packets is also larger for the proposed scheme. Since the average backoff time of WLAN becomes larger than the conventional scheme, WBAN nodes will experience idle channel more often. On the other hand, the number of WLAN channel access is smaller with the proposed algorithm to give more transmit opportunity to WBAN as observed in Fig. 8b.

The objective of next simulation is to investigate the effect of adaptability with respect to changes in the network. The WBAN nodes may undergo performance degradation when new WLAN nodes are added. So, in order to maintain



(a)

(b)

Fig. 10 Throughput performance with respect to the WBAN coverage: **a** Coverage of WBAN : 5 m, **b** coverage of WBAN: 10 m the performance of WBAN, the proposed algorithm should efficiently cope with the change of networks. If the number of WLAN nodes is changed, the information is given to the coordinator. Then, the coordinator restarts the proposed algorithm, and the contention window of WLAN will be converged to a new optimal value according to any changed situation. In the first simulation, initially there is no WLAN node while 20 WBAN nodes exist. Then, we add 5 WLAN nodes at 25 s to verify the adaptability of the proposed algorithm. Figure 9a shows the throughput of WBAN over time in this scenario. Similarly, Fig. 9b plots the throughput of WBAN as we add 5 WLAN nodes at 25 s when there are 5 WLAN nodes exist at the first time. From these figures, we can conclude that the proposed algorithm can cope well with changing circumstances.

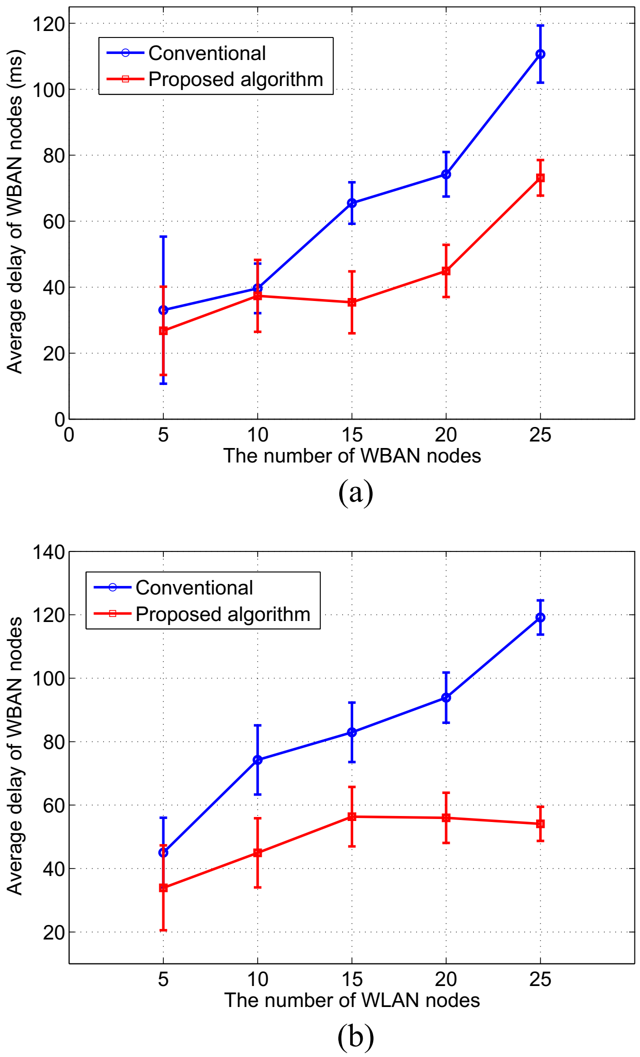


Fig. 11 Average packet delay of WBAN: **a** Changing the number of WBAN nodes while 10 WLAN nodes exist. **b** Changing the number of WLAN nodes while 20 WBAN nodes exist

Now, we check the effect of change in coverage of WBAN, which in fact results from change in transmit power. Figure 10a is the case when WBAN coverage is set to 5 m and Fig. 10b is when it is 15 m. Both cases have 5 WLAN nodes and 20 WBAN nodes. We can verify that our proposed algorithm provides more throughput than the conventional one. In addition, increased coverage of WBAN gives better throughput.

