An EMI-Aware Prioritized Wireless Access Scheme for e-Health Applications in Hospital Environments

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***Abstract*—Wireless communications technologies can support efficient healthcare services in medical and patient-care environments. However, using wireless communications in a healthcare environment raises two crucial issues. First, the RF transmission can cause electromagnetic interference (EMI) to biomedical devices, which could critically malfunction. Second, the different types of electronic health (e-Health) applications require different quality of service (QoS). In this paper, we introduce an innovative wireless access scheme, called EMI-aware prioritized wireless access, to address these issues. First, the system architecture for the proposed scheme is introduced. Then, an EMI-aware handshaking protocol is proposed for e-Health applications in a hospital environment. This protocol provides safety to the biomedical devices from harmful interference by adapting transmit power of wireless devices based on the EMI constraints. A prioritized wireless access scheme is proposed for channel access by two different types of applications with different priorities. A Markov chain model is presented to study the queuing behavior of the proposed system. Then, this queuing model is used to optimize the performance of the system given the QoS requirements. Finally, the performance of the proposed wireless access scheme is evaluated through extensive simulations.**

***Index Terms*—Electromagnetic interference (EMI), electronic health (e-Health) applications, quality of service (QoS), queueing analysis, wireless access.**

I. Introduction

RECENT advances in wireless technologies have enabled innovative applications for electronic health (e-Health) services. Wireless networks, especially wireless LANs (WLANs), are widely used in various e-Health applications (e.g., electronic medical record (EMR), clinician notifier, remote patient monitoring, and telemedicine applications) [1] to improve mobility and service flexibility in healthcare services. However, wireless transmission can cause electromagnetic interference (EMI), which leads to malfunctioning of EMI-sensitive medical devices such as automatic shutdown, automatic restart, waveform distortion, and howling [2]. This malfunctioning can potentially cause harm to patients who are using those medical devices. Consequently, design of wireless communications systems for e-Health applications must consider this EMI problem. International Electrotechnical Commission (IEC) 60601-1-2 Standard [3] specifies the immunity of the medical devices to the EMI. Unfortunately, the traditional IEEE 802.11-based WLANs do not take this EMI issue into account and do not comply with IEC 60601-1-2 Standard.

Another critical issue for e-Health applications is how to guarantee timely and reliable delivery of life-critical medical data in healthcare environments. Different medical applications have different quality of service (QoS) requirements. To meet the QoS requirements, prioritization of the channel access is required. In particular, real-time critical applications should have higher priority to access the channel to meet stricter loss and delay requirements than those for best-effort applications. Again, the conventional systems for nonmedical applications may not be able to support QoS guarantee (e.g., delay and loss probability) for medical applications [4].

In this paper, we address jointly the EMI and QoS provisioning issues in radio frequency (RF) WLAN for e-Health applications in hospital environments. We first design a system architecture for EMI-aware prioritized wireless access. An EMI-aware request to send/clear to send (RTS/CTS) protocol that complies with IEC 60601-1-2 Standard is designed to avoid EMI to sensitive medical devices, and a prioritized channel access scheme is developed to provide QoS guarantee for different e-Health applications. We consider two types of e-Health applications, namely, clinician notifier application and EMR application. The clinician notifier application provides real-time retrieval of vital signals (e.g., electrocardiograph (ECG), blood pressure, or sugar level) of patients for physician or supervising medical staffs, while the EMR application provides storage, retrieval, and processing of medical records for medical users. Clinician notifier applications (e.g., real-time critical applications) are sensitive to packet delay and loss, whereas EMR applications (e.g., medical information technology applications) are only sensitive to packet loss. Therefore, the users of clinician notifier applications are defined as high-priority users to have higher privilege to access the network, while the users of EMR applications are defined as low-priority users.

We then develop a Markov chain model to derive the performance metrics of the proposed access scheme which include the average transmission delay of high-priority users and the loss

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probability of low-priority users. The analytical model is also used to optimize system parameters (e.g., blocking probabilities) to guarantee the QoS performances for wireless access by e-Health applications while maximizing the system throughput (i.e., the number of users who can successfully transmit their data).

The rest of this paper is organized as follows. The related work are presented in Section II. The system architecture and the EMI-aware prioritized wireless access scheme for e-Health applications are introduced in Section III. Section IV presents the queueing analytical model and system performance optimization. The numerical and simulation results are presented in Section V. Finally, Section VI states the conclusion.

II. Related Work

In this section, we discuss the applications of WLANs in medical environments. Then, as background, we briefly introduce the basics of IEC 60601-1-2 Standard.

A. WLANs for Medical Environments

Recently, there have been a few studies on applications of WLANs in medical environments. An *IR* LAN was proposed in [5] to gather information from monitoring devices in the operating room (OR). This wireless network can increase the mobility and reduce the problem of cabling infrastructure especially when the layout of the OR is changed. Moreover, *IR* used in this network can avoid the EMI problem to life-sustaining devices in the OR. The concept of illuminating network was also proposed to address the EMI problem in [6]. This network uses high brightness LED as a transmitter. However, the use of both light and IR as the carrier does not allow seamless mobility and the transmissions can be easily interrupted by obstacles (e.g., medical devices or people moving in the hospital).

On the contrary, RF is more suitable for wireless communication in this respect. There exist two main technologies for the deployment of RF systems, namely, the wireless medical telemetry systems (WMTS), which are the proprietary networks in the allocated WMTS bands, and the IEEE 802.11 wireless networks in the unlicensed bands (e.g., industrial scientific medical bands in 2.4 GHz or unlicensed national information infrastructure bands at 5 GHz). Even though WMTS bands were dedicated to ensure that wireless medical telemetry devices can operate free of harmful interference, the WMTS telemetry systems, especially in dense metropolitan areas, are restricted by the limited bandwidth. In contrast, an IEEE 802.11-based network can provide large bandwidth in unlicensed bands. Moreover, WMTS-based network is restricted to support patient telemetry only and cannot be used for generalized medical applications [1]. The possibilities of exploiting wireless personal area network (WPAN) and WLAN technologies in medical environment were also discussed in [4].

In [7], a fully distributed contention control mechanism was designed to support medical-grade QoS in WLANs. The proposed design is based on the modifications of IEEE 802.11e MAC Standard that defines a set of QoS enhancements for WLAN applications. A QoS support mechanism was also proposed in [8]. However, all of these work related to medical-grade wireless networks did not take the EMI issue into account.

B. Electromagnetic Compatibility Standard for Medical Devices

The IEC has established two important standard series for medical electrical devices' electromagnetic compatibility (EMC), i.e., the IEC 60601-1 and the IEC 61000-4 Standard series. IEC 60601-1 series specifies general requirements for safety of medical equipments, while IEC 61000-4 series recommends testing and measurement techniques for EMC. IEC 60601-1-2 defines the immunity standard level and compliance level for medical equipments [3]. Immunity level is the maximum EM disturbance level in which medical devices can operate without performance degradation. Compliance level is the EM disturbance level, which is below or equal to the immunity level. The standard defines seven types of EM disturbances.

We consider the effects of radiated RF electromagnetic fields on medical devices (i.e., passive medical devices). There are two types of passive medical devices, namely, non-life-supporting devices (e.g., ECG monitors, blood pressure monitors, and infusion pumps) and life-supporting devices (e.g., defibrillators). IEC60601-1-2 specifies that non-life-supporting devices should be able to tolerate the EM field of at least 3 V/m, while life-supporting devices should be able to tolerate the maximum EM field of 3 V/m caused by RF transmission under 80–800 MHz and 10 V/m caused by RF transmission from 800 MHz to 2.5 GHz. To reduce the EM fields to those passive medical devices, the wireless transmitter should decrease the transmit power or increase the separation distance between itself and the medical devices.

