TRANSFORMING HEALTHCARE AND MEDICAL TELEMETRY THROUGH COGNITIVE RADIO NETWORKS

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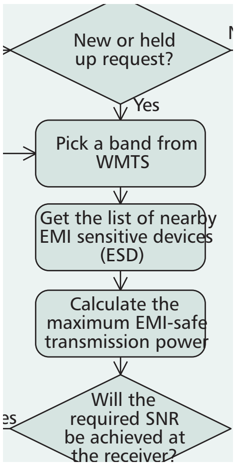

The authors propose the use of cognitive radio technology to dynamically utilize the WMTS frequencies based on the activity patterns of the high priority users, and the quality of service constraints of the patients' data, while ensuring protection and the safe operation of sensitive medical equipment.

ABSTRACT

The Wireless Medical Telemetry Services (WMTS) band has been established by the FCC in the United States for transmission of data related to a patient's health, and similar reserved channels exist for life-critical communications throughout the world. However, transmissions in the WMTS band are severely hampered by interferences from adjacent digital television channels, and due to non-uniform access priority, as this band is also shared by utility telemetry and government installations. In this article, we propose the use of cognitive radio technology to dynamically utilize the WMTS frequencies based on the activity patterns of the high priority users, and the quality of service constraints of the patients' data, while ensuring protection to existing higher priority transmissions and the safe operation of sensitive medical equipment. The priority users here are utility telemetry transmissions in certain portions of the WMTS band, government run radar sites, and legacy medical telemetry equipment without cognitive radio capability. We provide the first measurements on the complete WMTS spectrum activity at two major hospital locations in the Boston area, and outline an optimization framework that assigns frequency and transmission power jointly in this setting. The article also discusses the current state of the art and the major challenges in the implementation of this new cognitive radio assisted medical telemetry paradigm.

INTRODUCTION

Healthcare is facing increasing costs in the United States, with one of the contributing factors being infrastructure investment. Hospital spending by itself is projected to accelerate nearly 7.3 percent by 2019. However, projected benefits from information technology and networking alone may touch US$81 billion annually [1], giving further impetus for modernizing the data networks that carry digital patient information. Wiring all devices to transport this patient data has been a rather simplistic solution, and the situation has been described as *"patients becoming trapped in a sheer impenetrable net of wires and tubes, often resembling a spaghetti"* [2].

Since June 2000, the FCC has reserved wireless spectrum for medical telemetry in the:
- Current digital television (DTV) channel 37 between 608–614 MHz
- Lower-*L* band (1395–1400 MHz)
- Upper-*L* band (1427–1432 MHz)

together referred to as the Wireless Medical Telemetry Services (WMTS) band [3], as shown in Fig. 1.

Unfortunately, however, the same ruling raises several concerns of interference, access priority of medical devices, and limitations on multimedia transmission.

In this article, we propose cognitive radio (CR) as the enabling technology to solve fundamental problems of spectrum scarcity, low utilization efficiency, interference, and high-bandwidth communication [4]. In the healthcare environment, medical transceivers equipped with a frequency-agile front-end (i.e., CR users) may opportunistically use portions of the WMTS band without adversely affecting the operation of the priority users as well as the legacy medical equipment in operation. We envision a centralized network, where the CR devices (simply referred to as devices or nodes subsequently) interface with important medical equipment and forward traffic over a single hop to the central base station (BS). The BS then forwards the traffic to the end destination, such as an overhead monitor, medical data repository, or a distant doctor's office through out-of-band transmissions or the back-end wireline network. The BS also periodically performs spectrum sensing over the entire WMTS band to detect any potential interference caused by transmissions in neighboring TV channels to DTV channel 37, and also monitors for other transmission activities from utility telemetry or government operated installations on the L band. After determining the effective residual spectrum, it allocates this spectrum to requesting medical devices based on their needs. Strict adherence to the limits on the allowed electromagnetic interference (EMI) for

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Our spectrum and power allocation framework relies on obtaining an a priori estimate of the WMTS channel activity at a given location. The longer a specific portion of the channel is expected to be free, the better candidate it becomes for use.

