Dual-Band Cognitive Radio for Wearable Sensors in Hospitals

R. Chávez-Santiago, D. Jankūnas, V. V. Fomin, and I. Balasingham

Abstract—Wireless communication technology has the potential to impact beneficially modern medical practice through the use of biomedical sensors combined with small intercommunicating radio transceivers. This development will enable cost-effective continuous monitoring of patients in hospitals and other healthcare centers. It is anticipated that a large number of medical body area networks (MBANs) will soon operate in unlicensed frequency bands, a fact that will create a coexistence problem with legacy medical equipment. This situation is particularly challenging in small indoor areas like intensive care units (ICUs) and operating rooms (ORs). Electromagnetic interference (EMI) from wireless devices can disrupt the performance of non-communication electronic medical equipment located in ICUs and ORs. Cognitive radio (CR) is a promising technology that can ease the coexistence of the aforementioned systems. In this work we present an EMI-aware CR protocol for e-health applications. This protocol protects non-communication medical equipment from harmful interference while maintaining low outage probability for wireless communication devices and MBANs. We propose the use of an additional emergency channel in a different frequency band for control/data transmission, which exploits indoor propagation conditions to lower the outage probability. Performance evaluation of the proposed protocol through numerical simulations with realistic indoor propagation conditions is presented.

Index Terms—Body Area Network, Cognitive Radio, Exclusion Zone, Hospital Environment, Interference, Medical Sensor

I. INTRODUCTION

WIRELESS communication technology has the potential to impact beneficially modern medical practice through ubiquitous health monitoring solutions [1], [2]. This can be achieved by using biomedical sensors combined with small wireless intercommunicating radio transceivers for measuring, transmitting, and storing different physiological signals in real time. Although the dedicated frequency band of 2360-2400 MHz for the use of medical body area networks (MBANs) on a secondary basis has recently been designated in the United States, it is anticipated that a large number of wireless biomedical sensors will operate soon in unlicensed frequency bands too. In fact, the IEEE 802.15.6 standard [3] for wireless body area networks (WBANs) has recommended the unlicensed 2.4 GHz industrial, scientific, and medical (ISM) frequency band (2400-2500 MHz) as one alternative for the operation of wearable biomedical sensors. Moreover, small transceivers compliant with the IEEE 802.15.4 standard (ZigBee) are commercially available for operation in unlicensed ISM bands and have been found suitable for health and fitness monitoring in confined indoor areas [4]. In addition, a large number of wireless local area networks (WLAN) based on the family of IEEE 802.11 standards share the 2.4 GHz ISM band, making the coexistence of all these different wireless devices challenging [5]. Techniques to avoid mutual interference have to be applied in such cases. In hospital scenarios, the coexistence problem is even more critical in small areas like intensive care units (ICUs) and operating rooms (ORs), because the electromagnetic interference (EMI) from wireless devices can disrupt the performance of non-communication medical equipment that is routinely present therein. Cognitive radio (CR) is a promising technology that can ease the coexistence of wireless devices while protecting the electronic medical equipment in these environments. Despite the recognized potential benefits of CR for MBANs [6], this particular application has not been extensively investigated and just a few CR solutions for MBANs have been put forth in the literature.

In [7], CR was proposed as the enabling technology to tackle spectrum scarcity and interference in healthcare and medical telemetry. This solution enables dynamic utilization of the wireless medical telemetry services (WMTS) frequency band, which comprises different parts of the spectrum, namely 608-614 MHz, 1395-1400 MHz, and 1427-1432 MHz. A different CR solution for MBAN based on ultra wideband (UWB) technology was proposed in [8]. Regrettfully, the consumer communication industry has shown limited interest in producing small transceivers for the 3.1-10.6 GHz UWB frequency band. Hence, because of the readily availability of