Now, we pay more attention to the network performance in terms of the medical viewpoint. We consider when WBAN nodes carry the electrocardiogram (ECG) data. The

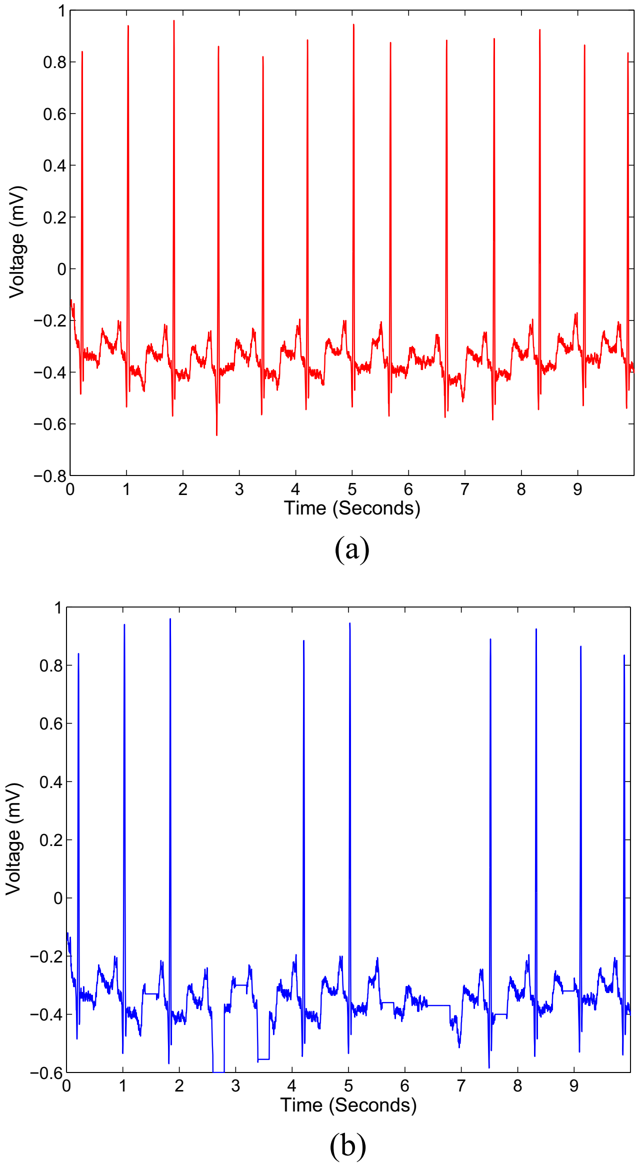


Fig. 12 Ten-second interval of ECG signal: **a** Received ECG signal with the proposed scheme. **b** Received ECG signal without the proposed scheme

heart activity is sensed from an ECG sensor and stored in the buffer and delivered.

We check the average delay of WBAN traffic, which is generally required to be less than 300 ms [18]. Figure 11a shows the average packet delay of WBAN. The observed average delay of the proposed algorithm is less than 100 ms, which is smaller than the conventional scheme.

To check the medical-grade QoS of WBAN, we further adopt the MIT-BIH arrhythmia database which is widely used for testing the ECG monitoring system [19]. The sampling rate is 360 samples per second and the sample size is 11 bits.

When there are 10 WLAN nodes and 10 WBAN nodes, the conventional schemes suffer from severe packet loss due to excessive delay over 300 ms, as shown in Fig. 12b. This phenomenon is due to WBAN's packet loss because WLAN stations is unable to sense WBAN ongoing transmission as it is below the ED threshold level. ECG monitoring applications generate packets every 200 ms, and the retransmitted packets arrived at the receiver can exceed the delay requirement of 300 ms. The average packet delay is larger than 100 ms when the number of WBAN and WLAN nodes is larger than 20 in Fig. 11. However, our proposed algorithm can reduce the WLAN channel access attempts by controlling the contention window of WLAN. Therefore, ECG packets can succeed their transmission during the WLAN backoff time and the retransmitted packet do not exceed the delay requirement. Consequently, the proposed scheme gives a well structured ECG signal at the receiver as given in Fig. 12a.

