COGNITIVE RADIO NETWORKS: A PRACTICAL PERSPECTIVE

COGNITIVE RADIO FOR MEDICAL BODY AREA NETWORKS USING ULTRA WIDEBAND

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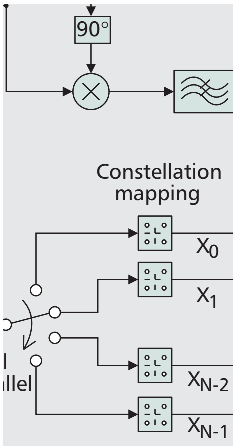

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ABSTRACT

Wearable wireless medical sensors beneficially impact the healthcare sector, and this market is experiencing rapid growth. In the United States alone, the telecommunications services market for the healthcare sector is forecast to increase from $7.5 billion in 2008 to $11.3 billion in 2013. Medical body area networks improve the mobility of patients and medical personnel during surgery, accelerate the patients' recovery, and facilitate the remote monitoring of patients suffering from chronic diseases. Currently, MBANs are being introduced in unlicensed frequency bands, where the risk of mutual interference with other electronic devices can be high. Techniques developed during the evolution of cognitive radio can potentially alleviate these problems in medical communication environments. In addition, these techniques can help increase the efficiency of spectrum usage to accommodate the rapidly growing demand for wireless MBAN solutions and enhance coexistence with other collocated wireless systems. This article proposes a viable architecture of an MBAN with practical CR features based on ultra wideband radio technology. UWB signals offer many advantages to MBANs, and some features of this technology can be exploited for effective implementation of CR. We discuss the physical and MAC layer aspects of the proposal in addition to the implementation challenges.

INTRODUCTION

In the United States alone, the telecommunications services market for the healthcare sector is forecast to increase from $7.5 billion in 2008 to $11.3 billion in 2013 according to an Insight Research Corporation study [1]. The healthcare sector is an ideal example of how cognitive networking and cognitive radio (CR) techniques can be employed to enhance the robustness, scalability, and utility of medical equipment and systems using wireless communications. Recently, there has been increasing interest in wireless communication technologies for medical applications, which can significantly enhance the patients' mobility, a key factor for speedy recovery after surgical procedures and interventions. Examples of these applications include electrocardiograms, pulse oximeters, dosimeters, and movement alarms. Additionally, the use of wearable biomedical sensors allows the remote monitoring of patients suffering from chronic diseases and the elderly at home by using telemedicine systems (Fig. 1).

The wireless body area network (WBAN) standardization working group (IEEE 802.15.6) has produced the first draft of a document specifying the physical (PHY) and medium access control (MAC) layer characteristics of the radio interfaces for WBAN applications [2]. A medical BAN (MBAN, i.e., a WBAN for medical applications) comprises multiple sensor nodes, each capable of sampling, processing, and communicating one or more vital signals. This biomedical information is transmitted to a body network controller (BNC) [3]. The MBAN constitutes the first tier of a telemedicine system (Fig. 1), which is referred to as intra-WBAN communications.

Although MBANs offer many benefits for healthcare, the surge in adoption rates across the healthcare sector will certainly create new interference scenarios with other collocated electronic systems. CR is a paradigm for opportunistic access of licensed (primary) parts of the electromagnetic spectrum by unlicensed (secondary) users that can provide solutions for these interference scenarios and also enhance scalability. A CR user (CRU) can combine spectrum sensing and geolocation database access to determine occupancy, and dynamic reconfiguration of its transceiver parameters in order to avoid interference with primary users (PUs).

In this article, a CR-based solution for a MBAN is proposed and we consider both the PHY and MAC layer aspects. The proposal is based on the use of ultra wideband (UWB), one of the technologies for radio interfaces adopted by IEEE 802.15.6. In this proposal, the cognitive capabilities are implemented in the BNC using two UWB modalities: impulse radio (IR) and multiband orthogonal frequency-division multiplexing (MB-OFDM). The main technical contribution of this work is the architecture for an MBAN with frequency agility and frequency-domain spectrum shaping capabilities that facili-