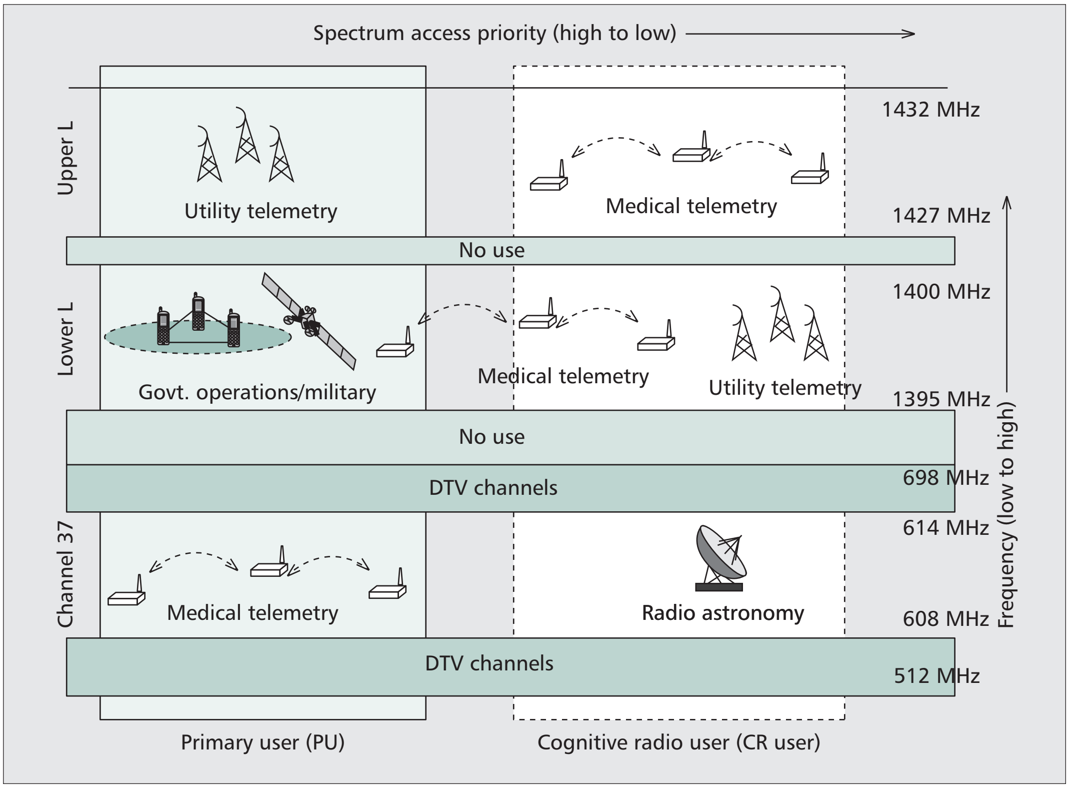

Figure 1. *Spectrum ranges for WMTS bands with varying levels of access priority.*

sensitive equipment using power control mechanisms that limits transmission range, ease of deployment of multiple types of sensing devices with heterogeneous performance constraints, and resilience to external interference and protection from self-congestion are some of the unique features of our proposed architecture.

The remainder of this article is organized as follows. We list major concerns and issues of the current medical telemetry systems and motivate the use of CR as a solution to these concerns. We undertake a thorough spectrum survey of the usages of the WMTS bands, and identify the characteristics of the channels. We describe a framework for sharing the spectrum for medical devices with different application constraints, and provide an idea of the performance of this framework. The key challenges in this area and future research directions are summarized, and finally, we conclude the article.

OVERVIEW OF WMTS LIMITATIONS

In this section, we summarize the major concerns impacting medical telemetry and describe the need for further research through the following three case studies.

Case I: Effect of DTV interference on medical telemetry: Hospitals in Kansas, New Jersey, and Ohio have documented recent outages in the WMTS bands due to increased transmission powers in the adjacent DTV channels 36 and 38 [5]. Here, the effective bandwidth in channel 37 was reduced to a third, and valuable time was lost for manually resurveying the spectrum and requesting the offending DTV operators to regulate their power. These incidents demonstrate that *a static licensed approach is unsuitable for guaranteeing connectivity, and dynamic spectrum access is required.*

Case II: Need for high-bandwidth intra-hospital communication: According to Dr. Julian Goldman, a Massachusetts General Hospital (MGH) anesthesiologist, many fatalities caused by human error could be prevented if medical devices are seamlessly connected. The operating room of the future moves toward this strongly connected paradigm that stresses high bandwidth availability both within the operating room and outside it [6]. However, *as FCC rules prohibit multimedia transmission in the WMTS bands, one possible option is using vacant DTV channels for audio and video.* Interestingly, prior to constituting the WMTS bands, medical devices were only allowed to operate on an unlicensed basis on vacant DTV channels 7–13 and 14–46 (i.e., 174–216 MHz and 470–668 MHz).

