A COGNITIVE RADIO SYSTEM FOR E-HEALTH APPLICATIONS IN A HOSPITAL ENVIRONMENT

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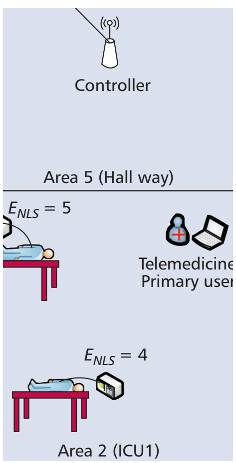

The authors introduce a novel cognitive radio-based approach to address the challenges in wireless communications for e-Health applications in a hospital environment.

ABSTRACT

Wireless communications technologies are used to support a variety of electronic health applications to transfer medical data and patient information. However, using wireless communications technology in a healthcare environment poses two major challenges. First, the electromagnetic interference caused to bio-medical devices by wireless devices could critically affect their performance. Second, since different types of e-health applications have different priorities, access to the wireless channel by the corresponding devices needs to be prioritized. In this article we introduce a novel cognitive-radio-based approach to address these challenges in wireless communications for e-health applications in a hospital environment. First, the requirements for a wireless communications system to be used in a healthcare environment are identified, and potential applications of cognitive radio technology for e-health applications are discussed. Then a cognitive radio system is proposed for e-health applications in a hospital environment, which protects the medical devices from harmful interference by adapting the transmit power of wireless devices based on EMI constraints. An EMI-aware handshaking protocol is proposed for channel access by two different types of applications with different priorities. The performance of this cognitive radio system for e-health applications is evaluated through simulations.

INTRODUCTION

Electronic health (e-health) integrates information processing and communications technologies for provisioning healthcare services. Wireless communication is a key technology to improve mobility and service flexibility for different e-health applications such as remote patient monitoring, telemedicine, and mobile hospital information system applications [1]. However, many medical devices are sensitive to electromagnetic interference (EMI) [2] caused by wireless transmissions. The interference can result in malfunctioning of medical devices (e.g., automatic shutdown, automatic restart, waveform distortion, and howling), which can potentially be harmful to patients using healthcare services. Therefore, wireless communications systems to be used for e-health applications, especially in healthcare centers such as hospitals or clinics, have to be carefully designed to avoid this EMI problem. Cognitive radio, which is implemented based on software-defined radio, has recently emerged as a promising technique to improve the efficiency of wireless communications by increasing the radio spectrum utilization and reducing unintended interference. A cognitive radio transceiver can observe and learn the status of the operating environment, make a decision, and adapt the wireless transmission parameters accordingly. The cognitive radio concept can be applied to the wireless communications for e-health applications by taking the stringent constraints on EMI to medical devices [3] and different quality of service (QoS) requirements of various e-health applications into account. The concept of an *illuminating network* was proposed to reduce the EMI problem in a healthcare environment [4]. This network uses high brightness light-emitting diodes as the carrier instead of radio frequency. However, the usability of this system is limited due to the use of light as the carrier, which is easily obstructed by the objects in the ambient environment.

This article deals with the problem of designing a wireless communications system for e-health applications based on the concept of cognitive radio. First, an overview of the requirements and challenges in using wireless communications for e-health applications is presented. The potential advantages of using cognitive radio for e-health applications are discussed. Then a cognitive radio system is proposed for wireless communications in a hospital environment. This system is designed to avoid harmful EMI caused to medical devices, which are considered to be *protected users* and at the same time to guarantee quality of service (QoS) for different e-health applications such as telemedicine and hospital information system applications. Telemedicine applications provide healthcare service delivery to distant users, whereas hospital information system applications provide storage, retrieval, and processing of medical records for medical users. Telemedicine

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applications are sensitive to both packet delay and packet loss while hospital information system applications are sensitive to packet loss only. Since telemedicine applications have higher priority, they can be considered *primary users*, while lower-priority hospital information system applications can be considered *secondary users*. A channel access mechanism is designed for this cognitive radio system that exploits information about the EMI tolerance of bio-medical devices to determine safe transmission parameters for wireless devices that comply with the EMI constraints.

E-HEALTH APPLICATIONS AND COGNITIVE RADIO SYSTEMS

REQUIREMENTS FOR WIRELESS COMMUNICATIONS SYSTEMS USED IN E-HEALTH APPLICATIONS

Electromagnetic Compatibility and EMI Requirement — Many medical devices in healthcare environment are sensitive to EMI. Therefore, all wireless communication systems to be used in e-health applications need to satisfy the electromagnetic compatibility (EMC) requirement. For example, the wireless devices used in e-health applications must limit the transmit power to avoid harmful interference to medical devices in their vicinity. In this case the transmission parameters of the wireless devices (e.g., frequency and transmit power) can be determined from the IEC 60601-1-2 standard [3], which describes the EMI immunity levels of medical devices.

QoS Provisioning for E-Health Applications — E-health applications can be classified into four classes based on their communications requirements: real-time critical applications, real-time non-critical applications, remote control applications, and office/support applications [5]. Loss and delay are two major communication QoS performance measures for these applications. For example, a cardiac patient could be continuously monitored through a real-time patient monitoring application. If the transmission of critical physiological data is delayed, the patient may not receive prompt aid when an abnormal condition arises. IEEE 802.11e is one wireless technology that has been adopted in e-health applications with QoS support [6]. IEEE 802.11e provides different privileges for channel access by fixing different backoff window sizes to different classes of applications.

