

# Wireless LAN with Medical-Grade QoS for E-Healthcare

Hyungho Lee, Kyung-Joon Park, Young-Bae Ko, and Chong-Ho Choi

**Abstract:** In this paper, we study the problem of how to design a medical-grade wireless local area network (WLAN) for healthcare facilities. First, unlike the IEEE 802.11e MAC, which categorizes traffic primarily by their delay constraints, we prioritize medical applications according to their medical urgency. Second, we propose a mechanism that can guarantee *absolute priority* to each traffic category, which is critical for medical-grade quality of service (QoS), while the conventional 802.11e MAC only provides relative priority to each traffic category. Based on absolute priority, we focus on the performance of real-time patient monitoring applications, and derive the optimal contention window size that can significantly improve the throughput performance. Finally, for proper performance evaluation from a medical viewpoint, we introduce the *weighted diagnostic distortion* (WDD) as a medical QoS metric to effectively measure the medical diagnosability by extracting the main diagnostic features of medical signal. Our simulation result shows that the proposed mechanism, together with medical categorization using absolute priority, can significantly improve the medical-grade QoS performance over the conventional IEEE 802.11e MAC.

**Index Terms:** Absolute priority, IEEE 802.11e wireless local area network (WLAN), medical-grade quality of service (QoS), wireless healthcare system.

## I. INTRODUCTION

Today's hospitals deploy numerous devices over wires for various medical applications such as monitoring, diagnosis, treatment, and alarms. In order to plug in more and more devices in hospitals, there has been a surge in demand to replace wires with wireless technologies [1]–[5]. This replacement not only reduces the deployment cost and time, but also gives patients increased mobility and comfort by releasing them from wires. In fact, major vendors are already manufacturing commercial medical devices based on wireless technologies [6]–[9].

The significance of introducing wireless technologies in healthcare facilities is far beyond the reduced cost and improved mobility. Wireless technologies are expected to significantly improve the safety of medical systems. For example, massive communication over wires in current healthcare environments often results in the so-called “malignant spaghetti” (a crisscross of ca-

bles from various devices), which is a serious potential hazard for patient safety [10]. Also, a stand-alone telemetry device for monitoring a patient's condition is ineffective unless a medical staff member is present in the room, resulting in a significant delay in response to a sudden change in the patient's condition. The use of wireless technologies enables healthcare personnel to remotely monitor the patient's condition in real time. In addition, by introducing wireless technologies, we can prevent infection due to wire contact.

However, due to the unpredictable variations in the wireless channel, wireless networking can become a safety hazard for medical applications when used without a proper investigation. Hence, for successful deployment of wireless technologies in healthcare applications, the main challenge is how to guarantee the required quality of service (QoS) level of medical applications when using a wireless connection, i.e., *medical-grade QoS* [11]–[14]. The IT industry is currently marketing IEEE 802.11 wireless local area network (WLAN) as a promising solution for wireless medical networks [15]. However, those deployment efforts have been treated by the industry as an ad hoc site-specific engineering issue rather than a fundamental network design issue for the research community. Although there have been some research efforts in wireless medical networks [1]–[4], [16]–[23], a systematic network design paradigm that properly takes into account medical-grade QoS is still lacking. Consequently, the successful deployment of IEEE 802.11 WLAN in healthcare facilities requires a proper input from the research community. In fact, in the recent IEEE 802 plenary tutorial [24], 802.11 QoS for medical devices is remarked upon as a main research issue.

In this paper, we focus on the design of a wireless LAN that can provide medical-grade QoS for healthcare facilities. In particular, our contributions are as follows:

- We study how to prioritize medical applications in healthcare facilities into access categories. Unlike the conventional 802.11e MAC, which categorizes traffic by their delay constraints, we determine the access priority of medical applications according to *medical urgency* in medical workflows.
- Under the medical categorization, we propose a multiple access mechanism that can guarantee *absolute priority* of each medical category over lower ones. Consequently, medical applications in each category can be protected from unexpected increases in less-critical traffic in lower categories. Furthermore, we derive the optimal contention window size for real-time patient monitoring applications to improve network performance.
- For proper evaluation of network performance from the medical viewpoint, we introduce the *weighted diagnostic distortion* (WDD) as an effective medical QoS metric for efficiently evaluating the level of medical diagnosability, i.e., whether the received signal can be used for diagnosis by healthcare personnel or not.

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H. Lee and C.-H. Choi are with the School of Electrical Engineering and Computer Science and ASRI, Seoul National University, Seoul, Republic of Korea, email: {dayghost24, chchoi}@csl.snu.ac.kr.

K.-J. Park is the corresponding author and with the Department of Information and Communication Engineering, DGIST, Daegu, Republic of Korea, email: kjp@dgist.ac.kr.

Y.-B. Ko is with the School of Information and Computer Engineering, Ajou University, Suwon, Republic of Korea, email: youngko@ajou.ac.kr.

The remainder of this paper is structured as follows. In Section II, we provide background on the connectivity of medical devices. Then, we briefly introduce IEEE 802.11e MAC. In Section III, we first study how to map medical applications into access categories according to their medical urgency. With the medical categorization, we propose a method that can guarantee the absolute priority of each category with respect to lower ones. In order to further improve the network performance, we derive the optimal contention window size for real-time patient monitoring. In Section IV, we introduce the WDD as an effective metric for evaluating medical-grade QoS of an electrocardiography (ECG) signal. In Section V, we provide simulation results that show that the proposed scheme significantly improves the network performance and guarantees absolute priority. The conclusion follows in Section VI with several important future research topics.

## II. PRELIMINARIES

In this section, we provide an overview on the connectivity between medical devices. We also discuss currently-deployed medical networks in healthcare facilities. Then, we introduce the basics of IEEE 802.11e MAC, which will be the starting point for our design of a medical-grade WLAN.

### A. Medical Device Connectivity

Connectivity between medical equipment goes back 20 years to the medical information bus [25] for bedside medical devices. This technology eventually led to a standardization effort for medical device communication, which resulted in the development of the joint ISO/IEEE-11073 standard [26]. Since 2004, nomenclature and domain information models, which specify various types of information exchange between devices, have been approved in IEEE 11073; they provide a sound framework for creating interoperable standards. In addition, several standards specifying everything from network topology to encoding strategy have been approved for cable connections and infrared wireless connections. Currently, many standard drafts are waiting for approval for specific medical devices (pulse-oximeters, blood-pressure monitor, weighing scale, etc.) and other communication mediums (Ethernet cable, RF wireless, etc.). Evaluation of these new technologies in medical environments is still in progress [27].

A representative example of wireless medical networks currently deployed in healthcare facilities is the wireless medical telemetry system (WMTS) for patient monitoring [28], as illustrated in Fig. 1. There are two main trends in the deployment of the WMTS; a vendor-specific network in the dedicated WMTS band and an IEEE 802.11 network in the shared industrial scientific and medical equipment (ISM) band [22]. Each of these two solutions has its own unique advantages and disadvantages. While a telemetry system in the WMTS band enjoys dedicated bands, it can only support a small number of channels because of its small bandwidth. In contrast, an IEEE 802.11-based telemetry system benefits in terms of cost for standard-based deployment as well as a significant gain in the number of channels due to the large bandwidth of the ISM band. Furthermore, the standard-based deployment provides solid ground

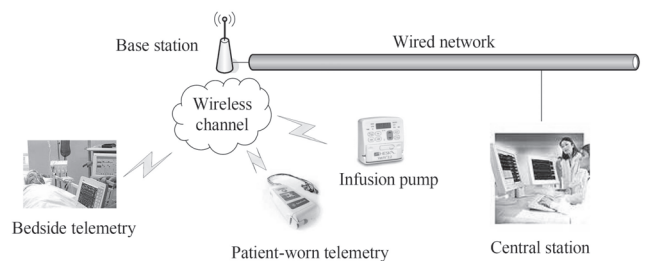


Fig. 1. Wireless medical telemetry system in healthcare facilities.

for medical device interoperability, which is a fundamental issue in the healthcare community [29]. However, the ISM band is unlicensed and subject to interference from other devices such as Bluetooth, microwave ovens, and cordless telephones. Nevertheless, it has been recently reported through substantial deployment experiences that an IEEE 802.11 network can significantly outperform a vendor-specific one in the WMTS band in medical facilities [22].