Case III: Navigating the maze of complex spectrum access rules: In Fig. 1, we depict how portions of the WMTS spectrum have varying priority access rights. As an example, military and governmental agencies have a priority access in the lower-*L* band spectrum with a number of operational radars, such as the FAA Air-Route Surveillance Radars (ARSR-1, –2, –3, and –4) and the Air Force AN/FPS-117 and –24 radars [7]. In addition, the upper-*L* and lower-*L* bands are used by non-medical telemetry companies on a priority access and equal access basis, respectively [3]. *Medical devices must defer access to high-priority users in the* L *bands and also deal with (unwanted) interference when access rights are equal.* This can be done by adding dynamic spectrum access capability to these devices to use WMTS bands as efficiently as possible while protecting the rights of priority users by not interfering with their transmission.

We would also like to mention that similar to the FCC mandated spectrum databases for the DTV channels, the American Society for Healthcare Engineering of the American Hospital Association (ASHE/AHA) is tasked to serve as the exclusive WMTS frequency coordinator. One of the reasons is that home usage of WMTS is forbidden as every provider must first provide channel usage data to the ASHE/AHA database before transmitting. However, if a large hospital reserves an entire width of the available channels (e.g., the entire lower-*L* band) but uses only a limited portion of this capacity, this results in an acute shortage of available channels. In a densely packed hospital area, such as Boston's Longwood area, this is an existing problem that can only be addressed through dynamic spectrum access.

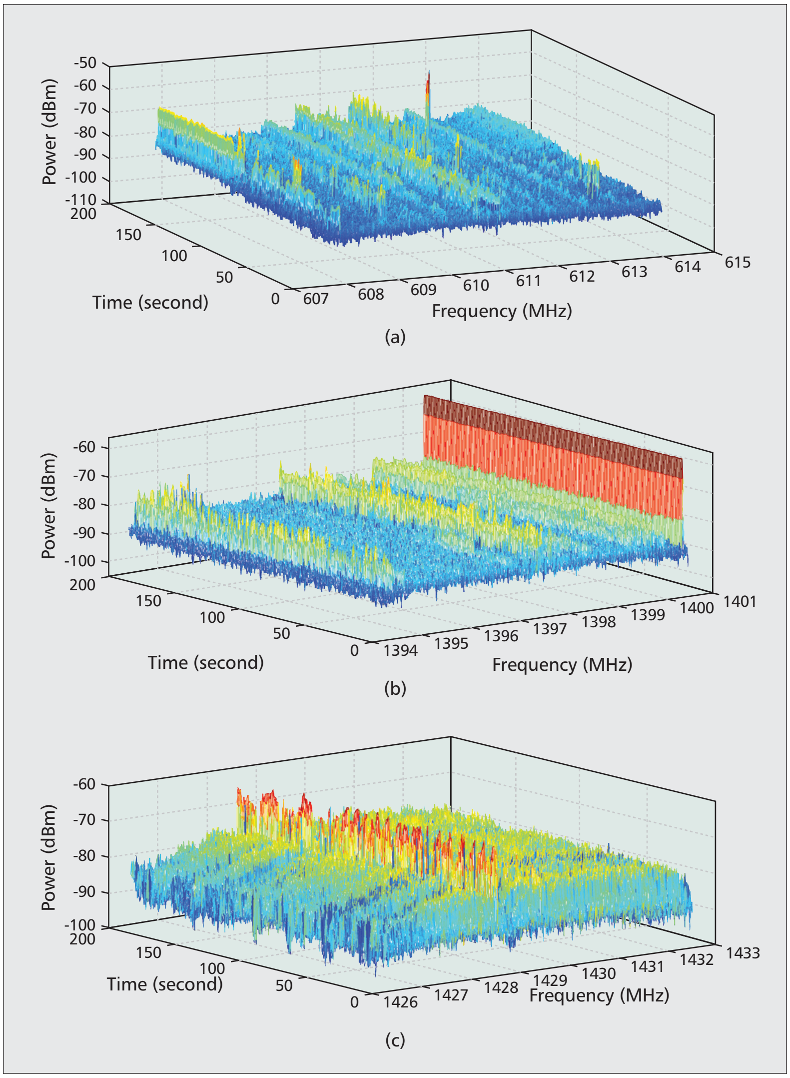

Figure 2. *Spectrum survey of the a) channel 37; b) lower L; c) upper L bands.*

SPECTRUM STUDY OF THE WMTS BAND

Our spectrum studies were conducted at two of the largest hospitals in the metropolitan Boston area, which are among the largest medical care complexes in the United States. We used a USRP2 device with a WBX antenna manufactured by Ettus Research LLC, and our setup was calibrated in the laboratory before the onsite experiments with the Agilent N9000 signal analyzer. Our measurements were undertaken over a one-week period, each session lasting for four hours, in which we obtained 6.25*M* samples/s. Figures 2a–c show a sample 200 s period of activity in channel 37 and the L-bands that is extracted from our measurements. The overall aim of this study is to characterize the channels forming the WMTS band, and establish site-specific activity patterns of the priority users.