In our study, we deal with the problem of designing a wireless communications protocol for e-Health applications by considering two critical issues in healthcare environments, i.e., EMI to medical devices and QoS of e-Health applications. To handle the EMI problem, our EMI-aware prioritized RTS/CTS protocol adapts the transmit power of wireless transmitter to avoid causing the EMI to passive medical devices in its vicinity greater than the requirements specified in IEC 60601-1-2 Standard. Moreover, the proposed protocol also provides admission control, which complies with the standard and the QoS requirements specified in [4], and differentiated scheduling and queue management, which enables data with higher priority to enjoy a better treatment in the network.

III. EMI-Aware Prioritized Wireless Access Scheme

This section describes the system architecture and access protocols of an EMI-aware prioritized wireless system for e-Health applications in hospital environments.

A. System Overview

We consider two types of e-Health applications and the corresponding users are referred to as *high-priority* and *low-priority* users. The low-priority users utilize the radio resources only when the high-priority users are not present. However, the

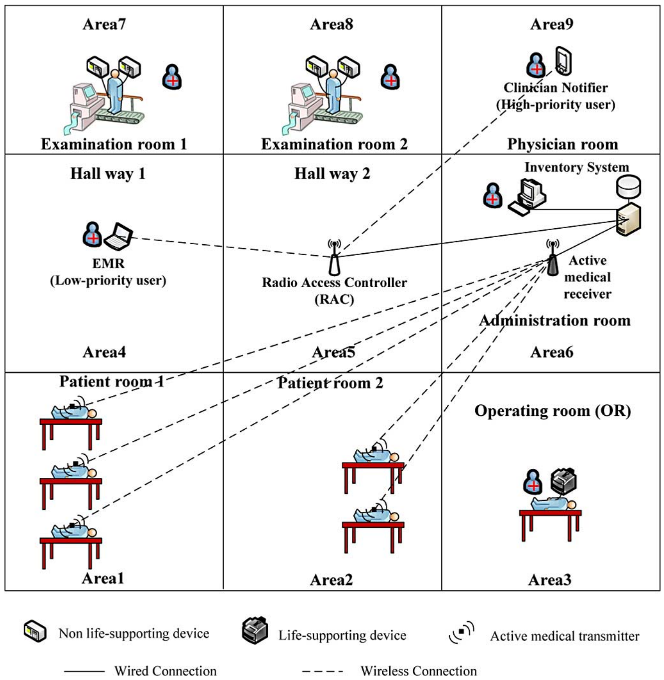


Fig. 1. Healthcare scenario with the proposed EMI-aware prioritized wireless system.

wireless access protocol must provide QoS guarantee to both types of users. Also, the wireless access protocol must be aware of EMI constraints to medical devices, which are referred to as *protected* users. Electronic medical devices can be classified either as passive or active devices. The passive devices (e.g., ECG monitors, blood pressure monitors, infusion pumps, and defibrillators) do not transmit any radio signal for communications. However, these medical devices can experience EMI from wireless transmissions. On the other hand, the active medical devices (e.g., telemetry monitors, wireless holter monitors, and wireless ECG monitors) can transmit radio signals. Wireless transmissions of these medical devices can also be interfered by other wireless nonmedical devices. The method to avoid EMI to these protected users will be described in Section III-C.

The proposed system operates on two channels under unlicensed spectrum bands. One is the control channel used to transmit control signals and the other is the data channel used to transmit data. We assume that the active medical transmitters also transmit data in the same channel as data channel of the proposed system.

B. System Architecture for EMI-Aware Prioritized Wireless Access

Fig. 1 illustrates a healthcare scenario in a cardiac department, which consists of active medical devices for remote patient monitoring system, passive medical devices, and our EMI-aware prioritized wireless access system. The proposed system is composed of three main components: the inventory system, the radio access controller (RAC), and the clients (i.e., high-priority and low-priority users). The clients communicate with the RAC over wireless links while the RAC is connected to the inventory system with wired infrastructure. The key functions of these components are as follows:

1) The *inventory system* is used to gather information about all electronic medical devices in the hospital (e.g., ON–OFF status, locations, EMI immunity levels, and signal-to-interference-plus-noise ratio (SINR) thresholds). This system can be supported by an effective tracking system [9] to maintain the locations of active and passive medical devices and wireless e-Health devices in a hospital environment.
2) The RAC is used to effectively control and manage dynamic spectrum sharing among various clients by using the updated information from the inventory system. The RAC defines safe transmission parameters (i.e., transmit power) for the clients to avoid harmful EMI to the medical devices. The RAC can perform effective channel allocation and control wireless access of the clients using an EMI-aware prioritized wireless access scheme, which will be described in Section III-C.
3) The *clients* are wireless nonmedical devices using high-priority and low-priority e-Health applications. These users/devices can transmit/receive data through the RAC (i.e., infrastructure mode of communication) by adaptively tuning the transmit power.

The RAC is equipped with two radio transceivers (i.e., one for common control channel and the other for data channel). Consequently, it can access both the channels simultaneously. On the other hand, the clients are equipped with a single dual-channel radio transceiver, which can access only one channel at a time (i.e., either the common control channel or the data channel).

C. EMI-Aware Prioritized Wireless Access Scheme

Under infrastructure mode, the high-priority and low-priority users first connect to the RAC in the common control channel by using a time-slotted RTS–CTS-based channel access mechanism. The users perform carrier sensing before transmitting RTS message to avoid collision with other users. The transmission of both high-priority and low-priority users must not cause any interference to the protected users. The wireless access mechanism consists of two steps, i.e., common control broadcasting and EMI-aware prioritized wireless access protocol (including EMI-aware RTS–CTS protocol and prioritized queue management and data transmission). The transmissions in both uplink and downlink are considered. For these uplink and downlink transmissions, the common control broadcasting is the same, while the EMI-aware prioritized wireless access mechanisms are slightly different. The operation of the entire wireless access procedure for uplink transmission is shown in Fig. 2.

1) Common Control Broadcasting: This step is used to broadcast P_{ctrl}, which is the maximum transmit power for transmitting either RTS or CTS message by a client on the control channel without causing too much EMI to the protected users. Each user has different P_{ctrl} depending on the locations of users. The upper bound on transmit power that active medical devices, passive non-life-supporting, and life-supporting devices can tolerate (i.e., P_A, P_{NLS}, and P_{LS}, respectively) can be obtained as in Appendix A.