There have also been studies on architectures and functions for patient monitoring, e.g., [21], [30]–[33]. The general requirements and analysis of wireless patient monitoring using wireless LANs are presented in [21] and [30], which include the use of wireless LANs for patient monitoring in several different scenarios, analyses, and architecture designs. Also, Zhou *et al.* [31] focuses on the network communication techniques used by a remote surveillance platform for real-time reliable cardiac monitoring. Similar architectures and functions are studied in [32] and [33].

### B. IEEE 802.11e MAC

The IEEE 802.11e MAC standard [34] provides a hybrid coordination function (HCF) that utilizes two medium access mechanisms: (i) Controlled channel access and (ii) contention-based channel access. The controlled channel access is referred to as HCF controlled channel access (HCCA), which supports deterministic channel access through a special coordinator node called the hybrid coordinator (HC). On the other hand, the contention-based channel access, i.e., the enhanced distributed channel access (EDCA), allows four access categories (ACs) to serve multiple traffic classes with different QoS requirements. Since we focus on the contention-based channel access for the traffic categories in medical applications, we briefly describe the EDCA mechanism for providing QoS here.

EDCA can be defined as a class-based QoS provisioning channel access mechanism. It provides traffic classification that has different user priorities mapped to four ACs as follows: Background (AC\_BK), best-effort (AC\_BE), video (AC\_VI), and voice (AC\_VO) in the ascending order of priority as shown in Table 1. Background traffic is assigned the lowest priority of level 3 whereas the voice traffic has the highest priority of level 0.

The AC queues are prioritized by differentiating channel access parameters such as an arbitrary inter-frame space number (AIFSN) and the contention window (CW) as given in Table 1. For the ACs of higher priorities, their AIFSN and CW duration are smaller compared to those of lower priorities. When a node

Table 1. Default values for EDCA parameters and access categories.

Service type	Access category	Symbol	AIFSN	CW <sub>MIN</sub>	CW <sub>MAX</sub>
Voice	AC_VO	Priority 0 (high)	2	7	15
Video	AC_VI	Priority 1	2	15	31
Best effort	AC_BE	Priority 2	3	31	1023
Background	AC_BK	Priority 3 (low)	7	31	1023

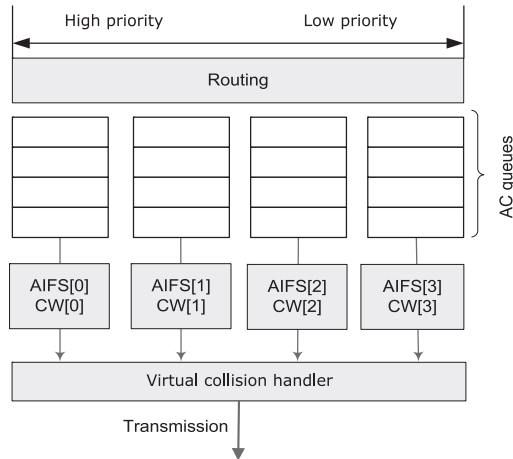


Fig. 2. The architecture of EDCA in IEEE 802.11e WLAN [35].

has a packet to transmit, it contends for a transmission opportunity by initiating channel sensing. If the channel state is sensed to be idle, it waits for an AIFS duration and starts to countdown its backoff timer for a random duration selected from the range of the allocated CW value.

The AIFS duration in EDCA varies for each traffic category and is referred to AIFS [AC] as shown in Fig. 2. For example, the duration for AIFS [AC\_VO] is less than the duration of AIFS [AC\_BE] as shown in Table 1. Therefore, the AC\_VO category has a higher priority than the AC\_BE category to initiate transmission even when the packets are residing in both queues at the same time. After waiting for the AIFS [AC] duration, if the station senses the channel is busy, it freezes the backoff timer and waits again for the next AIFS [AC] duration. If the channel is found to be free, a higher priority packet is transmitted when the backoff counter reaches zero.

A backoff counter value is randomly picked from  $[0, CW]$  and where the CW value is in the range of  $[CW_{MIN}, CW_{MAX}]$  as given in Table 1.  $CW_{MAX}$  is smaller for higher access priority traffic. Upon collision or packet loss, the sender node doubles its CW range until it reaches  $CW_{MAX}$  and waits for AIFS to attempt retransmission.

Many analytical studies exist to show the QoS performance of EDCA, in which the main features of EDCA such as virtual collision, different AIFS, and different CW are included. For example, in [36], the effects of the CW and AIFS on the priority differentiation ability of EDCA have been investigated. However, according to [37], the throughput of the highest priority degrades by about 40% when the number of lower ones exceeds 5. This phenomenon is caused from the fact that the priority between ACs in IEEE 802.11e is guaranteed only in a relative manner due to the randomness in the CW value. It should be noted that this limitation of IEEE 802.11e may become a poten-

tial hazard for patient safety in medical networks. Hence, it is of critical importance to guarantee the absolute priority of each AC over lower-priority ones.

### III. DESIGN OF MEDICAL-GRADE WLAN

In this section, we first categorize medical applications in healthcare facilities according to their medical urgency. With the medical categorization in hand, we propose a multiple access method that can assure the absolute priority of each category with respect to lower-priority ones. Then, we derive the optimal contention window size to improve the performance of real-time patient monitoring applications, which are prevalent and critical applications in medical networks.

#### A. Access Categorization by Medical Urgency

The typical QoS requirements for medical traffic in healthcare facilities can be found in [22], and are summarized in Table 2. Note that the values in Table 2 may be somewhat different from those in a particular facility. For example, a medical alarm should be announced within 10 s from the onset of an emergency. Hence, a value much smaller than 10 s, but a still achievable value of 200 ms is given in Table 2. In fact, 200 ms is the value typically used for testing [22].

From [38], the basic rule for the allowable latency is as follows. For life-critical information such as telemetry and infusion pump data, a latency smaller than 200 ms is required. For other medical applications, a latency of 200–500 ms is allowed, which is an acceptable waiting time. On the other hand, since guest access is an option for medical networks, 1000 ms is an acceptable latency. Data rates of medical applications are obtained as follows. For telemetry traffic, the data rate is obtained from the device specification of a major manufacturer. For barcode medication administration (BCMA), it is based on the amount of data for a typical bar code. The data rate for infusion pump is again from the device specifications of a major manufacturer. Data rates less than 0.1 kb/s are listed as 0.1 kb/s in Table 2.

In the conventional IEEE 802.11e MAC, applications are mainly categorized according to their latency constraints, i.e., how large a latency each traffic can tolerate. Hence, as given in Table 1, voice traffic is given the highest priority, video traffic is the next, best-effort traffic is the third, and background traffic is given the lowest priority. However, in medical environments, applications should be prioritized according to the consequences of its delivery failure. For example, the failure of a medical alarm could be a matter of life and death while that of guest access is irrelevant to the overall medical workflow.

Hence, we categorize medical traffic into four categories as given in Table 3. Alarm signals, such as telemetry alarms and infusion pump alerts, are given the highest priority. Real-time monitoring traffic for patient condition is considered as the sec-

Table 2. Representative values for QoS requirements for medical applications in healthcare facilities.

	Packets/s	kb/packet	Peak (kb/s)	Average (kb/s)	Events/h or duty cycle	Maximum latency (ms)
Telemetry (diagnostic)	5	5.1	25.6	25.6	Stream	200
Telemetry (alarms)	5	1.0	5.1	0.1	10/h	200
Infusion pump (status)	1	1.0	1	1	Continuous	200
Infusion pump (alert)	1	1.0	1	0.1	1/h	200
Clinician notifier	5	2.6	12.8	0.1	20/h	200
BCMA	2	0.4	0.8	0.1	30/h	500
EMR images	200	20.5	4,100	41	1%	200
Guest access	100	10	1,000	30	3%	1,000
Email	200	20.5	4,100	41	1%	200

Table 3. Access categorization for medical-grade wireless LAN according to medical urgency.

	Applications	Urgency
AC0	Alarm signals (telemetry alarms, infusion pump alert)	Highest
AC1	Real-time streaming data (telemetry, infusion pump)	High
AC2	Other medical applications	Medium
AC3	Non-medical applications (guest access, email)	Lowest

ond highest priority. The next priority is given to other medical applications. Since guest access and email service are optional for medical networks, they are given the lowest priority.