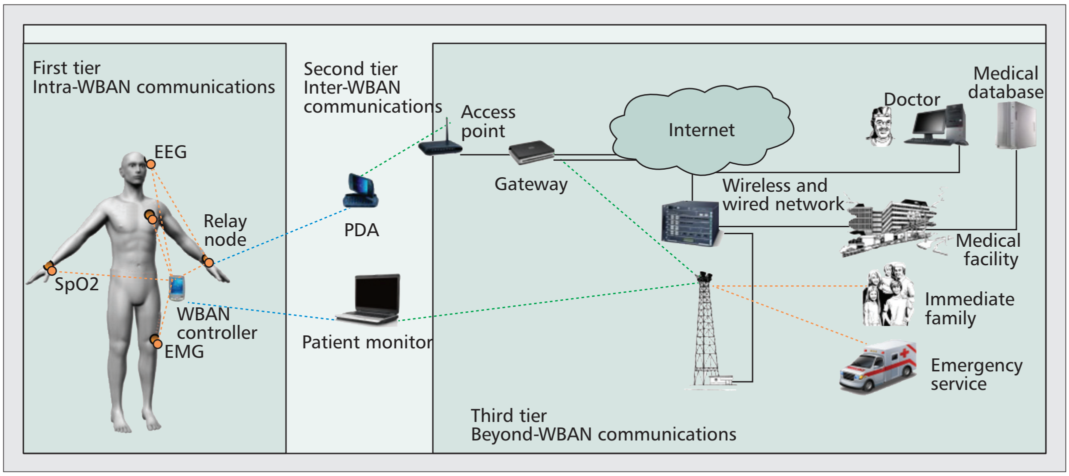

Figure 1. *Three-tier architecture of a telemedicine system.*

Regardless of the different spectrum regulatory constraints across the world, several bands designated for medical applications (or where their operation could be permitted) are mostly available on a license-exempt secondary basis.

tate interference avoidance in scenarios where many devices are operating in common spectrum segments and in close proximity to each other, as may occur in locations such as a busy medical center.

We survey the main characteristics of UWB radio technology. Cognitive radio techniques for a UWB-MBAN are discussed. We explore the PHY layer of the proposed CR-MBAN solution followed by the MAC sublayer. We highlight perspectives and challenges associated with this solution. We then conclude the article.

UWB WIRELESS TECHNOLOGIES

Spectrum regulatory policies affect the ability to deploy MBAN technologies on a global scale; however, they also offer unique opportunities for a CR-based solution. Regardless of the different spectrum regulatory constraints across the world, several bands designated for medical applications (or where their operation could be permitted) are mostly available on a license-exempt secondary basis. UWB technology shows interesting applicability for MBANs. Both the United States and Europe have regulated the parts of the spectrum that can be used by UWB on a license-exempt basis. The band made available in the United States corresponds to 3.1–10.6 GHz, whereas in Europe two spectrum segments have been defined, 3.4–4.8 GHz and 6–8.5 GHz. In addition, per ECC/DEC/(06)12 in Europe, UWB devices are allowed in supplementary bands subject to the implementation of specific mitigation techniques: in the 3.1–4.8 GHz and 8.5–9 GHz bands using detect and avoid (DAA) and in the band 3.1–4.8 GHz using low duty cycle (LDC).

IMPULSE RADIO UWB

Impulse radio UWB technology has been proposed as a solution in the IEEE 802.15.6 standard and is currently being developed by the IEEE 802.15 Task Group 6 [4]. The objectives include low-power, low-complexity, and low-cost body area wireless devices (not limited to humans) with highly reliable wireless communications. The application areas are divided into two major categories: medical (wearable and implanted systems) and non-medical (consumer electronics/personal entertainment, data transfer and command and control for interactive gaming) [2, 5]. The major goal of the standard is to specify a MAC sublayer supporting several PHY layers, including UWB, defined in two different flavors:

- IR-UWB, based on the transmission of a single and relative long pulse per symbol (new paradigm in UWB) or a concatenation or burst of short pulses per symbol (legacy), dedicated to high quality of service (QoS) mode
- Frequency modulated UWB (FM-UWB), optimized for low power consumption and reliable operation, especially in medical applications

MULTIBAND ORTHOGONAL FREQUENCY-DIVISION MULTIPLEXING UWB

ECMA-368 is a high-rate UWB PHY and MAC wireless standard for mixed populations of portable and fixed electronic devices. This standard uses MB-OFDM and divides the spectrum into 14 bands, each with a bandwidth of 528 MHz [6].