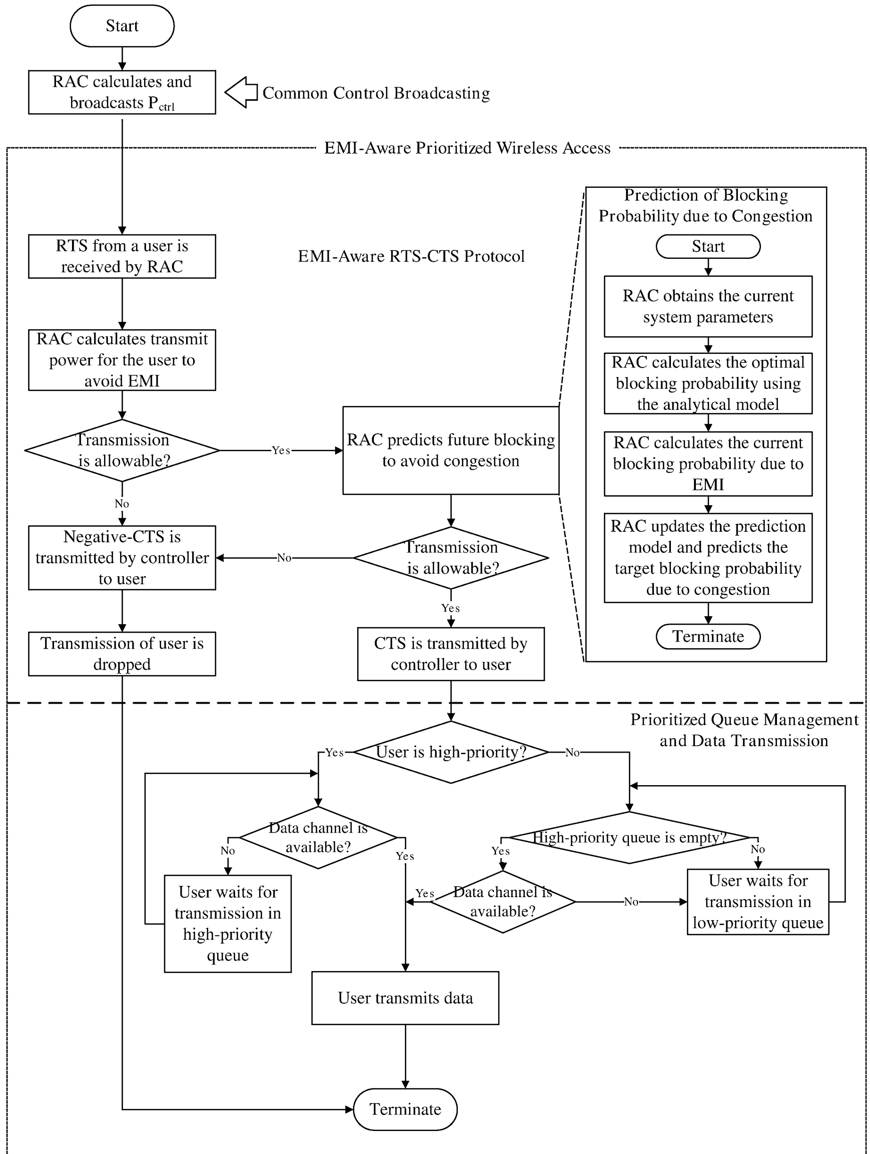


Fig. 2. Flowchart of the EMI-aware prioritized wireless access scheme for uplink request transmission.

The ON–OFF status and locations of medical devices and locations of clients (i.e., high-priority and low-priority users) can change dynamically over time. Therefore, the RAC computes and broadcasts P_{ctrl} when the state of a medical device changes. We assume that the status of the medical devices is always updated in the inventory system. If a device is switched ON or OFF, the inventory system will update this to the RAC. The RAC will calculate a new value of P_{ctrl} for every user and then broadcast it as follows. Similar to the IEEE 802.11 Standard, at the beginning of each time slot, each user will wait until the channel (i.e., control or transmission channel) is sensed idle for a distributed coordination function interframe space (DIFS) before transmitting an RTS message or a data packet. If the RAC has to update P_{ctrl}, it will broadcast a new message with information about P_{ctrl} after a short interframe space (SIFS) in both control and data channels. Since the SIFS is shorter than the DIFS, all users can detect the broadcasting and stop their transmissions so that the users can synchronize to the RAC. With this mechanism, the RAC can always capture the change of the hospital environment and does not cause EMI to the medical devices.

2) EMI-Aware RTS–CTS Protocol for Uplink Request Transmission: After common control channel broadcasting, a user can transmit its transmission requests by using an EMI-aware RTS–CTS protocol on the control channel. The protocol works as follows (see Fig. 2). Before transmitting data, the user transmits an RTS message to the RAC by using P_{ctrl}. If a high-priority user suffers collision, it will wait for a random time based on a constant backoff window, while a low-priority user will wait for a random time based on exponential backoff window. In this case, the users are said to be in the imaginary orbit and will retransmit the RTS message in near future. Note that the information about the user type will be indicated in the request message of the EMI-aware RTS–CTS protocol.

Once the RTS message is successfully received by the RAC, it calculates the upper bound of transmit power for the user on the data channel in the same way as P_{ctrl}. If the RAC cannot find a feasible transmit power, which meets the EMI constraints of the medical devices and satisfies the minimum QoS requirements (i.e., minimum data rate) of the user, the request for data transmission of the user will be dropped. In this case, the transmission of the user will be dropped due to the EMI effect with probabilities $P_{d1}^{\rm EMI}$ and $P_{d2}^{\rm EMI}$ for high-priority and low-priority users, respectively. In addition, to avoid congestion, the RAC will randomly drop the transmission requests with probabilities $P_{d1}^{\rm cong}$ and $P_{d2}^{\rm cong}$ for high-priority and low-priority users, respectively. These probabilities can be determined for each time slot from an analysis (i.e., prediction) of the future system performance [10].

If the transmission request of a user is dropped, a negative CTS message is transmitted to the user by the RAC. Otherwise, the RAC will transmit a CTS message with the maximum allowable transmit power. The user can adaptively tune its transmit power on the data channel accordingly. Once the CTS message is successfully received by the user, the user will immediately transmit an acknowledge (ACK) message to the RAC within the same time slot. A time slot of CTS transmission is composed of the CTS transmission period and the ACK transmission period. If the RAC does not receive the ACK message at the end of the time slot, it will automatically repeat the CTS transmission (e.g., using automatic repeat request (ARQ) protocol) in the next time slot.

Similar to the broadcasting, each user waits until the common control channel is sensed idle for a DIFS before transmitting an RTS message. Upon receiving the RTS message, the RAC will immediately transmit a CTS message to the user after a SIFS during the CTS time slot.

3) EMI-Aware RTS–CTS Protocol for Downlink Request Transmission: The flowchart of the EMI-aware RTS–CTS protocol for downlink request transmission is shown in Fig. 3. Once the RAC has a request from a user/device, it retrieves the location of the user and calculates the feasible transmit power to avoid the EMI. If the RAC cannot find the feasible transmit power, the transmission request will be dropped with probabilities $P_{d1}^{\rm EMI}$ and $P_{d2}^{\rm EMI}$ for high-priority and low-priority users, respectively. To avoid congestion, the downlink transmission request can be also dropped with probabilities $P_{d1}^{\rm cong}$ and $P_{d2}^{\rm cong}$ for high-priority and low-priority users, respectively. If the transmission request is granted, the RAC will transmit an RTS message along with the feasible transmit power on the control channel to the user after a SIFS to avoid collision with RTS message from other users. Upon receiving the RTS message, the user will respond with a CTS message after a SIFS period. In the same time slot of the CTS transmission, the RAC will immediately transmit an ACK message to the user. An ARQ mechanism is also used to recover from erroneous transmissions.

Even though the RTS/CTS protocol incurs overhead in data transmission, it can be used to avoid harmful interference to the medical devices, and the hidden terminal problem. In practice, RTS and CTS transmission lengths are very small (e.g., 18 ms each), while the duration of data transmissions of high-priority and low-priority users are several hundred milliseconds (e.g., 250 ms for high-priority and 810 ms for low-priority users). Compared with the data transmission length, the overhead caused by the RTS/CTS protocol is negligible.

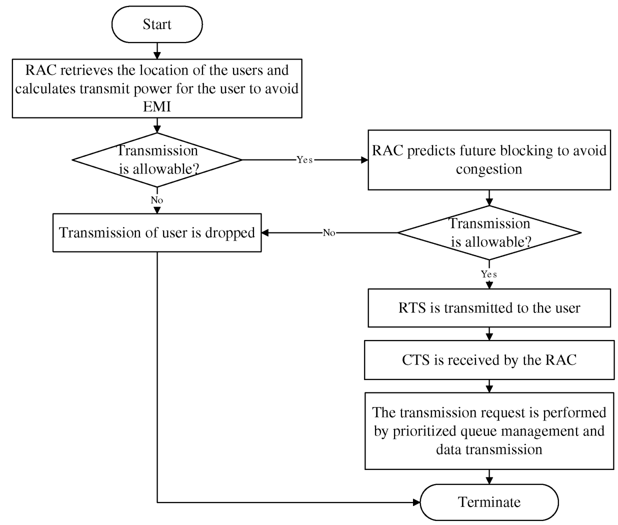


Fig. 3. Flowchart of the EMI-aware RTS/CTS protocol for downlink transmission.