Coexistence of Different Wireless Technologies for E-Health Applications — Several wireless technologies are used in the same area (e.g., in the hospital). For example, IEEE 802.11-based wireless LAN (WLAN) and IEEE 802.15.4a/ultra-wideband (UWB)-based wireless personal area network (WPAN) technologies can be used for e-health applications with high bandwidth requirements, (e.g., telemedicine and hospital information system applications). Bluetooth and ZigBee can be used in body area sensor networks for patient monitoring and physical rehabilitation applications. Many of these technologies operate on the same or overlapping frequency bands (e.g., IEEE 802.11b/g, Bluetooth, and ZigBee use the 2.4 GHz industrial, scientific, and medical [ISM] band); therefore, interference and spectrum access management are crucial issues [5].

Seamless Connectivity — Wireless communications can greatly improve the mobility of e-health applications. The biosignal data can be continuously monitored when the patient is mobile. The mobile medical staff should be able to access different healthcare and patient monitoring applications in an online manner. To support seamless service and achieve better performance for e-health applications, mobility management (i.e., roaming and handoff) is necessary.

Security of Healthcare Data — Healthcare data (including patient data, service data, and facility data) is security-sensitive. The system should have zero tolerance for unauthorized eavesdropping and intrusion. Therefore, strong authentication and encryption mechanisms are required for e-health applications. For example, in a WLAN, IEEE 802.11i-based key distribution and 802.1x-based authentication methods can be used [6].

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COGNITIVE RADIO FOR E-HEALTH APPLICATIONS

In a *horizontal spectrum sharing* scenario (e.g., radio access in the unlicensed band) cognitive radio techniques can be used for efficient coexistence of the different users/applications and thereby improve the utilization of the radio spectrum. On the other hand, in a *vertical spectrum sharing* scenario (e.g., radio access in the licensed band), cognitive radio techniques can be used by the secondary users to opportunistically access the radio spectrum licensed to the primary users and thereby achieve better utilization of the wireless communications systems [7]. Cognitive-radio-based wireless communication can be used in emergency networks designed for disaster situations [8]. The cognitive radio system identifies underutilized spectrum channels and adapts the transmission of multimedia data accordingly. In a cognitive radio system designed for e-health applications, spectrum access by secondary users (or low-priority users) should consider not only the presence of primary users (or high-priority users), but also the presence of protected users. The protected users are the medical devices, which are sensitive to interference caused by wireless transmission. These medical devices can be passive and active. Passive medical devices include incubators, infusion pumps, anesthesia machines, and defibrillators. These devices do not transmit any wireless signal, but their electronic components are sensitive to EMI. Active medical devices can transmit data using wireless signal (e.g., telemetry monitors, wireless holter monitors, and wireless electrocardiograph [ECG] monitors). The transmission of these active medical devices can be interfered with by wireless transmissions by other non-medical devices.

The Federal Communications Commission (FCC) has specified two wireless services for medical applications:

- *Wireless medical telemetry service* (WMTS) is used for remotely monitoring vital signs of a patient (e.g., blood pressure, body tempera-

There exist several electronic medical equipments such as infusion pumps, ECG monitors, and EMG monitors, operating in ICUs for different patients. Therefore, to avoid interference to the medical devices in ICUs, the wireless transmission parameters must be carefully chosen.

ture, and heart rate) from the external human body. The FCC allocated 14 MHz of spectrum bands (e.g., 608–614 MHz, 1395–1400 MHz, and 1427–1432 MHz) for licensed healthcare staff (e.g., physicians and supervised technicians).

- *Medical implant communications service* (MICS) is used for remotely monitoring vital signals from inside the human body. For example, heart conditions of a patient are transmitted by cardiac pacemakers and implanted defibrillators. The 402–405 MHz spectrum bands are reserved for this wireless service.

A cognitive radio system for e-health applications can operate on either unlicensed or licensed bands.

Cognitive Radio for E-Health Applications on Unlicensed Bands — Since every user has the same right to access the radio spectrum in this case, a secondary user does not need to be aware of the presence (i.e., activity) of primary users. However, the EMI constraints of the protected users/applications still exist. Also, prioritization among different users/applications would be required for channel access to achieve service differentiation. With an ability to observe, learn, and access spectrum dynamically, a cognitive radio system can support spectrum access with QoS differentiation among different healthcare applications with protection to the medical devices. Either a spectrum overlay or spectrum underlay approach can be used for channel access [7]. The details of such a cognitive radio system are presented in the next section.

The work in [9] proposed the use of the cognitive radio concept to reduce EM exposure, which may cause potential risks for public health. One scenario considered in this work is the use of a base station to obtain the spectrum occupancy information and make a decision on the optimal spectrum access policy in order to reduce electromagnetic radiation. However, QoS differentiation was not supported in this system.

In [10] a group-based medium access control (MAC) protocol was proposed for QoS provisioning in cognitive radio networks. Secondary users are grouped, and each group dynamically shares spectrum to guarantee bandwidth requirements for members in a dynamic environment. Another QoS provisioning algorithm for cognitive radio systems was proposed in [11] where a base station controls spectrum access to provide QoS guarantees (i.e., delay and throughput) for real-time applications. However, the above QoS framework is not applicable to e-health applications since the EMI constraint of medical devices was not taken into account.