OFDM is a bandwidth-efficient transmission technology used not only in ECMA-368, but also in a wide variety of existing communications standards including digital audio broadcast (DAB) and digital video broadcast (DVB), IEEE 802.11a/g wireless LAN (WLAN), IEEE 802.16 WiMAX, and wired power line carrier (PLC) standards PRIME and G3.

OFDM is a frequency-diversity-based transmission scheme that distributes modulated data across closely spaced and mutually overlapping carriers called subcarriers. These subcarriers are precisely spaced at exactly the reciprocal of the symbol interval, which ensures that they are orthogonal to each other. An OFDM signal is generated in the frequency domain using an inverse fast Fourier transform (IFFT) to create a time-domain multiplexed signal. Subcarriers are demultiplexed using a fast Fourier transform (FFT) at the receiver. These subcarriers can comprise data, pilot, and null carriers. Null carriers are commonly used at the band edges and zero frequency (DC) bin primarily for constraining the spectral leakage to within the desired

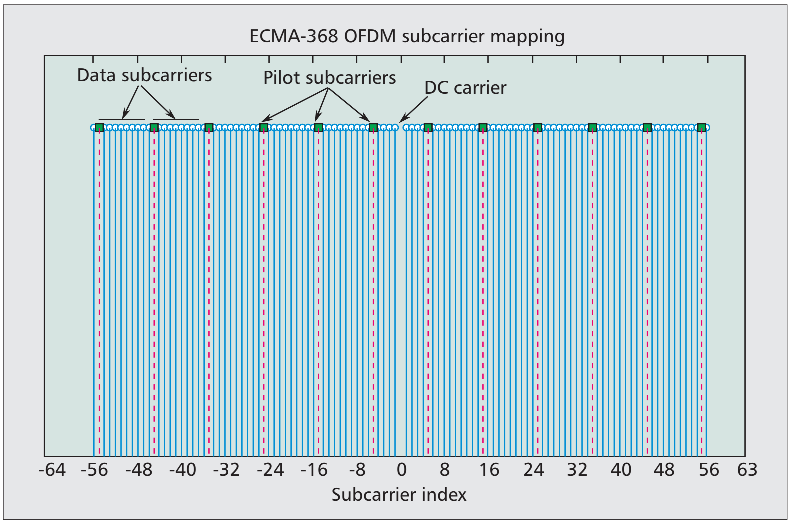

Figure 2. *An ECMA-368 OFDM symbol uses 12 pilot subcarriers and 100 data subcarriers.*

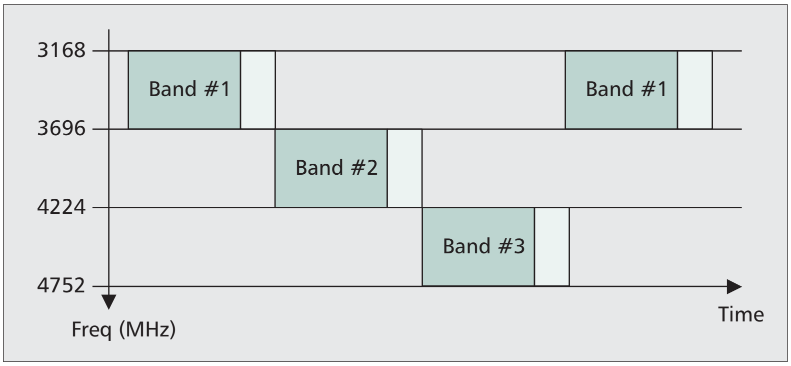

Figure 3. *Multiband OFDM.*

bandwidth and DC offset minimization, respectively. Pilot carriers are used for phase offset correction and equalization on an OFDM symbol by symbol basis. For ECMA-368, excluding guard and null subcarriers, 12 pilot subcarriers and 100 data subcarriers are used, as shown in Fig. 2.

Compared to single-carrier systems, OFDM does not require the complexity normally associated with single-carrier time-domain equalization. Equalization in OFDM systems can be carried out in the frequency domain using information derived from known transmitted pilots and the received values. The transceiver signal chain also lends itself well to the use of hardware accelerators for energy-optimized and low-cost deployment targets (Fig. 2).