OBSERVATIONS

For each given portion of the WMTS band, we measure the variation in power (z-axis) with time and frequency (x-y plane).

Channel 37: A common observation throughout Fig. 2a is that the existing transmissions exhibit narrowband behavior, and they are mostly contained within a few kilohertz. This is in line with the specification of the telemetry systems shown in [8]. Temporally, two types of transmissions are seen in the figures, those that are intermittent, such as the signal at 609 MHz up to the first 150 s, and the rest that are streamed, such as the continuous peaks present at 610 MHz. The streamed signals may correspond to the telemetry, indicating the fault-free operation of a medical device (e.g., an infusion pump). The intermittent signals could be alarms or device status report messages, among others.

***L*-Band:** We observe from Fig. 2c that the upper-*L*-band is somewhat different from the other two bands. The upper-L-band shows a wideband usage with occasional intermittent frequency changes. This activity pattern matches that of non-medical utility telemetry companies operating around this area. Moreover, the presence of a continuous peak around 1429 MHz in the available wedge in the spectral graph indicates the medical telemetry, as it is closely aligned with the shape and duration of the peaks observed for channel 37 (where no utility telemetry is allowed) in Fig. 2a. Finally, Fig. 2b shows continuous high-power received pulses at the far end of the frequency for the lower-*L*-band, which can only be attributed to active radar pings in the neighborhood.

Table 1 lists some of the popular medical telemetry systems used in hospitals. Our interaction with the wireless personnel in one of the two hospitals in which we did our measurements indicated that the GE Appex Pro CH was the most frequently used system. Our plots confirm a static allocation used in these devices since all the transmission activities are confined to their own assigned channel.

INFERENCE OF CHANNEL ACTIVITY

Our spectrum and power allocation framework relies on obtaining an a priori estimate of the WMTS channel activity at a given location. The longer a specific portion of the channel is expected to be free, the better candidate it becomes for use, as it can support a longer

Company	Product	Spectrum access	Standard/ protocol	Capacity (number of nodes)	Network type	Access type
GE	Apex Pro CH	FM (channelized)	—	438	WMTS (all)	Centralized
GE	Apex Pro FH	Frequency hopping	—	640	WMTS (all)	Centralized
Philips	1.4 GHz Intellivu	Smart Hopping (proprietary)	DECT	1028	1.4 GHz (L-band)	Centralized
Welch Allyn	FlexNet	OFDM	802.11a	1500	2.4/5 GHz	Centralized
Draeger	Infinity TruST	DSSS	802.11b/g	600	2.4 GHz	Centralized
Mindray	Panorama	FM (channelized)	—	500	WMTS (all)	Centralized

Table 1. *Commonly used wireless medical telemetry products.*

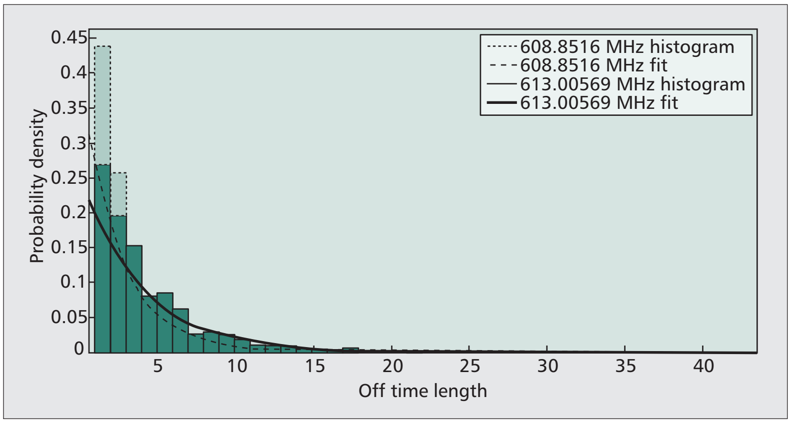

Figure 3. *PDF fitting for the "off" time duration of the bins centered at 608.8516MHz and 613.0569MHz.*