4) Prioritized Queue Management and Data Transmission: Upon receiving the CTS message for uplink transmission or RTS message for downlink transmission, the user will switch its radio from the control channel to the data channel. The user will wait in the data channel until the RAC transmits a message to allow the user to transmit/receive data when the data channel is available for the user. The duration of a time slot is assumed to be fixed during which one packet can be transmitted. This transmission time slot is composed of the data transmission period and the ACK transmission period. We also assume that an ARQ protocol is used in the data channel for error control.

Two finite-length queues at the RAC are used to store the transmission requests of the high-priority and low-priority users separately. If the queues are full, the RAC will transmit a negative CTS message to the user. The user will wait in the orbit and retransmit the request. High-priority users are always allowed to transmit, if there is any request in the transmission queue. The low-priority users have to wait in the queue until the queue for the high-priority users is empty.

IV. Queuing Analysis and System Performance Optimization

This section presents a queueing analysis and system performance optimization for the proposed prioritized wireless access scheme. The analysis considers only uplink request transmissions. We assume that there is no packet loss due to channel fading. A discrete-time queuing model is developed, and two performance metrics, namely, the average transmission delay of high-priority users and the loss probability of low-priority users are derived.

A. Modeling Assumptions

The queuing model for the EMI-aware prioritized wireless access scheme consists of two tandem servers (i.e., one for the control channel and the other for the data channel), two orbits and two buffers (i.e., each one for high-priority users and low-priority users) as shown in Fig. 4. We consider a scenario

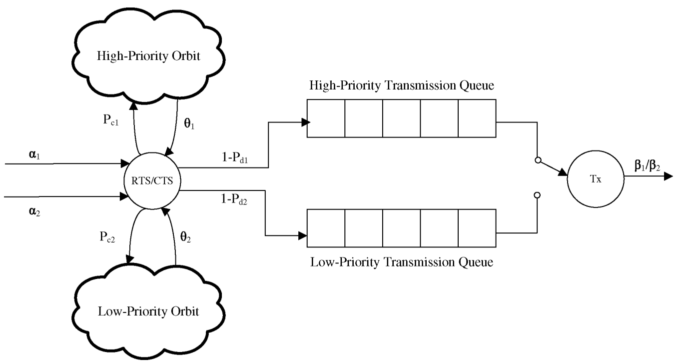


Fig. 4. Queuing model for the EMI-aware prioritized wireless access system.

where an RTS request arrives at the server in the control channel according to independent Bernoulli processes with arrival probabilities α_1 and α_2 for high-priority users and low-priority users, respectively. When a collision occurs, the users will go to the orbits. A high-priority user in the orbit retransmits the RTS message with probability θ_1 and a low-priority user will retry with probability θ_2. The derivations of θ_1 and θ_2 are shown in Appendix B.

The size of the orbit for RTS requests of high-priority users is not limited, while that of low-priority users is bounded to N in order to control the collision with high-priority users. The EMI-aware RTS–CTS process in the control channel requires two time slots (i.e., one time slot for RTS message and the other slot for CTS or negative CTS message). Hereafter, CTS refers to both CTS and negative CTS message. To avoid EMI and congestion effects, the transmission requests from users can be blocked with probabilities P_{d1} and P_{d2} for high-priority and low-priority users, respectively. The sizes of the buffers for high-priority and low-priority users are B_1 and B_2, respectively. The event of the user to finish its data transmission is assumed to be geometrically distributed with parameter β_1 for high-priority users and β_2 for low-priority users. β_1 and β_2 characterize the variable size of medical files (e.g., ECG files and patient profiles) for each e-Health application.

B. Discrete-Time Markov Chain Model

The state space of the discrete-time Markov chain (DTMC) is described in Appendix C. Assuming that successful RTS, CTS, and data packet transmissions occur at the end of equally-spaced discrete-time slots, a transition of the system from one state to another can be triggered by 1) a collision; 2) an RTS successfully arriving at the RAC on the control channel; 3) a CTS transmitted from the RAC on the control channel; and 4) a user finishing its transmission on the data channel. We show the transition probability matrix $\mathbf{P}$ of the DTMC in (1). $\mathbf{A}_{k,k-1}$, $\mathbf{A}_{k,k}$, and $\mathbf{A}_{k,k+x_1}$ are the transition probability matrices that the number of high-priority users in the orbit will be changed from k to $k-1$, from k to k, and from k to $k+x_1$, respectively. The details of each inner matrix $\mathbf{A}_{k,k-1}$, $\mathbf{A}_{k,k}$, and $\mathbf{A}_{k,k+x_1}$ are given in [10].

$$\mathbf{P} = \begin{bmatrix} \mathbf{A}_{0,0} & \mathbf{A}_{0,1} & \mathbf{A}_{0,2} & \mathbf{A}_{0,3} & \cdots & \mathbf{A}_{0,T_1-1} & \mathbf{A}_{0,T_1} \\ \mathbf{A}_{1,0} & \mathbf{A}_{1,1} & \mathbf{A}_{1,2} & \mathbf{A}_{1,3} & \cdots & \mathbf{A}_{1,T_1-1} & \mathbf{A}_{1,T_1} \\ \mathbf{0} & \mathbf{A}_{2,1} & \mathbf{A}_{2,2} & \mathbf{A}_{2,3} & \cdots & \mathbf{A}_{2,T_1-1} & \mathbf{A}_{2,T_1} \\ \mathbf{0} & \mathbf{0} & \mathbf{A}_{3,2} & \mathbf{A}_{3,3} & \cdots & \mathbf{A}_{3,T_1-1} & \mathbf{A}_{3,T_1} \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{A}_{T_1,T_1-1} & \mathbf{A}_{T_1,T_1} \end{bmatrix}. \tag{1}$$

After obtaining the transition probability matrix $\mathbf{P}$, we can compute the stationary probability vector π by solving (2) [11]

$$\pi = \pi\mathbf{P}, \quad \pi\mathbf{1} = 1 \tag{2}$$

where π is a row vector with dimension $[(T_1 - B_1 + 1) \times (N + 1) \times (B_1 + 1) \times (B_2 + 1) \times 5] + \sum_{ii=1}^{B_1} [(N+1) \times ii \times (B_2 + 1) \times 5]$ and $\mathbf{1}$ is a column vector of ones with the same dimension. Here, $\pi_k^{(j,i,h)}$ represents the stationary probability that there are k users in the high-priority orbit, j users in the low-priority orbit, i users in the high-priority queue, and h users in the low-priority queue. The structure of stationary probability vector π is presented in Appendix C.

C. Performance Measures

1) Average Transmission Delay of High-Priority Users: The average transmission delay, which accounts for the time from when a high-priority user transmits an RTS message on the control channel to when it successfully transmits all packets, can be computed as follows:

$$\overline{D} = \overline{D}_{\text{orbit}} + RTS + CTS + \overline{D}_{\text{queue}} \tag{3}$$

where $\overline{D}_{\text{orbit}}$ is the average waiting time in the orbit until the user successfully transmits the RTS message, RTS and CTS are the average time to transmit RTS and CTS messages, respectively, each of which requires one time slot, and $\overline{D}_{\text{queue}}$ is the average waiting time for transmission in the queue until the user successfully transmits all packets. $\overline{D}_{\text{orbit}}$ and $\overline{D}_{\text{queue}}$ can be obtained from Little's theorem [11] as follows:

$$\overline{D}_{\text{orbit}} = \frac{\bar{o_1}}{\alpha^e_{\text{orbit}}}, \quad \overline{D}_{\text{queue}} = \frac{\bar{q_1}}{\alpha^e_{\text{queue}}} \tag{4}$$

where $\bar{o_1}$ and α^e_{orbit} are the average number of transmission requests of high-priority users in the orbit and the effective arrival probability of high-priority users to the orbit, respectively. $\bar{q_1}$ and α^e_{queue} are the average number of transmission requests of high-priority users waiting in the transmission queue and the effective arrival probability to the queue, respectively. $\bar{o_1}$ can be expressed as $\bar{o_1} = \sum_{k=0}^{T_1} k\pi_k$ and $\bar{q_1}$ is given by $\bar{q_1} = \sum_{k=0}^{T_1} \sum_{j=0}^{N} \sum_{i=0}^{B_1} i\pi_k^{(j,i)}$.