COGNITIVE RADIO FOR AN ULTRA WIDEBAND MBAN

SUITABILITY OF UWB FOR MBANS

UWB technology has other attractive characteristics for MBANs beyond the large bandwidth capabilities of at least 500 MHz for high-rate communications. Ultra wideband signals have an inherent noise-like behavior due to their extremely low maximum effective isotropically radiated power (EIRP) spectral density of –41.3 dBm/MHz. This makes UWB difficult to detect and increases its robustness against jamming, potentially rescinding the need for complex encryption algorithms in small, low-cost transceivers. In addition, compared to single-band OFDM where symbols are continually sent on one frequency band, for MB-OFDM, symbols are interleaved over multiple sub-bands across both time and frequency as illustrated in Fig. 3. By interleaving the OFDM symbols across sub-bands in this manner, multiband UWB can maintain the power level associated with a single-band OFDM transmission yet the data throughput can be significantly increased. MB-OFDM UWB technology can currently achieve rates ranging from 53.3 to 480 Mb/s over distances up to 10 m.

Additionally, UWB signals do not represent a threat to patients' safety and are not significant sources of interference to other medical devices. Impulse radio transceivers have a simple structure and very low power consumption characteristics. These features facilitate their miniaturization for wearable biomedical sensors [7].

COGNITIVE RADIO CONTROLLER ARCHITECTURE

Characteristics of UWB technology can be exploited to turn a BNC into a cognitive radio controller (CRC) in a MBAN. The CRC is a central unit that controls the transmission parameters of CR clients (i.e., wearable sensors) for wireless access. Wearable sensors must be low cost, small in size, and with low power dissipation; this can be achieved through the use of an IR-UWB radio interface for communications in the first communications tier. Hence, the communication links between the sensors and the BNC should be implemented with IR-UWB as specified by IEEE 802.15.6. On the other hand, for the connection of the BNC with the second communication tier (Fig. 1), we propose using the ECMA-368 interface [6]. Besides supporting high data rates, MB-OFDM technology also provides a relatively straightforward way to implement DAA and CR.

The proposed architecture for the CRC, as shown in Fig. 4, consists of two transceivers, an IR-UWB transceiver with on-off keying (OOK) modulation (for illustration purposes only) and an MB-OFDM UWB transceiver. The division of the 3.1–10.6 GHz UWB spectrum into 14 subbands of 528 MHz, as suggested by the ECMA-368 standard, is adopted. The lower UWB frequency band (3.1–4.8 GHz) is covered by three subbands with center frequencies at 3232, 3960, and 4488 MHz, respectively. Due to better propagation characteristics, these three subbands should be preferred for first-tier communications. Second-tier communications can be implemented in higher frequencies.

The FFT engine monitors the UWB spectrum and broadcasts information on available subbands for data transmission. It has been demonstrated that the 128-bin FFT engine of the OFDM transceiver can act as a rudimentary spectrum analyzer with a sampling frequency of 528 MHz resulting in a frequency resolution of 4.125 MHz (528 MHz/128 bins) [8]. This enables the estimation of spectrum occupancy for oppor-