duration of medical telemetry transmissions. From the spectrum measurements shown in Figs. 2a–c, at each time instant, an output of a 1024-point fast Fourier transform (FFT) is calculated with a resolution of 6 kHz at each frequency bin. With this measurement setting, the activity at each bin can be analyzed independent of other bins based on the "on" and "off" times of the user of that bin. We use a simple probabilistic model of the channel, derived with the help of the exponential distribution, to approximate the "on" and "off" times at each bin. Figure 3 shows the histogram of "off" times at two separate bins (out of 1024 bins, one is shown with a bold line and the other with a broken line) within channel 37 and their fitted exponential probability distribution function (PDF). Similar results were obtained in all the other bins in channel 37 and the *L*-band. The resulting family of activity models is then utilized to estimate the channel availability in the optimization framework described later.

Power and Spectrum Allocation Framework

In this section, we shall provide a sketch of the optimization framework that carefully assigns the transmission power and the available portions of the WMTS channel with the help of the flowchart shown in Fig. 4.

Step 1: Initial Spectrum Sensing

We assume a one-hop architecture, in which devices wishing to transmit patient information to a central BS must first obtain the transmit power and specific start-end frequencies in the WMTS band that they may use, by sending a request message on the common control channel (CCC) to the BS. Here, the entire WMTS band is continuously sensed with a very fine frequency resolution of 6 kHz by the BS. After each sensing period, which according to our measurements is on the order of a few milliseconds, the empty and occupied frequency bins on the frequency scale are determined using energy detection. If any earlier assigned spectrum is found to be reclaimed, those ongoing CR medical data transmissions are inserted back in the pool of non-allotted but requested services. At this time, the BS also checks for any new incoming message on the CCC from the member devices, and based on the contents of the message, one of steps 2–4 is chosen. In the current setting, we assume an out-of-band CCC presumed to be on any unlicensed band, such as the industrial, scientific, and medical (ISM) band.

Step 2: New Request for Communication

If the incoming message at the BS contains a new request for communication by a node, we first identify the maximum permissible power that can be assigned to that node. During this procedure, first of all, the *L*-band is checked for availability. This band has the lowest preference as the radio frequency (RF) electromagnetic interference (EMI) caused by transmission below 800 MHz (i.e., in channel 37) is half that of comparatively higher frequencies (i.e., frequencies of the *L*-band). Then a list of nearby[1] EMI sensitive devices are queried for their measured values based on the current transmission environment. The transmission power of the requesting device is then gradually increased to a maximum that still contains the EMI within safe limits. Additionally, based on this amount of power, a node's distance to the base station and approximating path loss and fading, the signal-to-noise ratio (SNR) can be estimated. The BS

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[1] *It is shown in [9] that hazardous EMI to medical devices (depending on the type of device) above 5 m radiated by common mobile radios, like cellular phones, is highly unlikely.*