α^e_{orbit} is given by the probability of collision with high-priority users (P_{c1}), which can be computed in a way similar to that of P_{c2} as defined in (17). α^e_{queue} is the probability that an RTS message is successfully transmitted by a high-priority user and the transmission request is allowable. α^e_{queue} can be expressed as $\alpha^e_{\text{queue}} = (1 - P_{d1}) \times \sum_{k=0}^{T_1} \sum_{j=0}^{N} \sum_{i=0}^{B_1} \sum_{h=0}^{B_2} \sum_{g=0}^{2} \pi_k^{(j,i,h,g,1)}$.

2) Loss Probability of Low-Priority Users: Since we assume that the size of the orbit for high-priority users is unlimited, the transmission requests of high-priority users will never be lost. However, to limit the collisions between high-priority and low-priority users, the size of the low-priority orbit is limited to N. When the transmission requests of low-priority users in the orbit reaches N, any new transmission request of low-priority users on the control channel is dropped. Therefore, the loss probability of low-priority users (P_L) is given by

$$P_L = \sum_{k=0}^{T_1} \sum_{i=0}^{B_1} \sum_{h=0}^{B_2} \sum_{g=0}^{2} \sum_{f=0}^{4} \pi_k^{(N,i,h,g,f)}. \tag{5}$$

D. Optimization of Blocking Probabilities for EMI-Aware Prioritized Wireless Access Scheme

We optimize the system parameters (i.e., blocking probability P_{d1} and P_{d2}) by using the performance measures obtained from the queuing analysis. Optimal blocking probabilities can be selected to maximize the system throughput while the QoS requirements for wireless access by e-Health applications are satisfied.

The system throughput is defined as the ratio of the number of users that successfully transmit their data over the total number of users that successfully transmit RTS message on the control channel. Therefore, the system throughput can be expressed as $1 - P_d$. Given the system parameters (i.e., α_1, α_2, W_1, W_2, m, β_1, β_2, T_1, and T_2), a two-stage optimization problem can be formulated as follows:

$$\text{minimize:} \quad P_{d1} \tag{6}$$

$$\text{subject to:} \quad \overline{D}(P_{d1}) \leq D^{(\text{req})} \tag{7}$$

$$\text{minimize:} \quad P_{d2} \tag{8}$$

$$\text{subject to:} \quad P_L(P_{d1}, P_{d2}) \leq P_L{}^{(\text{req})} \tag{9}$$

where $D^{(\text{req})}$ and $P_L^{(\text{req})}$ are the QoS requirements of e-Health applications in term of the average transmission delay of high-priority users and the loss probability of low-priority users, respectively. $\overline{D}(P_{d1})$ and $P_L(P_{d1}, P_{d2})$ can be computed as shown in (3) and (5) by using queuing analysis. In the first stage, an optimal P_{d1} is selected to maximize the throughput of high-priority users while the average transmission delay of the users is satisfied as defined in (6) and (7). In the second stage [defined by (8) and (9)], an optimal P_{d2} is selected to maximize the throughput of low-priority users while maintaining the loss probability of the users below an acceptable level. The optimal P_{d1} obtained from the first stage is used to compute the loss probability of low-priority users as shown in (9). The optimization formulation in (6)–(9) can be solved numerically.

V. Performance Evaluation

We consider two e-Health applications, namely, clinician notifier and EMR applications. The clinician notifier applications (defined as high-priority applications) are used by physicians or medical staffs to retrieve real-time vital signals of patients when they receive an alarm notification. These applications have average delay requirement of 300 ms. EMR applications (defined as low-priority applications) are used by medical staffs to add, retrieve, and update medical data (e.g., patient profile, patient historical medications, and normal ECG recording files). EMR applications require loss probability less than 0.01 [4].

A. Simulation Scenario

We consider a service section over 27×22 m^2 in a cardiac department of a hospital including one operating room (OR), two examination rooms, two patient rooms, an administration room, a physician room, and a hall way. The service section is divided into nine areas as shown in Fig. 1. The RAC is located at the center of the service section.

We consider one life-supporting medical device (i.e., a defibrillator), four non-life-supporting medical devices (i.e., two ECG monitors and two blood pressure monitors), and one active medical receiver with five active medical transmitters. The locations of RAC, passive medical devices, and active medical receiver are fixed, while the locations of active medical transmitters and the users of high-priority and low-priority applications are uniformly random.

The defibrillator is used for cardiopulmonary resuscitation for a patient of cardiac arrest while the non-life-supporting medical devices are used for treadmill exercise tests. The EMI susceptibility of the defibrillator, the ECG monitors, and the blood pressure monitors conform to the IEC 60601-1-2 Standard [3]. The EMI immunity level of the defibrillator is specified to 10 V/m, while the EMI immunity levels of ECG and blood pressure monitors are 3 V/m. The active medical receiver is based on the IEEE 802.11g technology, which has the minimum SINR requirement of 16 dB to guarantee 11 Mb/s transmission rate [12]. We assume that the background noise is negligible. Five active medical transmitters are scheduled to transmit the ECG signals to the active medical receiver in a round-robin manner. Therefore, only one transmitter can transmit data in each time slot. The controller is assumed to have perfect knowledge of locations and status of all medical devices.

For the patient with cardiac arrest, the defibrillator is operated once and the arrival time is uniformly random. The duration of ON status is normally distributed with mean 4.68 min and standard deviation 5.27 [13]. The treadmill exercise tests are scheduled for two simultaneous tests every hour. Each test takes 10–15 min to set up, 10–15 min to operate, and 10–15 min to observe [14]. Two ECG monitors and two blood pressure monitors used in the test are operated every hour. Moreover, the in-hospital patient-monitoring application operates all time. The simulation is run for 12 h.

The receiver of the RAC is based on the IEEE 802.11b technology, which requires the received signal strength of -94 dBm to guarantee 1 Mb/s transmission rate [15]. We assume that both high-priority and low-priority users require the data rate of 1 Mb/s. The transmit power is attenuated due to indoor propagation path-loss and floor attenuation factor. Both high-priority and low-priority users operate in 2.4 GHz. The floor attenuation factor through one floor is 16.2 dB [16], the measured line-of-sight path loss at $d_0 = 1$ m is 37.7 dB, and obstructed path-loss exponent is 3.3 [17]. Based on this information, the RAC can calculate the appropriate transmit power for each user and then compute the received signal strength from the appropriate transmits power. A transmission is dropped due to EMI when the received signal strength at the receiver (either the RAC or the users) is less than -94 dBm.

B. System Configuration for EMI-Aware Prioritized Wireless Access System

For the clinician notifier application, the ECG signals from the monitoring devices are transmitted to the central server. When an abnormal condition is detected, an alarm will be sent to a supervising medical staff. Once the medical staffs receive the alarm, they will transmit a request to retrieve the real-time ECG signals of the patients as high-priority users in the system. A sampling rate of 250 Hz with 8-bit resolution is used to capture the ECG data [18]. The ECG signals captured for 120 s on average (i.e., $250 \times 8 \times 120 = 240$ kb) will be transmitted to the high-priority application users. The clinician notifier applications are assumed to run 40 times an hour on average.

For EMR, the medical data size ranges from 10 (i.e., patient profile) to 100 kB (i.e., normal ECG recording files). A medical staff is assumed to access an EMR application 60 times in an hour on average.

The maximum size of low-priority orbit is $N = 3$. The maximum queue size for high-priority and low-priority users is $B_1 = B_2 = 3$. Both high-priority and low-priority users have the same backoff window sizes equal to 32 (i.e., $W_1 = W_2 = 32$). The maximum backoff stage for low-priority users is $m = 5$. The duration of a time slot is 18 ms, which is the transmission duration for one data packet (i.e., 2200 bits per packet).