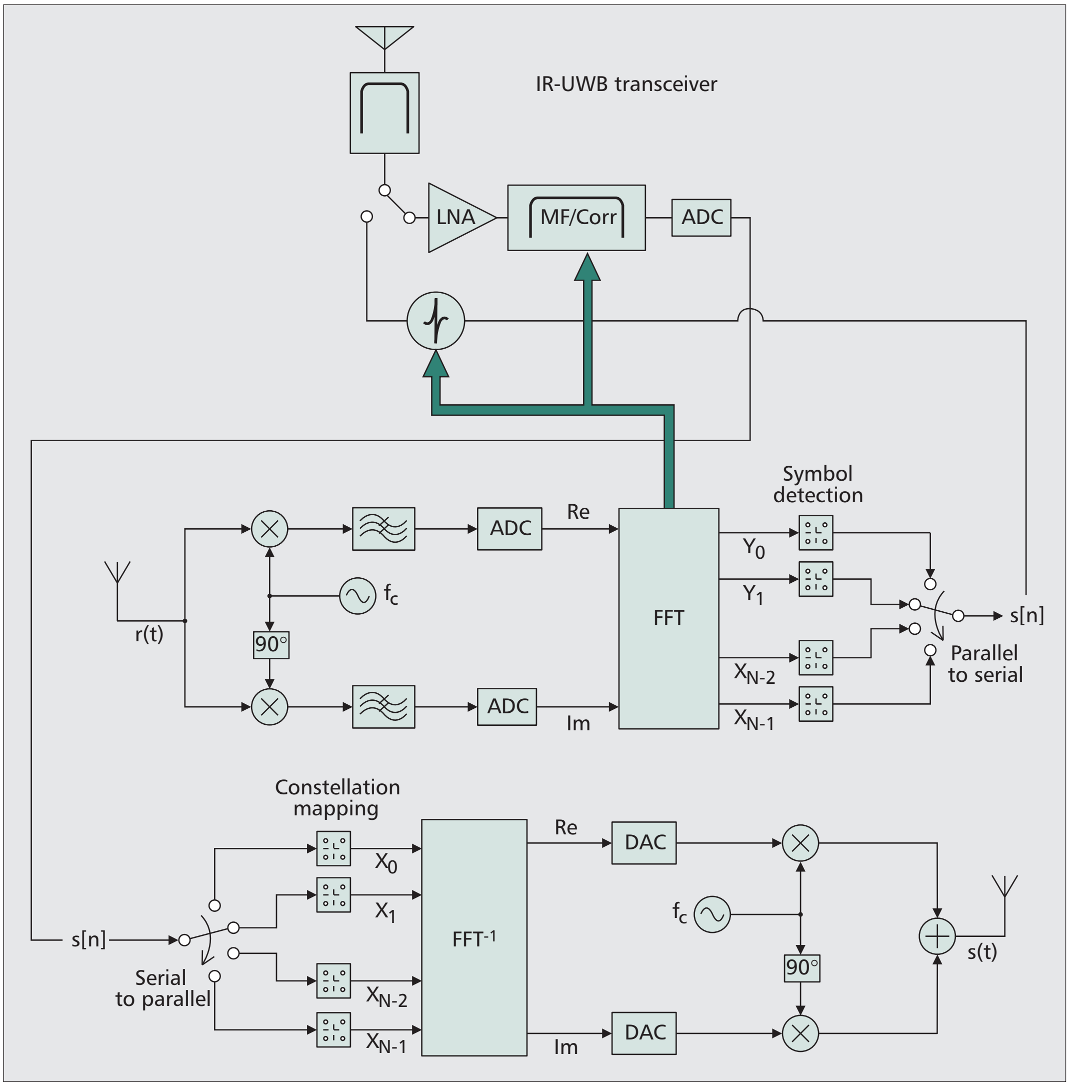

Figure 4. *Proposed architecture of a BNC performing the role of a CRC for an MBAN by using UWB technology. The bold arrows indicate the flow of information on spectrum availability from the MB-OFDM UWB transceiver to the IR-UWB transceiver.*

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tunistic spectrum usage purposes with minimal additional implementation costs. An MB-OFDM transceiver also facilitates the protection of sensitive receivers or protected medical devices from UWB interference by using frequency-domain spectrum shaping. This can be achieved by zeroing a range of subcarriers that overlap with the frequency band one intends to protect during transmission.

The broadcast channel is one of the three subbands of the lower UWB frequency band, which is chosen based on spectrum usage statistics obtained through a spectrum monitoring campaign. The least congested frequency subband is the most convenient choice for the broadcast channel, and this information is stored in the memory of each of the sensor nodes and the CNC. When a wearable sensor is turned on, the device is informed (through the broadcast channel) of which subband it can use for data transmission. Then it adapts accordingly the matched filter (MF) of the correlator in the receiver and the pulse generator of the transmitter. The same is done in the IR-UWB transceiver of the CNC. This can be implemented through a simple lookup table for the MF and pulse generator.

We now describe the PHY and MAC layer characteristics to enable CR for MBANs under this proposal in the following sections.

PHYSICAL LAYER FOR CR-MBAN

IMPULSE RADIO UWB FOR LOW-POWER COMMUNICATIONS

Ultra wideband has the advantage of high processing gain, and the additional advantage of allowing for coexistence with narrowband systems by means of spectrum shaping. Spectrum shaping in IR-UWB signals can be achieved by acting on two signal parameters: the code (typically, but not necessarily, a time hopping code adopted in combination with a pulse position modulation scheme) or the pulse shape adopted at the transmitter.