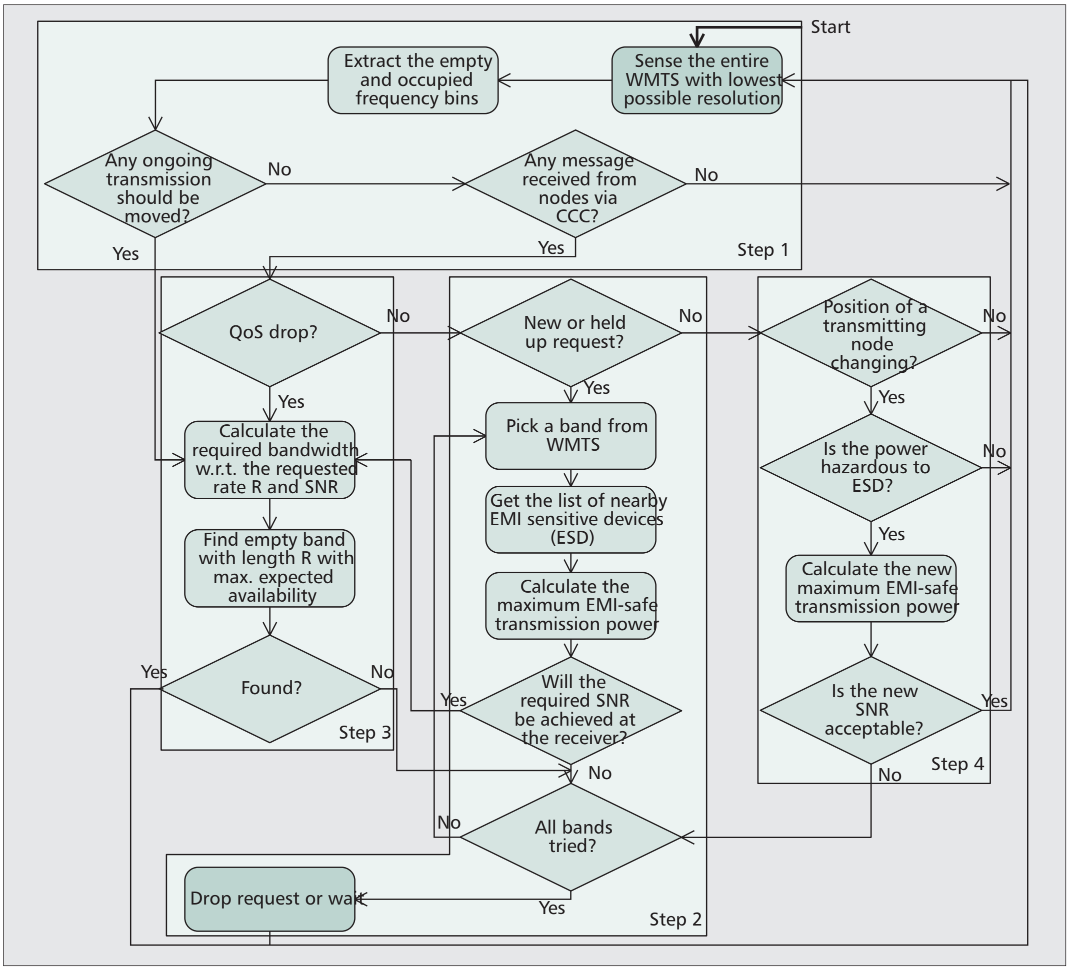

Figure 4. *Flowchart of the proposed transmission parameter optimization framework.*

A drop in service quality indicates that the current bandwidth is insufficient to meet the application demands, possibly due to congestion or errors caused by non-PU entities. In such cases, the BS attempts to find an alternate portion of the frequency.

decides whether the resulting SNR will guarantee the application specified outage ratio (in terms of packet error rate) for the corresponding node. If not, and after all frequency bands are explored with a similar negative outcome, the incoming request is dropped and a notification is sent to the doctor for in-person monitoring. If the power assignment has a feasible solution, the frequency assignment is undertaken (which is also the action performed on a drop in service quality, as explained in step 3).

STEP 3: DROP IN QUALITY OF SERVICE

A drop in service quality indicates that the current bandwidth is insufficient to meet the application demands, possibly due to congestion or errors caused by non-PU entities. In such cases, the BS attempts to find an alternate portion of the frequency. Additionally, if the power assignment from step 2 is feasible, a spectrum assignment procedure is carried out. In this step, according to the requested rate from the node, the bandwidth value is calculated. Then the empty bins (identified in step 1) are exhaustively searched for a contiguous band with maximum expected available time (statistics are drawn from the PU activity model estimated earlier). Upon determining a suitable frequency range, the node can be immediately asked to begin transmission by the BS.

STEP 4: MOVEMENT DETECTED

In case a node detects persistent mobility, say through a pre-installed grid of radio frequency identification (RFID) tags and readers in the hospital floor, the impact of the new location is assessed. This can be a key issue during hours where multiple patients may congregate at a common location. The immediate response of the BS in this case is to lower the transmit power, and if that results in an unacceptable estimated SNR, then it searches for a slot in channel 37. Steps 2 and 3 are now repeated in order to find the optimal assignment, failing which a doctor alert is issued.

PERFORMANCE EVALUATION

In this section, we show indicative performance of our proposed method assuming a network of static nodes, and preliminary results are shown in Figs. 5a–b. Our simulations were run in MATLAB, based on a service area of 140 × 140 m^2 with seven types of medical telemetry applications, including device telemetry, diagnostic telemetry, telemetry alarm, clinician notifier, BCMA, infusion pump status, and infusion pump alarm, randomly deployed in the area, whose specific latency, bandwidth, and error rate requirements are listed in [10]. Also, 20