Cognitive Radio for E-Health Applications on Licensed Bands — For a cognitive radio system operating in the licensed spectrum bands (e.g., WMTS and MICS bands), secondary users must be aware of primary users and opportunistically share the spectrum in a noninterfering manner. In the healthcare environment a cognitive radio user must observe the status of both active and passive medical devices.

A cognitive radio system for e-health applications can be deployed in different locations, such as intensive care units (ICUs) in a hospital. There are several e-health applications such as patient monitoring systems, telemedicine for remote consultation among physicians, hospital information systems for retrieving patients' data, and remote medical assets tracking systems to locate medical devices. Each service uses different wireless technologies (e.g., Bluetooth wireless sensors in patient monitoring systems and WLAN for telemedicine and hospital information system applications). In addition, there are several types of electronic medical equipment such as infusion pumps, ECG monitors, and electromyography (EMG) monitors operating in ICUs for different patients. Therefore, to avoid interference with the medical devices in ICUs, the wireless transmission parameters must be carefully chosen.

A Cognitive Radio System for E-Health Applications

This section describes a cognitive radio system for e-health applications. The objectives of this cognitive radio system are to avoid harmful EMI to the medical devices and provide QoS differentiation to the different e-health applications. We consider two e-health applications: real-time non-critical telemedicine and a hospital information system. Telemedicine applications include remote consultation, remote diagnosis, and patient information transfers, which are delay- and loss-sensitive. On the other hand, hospital information system applications collect medical data such as patient data, technical data, and facility data, to be processed and presented to medical staff, and stored in a database.

Architecture of the Cognitive Radio System for E-Health Applications

The proposed cognitive radio system consists of three components: an inventory system, the cognitive radio controller, and cognitive radio clients, as shown in Fig. 1. The inventory system maintains information about all medical devices in the hospital (e.g., location, activity status, and EMI immunity level). The inventory system can be supported by an effective tracking system to maintain location information of active and passive medical devices and wireless e-health devices in a hospital environment. For example, a tracking system based on RFID technology [12] can be used. In this case RFID tags are attached to the devices. RFID readers are installed throughout the hospital. As the devices are moved around the hospital, the RFID readers can communicate with the RFID tags to identify the locations of the medical devices. Subsequently, this location information is sent to the inventory system.

The cognitive radio system operates using a common control channel and a data channel, both of which are in the unlicensed spectrum band, and an interference avoidance approach (i.e., spectrum overlay) is used for wireless access. To provide QoS differentiation, the telemedicine application is treated as the prima-