Pulse generation in general is a problem widely covered in the literature with respect to

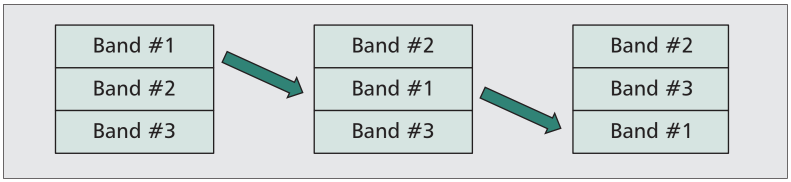

Figure 5. *Illustration of channel ranking for MB-OFDM. Subbands are reduced in rank if they are affected by interference and increased in rank if not affected by interference. In this case, the two top-ranked subbands can be used for data transmission in the UWB MB-OFDM system.*

implementation efficiency and accuracy, aiming at encoding information in the pulse shape itself; see for example [9, 10]. Moving to the specific problem of addressing coexistence issues by means of pulse shaping, several algorithms for selecting the best pulse shape given external constraints set by regulation and/or interference profiles were proposed in the literature. In [11] an algorithm for the generation of the pulse to be adopted in a time-hopping IR-UWB system was proposed, where a linear combination of pulses obtained as the derivatives of the Gaussian pulse was introduced.

In the case of the code, several solutions were proposed in the literature for designing codes that increase the coexistence capabilities of an UWB signal. Code design adds an additional opportunity to meet coexistence requirements when pulse shaping cannot efficiently be used to address such issues. As an example, in [10], code design is used to satisfy coexistence constraints by forcing nulls in the UWB spectrum at frequencies used by other narrowband systems.

MB-OFDM UWB for Sensing and Interference Avoidance

The ability to sense other narrowband or wideband systems in an IR-UWB system can be difficult in IR-UWB systems; it can be impractical to identify which specific frequencies are actually affected by interference over the wide bandwidth of the UWB front-end filter. MB-OFDM UWB systems therefore provide a clear advantage over IR-UWB in terms of sensing capabilities using power spectral density (PSD) information for each subband derived from the FFT stage in an MB-OFDM receiver. Using this technique, UWB devices can determine the presence of coexisting systems with a spectral resolution at least equal to the subcarrier spacing in the UWB signal. A subband or channel ranking scheme can be implemented using a combination of two methods. The first method is to use the subband PSD information to identify available channels. However, this does not necessarily indicate the quality of the channel (i.e., the measured bit error rate [BER]). To address this, the second method involves using the BER information obtained from active channels to yield channel quality estimation information for more in-depth subsequent ranking information in a manner somewhat similar to the use of received signal strength indication described in [12]. The channel ranking information can be stored and retrieved using a lookup table (LUT) in the transceiver. Compared to OFDM spectral shaping and the creation of spectral holes in the waveform to avoid interference, subband ranking and selective subband selection offer energy and cost savings in addition to a reduction in implementation complexity. The PSD information is already available from the receiver signal processing chain; therefore, this approach can be considered a low-processing overhead method. BER-based channel ranking requires additional logic to maintain the channel ranking LUT. This technique can yield information about the quality of the active subbands, whereas the PSD approach just indicates the availability of subbands. Both approaches give us the capability to be selective in how we use the spectrum, the agility to avoid subbands where interference may be present, and to trade cost for subband selection accuracy. Figure 5 is an illustration of channel ranking for MB-OFDM over example observation periods. Subbands are reduced in rank if they are affected by interference or in use, and increased in rank if deemed unoccupied. The top-ranked subbands can be used for data transmission in the UWB MB-OFDM system.

In the context of WBANs, therefore, a multiband approach using OFDM allows for a reduction in design complexity, improved flexibility in how spectrum is used, and better compliance with standards and frequency plans used worldwide. We can trade data throughput for agility, resilience to interference, and seamless operation across countries using different spectrum regulatory policies. We can use CR features for practical deployments that result in reduced device cost yet increased robustness in interference-prone environments.

Energy Consumption

Energy consumption is an important issue for MBANs and elements therein, particularly for communications at the first tier of operation (Fig. 1). Energy efficiency facilitates operation for the user through reducing frequency of battery charges whereby the user may find it difficult to carry out such tasks due to his or her current condition. It also improves reliability through reducing the probability of the network or the sensors therein being rendered inoperable due to energy depletion.