### B. Assurance of Absolute Priority Among Access Categories

As already mentioned in Section II, IEEE 802.11e MAC only provides a relative priority service depending on access category. In general, there are two ways of priority differentiation for achieving QoS provision. The first one is relative priority, under which the throughput of a node is allocated proportionally according to its priority. The main advantage of relative priority is that higher priority traffic does not starve lower priority traffic. However, the throughput degradation of higher priority traffic becomes more severe as lower priority traffic increases. Though this might not be a critical issue in general wireless networks, it may result in a serious problem, and even be a matter of life and death, in healthcare facilities.

Another way of priority differentiation is *absolute priority*, where high-priority traffic can fully use the available bandwidth if needed even when low-priority traffic exists regardless of whether low-priority traffic is starved or not. In fact, the performance of critical healthcare applications such as medical alarms and real-time patient monitoring can be seriously degraded due to an increase of lower priority traffic in conventional IEEE 802.11e. Hence, we need to assure absolute priority service for healthcare applications in order to guarantee medical-grade QoS.

Here, we propose an effective method for assuring absolute priority service. IEEE 802.11e EDCA uses different values of AIFS for each AC, which results in a different waiting time for each AC to start its backoff counter. However, the difference between AIFS values of high and low priority is not sufficient for guaranteeing absolute priority. In IEEE 802.11e EDCA,  $AIFS_i$  is bigger than  $AIFS_{i-1}$  and smaller than  $AIFS_{i-1} + CW_{i-1}$  as shown in Fig. 3(a), where  $i$  denotes access category  $i$ . Consequently, there are periods when only the high priority node can contend for the channel (period 1 in Fig. 3(a)) and periods when both high and low priority nodes can contend (period 2 in Fig. 3(a)). Therefore, in IEEE 802.11e EDCA, some probability exists that low-priority nodes contend for the channel with

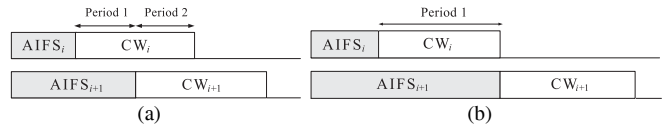


Fig. 3. AIFS and CW settings: (a) IEEE 802.11e EDCA and (b) the proposed scheme.

high-priority nodes, which may degrade the performance of the latter.

In order to assure absolute priority, we set the AIFS value of each AC as follows:

$$AIFS_i = \begin{cases} AIFS_0, & \text{if } i = 0, \\ AIFS_{i-1} + CW_{i-1}, & \text{otherwise.} \end{cases} \quad (1)$$

Fig. 3(b) shows the relation between  $AIFS_i$  and  $CW_i$  for access category  $i$  in the proposed scheme. By setting  $AIFS_i$  and  $CW_i$  as in (1), period 2 in Fig. 3(a) now becomes zero in Fig. 3(b), and the lower-priority node contends for the channel only when the network is not saturated by the high-priority node. In this manner, the proposed scheme can assure absolute priority of a high-priority category over lower-priority ones.

### C. Contention Control for Medical-Grade QoS

Based on the categorization in Table 3, we study how to efficiently utilize the wireless channel, while providing absolute priority. In particular, we focus on the traffic in AC1 in Table 3, which is prevalent and critical in healthcare environments. Instead of the conventional binary exponential backoff (BEB) mechanism in IEEE 802.11 MAC, we derive the optimal contention window size for AC1 in order to improve the network performance. According to the categorization in Table 3, the traffic in AC1 corresponds to real-time patient monitoring applications. Hence, we assume that each traffic in AC1 demands the same throughput and delay requirements. Extension to a more general case will be a subject of future work.

To use the wireless channel in an efficient manner, we first focus on the characteristics of medical traffic. First, we can observe from Table 2 that the event of an alarm signal rarely occurs and its packet size is very small. Hence, we fix the CW value to  $CW_{MIN}$  for AC0 traffic in order to ensure the highest priority. It should be noted that this setting does not cause significant collision because of the rare event characteristics and small packet size of AC0 traffic.

Now, we look into the problem of how to ensure the QoS of AC1 traffic in Table 3. One key observation for AC1 applications is that they are real-time streams with a fixed data rate. Hence, we derive the optimal contention window size that maximizes

the aggregate throughput of AC1. Suppose that there are a total of  $n$  nodes for real-time patient monitoring in AC1. Let  $\tau = (\tau_1, \dots, \tau_n)$ , where  $\tau_i$  denotes the attempt probability of node  $i$  with  $\tau_i \in [\tau_{\min}, \tau_{\max}]$ , and  $\tau_{\min}$  and  $\tau_{\max}$  denote the minimum and maximum of  $\tau_i$ , respectively. Then, the problem of maximizing the aggregate throughput can be described as

$$\max_{\tau=(\tau_1, \dots, \tau_n)} Th_{agg} = \sum_{i=1}^n Th_i \quad (2)$$

where  $Th_{agg}$  and  $Th_i$  denote the aggregate throughput of AC1 traffic and node  $i$ 's throughput, respectively. In a similar manner as in [39], we have

$$\begin{aligned} Th_i &= \frac{\text{(Average of node } i\text{'s payload size)}}{\text{(Average of a slot time)}} \\ &= \frac{P_{s,i} L_i}{P_{\text{idle}} \delta + P_s T_s + P_c T_c} \end{aligned} \quad (3)$$

where  $L_i$  is the payload size of node  $i$ ,  $P_s$  and  $P_c$  are the probabilities of success and collision of a transmission in a slot, and  $P_{s,i}$  denote the success probability of node  $i$ 's transmission. In addition,  $\delta$ ,  $T_s$ , and  $T_c$  are the durations of an empty slot, successful transmission, and collision, respectively.

As already mentioned, we consider the case of the same throughput requirement for each traffic in AC1. Hence,  $L_i$ 's are the same for every node in AC1, and then  $Th_i$  becomes the same. Consequently, maximizing the aggregate throughput in (2) maximizes the throughput of node  $i$ . Hence, from now on, we omit the subscript  $i$  for notational simplicity unless otherwise mentioned.

Now, the remaining issue is to express the throughput of node  $i$ , i.e.,  $Th_i$ , in terms of its attempt probability  $\tau$ . First, we can express  $P_{\text{idle}}$  as

$$P_{\text{idle}} = \prod_{k=0}^{n-1} (1 - \tau_k) = (1 - \tau)^n. \quad (4)$$

In addition, the numerator in (3) of  $P_{s,i} L_i$  can be further expressed as

$$P_{s,i} = \tau(1 - P_c) \quad (5)$$

where  $P_c = 1 - (1 - \tau)^{n-1}$ . By combining (4) and (5), we have

$$P_{s,i} = \frac{\tau}{1 - \tau} P_{\text{idle}}. \quad (6)$$

On the other hand, let  $b_i$  denote the time duration for successful transmission of node  $i$ . Then,

$$b_i = \text{PLCP}_{\text{oh}} + \frac{\text{MAC}_{\text{oh}} + L_i}{r_i} + \text{SIFS} + \text{ACK} + \text{AIFS}$$

where  $\text{PLCP}_{\text{oh}}$  is the physical layer convergence protocol (PLCP) preamble time,  $\text{MAC}_{\text{oh}}$  is the MAC header size,  $r_i$  is the PHY data rate of node  $i$  and ACK is the duration of time for transmitting an ACK frame. Then,  $T_s P_s$  in (2), which is the expected duration for a successful transmission, can be expressed

as follows

$$\begin{aligned} T_s P_s &= \sum_{i=0}^{n-1} b_i \tau (1 - P_c) = P_{\text{idle}} \sum_{i=0}^{n-1} b_i \left( \frac{\tau}{1 - \tau} \right) \\ &= P_{\text{idle}} \left( \frac{\tau}{1 - \tau} \right) \sum_{i=0}^{n-1} b_i. \end{aligned} \quad (7)$$