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small transceivers for MBAN in the 2.4 GHz ISM band, the CR request-to-send/clear-to-send (RTS/CTS) protocol for e-health applications proposed in [9] is particularly relevant. This protocol adapts the transmit power of wireless devices operating in 2.4 GHz according to standardized EMI immunity constraints. In addition, the protocol effectively handles two different types of medical application traffic with different priorities. Through computer simulations it was demonstrated that this EMI-aware RTS/CTS protocol can reduce significantly the interference to protected non-communication medical devices in comparison to traditional RTS/CTS protocols like the specified by IEEE 802.15.4 [10]; however, this interference reduction comes at the expense of high outage probability for the wireless devices in areas where protected medical equipments are located. Hence, in this work we present an EMI-aware RTS/CTS protocol that includes dual-band operation. We considered a CR system operating in the 2.4 GHz ISM band with two channels, namely a dedicated control channel (DCC) and a data channel (DATC). We propose the use of an additional “emergency” channel (AEC) in a different frequency band that can serve as a control/data channel for potential interferers in order to reduce the outage probability. We considered the recently allocated 2360-2400 MHz MBAN frequency band and the 900 MHz ISM band (902-928 MHz) for the AEC. Through computer simulations we evaluated the performance of this multiband medium access control (MAC) scheme in terms of the outage probability and compared it to the EMI-aware RTS/CTS protocol in [9]. Clearly, the use of an AEC reduced the outage probability. However, the obtained level of improvement was determined by the center frequency of the AEC. Marginal improvement was obtained with an AEC in the 2360-2400 MHz MBAN frequency band, whereas significant improvement was obtained by using an AEC in the 900 MHz ISM band. We also compared the size of the exclusion zones (i.e., areas in which wireless medical devices cannot operate in order to prevent interference) for the chirurgical premises of the Intervention Centre, Oslo University Hospital, Norway. Our simulations demonstrated that the use of the proposed dual-band CR EMI-aware RTS/CTS protocol allows wireless transmissions in larger areas without causing interference to non-communication legacy equipment and with relatively low outage probability. The best results were obtained using an AEC in the 900 MHz ISM band.

The remainder of the paper is organized as follows: In Section II we describe briefly the CR system for hospital environments that was used as the basis for further development and improvement. Section III presents our proposed dual-band EMI-aware RTS/CTS protocol and its evaluation in terms of outage probability through computer simulations. In Section IV the study of exclusions zones for a realistic hospital scenario is presented. We discuss our results and summarize our conclusions in Section V.

II. EMI-AWARE RTS/CTS MAC MECHANISM

We used the CR EMI-aware RTS/CTS MAC mechanism that was introduced in [9] as the basis for further development. Hence, we refer the reader to the original source for details.

Two different types of traffic from two wireless e-health applications were considered to be handled by the CR system:

1) Real-time non-critical telemedicine, which transmits data that are not delay/loss-sensitive, e.g., remote consultation, patient record transfers, and remote diagnosis.
2) Hospital information system, which collects patient, technical, and facility data that are intended for better clinical decisions and to prevent patient complications. This system collects information with the aim of MBANs and other wireless sensor networks (WSNs) located in the hospital.

In the CR context, the telemedicine system is treated as primary user (PU) and the hospital information system as secondary user (SU).

The CR system consists of three components, namely an inventory system, a CR controller (CRC), and CR clients. The inventory system is a database containing information about all the medical devices in the hospital premises. The CRC is a computer that controls the transmission parameters of the CR clients, i.e., PUs and SUs. For this sake, the CRC uses the information in the inventory system to compute the appropriate transmit power for each CR client in order to avoid interference that exceeds the EMI immunity levels of non-communication medical devices located in the vicinity.

The CR system operates using a DCC and a DATC. Both channels are in unlicensed spectrum, e.g., the 2.4 GHz ISM band. Every CR client transmits its data through the CRC. A time slotted RTS/CTS-based channel access mechanism is used by PUs and SUs to access the transmission medium. The flowchart of this mechanism can be found in [9].

This EMI-aware protocol was evaluated through numerical simulations in terms of interference probability and outage probability. We reproduced in [11] those simulations in order to have a basis for fair comparison and assessment of our subsequent proposed improvements. Our results were in agreement with [9].

The simulation scenario consisted of hospital premises over 27 m² arranged in nine areas of equal size as illustrated in Fig. 1. Ten non-life-supporting (NLS) and life-supporting (LS) non-communication medical devices were located in the ICUs, and their corresponding EMI immunity levels are also given in Fig. 1. The locations of the NLS and LS medical devices and the CRC were fixed, whereas the CR clients were mobile and uniformly distributed over the area. We implemented a random pedestrian mobility model for the CR clients to mimic random wandering of the CR clients over the nine areas. In order to compute EMI immunity constraints (see [9]) the following indoor path loss (PL) formula as a function of the distance in meters, \( d \) (\( d > 1 \)), was applied:

\[
P^{-PL}_{total} = 37.7 + 3.3\log_{10}(d) + 16.2 \theta
\]  

where \( \theta \) is the number of floors (or walls) the radio signal has to traverse and PL is given in decibels (dB).
because of EMI immunity constraint violations. The AEC must practically the same for both protocols.

power of CR clients in order to protect LS and NLS medical devices. However, in other areas where the density of devices in areas in which the EMI immunity values of (mainly LS) medical devices are high, the transmissions from a number of CR clients cannot reach the CRC with the minimum required signal strength and outage occurs. This is a drawback of the original EMI-aware RTS/CTS protocol that hinders its implementation in areas with a large number of LS and NLS medical devices. However, in other areas where the density of highly protected devices is lower the outage probability was practically the same for both protocols.