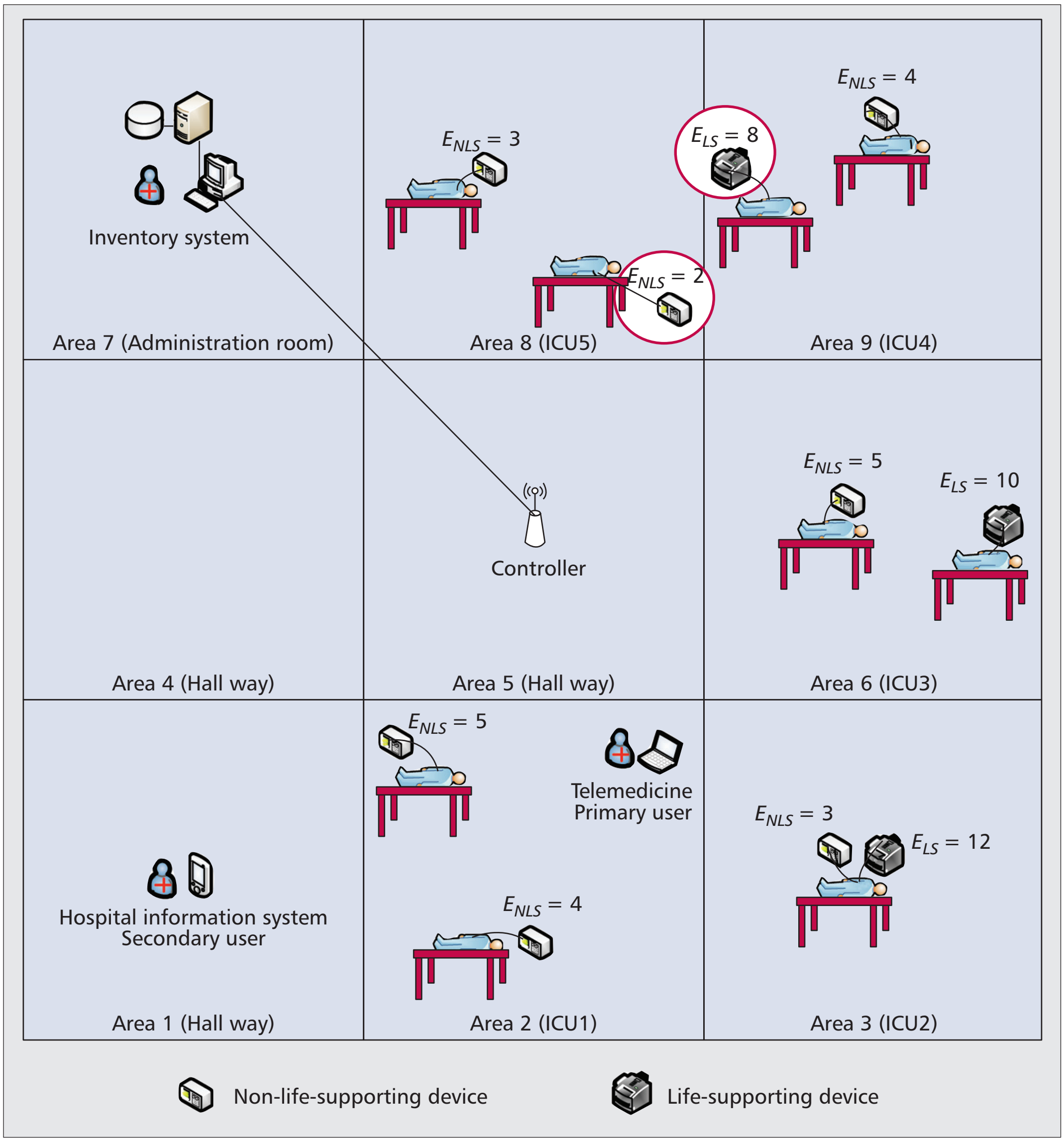

Figure 1. *A cognitive radio system in a hospital environment.*

The controller can transmit/receive data from both channels simultaneously. On the other hand, the cognitive radio client has one radio interface, which can transmit and receive either in control channel or data channel (i.e., one channel at a time).

ry user, which has higher priority to access the channel, while the hospital information system application is treated as the secondary user. The transmission parameters of the cognitive radio clients for wireless access are controlled by the cognitive radio controller.

Under this infrastructure-based cognitive radio system model, every cognitive radio client transmits its data through the cognitive controller. The controller uses the information about the medical devices from the inventory system to compute the appropriate transmission parameters (i.e., transmit power) on the data channel for primary and secondary users. The controller can control the transmit power of a cognitive radio client using an EMI-aware request to send/clear to send (RTS/CTS) protocol. The detail of this protocol is described later. The cognitive radio controller uses two radio interfaces, one for the control channel and the other for the data channel. The controller can transmit/receive data from both channels simultaneously. On the other hand, the cognitive radio client has one radio interface, which can transmit and receive in either the control channel or data channel (i.e., one channel at a time).

Channel Allocation and Access

In this cognitive radio system the primary user has higher priority to access the data channel, while the secondary user can access only when the data channel is not occupied by the primary user. The transmissions from both primary and secondary users must satisfy the EMI constraints of the protected users. A time slotted RTS/CTS-based channel access mechanism is used by the primary and secondary users, which consists of two steps: common control broadcasting and EMI-aware RTS/CTS protocol. The flowchart of this channel access scheme is shown in Fig. 2.

Common Control Channel Broadcasting — Common control channel broadcasting is used to broadcast information about P_{ctrl}, that is, the maximum transmit power for transmitting the RTS message by a cognitive radio client on the control channel without any harmful interference to

Two queues are used at the controller to store the requests from primary and secondary users separately. The sizes of these queues are finite. If the transmission queue is full, the user's request will be dropped which is considered to be a collision from user's perspective.