Based on the aforementioned scenario, the arrival probabilities for a high-priority user (α_1) and low-priority user (α_2) are 0.0002 and 0.0003, respectively. The probability that a user finishes its transmission in one time slot is 0.0714 for high-priority users (β_1) and 0.0222 for low-priority users (β_2). The simulation results obtained using MATLAB are averaged over five simulation runs.

C. Performance Evaluation of the EMI-Aware RTS–CTS Protocol

We consider the uplink transmission scenario on the data channel in which only one user can transmit data at a time. Two performance measures, namely, the *interference probability* and the *outage probability* are studied. The interference probability is the probability that the user causes EMI to the medical devices when the transmit power is higher than the acceptable level, while the outage probability is the probability that the received signal strength at the RAC is less than -94 dBm.

Fig. 5 shows the interference probability over nine service areas for the EMI-aware protocol and the traditional carrier sense multiple access with collision avoidance (CSMA/CA) protocol with transmit power fixed at 10, 0, and -5 dBm. As expected, the proposed protocol never causes EMI, while the traditional CSMA/CA protocol causes interference to the medical devices. The higher the transmit power, the more the probability of interference is. The traditional protocol can cause severe interference to the medical devices, especially in area 6, since the active medical receiver is located in this area. It can also cause interference to the passive medical devices in areas 3, 7, and 8. However, the passive devices operate occasionally, while the active devices operate all the time. Therefore, there are more chances that the wireless device causes interference to the active medical devices. The average interference probabilities of the traditional protocol with transmit power of 10, 0, and -5 dBm are 81.96%, 43.73%, and 25.50%, respectively.

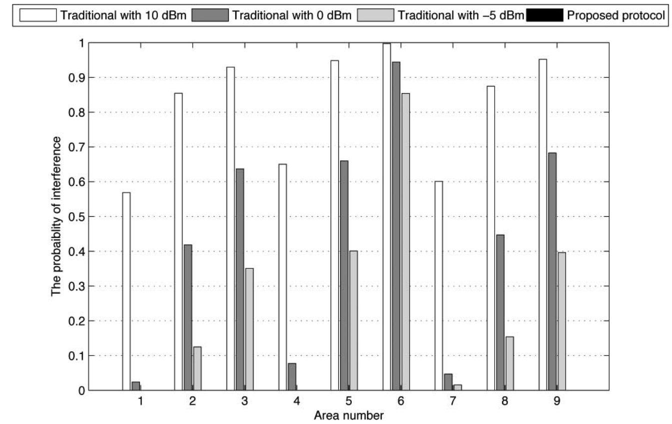


Fig. 5. Interference probability over nine service areas.

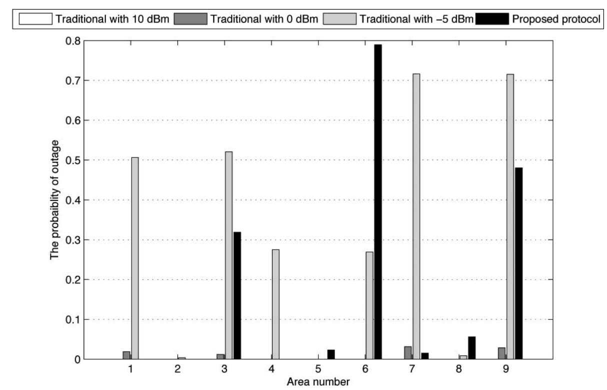
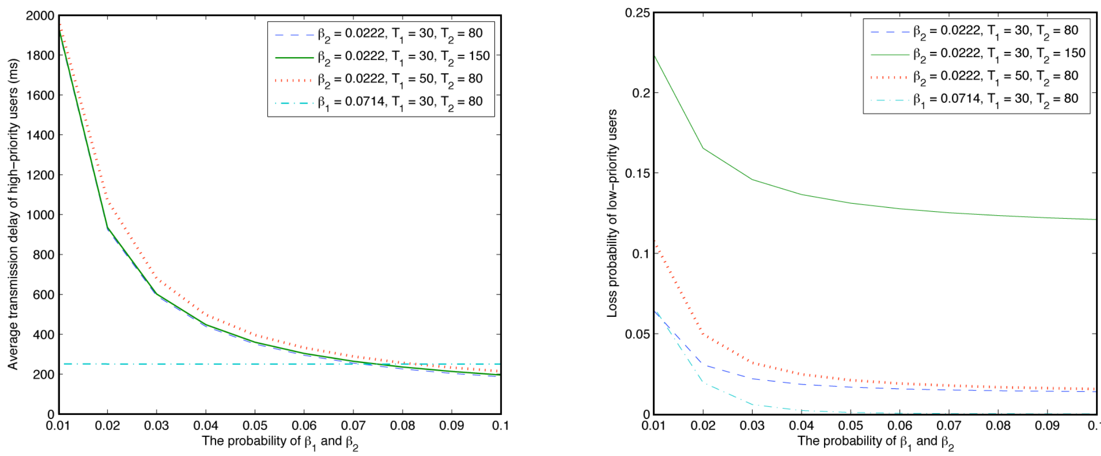


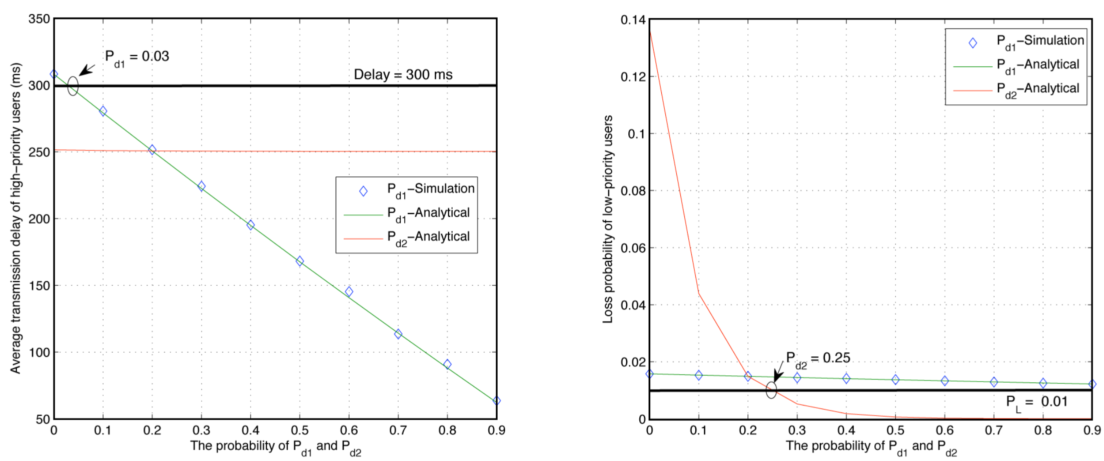
Fig. 6. Outage probability over nine service areas.

The outage probability of the EMI-aware protocol is greater than that due to the traditional protocol with transmit power of 10 and 0 dBm in most of the areas (see Fig. 6). This is due to the fact that the EMI-aware protocol limits the transmit power of an active device/user to avoid EMI to the medical devices in the vicinity. The outage probabilities around area 6 are high to avoid EMI to the active medical receiver. However, the EMI-aware RTS–CTS protocol can adaptively increase the transmit power in the different areas according to the presence and the activity of the medical devices. Consequently, with the EMI-aware RTS–CTS protocol, the outage probability in these areas is less than that due to the traditional protocol with transmit power of 0 and -5 dBm. The traditional protocol with transmit power of 10 dBm never has the outage problem due to high transmit power, but it results in the highest interference probability. The average outage probability for the traditional protocol with transmit



(a) (b)

Fig. 7. (a) Average transmission delay of high-priority users and (b) loss probability of low-priority users versus β_1 and β_2.