Therefore, in order to alleviate the outage probability problem we investigated the use of an AEC to handle the CR clients’ transmission requests that are dropped by the CRC because of EMI immunity constraint violations. The AEC must allow transmission with lower power while ensuring that the received signal strength at the CRC will be at least −65 dBm.

In indoor propagation environments the path loss is frequency-dependent, e.g., as expressed in the ITU indoor path loss model [12] given by

\[ PL_{\text{total}} = 20 \log_{10}(f) + N \log_{10}(d) + L_F(\theta) - 28 \]  

(2)

where \( N \) is an empirical path loss exponent, \( f \) is the signal frequency in MHz, and \( L_F(\theta) \) is the floor (or wall) penetration loss factor. Notice that (1) is a particular case of (2) for \( f = 2400 \) MHz. This model covers a wide range of frequencies, from 900 MHz to 5.2 GHz. The values of \( N \) and \( L_F(\theta) \) for different frequencies can be found in [12, page 211]. It is evident that frequencies below 2.4 GHz produce lower path loss, which means that less transmit power is necessary to reach the CRC with the required signal strength of −65 dBm. Hence, the AEC must be allocated in a frequency band below 2.4 GHz.

We assumed that the DCC was centered at 2480 MHz and the DATC at 2475 MHz. We chose these frequencies because they do not overlap with the three most commonly used IEEE 802.11 channels in the 2.4 GHz ISM band centered at 2412 MHz, 2437 MHz, and 2462 MHz, respectively. For the implementation of the dual-band EMI-aware channel access mechanism we considered the 2360-2400 MHz MBAN and 902-928 MHz ISM frequency bands. In each case we assumed that the AEC was centered at 2365 MHz and 906 MHz and we denoted them as AEC1 and AEC2, respectively.

In the dual-band EMI-aware RTS/CTS protocol, if a CR client wants to transmit data, it sends a RTS message on the DCC to the CRC. If the CRC estimates that the CR client will not cause interference to any protected medical equipment, then the CR client is allowed to transmit its RTS message on the DCC. Otherwise, the CR client is denied transmission on the DCC and tries to switch to the AEC for RTS transmission. The maximum transmit power on the AEC, \( P_{\text{add}} \), is then calculated. If \( P_{\text{add}} \) meets the minimum signal strength requirement without causing interference, the CR client is allowed to transmit data on the AEC. In this case, however, there is no transmission queue. Hence, before sending the RTS message on the AEC the CR client has to ensure the AEC is unoccupied. If the AEC is not free or a collision occurs, then the CR client’s transmission request is dropped immediately. Both PUs and SUs can equally access the AEC for control/data transmission. If only SUs were allowed to access the AEC, then there would be situations in which SUs have more probability of successfully transmitting their data than PUs.

We performed simulations of the proposed dual-band multichannel scheme using the AEC1, the AEC2, and both AECs at the same time. Similar traffic conditions were simulated for all the cases and the results are shown in Fig. 2. As seen, little reduction of outage probability resulting from the use of AEC1 was observed in the areas 3, 7, and 9, whereas in the other areas there was no improvement. This was expected because the spectral separation between the DCC (2480 MHz) and AEC1 (2365 MHz) was relatively small. The improvement, however, was much more significant when AEC2 was used. In this case, a maximal outage probability reduction of 84.7% with respect to the original EMI-aware RTS/CTS protocol was obtained. Similar high improvement was observed in area 3. In area 7, the achieved outage probability reduction was 19.9%. For the rest of the areas there was no significant improvement. Finally, we investigated the performance of the EMI-aware multichannel MAC scheme when both AEC1 and AEC2 were used. In this approach, if a CR client cannot transmit on the DCC, then it will attempt first to use AEC1. If allowed, the CR client will transmit its data on this channel; otherwise, instead of being immediately dropped the CR client will be allowed to attempt transmission on AEC2. Only if the CR client cannot transmit on AEC2, its transmission request is dropped. As seen in Fig. 2, the latter approach did not provide any further improvement. Therefore, the use of only one AEC is recommended, particularly AEC2.
IV. EXCLUSION ZONES

In the previous sections we used the hospital scenario in Fig. 1 as a benchmark example. In this section we apply the multiband EMI-aware RTS/CTS protocol to simulate a CR system in the chirurgical facilities of the Intervention Centre, Oslo University Hospital, Norway. These facilities occupy 420 m² and comprise 10 areas, 2 of which are ORs where NLS and LS medical devices operate routinely. These areas and the medical devices therein are described in Table I.