In a similar manner, let  $c_i$  denote the duration of a collision for node  $i$ . Then,  $c_i$  is given as

$$c_i = \text{PLCP}_{\text{oh}} + \frac{\text{MAC}_{\text{oh}} + L_i}{r_i} + \text{EIFS} + \text{AIFS}$$

where EIFS is the extended IFS defined in IEEE 802.11. Here, we assume that there is no simultaneous transmission by more than two nodes, which is a reasonable approximation. Since the duration of a collision is determined by the colliding node whose transmission lasts longer than the other colliding node, when the transmissions of node  $i$  and node  $j$  collide, the expected duration of a collision  $T_c P_c$  in (3) becomes

$$\begin{aligned} T_c P_c &= \sum_{i=0}^{n-1} c_i \sum_{j=0}^{i-1} \tau_i \tau_j \prod_{k \neq i, j} (1 - \tau_k) \\ &= \sum_{i=0}^{n-1} c_i \sum_{j=0}^{i-1} \frac{\tau_i \tau_j P_{\text{idle}}}{(1 - \tau_i)(1 - \tau_j)} = \left( \frac{\tau}{1 - \tau} \right)^2 P_{\text{idle}} \sum_{i=0}^{n-1} i c_i. \end{aligned} \quad (8)$$

From (6), (7), and (8), (3) can be expressed as a function of  $\tau$  as follows

$$Th_i = \frac{P_{\text{idle}} L \left( \frac{\tau}{1 - \tau} \right)}{P_{\text{idle}} \delta + P_{\text{idle}} \left( \frac{\tau}{1 - \tau} \right) \sum_{i=0}^{n-1} b_i + P_{\text{idle}} \left( \frac{\tau}{1 - \tau} \right)^2 \sum_{i=0}^{n-1} i c_i}. \quad (9)$$

We further denote  $x := \tau/(1 - \tau)$  and (9) becomes a function of  $x$  as follows

$$Th_i(x) = \frac{Lx}{Cx^2 + Bx + \delta} \quad (10)$$

where  $B = \sum_{i=0}^{n-1} b_i$  and  $C = \sum_{i=0}^{n-1} i c_i$ .

Now, finding the optimal  $x$  that maximizes the throughput is fairly straightforward;  $dTh_i(x)/dx = 0$  is solved as follows

$$L(Cx^2 + Bx + \delta)^{-1} - Lx(2Cx + B)(Cx^2 + Bx + \delta)^{-2} = 0. \quad (11)$$

From (11), the optimal solution for maximizing (10)  $x^*$  is given as

$$x^* = \sqrt{\frac{\delta}{C}}$$

which then gives the optimal attempt probability  $\tau^*$ :

$$\tau^* = \frac{\sqrt{\frac{\delta}{C}}}{1 + \sqrt{\frac{\delta}{C}}}. \quad (12)$$

Finally, the optimal CW value  $CW^*$  is given from (12) by using  $\tau = 2/(CW + 1)$  in [39], where  $CW$  is an integer:

$$CW^* = \left\lceil \frac{2}{\tau^*} - 1 \right\rceil. \quad (13)$$

From (13), we can determine the contention window size of nodes in AC1.

#### IV. MEDICAL-GRADE QoS METRIC

In order to properly evaluate the QoS level of medical applications in wireless environments, we have to consider not only conventional QoS metrics such as the delay, throughput, and packet error rate (PER), but also the level of medical diagnosability of the data. To this end, the key task is determining a proper QoS metric for medical-grade transmission, which can measure the amount of diagnostic information in the received data. Since the diagnostic features differ depending on medical applications, a QoS metric must be developed for each medical application. Here, we focus on the application of wireless ECG transmission for patient monitoring in AC1, and develop an effective metric for medical-grade QoS.

##### A. Main Features of ECG Signal

In order to design a QoS metric for wireless ECG transmission, we first need to understand the key features of the ECG signal from the medical point of view. The ECG signal has several diagnostic features that are crucial for medical interpretation. In general, the diagnostic features can be categorized into three groups: Duration, amplitude, and shape. Among these three categories, the duration features are the most critical in most cases. Some of the duration and amplitude features of the ECG signal are shown in Fig. 4(a). More detailed descriptions on important duration and amplitude features are given in Table 4.

In general, the relevant diagnostic information lies in the PQRST complex features, i.e., the P wave duration, QT interval, T shape and ST elevation as shown in Fig. 4(b). The main features in the PQRST complex are the location, duration, amplitude, and shape of the waves. In order to extract these features, we first need to segment the ECG signal, i.e., determine the location of each wave shown in Fig. 4(b). In order to locate the waves, we determine the QRS complex, which has the highest frequency component in the ECG signal. Then, the T wave is recognized, and finally, the P wave is determined. Currently, there are several algorithms available for ECG segmentation [40]. After finding the locations of the P, Q, R, S, and T points, the duration, amplitude, and shape of each wave are easily determined.

##### B. QoS Metric for Wireless ECG Transmission

As we have already mentioned, the most important criterion for evaluating the QoS level of medical applications is the diagnosability of the received data. For example, in the case of wireless ECG transmission, the QoS criterion should be based on the level of relevant diagnostic information. Conventional QoS metrics such as PER are insufficient for evaluating medical-grade QoS because these metrics treat each packet equally. In medical applications, the amount of diagnostic information varies

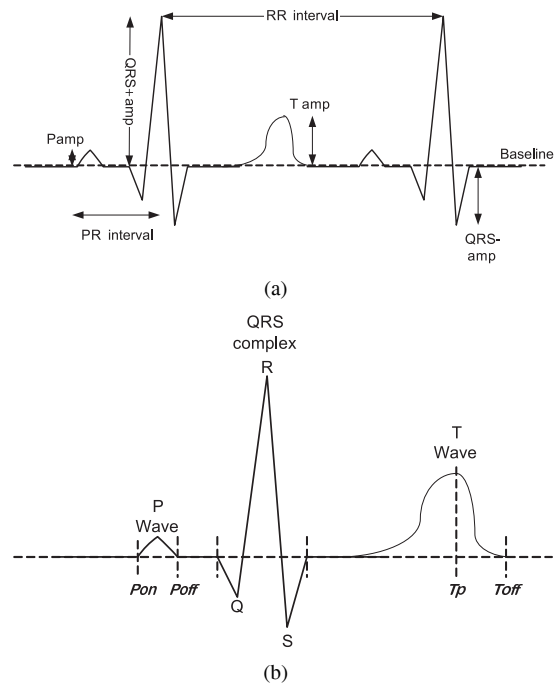


Fig. 4. Overview of an ECG signal: (a) Amplitude and duration features of an ECG signal and (b) PQRST waves in one interval.

depending on packet, and this should be properly incorporated into the design of a medical-grade QoS metric.

In order to develop a quantitative measure for medical-grade QoS of wireless ECG transmission, we first identify the main features of the ECG signal. Then, as a QoS metric for wireless ECG transmission, we investigate the weighted diagnostic distortion (WDD), which was originally proposed for evaluating the distortion level of ECG signal compression [41]. The WDD compares the original ECG signal and the received one by focusing on the key diagnostic features described as below. It should be noted that a higher WDD implies worse QoS.

For the original and received ECG signal, a vector of diagnostic features such as those in Table 4 can be derived as follows:

$$f^T = [f_1 \ f_2 \ \cdots \ f_p]; \text{ features of the original signal,}$$

$$\hat{f}^T = [\hat{f}_1 \ \hat{f}_2 \ \cdots \ \hat{f}_p]; \text{ features of the received signal}$$

where  $p$  is the total number of features used in the WDD measure. Here, each  $f_i$  is scalar. For example, the time duration features are scalar values in milliseconds as described in Table 4.

With the given  $f$  and  $\hat{f}$ , the WDD measure is determined as

$$WDD(f, \hat{f}) = \Delta f^T \frac{\Lambda}{tr[\Lambda]} \Delta f \quad (14)$$

where  $\Delta f$  is the the normalized difference vector given as

$$\Delta f^T = [\Delta f_1 \ \Delta f_2 \ \cdots \ \Delta f_p] \text{ where } \Delta f_i = \frac{|f_i - \hat{f}_i|}{\max\{|f_i|, |\hat{f}_i|\}}$$

and  $\Lambda$  is a diagonal matrix of weights for features, i.e.,  $\Lambda = \text{diag}[\lambda_i], i = 1, 2, \dots, p$ . The values of  $\lambda_i$ , i.e., the relative importance of each feature, can be determined based on the medical knowledge of healthcare personnel.

Table 4. Duration and amplitude features of an ECG signal.