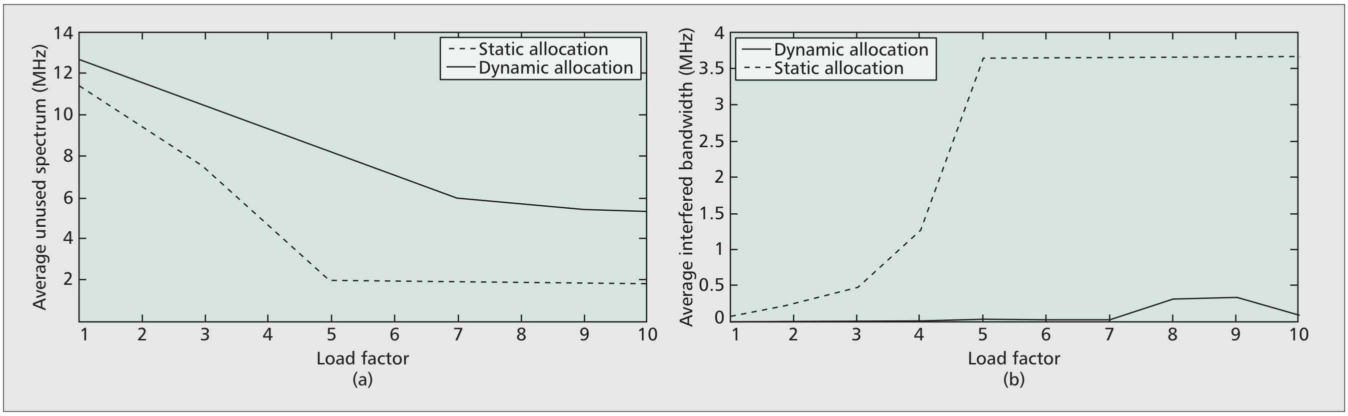

Figure 5. *a) Performance comparison of dynamic spectrum allocation vs. static allocation based on, average unused bandwidth and b) average interfered bandwidth.*

EMI-sensitive devices were randomly deployed in the area. Our simulations are conducted starting with the vector (60,21,22,20,19,81,18) that, based on [10], gives a realistic number of active transmitters of each telemetry application listed above, and then scaling up the numbers by a *load factor* (i.e., an integral multiplier) at every run. We evaluated two metrics for performance comparison against static frequency allocation of these devices (where no spectrum switching is performed and each node transmits on a fixed frequency), *average unused WMTS bandwidth* and *average interfered bandwidth* to the higher-priority users due to dynamic spectrum assignment. Figure 5a shows that the proposed dynamic spectrum access achieves a significant increase in the efficient use of unused bins and a graceful reduction of residual capacity with increasing load. Figure 5a shows that interference averaged over the various telemetry devices are tremendously reduced. Specifically, it can be seen in both figures that interfered bandwidth and unused bandwidth stay constant above a certain load factor for the static allocation, a direct impact of the rigidity of the allocation when the performance requirements are not met and channels are not re-allocated.

OPEN RESEARCH CHALLENGES

We identify the following research challenges that need to be addressed for deploying a feasible CR enabled medical telemetry network:

Identifying low-power priority users: Priority users such as utility telemetry have priority access in portions of the *L*-band, but the detected peak power for these applications may still be in the range of –100 to –70 dBm. Thus, clearly distinguishing the presence of these users and establishing a dynamic noise floor is a prerequisite for successful operation of the system. The noise floor includes the thermal white noise incurring at the RF input plus the noise added by the intermediate frequency (IF) components. Our own method for countering the effect of noise was to detect the spurious power in the USRP2 by terminating its RF input with a 50 Ω SMA terminator, and then tuning it to each of the WMTS bands. However, automatic noise floor diagnostic tools in software need to be devised for seamless operation of the system.

Meeting application requirements: One of the key requirements of the electronic medical record (EMR)-based information access for hospitals is the specified packet delivery rate of 99.95 percent for patient data that includes the formats of X-ray, CT, PET, MRI, ultrasound, and any other test results [10]. Additionally, various types of telemetry data (e.g., EMR images and numerical data wirelessly) requires peak data rates values of 4100 kb/s and 49.2 kb/s, respectively [10], with a maximum allowed latency of 200 ms. With such strict bounds, an end-to-end reliable delivery mechanism is needed. The field of transport protocol design for CR networks is still in a nascent stage, and rapid strides need to be made in this direction to ensure life-critical communication is provided with error recovery and congestion control capabilities. The access method described in this article looks at a single hop (i.e., device to BS), but distributed architectures will involve careful design of the end-to-end protocols. A similar cognitive radio architecture with power allocation and link-layer-based quality of service (QoS) provisioning has been presented in [11], although dynamic spectrum access capability is not foreseen in the model.