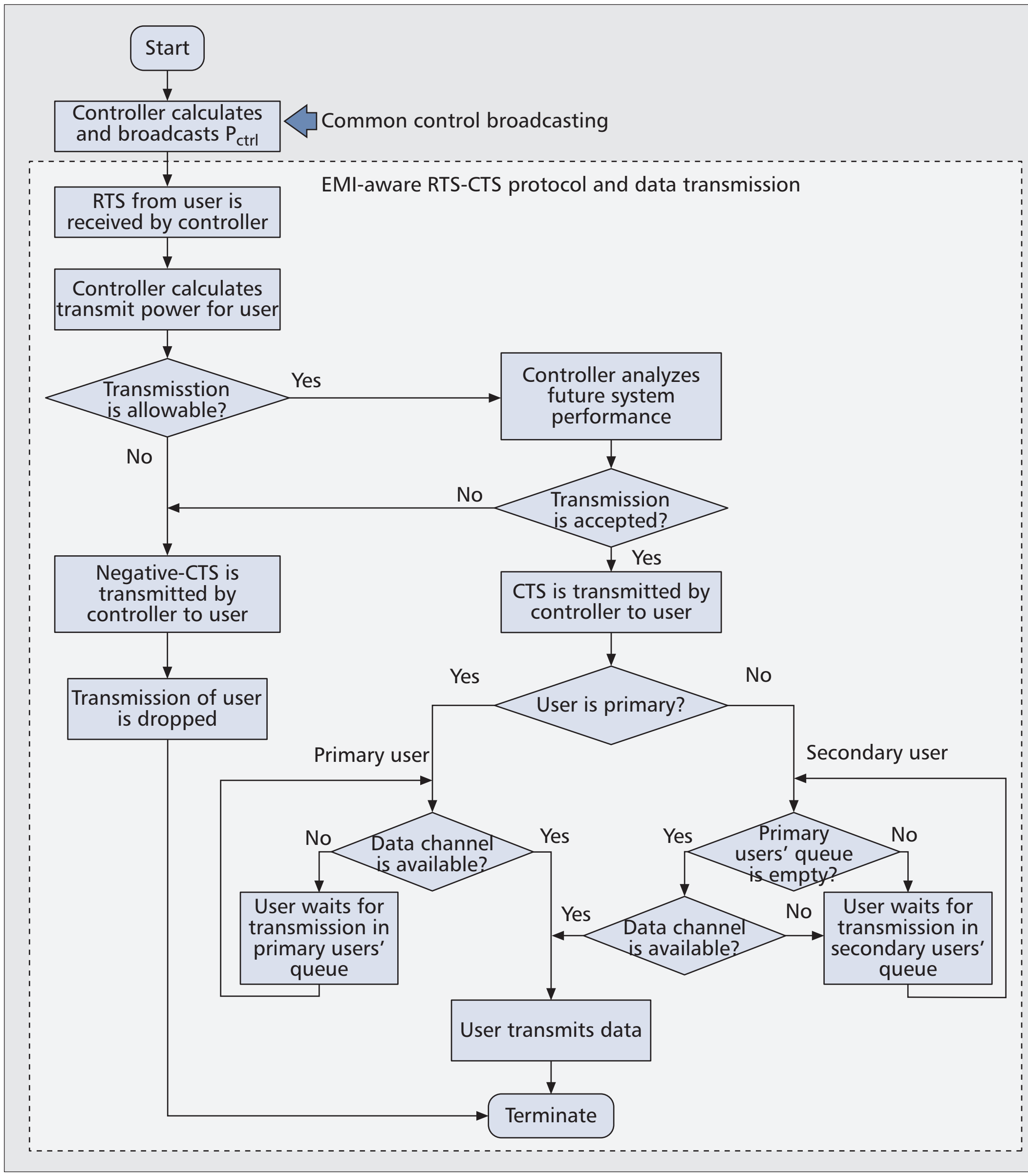

Figure 2. *Flowchart of the channel access mechanism.*

any medical device. Each user has different P_{ctrl} depending on the location of the user. The value of P_{ctrl} can be obtained from $P_{ctrl} = \min\{\min_n (P_{NLS}(n)), \min_m (P_{LS}(m))\}$, where $P_{NLS}(n)$ and $P_{LS}(m)$ are the upper bound on transmit powers corresponding to non-life-supporting medical device n (e.g., infusion pump, electrocardiograph monitor, and electroencephalograph monitor) and life-supporting device m (e.g., incubator, defibrillator), respectively. For radio frequency in the range of 800 MHz–2.5 GHz, these transmit powers can be obtained from [3]

$$P_{NLS}(n) = \left(\frac{D_{NLS}(n)E_{NLS}(n)}{7}\right)^2, \qquad (1)$$
$$P_{LS}(m) = \left(\frac{D_{LS}(m)E_{LS}(m)}{23}\right)^2,$$

where $D_{NLS}(n)$ and $D_{LS}(m)$ are the distances from the user to non-life-supporting device n and from the user to life-supporting device m, respectively. $E_{NLS}(n)$ and $E_{LS}(m)$ are the EMI immunity levels for non-life-supporting device n and life-supporting device m, respectively. The EMI immunity level here is defined in terms of the electric field (measured in volts per meter) in which the medical devices can operate normally. This equation is calculated from the basic relationship between radiated power and electric field (i.e., $E = k\sqrt{P}/D$). The constant k^2 is the free space impedance, which has units of ohms. Again, D is the distance between the medical device and the wireless transmitter. The controller can retrieve this information about EMI immunity levels for the different medical devices from the inventory system.

Since the status of medical devices (e.g., whether they are turned on or off) and locations of cognitive clients can change dynamically, P_{ctrl} is computed and broadcast periodically every t_p

time slots on the control channel. t_p can also be adjusted dynamically according to the on-off periods of the medical devices. In this case the value of t_p is the minimum duration fthat the medical devices are in on or off state. t_p is also broadcast to every user along with P_{ctrl}. Therefore, every user can determine the transmission slot and transmit power accurately. During broadcasting of P_{ctrl}, all transmissions of users in both control and transmission channels have to be paused to synchronize with the controller.

EMI-Aware RTS/CTS Protocol — The EMI-aware RTS/CTS protocol for data transmission by a client node works as follows (Fig. 2). Before transmitting data, the client node (i.e., primary or secondary user) transmits an RTS message to the controller on the control channel. If a collision occurs, the primary users will wait for a random time based on a constant backoff window, while the secondary users will wait for a random time based on exponential backoff. In this case the primary and secondary users are said to be in the imaginary orbit. A primary user in the orbit retransmits the RTS message again with probability α_1, and a secondary user will retry with probability α_2. These probabilities α_1 and α_2 can be obtained from the backoff window sizes and the maximum backoff stage of secondary users as in [13, 14], respectively. The maximum size of orbit for secondary users is limited, while that of primary users is infinite.

Upon receiving the RTS message, the controller calculates the maximum allowable transmit power for the client on the data channel in the same way as that of P_{ctrl}. If the controller cannot find a feasible transmit power that satisfies the minimum QoS requirements (i.e., minimum data rate) of the user and the EMI constraint of the medical devices, the request for data transmission from the user will be dropped. Also, to avoid congestion, the controller will randomly drop a request with some probabilities. The transmissions of primary and secondary users can be dropped with P_{d1} and P_{d2}, respectively. When the transmission of the user is dropped, a negative-CTS message is sent by the controller. The user will wait for a random number of time slots and then retransmit the RTS message. If the request from a user is not dropped, a CTS message is sent to the user.