Feature	Feature description	Unit
$RR_{int}$	Time duration between the current and previous locations of the R wave	ms
$QRS_{dur}$	Time duration between the onset and offset of the QRS complex	ms
$QT_{int}$	Time duration between $QRS_{on}$ and $T_{off}$	ms
$QT_{pint}$	Time duration between $QRS_{on}$ and $T_p$	ms
$P_{dur}$	Time duration between $P_{on}$ and $P_{off}$	ms
$PR_{int}$	Time duration between $P_{on}$ and $QRS_{on}$	ms
$QRS_{amp}^+$	Maximum positive amplitude of QRS complex	0.1 mV
$QRS_{amp}^-$	Maximum negative amplitude of QRS complex	0.1 mV
$P_{amp}$	Amplitude of P wave	0.1 mV
$T_{amp}$	Amplitude of T wave	0.1 mV

From (14), unlike the conventional QoS metrics, WDD can properly quantify the distortion in medical diagnostic information in an ECG signal. Consequently, we can evaluate the medical-grade QoS level of each wireless technology by calculating WDD rather than conventional QoS metrics. We anticipate that a medical-grade QoS metric such as WDD will be vital for research on medical-grade wireless networks.

## V. SIMULATION STUDY

### A. Simulation Setup

In this section, we present our evaluation of the proposed scheme by ns-2 simulation [42]. We compare our scheme with IEEE 802.11e EDCA. The medical traffic in each AC is generated according to Table 2. In particular, the alarm in AC0 and FTP in AC2 are transported by TCP while ECG monitoring in AC1 is transported by UDP. We use the 1-lead ECG data in the MIT-BIH arrhythmia data set for monitoring the ECG signal at a central station [43]. Although the database was originally created as the standard test material for the evaluation of arrhythmia detectors, it has been used for testing new ECG monitoring schemes. In calculating WDD, we use the three features  $f_1 = RR_{int}$ ,  $f_2 = QRS_{amp}^+$ , and  $f_3 = QRS_{amp}^-$  in Table 4, which are the most critical features with the weight vector  $\Lambda = \text{diag}[2 \ 2 \ 2]$  according to [41].

### B. Simulation Results

First, in order to validate the analysis in subsection III-C, we compare the aggregate network throughput obtained by analysis with the simulation results under several different scenarios. We vary the attempt probability  $\tau$  from 0 to 0.1. In the first simulation, we investigate the effect of the PHY data rate. There are a total of four nodes, and the payload size is fixed to 1,500 bytes. The PHY data rate is either 1 or 11 Mb/s. Fig. 5(a) shows that our analysis for both cases match very well with the simulation results. We further perform a simulation with 12 nodes. Similarly, the analytical results fit very well with that of the simulation as shown in Fig. 5(b), except for a small difference when  $\tau$  is around 0.1 in the case of 12 nodes. From Fig. 5, we can conclude that our analysis is very accurate for a reasonable range of  $\tau$  and the optimal value of  $\tau$  can be efficiently found by our analysis.

Next, in order to show the performance improvement by the proposed scheme over IEEE 802.11e, we carry out a simulation using WDD as a QoS metric by increasing the number of ECG flows. It should be noted that there is no TCP traffic in this

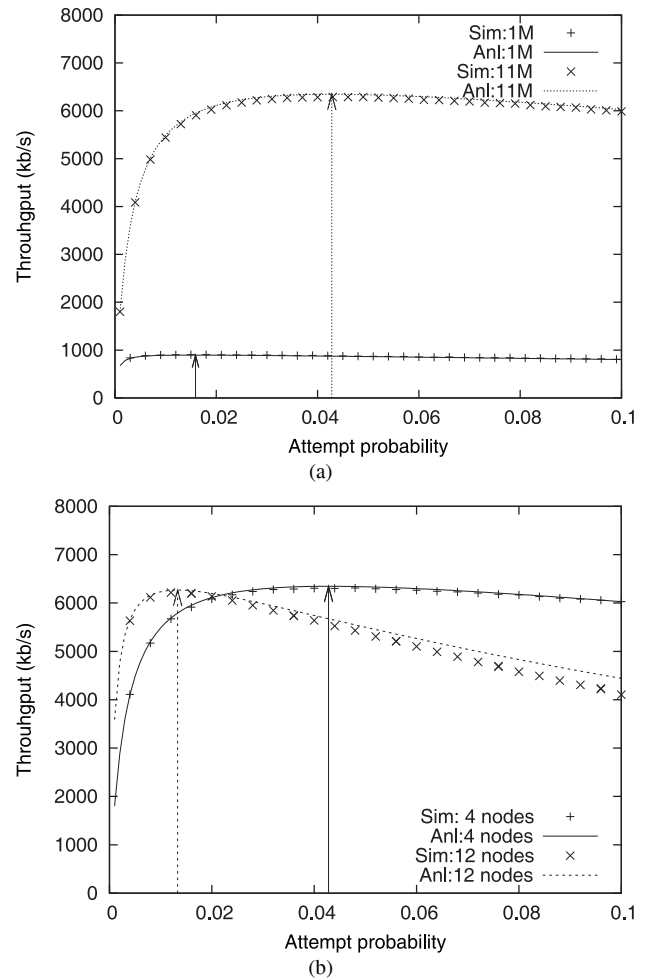


Fig. 5. Aggregate throughput obtained by the analysis and simulation: (a) Throughput for the different data rates and (b) the number of nodes is 4 and 12, and the PHY data rate is 11 Mb/s.

simulation. Fig. 6(a) shows the average WDD of ECG flows as the number of ECG flows increases from 15 to 30. Since a higher WDD implies worse QoS, we can easily see that the proposed scheme significantly increases the capacity of ECG flows compared to the conventional IEEE 802.11e. In particular, the capacity for ECG flows increases from 22 to 28 by the proposed scheme. Fig. 6 shows the performance of the delivery ratio of ECG flows, i.e., the ratio between the number of packets sent from the sender and that received by the receiver. Packets not delivered are due to MAC buffer overflow. Similarly to Fig. 6(a), we can see that the proposed scheme significantly improves the

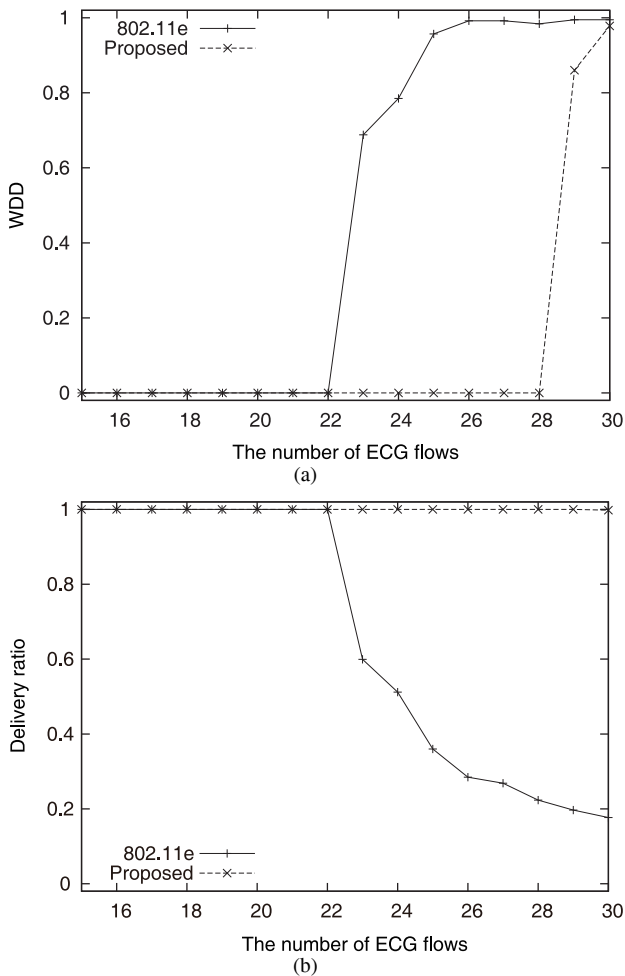


Fig. 6. WDD and delivery ratio: (a) WDD vs. number of ECG flows and (b) delivery ratio vs. number of ECG flows.

network performance. As shown in Fig. 6, the delivery ratio of 802.11e significantly degrades when there are 30 ECG flows, which implies that the MAC buffer overflow is negligible with the proposed scheme. Note that the increase in WDD when there are more than 28 ECG flows in Fig. 6 is due to the delay violation at the receiver.