MBANs employ a range of means to reduce communications energy consumption [3]. CR is also highly pertinent to energy saving in MBANs through at least two key means. The first is better dynamic selection of spectrum, avoiding interference and therefore reducing necessary received power and hence transmitted power. MB-OFDM-based UWB leaves scope to tailor transmissions toward the lowest interference spectrum, as discussed earlier in this article.

The second energy-saving advantage of using CR involves the use of cognition to achieve better awareness of context, including higher-layer communication requirements, the changing general environment, and the battery energy level. This awareness can be used to improve timing of transmissions and dynamic MAC and PHY positioning given the current and projected interference conditions, variations in required data rates and constraints such as delay, and variations in general channel conditions and sensor energy availability. For example, MBAN sensor readings such as blood pressure, oxygen saturation, and blood sugar levels might be sampled at changing intervals and rates, depending on the condition of the patient and time of day. In order to dynamically maintain the appropriate configuration of the MBAN communication with minimized outage due to battery energy depletion while still aiming to communicate all data with appropriate delay constraints, learning and cognition can play a key part in estimating the future in terms of how requirements for these readings and battery levels are likely to vary. This can be matched to sensor transmission timing, rate, and MAC/PHY characteristics dependent on battery conditions. Moreover, battery conditions might also be driven by energy harvesting, through kinetic means through the patient's movements, for example, an hence can increase as well as decrease. Learning and prediction of such increases is also a key use for cognition, particularly given that the temporal characteristics of such an incoming charge are highly dependent on the specific patient's nature.

MAC SUBLAYER FOR CR-MBAN

Since the wireless telemedicine medium is shared, devices need to coordinate access time periods with their neighbors in order to avoid interference and collisions; this coordination is performed by the MAC sublayer. To this end, as anticipated earlier, the proposed solution adopts the IEEE 802.15.6 standard for communications in the intra-WBAN tier, while inter-WBAN tier access is provided by the ECMA-368 standard [6]. A description of the main features of the two standards and a discussion of the specific requirements imposed by the proposed solution are provided in the following subsections.

THE IEEE 802.15.6 STANDARD

This MAC sublayer intends to define short-range communications in and around the body. IEEE 802.15.6 supports two modes of operation for that communication: beacon and non-beacon enabled modes. It does not differ significantly from the MAC defined for IEEE 802.15.4, with the exception of the definition of multiple different phases in the TDMA frame where the standard defines exclusive access phases (EAPs) for high-priority devices (e.g., emergency signals related to a patient's vital signs), random access phases (RAPs) based on slotted Aloha, contention access phases (CAPs), and type I/II phases based on polling.

THE ECMA-368 MAC

The ECMA-368 MAC provides a distributed reservation-based channel access mechanism as well as a prioritized contention-based channel access mechanism. Besides mechanisms for handling mobility and interference situations, this MAC sublayer supports a synchronization facility for coordinated applications, device power management, secure communication, and a mechanism for measuring the distance between two devices.

The architecture of the ECMA-368 MAC is fully distributed. All devices provide all required MAC functions and optional functions as determined by the application. No device acts as a central coordinator. Channel time is divided into superframes, with each superframe composed of two major parts: the beacon period (BP) and the data period. The BP is organized in slots, and is used to achieve network synchronization and exchange reservation and scheduling information for medium access purposes. As for network synchronization, devices are required to listen for beacons for a time corresponding to a minimum number of superframes before starting transmission; if a device detects a beacon sent by another device, it synchronizes to such beacon, otherwise it starts emitting beacons to allow later devices to achieve synchronization. During the data period, devices send and receive data using prioritized contention access (PCA), or in reservations established using the distributed reservation protocol (DRP). PCA permits multiple devices to contend for access to the medium, based on traffic priority. The DRP allows a device to gain scheduled access to the medium within a negotiated reservation.

Although beacons make network operations significantly simpler, it should be noted that beaconless operation is possible as well, by relying on header extensions within the physical layer service data unit (PSDU) used for piggybacking control information. Details on beaconless operations can be found in the ECMA-368 standard but are outside the scope of this work.