Similar to IEEE 802.11, at the beginning of an RTS time slot, each user will wait until the common control channel is sensed idle for a distributed interframe space (DIFS) period before transmitting an RTS message. Once the controller successfully receives an RTS message, the controller immediately transmits a CTS message to the user after a short interframe space (SIFS) period during the CTS time slot. Since the SIFS period is shorter than the DIFS period, all users can detect whether a certain time slot is used for transmitting the CTS message or not. Note that this mechanism is similar to the carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

Data Transmission and Queue Management — If the CTS message is successfully received by the user, the user will wait in the transmission queue at the controller. In this step the user will switch its radio from the common control channel to the data channel. The user waits in the data channel until the controller transmits a message to allow the user to transmit data if the data channel is free.

Two queues are used at the controller to store requests from primary and secondary users separately. The sizes of these queues are finite. If the transmission queue is full (e.g., there are many users requesting to transmit data), the user's request will be dropped, which is considered to be a collision from the user's perspective.

Primary users always have higher priority to transmit data in the data channel. Therefore, the controller always allows the primary user to transmit first if its request is in the transmission queue. Secondary users have to wait in the transmission queue until there are no requests of primary users in the transmission queue. The number of time slots for data transmission is assumed to be geometrically distributed with parameters β_1 and β_2 for primary user and secondary user, respectively.

Numerical Results

Performance of the EMI-Aware RTS/CTS Protocol — The performance of the EMI-aware RTS/CTS protocol is evaluated by simulations using MATLAB. We consider a service area over 27 m^2 with five ICU rooms, one administration room, and a hallway in a hospital. The service area is divided into nine areas, as shown in Fig. 1. A controller is located at the center of the service area. There are three life-supporting medical devices, seven non-life-supporting medical devices, and one wireless transmitter for the hospital information system application (i.e., a cognitive radio client). The locations of the controller and medical devices are fixed, while those of the wireless transmitters are uniformly random. The transmit power is attenuated due to indoor propagation path loss and floor attenuation factors. The wireless transmitter operates in 2.4 GHz. The floor attenuation factor is 16.2 dB [15], the measured line-of-sight (LOS) path loss at d_0 = 1 m is 37.7 dB, and the obstructed path loss exponent is 3.3 [16].

We study two performance measures, the *outage probability* and *interference probability*. The outage probability is the probability that the received signal strength at the controller is less than –65 dBm, which is the minimum level for the controller to decode signal correctly. The interference probability indicates the chance that the wireless device causes interference to the medical devices. The interference occurs when the actual transmit power is higher than the acceptable level. For the EMI-aware RTS/CTS protocol, interference occurs when the on status of medical devices is incorrectly reported to the controller. We assume that the *probability of misdetection* is 0.01. The EMI immunity levels of the medical devices are also shown in Fig. 1. Compared to the non-life-upporting devices, the life-supporting medical devices are more sensitive to EMI. Therefore, the life-supporting medical devices are built to tolerate higher EMI levels than non-life-supporting devices.

Figure 3 shows the interference probability

Compared to the non-life supporting devices, the life-supporting medical devices are more sensitive to EMI. Therefore, the life-supporting medical devices are built to tolerate higher EMI level than that of non-life supporting devices.

over nine areas. As expected, the interference probability of the proposed EMI-aware RTS/CTS protocol is always less than the traditional CSMA/CA protocol. The traditional protocol can cause severe interference to the medical devices, especially in areas 8 and 9 since the medical devices in these areas have low EMI immunity levels. The EMI-aware RTS/CTS protocol can decrease the interference probability 99.98 percent over the traditional protocol.

However, the outage probability of the EMI-aware RTS/CTS protocol in most areas is greater than the traditional protocol (Fig. 4). Since the EMI-aware RTS/CTS protocol limits the transmit power to avoid interference to the medical devices in the vicinity, the transmit power of the cognitive radio client in the areas with medical devices (i.e., areas 2, 3, 6, 8, and 9) is less than the receive sensitivity. However, in areas 1 and 7, the EMI-aware RTS/CTS protocol can adaptively increase the transmit power, since there is no medical device in these areas. Consequently, the outage probability of the EMI-aware RTS/CTS protocol in these areas is less than the traditional protocol.