Fig. 7 shows the aggregate throughput performance as the number of ECG flows increases. Note that both the aggregate and per-flow throughputs of the proposed scheme do not degrade at all up to 28 ECG flows while those of IEEE 802.11e drastically decrease at 22 ECG flows due to extensive collisions. We then investigate the delay performance. According to Table 2, packets that violate the delay constraint of 200 ms are assumed to be discarded at the receiver. Fig. 8 shows that the end-to-end delay and delay violation ratio of IEEE 802.11e begin to increase abruptly when the number of ECG flows is 22 while those of the proposed scheme increase when the number of ECG flows is 28.

Now, in order to see how well the proposed scheme works to support absolute priority, we consider the case when there are 10 ECG flows in AC1 and the number of TCP flows in AC2 varies from 1 to 15. Fig. 9(a) shows the WDD performance of ECG flows. Since IEEE 802.11e only provides relative priority,

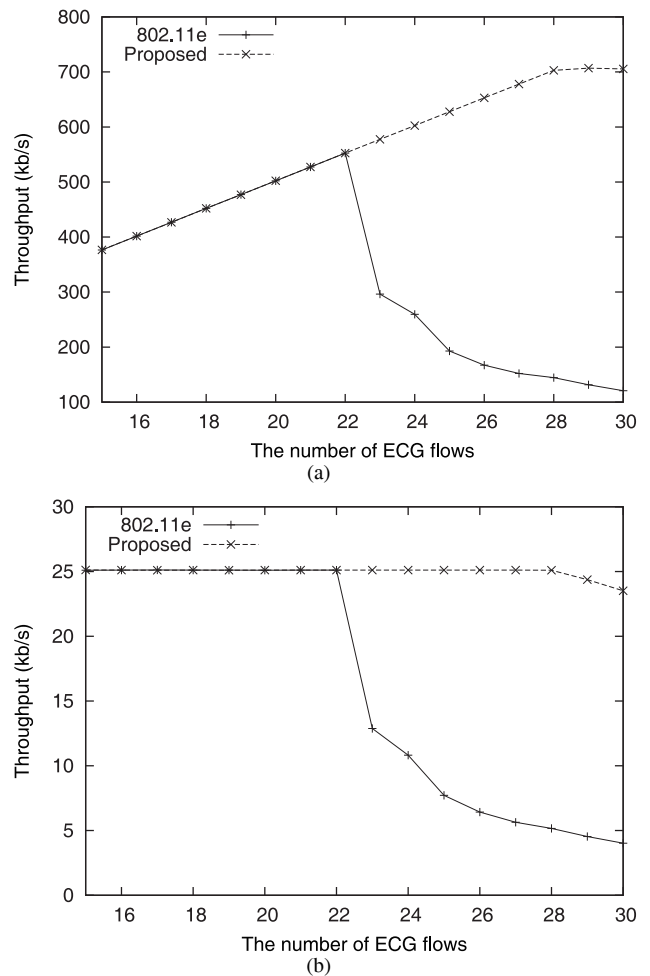


Fig. 7. Throughput performance vs. the number of ECG flows: (a) Aggregate throughput and (b) per-flow throughput.

the WDD of ECG flows significantly increases as the number of TCP flows increases. Hence, the real-time ECG flows in AC1 cannot be well protected in the case of IEEE 802.11e, which can be a serious potential hazard from a medical point of view. On the other hand, the proposed scheme keeps the WDD of ECG flows around zero regardless of the number of TCP flows in AC2, which validates that absolute priority is assured. In fact, since there is a tradeoff between the performance of AC1 traffic and AC2 traffic, absolute priority is ensured at the expense of TCP flows in AC2 as shown in Fig. 9(b), where the TCP aggregate throughput is higher under IEEE 802.11e than the proposed scheme. In a similar manner, Fig. 10 shows the simulation result with 15 ECG flows instead of 10 ECG flows. Overall, the trend is quite similar to that in Fig. 9. However, it should be noted that IEEE 802.11e performs even worse than the proposed scheme in the aggregate TCP throughput when the number of TCP is larger than 8. Again, we can see that the proposed scheme guarantees absolute priority of ECG flows in AC1.

Last, we carry out a simulation in the presence of channel error. In general, the channel error influences the overall performance of IEEE 802.11 WLAN because it causes retransmissions. We perform a simulation under the same conditions as in Figs. 6(a) and 10(a) except that the bit error rate (BER) is  $10^{-5}$



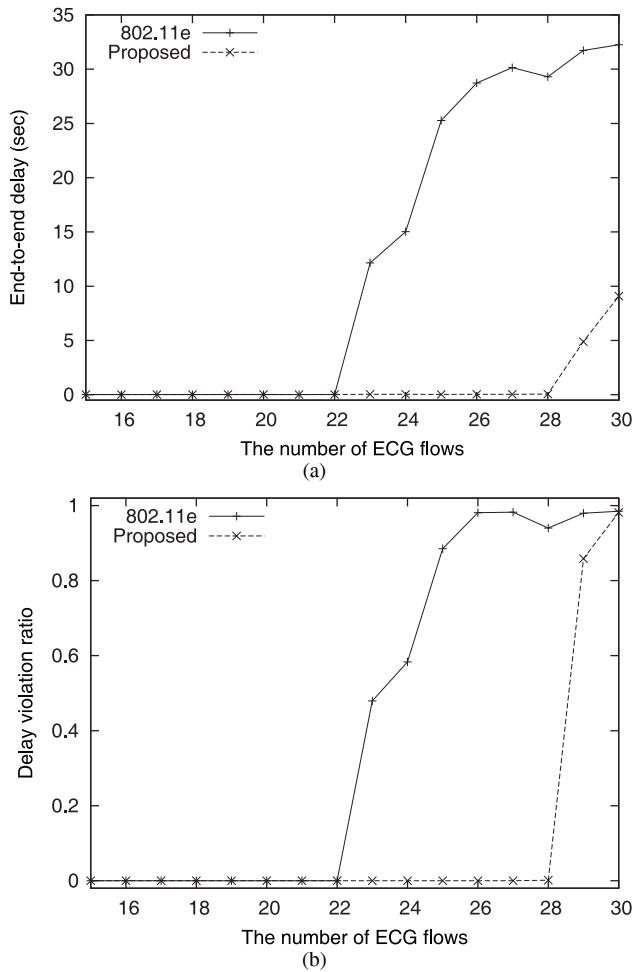


Fig. 8. Delay comparison vs. the number of ECG flows: (a) End-to-end delay and (b) delay violation ratio.

instead of 0. The simulation results are shown in Figs. 11(a) and 11(b), respectively. Fig. 11(a) shows that the performance of WDD for each scheme becomes worse only after the number of ECG flows exceeds its capacity, which is 22 for IEEE 802.11e and 28 for the proposed scheme. In Fig. 11(b), the performance of IEEE 802.11e severely degrades when there are channel errors, while the proposed scheme shows slight performance degradation.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we have presented an effective scheme for designing a medical-grade WLAN based on the conventional IEEE 802.11e MAC without any significant modification. The simulation results have shown that the proposed scheme can significantly improve the network performance while supporting the absolute priority service. We expect that this study will be an effective building block for improving the overall reliability and interoperability of wireless e-healthcare systems.

We point out some important topics for future research. Studying admission control is important for ensuring the required medical-grade QoS. In addition, the effects of other mechanisms such as rate control, power control, and carrier sense need to be thoroughly investigated for the overall reliability and the performance of medical networks.