(a) (b)

Fig. 8. (a) Average transmission delay of high-priority users and (b) loss probability of low-priority users versus blocking probability P_{d1} and P_{d2}.

power of 0 and -5 dBm is 1.01% and 33.51%, respectively, while that due to the EMI-aware protocol is 18.71%.

D. Performance Evaluation of the EMI-Aware Prioritized Wireless Access Protocol

We study two performance metrics, namely, *average transmission delay* of high-priority users ($\overline{D}$) and *loss probability* of low-priority users (P_L), for the EMI-aware prioritized wireless access protocol.

1) Effects of Transmission Durations: The transmission durations are based on the probabilities that users finish their transmissions in a certain time slot (β_1 and β_2). We fix the blocking probabilities of high-priority and low-priority users to 0.1972 and 0.2012, respectively, which are the blocking probabilities of high-priority and low-priority users (P_{d1}^{EMI} and P_{d2}^{EMI}) due to the EMI effect. The average transmission delay of high-priority users ($\overline{D}$) and the loss probability of low-priority users (P_L) obtained from the queuing model are shown in Fig. 7.

Clearly, as the transmission duration of high-priority users decreases (i.e., β_1 increases), $\overline{D}$ decreases. The average transmission duration of low-priority users (i.e., $1/\beta_2$) does not affect the performance of high-priority users. Moreover, $\overline{D}$ also increases when the number of high-priority and low-priority users increase. As the number of users increase, the chance that a collision will occur also increases. Therefore, the high-priority users have to spend more time in the orbit. As is evident from Fig. 7(b), P_L is sensitive to β_1, β_2, and number of users in the system.

2) Effects of Blocking Probabilities: We also investigate the impact of blocking probabilities of high-priority and low-priority users (P_{d1} and P_{d2}, respectively). We fix the number of high-priority and low-priority users to 30 and 80, respectively. We also fix P_{d1} at 0.1972, while P_{d2} is varied. Alternatively, P_{d2} is fixed at 0.2012, while P_{d1} is varied. We show the analytical and simulation results on $\overline{D}$ and P_L in Fig. 8.

As expected, the average transmission delay $\overline{D}$ decreases when P_{d1} increases. As P_{d1} increases, the average number of requests from high-priority users in the queue decrease. However, $\overline{D}$ is not sensitive to P_{d2}. In Fig. 8(b), as P_{d1} increases, low-priority users have higher probability to transmit their data and the probabilities that the queue and the orbit of low-priority users are full are smaller. Therefore, P_L decreases as P_{d1} increases. Similarly, when P_{d2} increases, the average number of requests from low-priority users in the queue decrease. In this case, there is a high probability that the requests from low-priority users in the orbit are transmitted, and therefore, the number of low-priority users in the orbit significantly decrease. Consequently, when P_{d2} increases, P_L decreases.

Based on the aforementioned results, the RAC can optimize the blocking probabilities to guarantee the QoS of users in the system while maximizing the system throughput. In Fig. 8, P_{d1} should be equal to 0.03 to guarantee $\overline{D}$ below 300 ms while P_{d2} should be equal to 0.25, which is the minimum P_{d2} to maintain P_L below 0.01. However, since P_{d1}^{EMI} is 0.1972, P_{d1}^{cong} should be zero. On the other hand, since P_{d2}^{EMI} is 0.2012, P_{d2}^{cong} is fixed at 0.0488 (i.e., $0.25 - 0.2012$). In this way, the system can achieve both the maximum throughput and guarantee QoS while avoiding EMI to medical devices at the same time.

VI. Conclusion

We have proposed an EMI-aware prioritized wireless access scheme for e-Health applications. This scheme considers two major issues, namely, EMI to medical devices and QoS differentiation in healthcare environment. Two e-Health applications, namely, clinical notifier and EMR applications have been considered. A queuing analytical model has been developed to study the behavior of the proposed scheme. Performance evaluation results have shown that the proposed scheme can protect the active and passive biomedical devices from the harmful interference and also achieve service differentiation among different e-Health applications. The performance (i.e., delay and loss probability) of the proposed scheme can be optimized by adjusting the blocking probabilities. The results from the queuing model can be used to optimize the blocking probabilities to maximize the system throughput while satisfying the QoS requirements of the e-Health applications.

Appendix A
Derivations of Transmit Power of Active and Passive Medical Devices

1) *Active medical devices*: The interference from the other wireless users should not cause the SINR of the active medical devices to fall below the required threshold. By simplifying the SINR equations, the upper bound on transmit power by a transmitter of e-Health applications that active medical user/device x can tolerate ($P_A(x)$) can be obtained from (10), as shown at the bottom of this page, where $P_t(x)$ is the transmit power of the active medical transmitter x in watts. $D_x(x)$ is the distance between the transmitter and the receiver of active medical x in meters. $\gamma(x)$ and $N(x)$ are the SINR threshold and the background noise of the active medical receiver x in watts, respectively. $D_A(x)$ is the distance between the user and the active medical receiver x in meters. $L(d)$ is the total indoor propagation path loss that is given as $L(d)[\text{in dB}] = L(d_0)[\text{in dB}] + 10n_{\mathrm{SF}}\log(d/d_0) + \text{FAF}[\text{in dB}]$ [16], where d_0 is the reference distance, FAF is the average floor attenuation factor, and n_{SF} is the path-loss exponent for the same floor measurement. The RAC can retrieve the locations of the transmitter and receiver and SINR threshold of the active medical device x from the inventory system. $\sum_{\chi=1,\chi\neq x}^{X} \frac{P_t(\chi)}{L(D_\chi(x))}$ is the aggregate interference from other active wireless transmitters to the active receiver x, where X is the number of active wireless transmitters that simultaneously transmit data at a time slot. We assume that active medical devices do not interfere with passive medical devices.

2) *Passive medical devices*: The RF emission due to wireless transmissions should not cause the EM field to passive medical devices greater than their EMI immunity level. Let $P_{\mathrm{NLS}}(y)$ and $P_{\mathrm{LS}}(z)$ be the upper bound on transmit power by a transmitter that non-life-supporting device y and life-supporting device z can tolerate. $P_{\mathrm{NLS}}(y)$ and $P_{\mathrm{LS}}(z)$ can be obtained from

$$P_{NLS}(y) = \left(\frac{D_{\mathrm{NLS}}(y)\left(E_{\mathrm{NLS}}(y) - \frac{7\sum_{\chi=1}^{X}\sqrt{P_t(\chi)}}{D_\chi(x)}\right)}{7} \right)^2$$

$$P_{LS}(z) = \left(\frac{D_{\mathrm{LS}}(z)\left(E_{\mathrm{LS}}(z) - \frac{23\sum_{\chi=1}^{X}\sqrt{P_t(\chi)}}{D_\chi(x)}\right)}{23} \right)^2 \qquad (11)$$

Note that (11) [3] holds for the RF spectrum in the range of 800 MHz–2.5 GHz. This equation is calculated from the basic relationship between radiated power and electric field (i.e., $E = \sqrt{Z_0 P}/D$). The constant Z_0 comes from the free-space impedance, which has unit of ohms (Ω). D is the distance between the wireless transmitter and the medical device in meters. $D_{\mathrm{NLS}}(y)$ and $D_{\mathrm{LS}}(z)$ are the distances from the non-life-supporting device y to the user and from the life-supporting device z to the user, respectively. $E_{\mathrm{NLS}}(y)$ and $E_{\mathrm{LS}}(z)$ are the EMI immunity (i.e., the radiated RF immunity) levels of non-life-supporting device y and life-supporting device z, respectively. The EMI immunity level here is defined in terms of the electric field (measured in V/m) for which the medical devices can operate properly. Therefore, the aggregate transmit power

$$P_A(x) = L(D_A(x)) \left[\frac{P_t(x)}{L(D_x(x))\gamma(x)} - \sum_{\chi=1,\chi\neq x}^{X} \frac{P_t(\chi)}{L(D_\chi(x))} - N(x) \right] \qquad (10)$$

of the active medical devices and the wireless transmitter will not cause the EM energy to rise above the EMI immunity levels of the passive medical devices. Again, the RAC can retrieve these EMI immunity levels and locations of the passive medical devices from the inventory system.