Predicting mobility and impact on EMI: In our work, the mobility is self-detected by a telemetry device. Instead, with assistance from the network, the mobility of each user can be predicted and the change in the EMI at the various sensitive equipments can be calculated in advance. As an example, Kalman filtering could be used with restrictions on the number of degrees of freedom, given that hospital corridors are linear and motion is generally along a single dimension. Moreover, accurate channel-specific EMI formulations and data from non-networking related sources, such as break times, need to be integrated in the framework, which will allow fine-grained prediction of the impact of simultaneous transmissions.

Video/audio transmission: Current FCC regulations do not allow the use of the WMTS bands for audio/video transmission. One possible solution is to leverage the vacant DTV channels 21–51 for this purpose.[2] There is a growing trend

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[2] *Note: Channel 37 is assigned for WMTS and unavailable for TV use.*

toward enabling high-bandwidth video access to doctors within operating rooms to allow them to visualize not only feeds from the operating table, but also inputs from distant experts without the clutter of wires [6]. The recent ruling by the FCC on spectrum databases provides guarantees on detecting available spectrum in these permissible DTV bands, which will help realize the video and audio needs of the future.

CONCLUSION

In this article, we have outlined an innovative application of cognitive radio technology in the medical domain. The different priority access rights of the medical devices in portions of the WMTS frequency spectrum in the L-band, the interference from the DTV operators in channel 37, and the variable tolerance to EMI with the change in frequency result in a complex environment, where dynamic spectrum and power assignment is a candidate solution. We envisage CR enabled devices enabling telemetry applications in ambulances and home environments, as well as utilizing rich multimedia data, both of which are not allowed under current regulations. Thus, critical life saving applications can be realized in this new communication paradigm, which will be a driving force for societal well being in the future.

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REFERENCES

[1] R. Hillestad *et al.*, "Can Electronic Medical Record Systems Transform Health Care? Potential Health Benefits, Savings, And Costs," *Health Affairs*, vol. 24, no. 5, 2005, pp. 1103–17.

[2] M. Imhoff, "The Spaghetti Syndrome Revisited," *Anesthesia & Analgesia J.*, Editorial, vol. 98, no. 3, Mar. 2004, pp. 566–67.

[3] FCC, Amendment of Parts 2 and 95 of the Commission's Rules to Create a Wireless Medical Telemetry Service, ET Docket No. 99-255, June 2000.

[4] I. F. Akyildiz *et al.*, "NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey," *Computer Networks J.*, Elsevier, vol. 50, no. 13, Sept 2006, pp. 2127–59.

[5] R. Hampton, "Lessons Learned from Interference to Wireless Medical Telemetry Service Systems," *IT Horizons*, published by Association for the Advancement of Medical Instrumentation, 2006, pp. 37–39.

[6] M. R. Mahfouz, "Operating Room of the Future Orthopedic Perspective," *Cairo Int'l. Biomedical Eng. Conf.*, Dec. 2008, pp. 1–9.

[7] J. E. F. Drocella, S. Jones, and J. W. T. Druhan, "Spectrum Reallocation Report: Response to Title III of the Balanced Budget Act of 1997," tech. rep. NTIA Special Publication, Feb. 1998.

[8] J. F. Dyro, *Clinical Engineering Handbook (Biomedical Engineering)*, Academic Press, 1st ed., Sept. 2004.

[9] R. van der Togt *et al.*, "Electromagnetic Interference From Radio Frequency Identification Inducing Potentially Hazardous Incidents in Critical Care Medical Equipment," *J. American Medical Assn.*, vol. 299, no. 24, June 2008, pp. 2884–90.

[10] S. D. Baker and D. H. Hoglund, "Medical-Grade Mission-Critical Wireless Networks," *IEEE Eng. in Medicine and Biology Mag.*, vol. 27, no. 2, Mar. 2008, pp. 86–95.

[11] P. Phunchongharn *et al.*, "A Cognitive Radio System for e-Health Applications in Hospital Environment," *IEEE Wireless Commun. Mag.*, vol. 17, no. 1, Feb. 2010, pp. 20–28.

BIOGRAPHIES

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We envisage CR enabled devices enabling telemetry applications in ambulances and home environments, as well as utilizing rich multimedia data, both of which are not allowed under current regulations. Thus, critical life saving applications can be realized in this new communication paradigm.