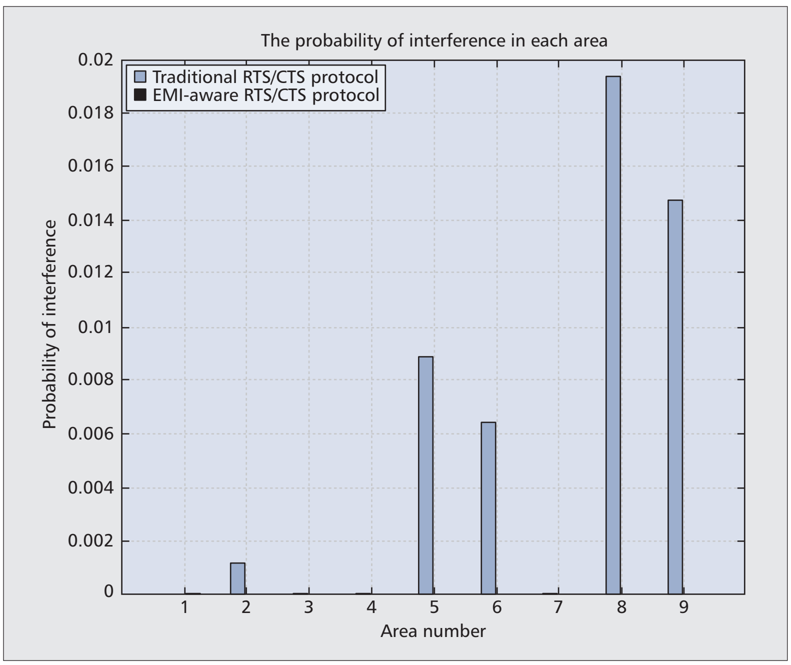

Figure 3. *Interference probability over nine areas.*

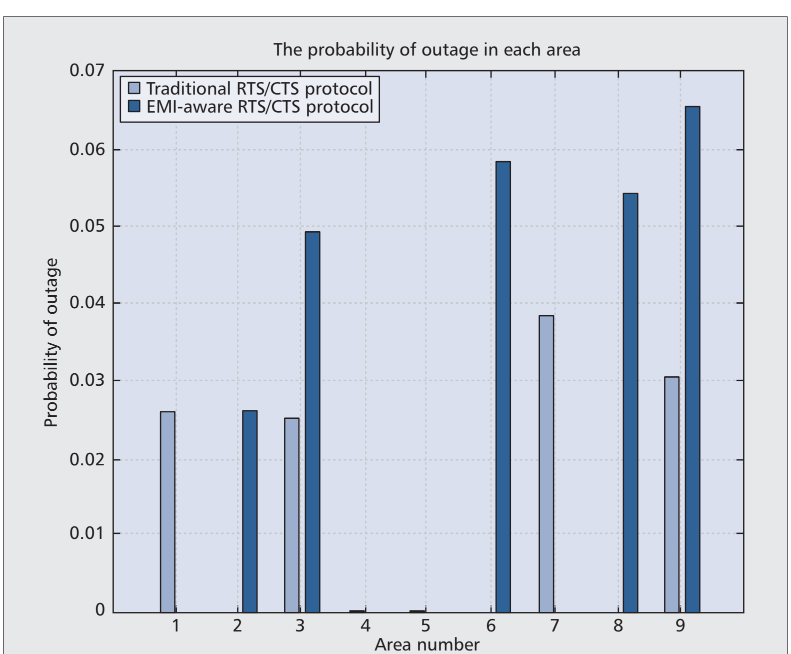

Figure 4. *Outage probability over nine areas.*

Performances of Primary and Secondary Users — We investigate the performance of the primary and secondary users using a simulation. Two e-health applications are considered, telemedicine and hospital information system applications. Telemedicine applications require average transmission delay less than 250 ms [5]. Cognitive wireless devices using telemedicine applications are defined as primary users, while devices using hospital information system applications are secondary users. Both primary and secondary users have backoff window sizes of 16. The maximum backoff stage of secondary users is 5. The maximum size of secondary orbit is 3. The maximum size of the queue for primary and secondary users is 3. The length of a time slot is 30 ms. The simulation is run until the number of either primary or secondary users is greater than 2000 users. We then collect and average the performance measures for ten simulation runs.

We study two performance matrices, the *average transmission delay* of data transmission by the primary users and the *loss probability* for the secondary users. The average transmission delay accounts for the time from when a primary user transmits an RTS message to when the corresponding data is successfully transmitted. Therefore, the average delay is the sum of waiting time in the orbit plus RTS/CTS service time and the waiting time in the queue until the transmission is finished. The loss probability is determined as the probability that the orbit is full, since the data transmission request from secondary user will be dropped.

Specifically, β_1 and β_2 are the probabilities that primary and secondary users finish their transmissions in a certain time slot (e.g., $\beta_1 = 0.3$ and $\beta_2 = 0.2$, respectively). The impacts of P_{d1} and P_{d2} (i.e., the probabilities that the controller randomly drops request of primary and secondary users to avoid EMI and congestion) on the average transmission delay of primary users are shown in Fig. 5. Note that P_{d1} is fixed at 0.5 while P_{d2} is varied. Alternatively, P_{d2} is fixed at 0.7 while P_{d1} is varied. As expected, the average transmission delay decreases as P_{d1} increases. As P_{d1} increases, the average number of requests from primary users in the queue decreases. Similarly, when P_{d2} increases, the probability that the queue for the request from a secondary user is full decreases. As P_{d2} decreases, the primary users also have more opportunity to transmit data. Consequently, the average delay decreases.

The effects of P_{d1} and P_{d2} on the loss probability of secondary users are shown in Fig. 6. When P_{d1} increases, the number of requests from primary users in the queue decreases. Therefore, there is a higher probability that the request from a secondary user is transmitted, and the probability that the queue and orbit of secondary users are full is smaller. The loss probability decreases as P_{d1} increases. Similarly, as P_{d2} increases, the probability that the queue of secondary users is full decreases. In this case the secondary users in the orbit have higher probability to transmit their data, and thus the number of secondary users in the orbit decreases. Therefore, when P_{d2} increases, the loss probability decreases.