The maximum transmit power for a user can be obtained by solving the following:

$$P_{\max} = \min\left\{ \min_x(P_A(x)), \min_y(P_{\rm NLS}(y)), \min_z(P_{\rm LS}(z))\right\}. \quad (12)$$

However, multiple users can transmit at the same time. In such a case, $P_{\rm ctrl}$ should be calculated by considering the aggregate transmit power when multiple users simultaneously transmit RTS messages on the control channel. Therefore, $P_{\rm ctrl}$ can be computed as follows:

$$P^H_{\rm ctrl} = \sum_{n_1=0}^{T_1-1} \binom{T_1-1}{n_1} \alpha_1^{n_1}(1-\alpha_1)^{(T_1-1-n_1)} \times \sum_{n_2=0}^{T_2} \binom{T_2}{n_2} \alpha_2^{n_2}(1-\alpha_2)^{(T_2-n_2)} \frac{P_{\max}}{n_1+n_2+1} \quad (13)$$

$$P^L_{\rm ctrl} = \sum_{n_1=0}^{T_1} \binom{T_1}{n_1} \alpha_1^{n_1}(1-\alpha_1)^{(T_1-n_1)} \times \sum_{n_2=0}^{T_2-1} \binom{T_2-1}{n_2} \alpha_2^{n_2}(1-\alpha_2)^{(T_2-1-n_2)} \frac{P_{\max}}{n_1+n_2+1} \quad (14)$$

where $P^H_{\rm ctrl}$ and $P^L_{\rm ctrl}$ denote $P_{\rm ctrl}$ of a high-priority and low-priority user, respectively. T_1 and T_2 are the total number of high-priority and low-priority users, respectively. α_1 and α_2 are the arrival probabilities of a high-priority and low-priority users at a certain time slot, respectively. Considering when a high-priority user is transmitting on the data channel, $T_1 - 1$ in (13) and T_1 in (14) will be replaced by $T_1 - 2$ and $T_1 - 1$, respectively, and $n_1 + n_2 + 1$ in both (13) and (14) can be substituted by $n_1 + n_2 + 2$. On the other hand, if a low-priority user is transmitting on the data channel, T_2 in (13) and $T_2 - 1$ in (14) will be replaced with $T_2 - 1$ and $T_2 - 2$, respectively, and $n_1 + n_2 + 1$ in both (13) and (14) will be replaced with $n_1 + n_2 + 2$.

APPENDIX B
DERIVATIONS OF θ_1 AND θ_2

θ_1 and θ_2 can be computed using (15) [19] and (16) [20], respectively, as follows:

$$\theta_1 = \frac{2}{W_1+1} \quad (15)$$

where W_1 is the constant backoff window size of high-priority users, and

$$\theta_2 = \frac{2}{W_2 P_{c2}\sum_{j=0}^{m-1}(2P_{c2})^j + W_2 + 1} \quad (16)$$

in which W_2 is the minimum backoff window size of low-priority users. Here m is the maximum backoff stage and P_{c2} is the collision probability of the low-priority users when transmitting RTS messages. P_{c2} can be computed as $P_{c2} = 1 - P_{\rm nc2}$, where $P_{\rm nc2}$ is the probability that the collision of low-priority users does not occur during an RTS time slot. $P_{\rm nc2}$ is obtained from

$$P_{\rm nc2} = \begin{cases} (n_2)\alpha_2(1-\alpha_2)^{n_2-1}(1-\theta_2)^{o_2}(1-\alpha_1)^{n_1}(1-\theta_1)^{o_1} \\ +(o_2)\theta_2(1-\theta_2)^{o_2-1}(1-\alpha_2)^{n_2}(1-\alpha_1)^{n_1}(1-\theta_1)^{o_1} \\ +(1-\alpha_2)^{n_2}(1-\theta_2)^{o_2} \end{cases} \quad (17)$$

where o_1 and o_2 are the number of high-priority and low-priority users in the orbits, respectively. n_1 and n_2 are the number of high-priority and low-priority users remaining in the control channel (i.e., not including the users waiting in the orbit and in the data channel), respectively. The first and the second terms denote, respectively, the probabilities that a low-priority user remaining in the control channel and in the orbit successfully transmits an RTS message. The last term is the probability that there is no RTS transmission of low-priority users.

APPENDIX C
THE STATE SPACE OF DTMC AND STRUCTURE OF STATIONARY PROBABILITY VECTOR

The state space of DTMC is given by $\mathcal{S} = \{(k,j,i,h,g,f), k = 0,1,2,\ldots,T_1, j = 0,1,2,\ldots,N, i = 0,1,2,\ldots,B_1, h = 0,1,2,\ldots,B_2, g = 0,1,2, f = 0,1,2,3,4\}$. Here, k represents the number of high-priority users in the orbit, which is limited by the total number of high-priority users in the system T_1. Also, j represents the number of low-priority users in the orbit, which is limited to N. i and h refer to the number of transmission requests waiting in the high-priority and low-priority buffers, respectively, plus one in service. i and h are limited by $B1$ and $B2$. g represents the status of the server on the data channel for $g = 0$ referring to the idle server (i.e., the buffers are empty), $g = 1$ referring to that a high-priority user is transmitting/receiving, and $g = 2$ referring to that a low-priority user is transmitting/receiving (i.e., there is no transmission request in the high-priority buffer). f represents the status of the server on the control channel, where $f = 0$ refers to the idle server, $f = 1$ refers to that an RTS of a high-priority user is transmitting, $f = 2$ refers to that an RTS of a low-priority user is transmitting, $f = 3$ refers to that a CTS of a high-priority is transmitting, and $f = 4$ refers to that a CTS of a low-priority user is transmitting.

The stationary probability vector π is partitioned as follows:

$$\begin{aligned} \pi &= [\pi_0 \cdots \pi_k \cdots \pi_{T_1}] \\ \pi_k &= [\pi_k^{(0)} \cdots \pi_k^{(j)} \cdots \pi_k^{(N)}] \\ \pi_k^{(j)} &= [\pi_k^{(j,0)} \cdots \pi_k^{(j,i)} \cdots \pi_k^{(j,B_1)}] \\ \pi_k^{(j,i)} &= [\pi_k^{(j,i,0)} \cdots \pi_k^{(j,i,h)} \cdots \pi_k^{(j,i,B_2)}] \\ \pi_k^{(j,0,0)} &= [\pi_k^{(j,0,0,0)}], \qquad h = 0; i = 0 \end{aligned}$$

$$\pi_k^{(j,0,h)} = [\pi_k^{(j,0,h,2)}], \qquad h > 0; i = 0$$
$$\pi_k^{(j,i,h)} = [\pi_k^{(j,i,h,1)}], \qquad h \geq 0; i > 0$$
$$\pi_k^{(j,i,h,g)} = [\pi_k^{(j,i,h,g,0)} \pi_k^{(j,i,h,g,1)} \pi_k^{(j,i,h,g,2)} \pi_k^{(j,i,h,g,3)} \pi_k^{(j,i,h,g,4)}]$$

where $k \in \{0, 1, \ldots, T_1\}$, $j \in \{0, 1, \ldots, N\}$, $i \in \{0, 1, \ldots, B_1\}$, $h \in \{0, 1, \ldots, B_2\}$, and $g \in \{0, 1, 2\}$. By partitioning π in this manner, each element of π can be mapped to each state in the state space $\mathcal{S}$.

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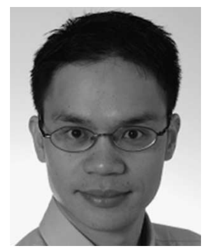

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