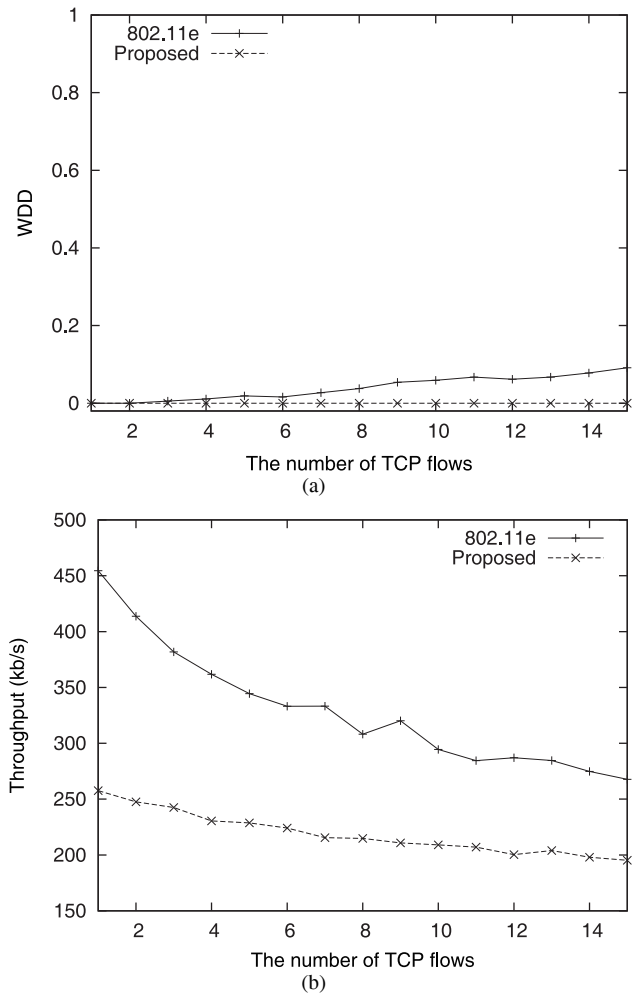


Fig. 9. Network performance vs. the number of TCP flows in AC2 when the number of ECG flows in AC1 is 10: (a) WDD and (b) aggregate TCP throughput.

## REFERENCES

- [1] E. Kershaw, "Wireless networking reshapes the face of patient monitoring systems," *Biomed. Instrum. & Technol.*, May/June 2002.
- [2] I. A. Gieras, "The proliferation of patient-worn wireless telemetry technologies within the U.S. healthcare environment," in *Proc. IEEE Conf. Inf. Technol. Appl. Biomedicine*, 2003.
- [3] NIST Advanced Network Technologies Division. Healthcare goes wireless. [Online]. Available: <http://w3.antd.nist.gov/Health.shtml>
- [4] N. Chevrollier and N. Golmi, "On the use of wireless network technologies in healthcare environments," in *Proc. IEEE ASWN*, June 2005, pp. 147–152.
- [5] US FDA/Center for Device and Radiological Health (CDRH) (2007. Jan.). Draft guidance for industry and FDA staff—radio frequency wireless technology in medical devices. [Online]. Available: <http://www.fda.gov/cdrh/osell/guidance/1618.html>
- [6] GE Healthcare. Product features—wireless technologies. [Online]. Available: <http://www.gehealthcare.com>
- [7] Philips. Patient monitoring—intellivue telemetry system. [Online]. Available: <http://www.medical.philips.com>
- [8] Welch Allyn. Micropaq wearable monitor. [Online]. Available: <http://www.welchallyn.com>
- [9] Dräger medical. [Online]. Available: <http://www.draeger.com>
- [10] M. Spaghetti (2008. Nov). A symposium on wireless technologies in hospital health care. [Online]. Available: <http://wirelesshealth.poly.edu/index.php?view=home>

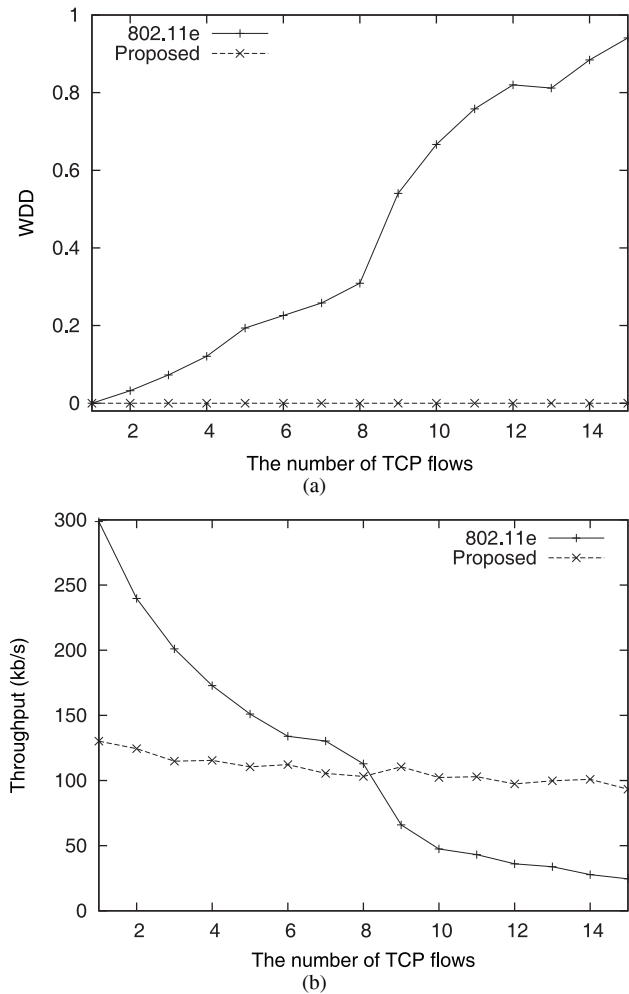


Fig. 10. Network performance vs. the number of TCP flows in AC2 when the number of ECG flows in AC1 is 15: (a) WDD and (b) aggregate TCP throughput.

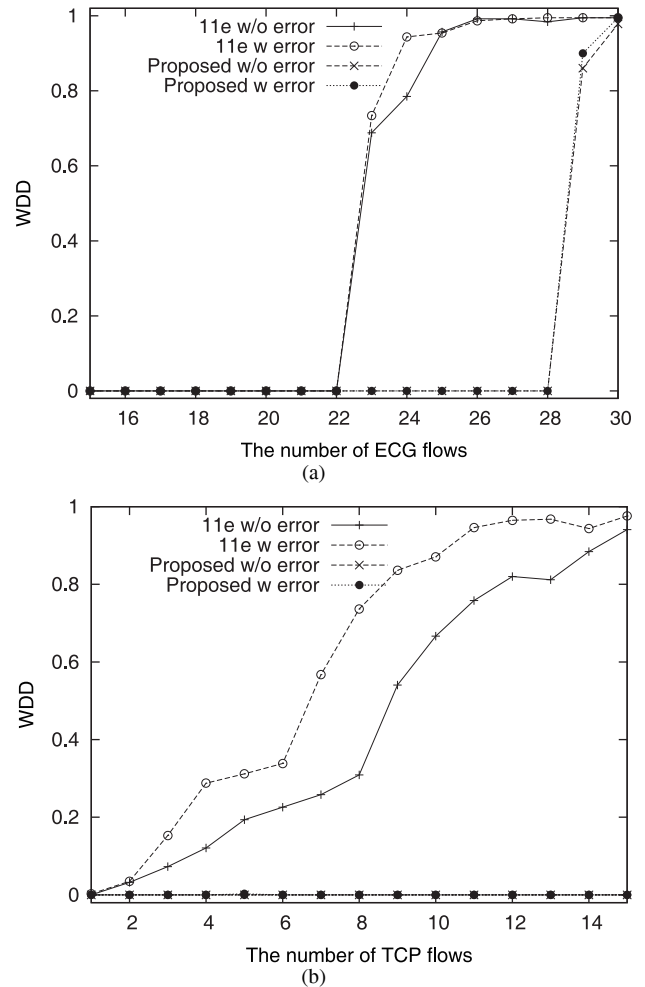


Fig. 11. Network performance with and without channel errors: (a) WDD vs. the number of ECG flows in AC1 when the number of TCP flows in AC2 is 0 and (b) WDD vs. number of TCP flows in AC2 when the number of ECG flows in AC1 is 15.