Based on the above results, the cognitive radio controller can optimize the system performance by predicting future channel occupancy. Consequently, the spectrum access decision can be made adaptively and optimally. For example, the controller can learn and predict the activity of both primary and secondary users on the data channel (e.g., the probability of finishing data transmission β_1 and β_2. If β_1 decreases, the primary users will occupy the channel longer. Consequently, the average transmission delay of primary users and the loss probability of secondary users will increase, which may violate the QoS requirements. In this case the controller can control the channel access by increasing the dropping probability P_{d1} and P_{d2} so that the average delay and loss probability can be maintained below the target levels.

Conclusion

We have proposed a cognitive radio system for e-health applications. This system considers the issues of EMI to medical devices and QoS differentiation, which are crucial in healthcare environment. The *cognitive* capability of the system arises due to its EMI awareness to control the wireless access parameters in order to achieve the desired QoS differentiation among different users/applications. Two e-health applications, telemedicine and a hospital information system, have been considered in this cognitive radio system. Performance evaluation results show that the proposed scheme protects the bio-medical devices from harmful EMI and also achieves service differentiation among different e-health applications. The performance (i.e., delay and loss probability) of the cognitive radio system can be improved by incorporating multiple data channels. Therefore, a multichannel and multiradio wireless access protocol will be required. Also, instead of a prioritized first-in first-out queuing policy, an optimal scheduling algorithm can be developed for the cognitive radio controller. In addition, an admission control algorithm can be used to limit the number of secondary users in the system. This admission control algorithm can be jointly designed with a transmit power control method to achieve the optimal system performance.

Acknowledgments

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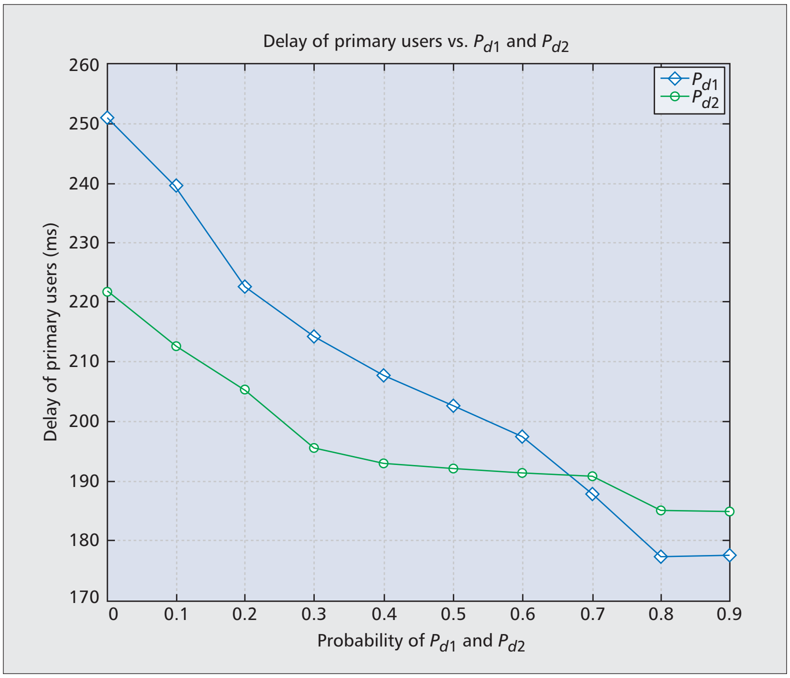

Figure 5. *Effects of* P_{d1} *and* P_{d2} *on the average transmission delay of primary users.*

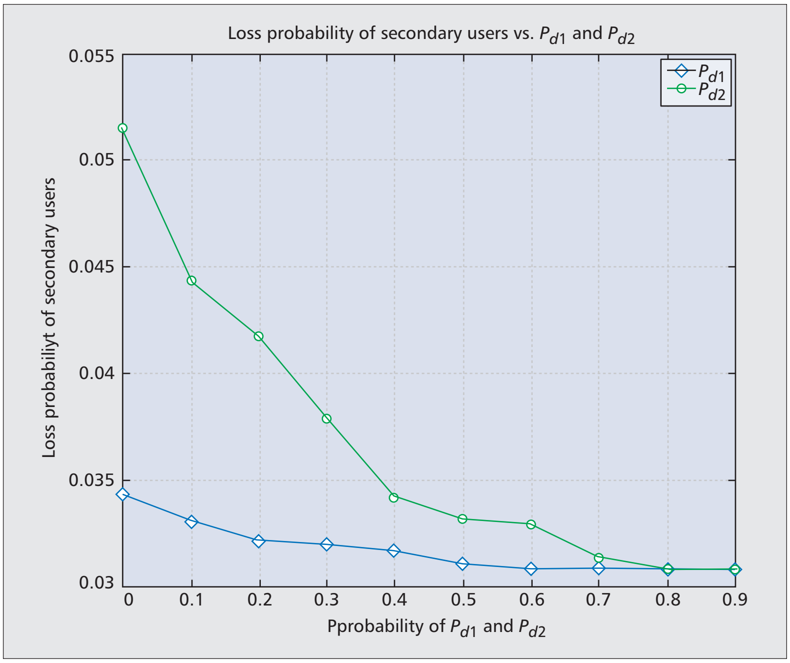

Figure 6. *Effects of* P_{d1} *and* P_{d2} *on the loss probability of secondary users.*

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