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REQUIREMENTS OF A CR MAC PROTOCOL FOR MBAN

The architecture proposed earlier relies on the interaction between the CRC, equipped with multiple radio access technologies (at a minimum, IR-UWB and MB-OFDM), and the less complex MBAN devices transmitting data acquired by sensors over the IR-UWB interface. The CRC will send the following information to the IR-UWB devices:

- Schedule of sensing and data reporting
- Input on selected pulse shape according to the results of sensing carried out

In turn, each IR-UWB device will send the data gathered by its associated sensor back to the CRC. Furthermore, since the operation of the CR-MBAN relies on the capability of the CRC to carry out sensing in order to determine the optimal settings to be adopted by IR-UWB devices, the MAC protocol should foresee the possibility of reserving time durations for the sensing phase. In these durations, the MAC protocol should force all devices in the MBAN to stay silent in order to avoid creating interference affecting sensing performance.

The IEEE 802.15.6 MAC has been tailored for the specific needs of MBAN devices in terms of expected bit rates and latencies; it is not tailored for CR capabilities. It is therefore worth looking into the possibility of tuning the IEEE 802.15.6 MAC to address the requirements introduced by the CR-related features described above. As discussed previously, the 802.15.6

The implementation of a CRC for an MBAN as proposed in this article can be achieved with currently available technology. The so-called CogniPHY™ technology can be added to an OFDM transceiver for full DAA capabilities, at no additional cost in complexity or power consumption.

MAC operates in a TDMA fashion, and supports a beacon mode where the BNC sends broadcast information toward the WBAN devices using a beacon, followed by the rest of the TDMA frame organized as a mixture of contention periods and contention-free periods, according to the instruction provided by the beacon control. Through the following means, such a structure can be efficiently tuned to support the proposed CR architecture:

- The beacon can be modified to include specific spectrum shaping information (e.g., pulse shape, code parameters) for the IR-UWB devices, determined according to the sensing carried out by the MB-OFDM radio.
- The BNC can reserve a portion of the frame (e.g., by allocating it as an EAP without allowing any device to use it), thus effectively forcing all devices in the WBAN to keep silent in this phase and therefore enabling sensing by the WBAN controller.

The proposed modification will ensure the correct operation of the sensing phase; it is worth noting, however, that additional primitives will have to be defined in the standard in order to support the selection of different pulse shapes and code settings at the PHY layer based on the information received at the MAC layer.

PERSPECTIVES AND CHALLENGES

The implementation of a CRC for a MBAN as proposed in this article can be achieved with currently available technology. The so-called CogniPHY™ technology can be added to an OFDM transceiver for full DAA capabilities, at no additional cost in complexity or power consumption [13]. It is clear that an efficient way of communicating information to the IR-UWB part of the CRC on available spectrum segments identified by the OFDM transceiver must be devised. This spectrum availability information can be encoded and forwarded to the IR-UWB transceiver in the CRC by a programmable microcontroller.

Moving to the MAC layer, the design of a MAC protocol for a CR network is in general a challenging task, particularly if the network is required to operate in a distributed fashion [14].

The proposed solution addresses the issue by introducing the role of the CRC, which will control the IR-UWB subnetwork by acting as its BNC, and will at the same time be participating in the inter-WBAN network through the ECMA-368 interface. Careful design will be required in order to enable the two interfaces to work seamlessly (e.g., by enforcing a time or frequency division between the intra-WBAN and inter-WBAN operations, as detailed earlier). An additional research line can be foreseen for the design of the algorithm managing the multiple radio access technologies (RATs) available at the CRC; although this work mainly focused on IR-UWB and MB-OFDM, it can be expected that other technologies will be available at the CRC as well. The design of advanced algorithms for optimal selection and combination of the RATs as a function of network and external environment conditions will constitute a challenging research problem.

CONCLUSIONS

This article has discussed several cognitive radio techniques that can be applied to ultra wideband medical body area networks to improve their coexistence with other electronic systems through frequency agility and frequency-domain spectrum shaping. Frequency agility allows the sensor nodes to transmit in unoccupied parts of the spectrum, thereby reducing the risk of interference with other systems, whereas spectrum shaping creates notches in the spectrum of the transmitted signals in order to protect very sensitive receivers in the vicinity of the medical body area network. These networks are being deployed mostly on a license-exempt secondary basis. This fact, and the growing use of radio communication technology for healthcare, motivates further research on interference mitigation techniques for medical communication environments. Cognitive radio offers viable cost-effective and future-proof solutions addressing both scalability and coexistence issues, and the associated implementation challenges represent new and exciting research opportunities.

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Cognitive radio offers viable cost-effective and future-proof solutions addressing both scalability and coexistence issues, and the associated implementation challenges represent new and exciting research opportunities.