- [11] P. Sherman and C. Campbell, "Assessing existing telemetry systems for risk of electromagnetic interference," *J. Clinical Eng.*, pp. 144–154, 2001.
- [12] S. D. Baker, "Building reliability into your digital telemetry system," *Health Management Technol.*, vol. 23, no. 6, June 23, 2002.
- [13] US FDA/Center for Device and Radiological Health (CDRH) (2006, May). Medical product safety network—current issues in medical telemetry and wireless connectivity. [Online]. Available: <http://www.fda.gov/cdrh/medsun/AudioConffiles/MedicalTelemetryWireless/telemetry.html>
- [14] M. Sun, Q. Wang, and L. Sha, "Building reliable MD PnP systems," in *Proc. Joint Workshop on High Confidence Medical Devices, Software, and Systems and Medical Device Plug-and-Play Interoperability*, June 25–27, 2007.
- [15] R. Hampton (2008, July). A day in the life: Wireless risks in the hospital environment. IEEE 802 Plenary Tutorials. [Online]. Available: <http://www.ieee802.org/802tutorials/july08/IEEE802dot15Presentation-Hampton.ppt>
- [16] N. Golmie, D. Cypher, and O. Rebal, "Performance analysis of low rate wireless technologies for medical applications," *Comput. Commun.*, vol. 28, no. 10, pp. 1266–1275, June 16, 2005.
- [17] K. A. Townsend, J. W. Haslett, T. K. K. Tsang, M. N. El-Gamal, and K. Iniewski, "Recent advances and future trends in low power wireless systems for medical applications," in *Proc. IDEAS*, July 20–24, 2005.
- [18] N. Ansari, "Wireless technology advances and challenges for telemedicine," *IEEE Commun. Mag.*, Apr. 2006.
- [19] D. Cypher, N. Chevrollier, N. Montavont, and N. Golmie, "Prevailing over wires in healthcare environments: Benefits and challenges," *IEEE Commun. Mag.*, pp. 56–63, Apr. 2006.
- [20] U. Varshney, "Using wireless technologies in healthcare," *Int. J. Mobile Commun.*, vol. 4, no. 3, pp. 354–368, 2006.
- [21] U. Varshney, "Pervasive healthcare and wireless health monitoring," *Mobile Networks Appl.*, vol. 12, pp. 113–127, 2007.
- [22] S. D. Baker and D. H. Hoglund, "Medical-grade, mission-critical wireless networks," *IEEE Eng. Med. Biol. Mag.*, vol. 27, no. 2, pp. 86–95, Mar./Apr. 2008.
- [23] K.-J. Park, D. M. Shrestha, Y.-B. Ko, N. H. Vaidya, and L. Sha, "IEEE 802.11 WLAN for medical-grade QoS," in *Proc. ACM WiMD*, May 18, 2009.
- [24] Tutorial #2: Wireless and wired network requirements for safety in healthcare. IEEE 802 Plenary Tutorials. [Online]. Available: <http://www.ieee802.org/802tutorials/index.html>
- [25] L. S. Nolan-Avila, B. E. Paganelli, and R. E. Norden-Paul, "The medical information bus: An automated method of capturing data at the bedside," *Computers in Nursing*, pp. 115–121, 1988.
- [26] IEEE, "IEEE standard for medical device communications—overview and framework," IEEE Std. 1073–1996, 1996.
- [27] R. van der Togt, E. J. van Lieshout, R. Hensbroek, E. Beinat, J. M. Binnekade, and P. J. M. Bakker, "Electromagnetic interference from radio frequency identification inducing potentially hazardous incidents in critical care medical equipment," *JAMA*, vol. 299, pp. 2884–2890, 2008.
- [28] FCC. Wireless services—wireless medical telemetry (WMTS Home). [Online]. Available: <http://wireless.fcc.gov/services/index.htm?job=service-home&id=wirelessmedicaltelemetry>
- [29] MD PnP Program. Medical device "Plug-and-play" interoperability program. [Online]. Available: <http://mdpnp.org/HomePage.php>
- [30] U. Varshney, "Patient monitoring using infrastructure-oriented wireless LANs," *Int. J. Electron. Healthcare*, vol. 2, no. 2, pp. 149–163, 2006.
- [31] H. Y. Zhou, K. M. Hou, J. Ponnouaille, L. Gineste, and C. de Vault,

- "A real-time continuous arrhythmias detection system: RECAD," in *Proc. IEEE Eng. Med. Biol. Soc.*, Jan. 2006, pp. 875–881.
- [32] M. Paksumiemi, H. Sorvoja, E. Alasaarela, and R. Myllyla, "Wireless sensor and data transmission needs and technologies for patient monitoring in the operating room and intensive care unit," in *Proc. IEEE Eng. Med. Biol. Soc.*, Jan. 2006, pp. 5182–5185.
- [33] K. W. Goh, J. Lavanya, Y. Kim, E. K. Tan, and C. B. Soh, "A PDA-based ECG beat detector for home cardiac care," in *Proc. IEEE Eng. Med. Biol. Soc.*, Jan. 2006, pp. 375–378.
- [34] IEEE, "IEEE Standard for Information Technology–Telecommunication and Information Exchange Between Systems–LAN/MAN Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Amendment 8: Medium Access control (MAC) Quality of Service Enhancements," IEEE Std 802.11e-2005, 2005.
- [35] S. Choi, J. Del Prado, and S. Mangold, "IEEE 802.11e contention-based channel access (EDCF) performance evaluation," in *Proc. IEEE ICC*, vol. 2, 2003, pp. 1151–1156.
- [36] Z. Kong, D. H. K. Tsang, B. Bensau, and D. Gao, "Performance analysis of IEEE 802.11e contention-based channel access," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 10, pp. 2095–2106, 2004.
- [37] J. Hui and M. Devetsikiotis, "A unified model for the performance analysis of IEEE 802.11e EDCA," *IEEE Trans. Commun.*, vol. 53, no. 9, pp. 1498–1510, 2005.
- [38] IEEE, "Draft health informatics–point-of-care medical device communication–technical report–guidelines for the use of RF wireless technology," P11073-00101/D5, Jun 2008.
- [39] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, 2000.
- [40] P. S. Hamilton and W. J. Tompkins, "Quantitative investigation of QRS detection rules using the MIT/BIH arrhythmia database," *IEEE Trans. Biomed. Eng.*, vol. 33, no. 12, pp. 1157–1165, Dec. 1986.
- [41] Y. Zigel, A. Cohen, and A. Katz, "The weighted diagnostic distortion (WDD) measure for ECG signal compression," *IEEE Trans. Biomed. Eng.*, vol. 47, no. 11, pp. 1422–1430, Nov. 2000.
- [42] The network simulator (ns-2). [Online]. Available: <http://www.isi.edu/nsnam/ns>
- [43] G. B. Moody and R. G. Mark, "The impact of the MIT-BIH arrhythmia database," *IEEE Eng. Med. Biol. Mag.*, vol. 20, no. 3, pp. 45–50, May/June 2001.



**Hyungho Lee** received his B.S. and M.S. degrees from the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea, in 2004 and 2006, respectively. He is currently pursuing a Ph.D. degree at the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea. His research interests include wireless TCP, WLAN, providing QoS, and cross-layer optimization.



**Kyung-Joon Park** graduated from Seoul Science High School, and received his B.S., M.S., and Ph.D. degrees from the School of Electrical Engineering and Computer Science (EECS), Seoul National University (SNU), Seoul, Korea in 1998, 2000, and 2005, respectively. He is currently an Assistant Professor in the Department of Information and Communication Engineering at DGIST, Daegu, Korea. He was a postdoctoral research associate in the Department of Computer Science, University of Illinois at Urbana-Champaign (UIUC), IL, USA from 2006 to 2010. He worked for Samsung Electronics, Suwon, Korea as a Senior Engineer from 2005 to 2006, and was a visiting graduate student in the Department of Electrical and Computer Engineering at UIUC in 2001–2002. His current research interests include design of medical-grade protocols for wireless healthcare systems and modeling and analysis of cyber-physical systems.



**Young-Bae Ko** is an Associate Professor in the School of Information and Computer Engineering at Ajou University, Korea, and leads the Ubiquitous Networked Systems (UbiNeS) Lab. He was also a Visiting Professor of Coordinated Science Lab in University of Illinois at Urbana Champaign (UIUC) for the 2008–2009 academic year. Prior to joining Ajou University, he was with IBM T.J. Watson Research Center (New York) as a research staff member in the department of Ubiquitous Networking and Security. He received his Ph.D. degree in computer science from Texas A&M University, USA, and B.S. and M.B.A. from Ajou University, Korea. His research interests are in the areas of mobile computing and wireless networking. In particular, he is actively working on mobile ad hoc networks, wireless mesh networks, smart grid networks, and tactical wireless networks. He is also an expert on various wireless access technologies such as WLAN, WPAN, and WMAN. He has served on the program committees of several conferences and workshops such as IEEE Infocom, SECON, ICC, etc.



**Chong-Ho Choi** received his B.S. degree from Seoul National University, Seoul, Korea, in 1970 and his M.S. and Ph.D. degrees from University of Florida, Gainesville, in 1975 and 1978, respectively. He is a Professor in the School of Electrical Engineering and Computer Science, Seoul National University. His current research interests include adaptive control and WLAN communication.