Likewise, we simulated a CR system supporting a telemedicine system and a hospital information system. In this case, however, we depicted the transmission exclusion zones that LS and NLS medical devices in both ORs generated around them. It is clear that in proximity of protected devices, particularly LS ones, wireless devices (i.e., CR clients) will not be allowed to transmit to avoid harmful interference. We computed the exclusion zones for the EMI-aware RTS/CTS protocol with DCC and DATC and depicted them as green zones in Fig. 3. In area 1 it is evident that the exclusion zone surrounding the LS device located at the furthest point from the CRC is significantly larger than it is for the LS and NLS devices closer to the CRC. This is explained by the fact that generally CR clients must transmit less power to reach the CRC with the appropriate signal level as they get closer to the CRC due to lower path loss. However, in area 5 the exclusion zone extends over almost the entire OR. This is caused by the additional wall that signals from CR clients in area 5 must traverse to reach the CRC, which forces CR clients to increase their transmit power to the point in which they are not allowed to transmit. A similar situation is observed in areas 7, 8, 9, and 10. CR clients in the corridor (area 6) never exceed the allowed transmit power because of more favorable propagation conditions. The same is true for areas 2 and 3. In area 4, where a NLS medical device is located, the exclusion zone is practically inexistent.

<table>
<thead>
<tr>
<th>Area Number</th>
<th>Description</th>
<th>Medical Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Angio operating room</td>
<td>2 LS 1 NLS</td>
</tr>
<tr>
<td>2</td>
<td>Computer room</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Angio control room</td>
<td>1 NLS CRC</td>
</tr>
<tr>
<td>4</td>
<td>Laparoscopic control room</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Laparoscopic operating</td>
<td>2 LS 1 NLS</td>
</tr>
<tr>
<td>6</td>
<td>corridor</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Offices and services rooms</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Medical equipment storage room</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>Anesthesia room</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>Medical equipment storage room</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 2. Outage probability over the nine areas of the hospital scenario for different multiband EMI-aware RTS/CTS protocols.

Fig. 3. Exclusion zones on the chirurgical premises of the Intervention Centre.

Fig. 4. Outage probability over the ten areas of the chirurgical premises of the Intervention Centre for different multiband EMI-aware RTS/CTS protocols.
Next, we simulated the proposed dual-band EMI-aware RTS/CTS protocol with DCC, DATC, and AEC1 and depicted the exclusion zones in yellow color in Fig. 3 (superimposed to the exclusion zones in green). Notice that practically no changes in the size of the exclusion zones can be observed in both ORs (areas 1 and 5), whereas marginal reduction of the exclusion zone can be observed in areas 7, 8, and 9. This is explained by the spectral proximity between DATC and AEC1 as hinted in the previous section.

However, when AEC2 was used in the dual-band EMI-aware RTS/CTS protocol the exclusions zones disappeared in areas 7, 8, 9, and 10. Moreover, CR clients were allowed to transmit in area 5 except in the exclusion zones shown in red color (see Fig. 3). In area 1 the exclusion zones practically disappeared, except for a few centimeters around the protected medical devices. In all the other areas CR clients were allowed to transmit without restrictions.

It is clear that the use of agility over different frequency bands with mutual large spectral separation eases the coexistence of wireless devices in proximity with protected medical devices. In addition to reducing the transmission exclusion zones significantly, the use of AEC2 also diminished outage probability in the majority of the ten areas as shown in Fig. 4. Although outage probabilities in areas 1 and 6 are higher than in the other areas for the dual-band EMI-aware RTS/CTS protocol, this is caused mainly by packet collisions. The reduction of outage probability in areas 7, 8, 9, and 10 is clearly correlated with the reduction of the size of the transmission exclusion zones.

V. CONCLUSION

The use of an EMI-aware MAC protocol can ease the integration of medical wireless sensors into telemedicine systems. An EMI-aware MAC protocol can effectively protect non-communication medical equipment from harmful interference. The main drawback is the large outage probability for wireless devices that said protocol can cause. This can be alleviated with the use of dual-band operation, in which an additional lower-frequency channel is used for control/data transmission by wireless devices that can interfere with legacy medical equipment. Significant spectral separation between the two frequency bands ensures better performance at reducing outage probability and transmission exclusion zones. The unlicensed spectrum 2360-2400 MHz and 902-928 MHz are examples of the frequency bands that can be used for the dual-band approach. However, a practical implementation of a cognitive radio system in a hospital for wireless medical devices requires the fabrication of frequency-agile transceivers, a distributed wireless sensor network for detecting spectrum holes, and a localization and tracking system for all medical devices in the hospital premises.

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