4 Conclusion

It is a challenging issue how to resolve the coexistence between WBAN and WLAN in medical environments. We have focused on a two-hop wireless scenario where WBAN and WLAN coexist. We have proposed a novel channel access scheme for achieving effective channel sharing in the aspect of efficiency and fairness. The proposed protocol adaptively controls the contention window size of WLAN according to delay information of WBAN. Our simulation results have shown that the proposed algorithm provides the required quality of service for WBAN. We expect that the proposed scheme will be an effective solution for resolving the coexistence of WBAN and WLAN.

Acknowledgments This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No. B0101-15-0557, Resilient Cyber-Physical Systems Research).

References

1. Korhonen I, Bardram JE (2004) Guest editorial: Introduction to the special section on pervasive healthcare. IEEE Trans Inf Technol Biomed 8(3):229
2. Lee H, Park KJ, Ko YB, Choi CH (2011) Wireless LAN with medical-grade QoS for e-healthcare. Journal of Communications and Networks 13(2):149–159
3. Park KJ, Lee HH, Choi s, Kang K (2015) Design of a medical-grade QoS metric for wireless environments. Transactions on Emerging Telecommunications Technologies (to appear)
4. Kang K, Park KJ, Song JJ, Yoon CH, Sha L (2011) A medical-grade wireless architecture for remote electrocardiography. IEEE Trans Inf Technol Biomed 15(2):260–267
5. Kang K, Wang Q, Hur J, Park KJ, Sha L (2015) Medical-grade quality of service for real-time mobile healthcare. Computer 48(2):41–49
6. Camps-Mur D, Garcia-Saavedra A, Serrano P (2013) Device-to-device communications with Wi-Fi Direct: overview and experimentation. IEEE Wirel Commun 20(3)
7. Yi P, Iwayemi A, Zhou C (2011) Developing ZigBee deployment guideline under WiFi interference for smart grid applications. IEEE Transactions on Smart Grid 2(1):110–120
8. Zhang X, Shin KG (2011) Enabling coexistence of heterogeneous wireless systems: case for ZigBee and WiFi. In: Proceedings of the Twelfth ACM International Symposium on Mobile Ad Hoc Networking and Computing, p 6
9. Wang Y, Wang Q, Zeng Z, Zheng G, Zheng R (2011) WiCop: Engineering Wi-Fi temporal white-spaces for safe operations of wireless body area networks in medical applications. In: IEEE Real-Time Systems Symposium (RTSS), pp 170–179
10. IEEE Computer Society LAN MAN Standards Committee (1997) Wireless LAN medium access control (MAC) and physical layer (PHY) specifications
11. Misic J, Misic VB (2010) Bridge performance in a multitier wireless network for healthcare monitoring. IEEE Wirel Commun 17(1):90–95
12. Bianchi G (2010) Performance analysis of the IEEE 802.11 distributed coordination function. IEEE Journal Seleted Areas in Communications 18:535–547
13. Haykin S, Moher MB (2006) An introduction to analog and digital communications. Wiley, London
14. LAN/MAN Standards Committee (2003) Part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs). IEEE Computer Society
15. Jain R, Chiu DM, Hawe WR (1984) A quantitative measure of fairness and discrimination for resource allocation in shared computer system. DEC Research Report
16. Park EC, Rim M (2011) Fair coexistence MAC protocol for contention-based heterogeneous networks. Comput J 54(8):1382–1397
17. Chong EK, Zak SH (2013) An Introduction to Optimization, vol 76. Wiley
18. Zhou P, Lock B, Kuiken TA (2007) Real time ECG artifact removal for myoelectric prosthesis control. Physiol Meas 28(4):397
19. Moody GB, Mark RG (1990) The MIT-BIH arrhythmia database on CD-ROM and software for use with it. In: Proceedings of IEEE Computers in Cardiology, pp 185–188