IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received April 30, 2018, accepted May 29, 2018, date of publication June 1, 2018, date of current version June 20, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2843259

Technologies and Challenges for Cognitive Radio Enabled Medical Wireless Body Area Networks

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ABSTRACT We present a review of spectrum sharing wireless body area networks. We investigate how cognitive radio (CR) and dynamic spectrum access are used for body area networks to save spectral resources. Specifically, we study the features associated with the usage of the three major CR paradigms of underlay, interweave, and overlay in these networks. We further put forward some use cases in medical applications. In this regard, we provide an overview of the existing schemes on interference mitigation for coexistence of different devices involving wireless body area networks. Further, we proceed with existing energy efficient medium access control protocols for CR-enabled body area networks. In addition, we outline the challenges and obstacles of implementing spectrum sharing concepts for body sensor networks.

INDEX TERMS Body area networks, cognitive radio, dynamic spectrum access, medical wireless body area networks, spectrum sharing.

I. INTRODUCTION

Due to the advances of wireless technologies, interest in exploring these technological advancements within the medical field has increased. This area of research is called medical wireless body area networks (MWBANs or medical WBANs). Some of the advantages of MWBANs are [1]:

- speeding up patients' recovery by continuous monitoring [2],
- decreasing health care expenditures,
- monitoring patients in remote areas,
- reducing the risk of spreading infection to other parts of the body that may be caused by wires connected to the patient,
- increasing patients' mobility and enhancing the degree of patients' comfort, and
- increasing the quality of critical medical decision making.

WBAN sensors are responsible for sampling, monitoring, and processing of environmental parameters (e.g., room temperature) or various kinds of vital signs, such as blood pressure, electrocardiogram (ECG) signals, temperature, heart rate, *etc* [3], [4]. Aside from MWBANs, in general, WBANs can be used for non-medical purposes, such as games, entertainment, firefighting, sports, etc. As shown in Figure 1, WBAN sensors can be classified into three subcategories based on the sensors location relative to the body.

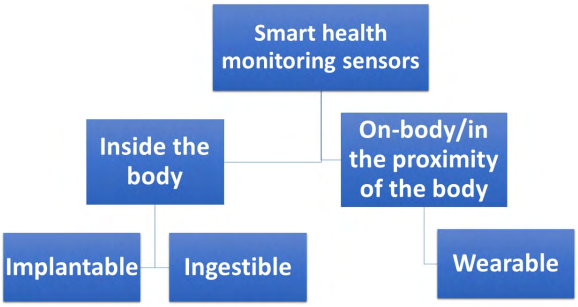

FIGURE 1. Subcategories of WBANs, based on the location of sensors (based on [5]).

Cognitive Radio (CR) is a paradigm to mitigate the interference and improve the efficiency of electromagnetic spectrum usage with an opportunistic access to the permitted parts of electromagnetic spectrum. In terms of the degree of priority of access to the channel, two kinds of users are defined: primary users (PUs) and secondary users (SUs). The PUs have the higher priority to access the licensed bands than SUs [6]. Therefore, PUs are preferred to SUs for applications involving real-time or critical data transmission.

In the design of WBANs, the harmful health risk of electromagnetic propagations to patients raises many challenges. The electromagnetic waves have different propagation forms inside, or on human bodies. To protect patients and body tissues against harmful effects, increasing transmission power of WBAN sensors cannot go further than a certain threshold to compensate for the transmission loss [2]. Specific absorption rate (SAR), which is the rate of RF energy of implanted, ingestible, and wearable WBANs absorbed by mass or volume tissue, is defined as the power loss density ($\frac{W}{m^3}$) over the mass density ($\frac{Kg}{m^3}$) and must be low. SAR, measured in Watts per Kilogram, can be defined in many forms, such as point, total, mass averaged, and volume averaged SAR. According to the International Commission on Non-Ionizing Radiation Protection, the maximum limits of SAR for a cube of body tissue with 1 gram or 10 grams of mass are 1.6 and 2 ($\frac{W}{Kg}$), respectively [7].

This survey presents a review of CR-based WBANs, specifically for medical applications. We categorize CR enabled MWBANs based on different parameters. The rest of the survey is organized as follows. In Section IA, we summarize the operation bands of WBANs. In Section II, we outline the building blocks for CR-enabled WBANs. In Section III, we emphasize the spectrum sensing and spectrum access mechanisms in spectrum sharing WBANs. Section IV contains the implementation issues of WBANs with CR capability. Failure avoidance and reliability of CR-based WBANs are explored in Section V. Following this, we highlight the decisive parameters that determine the performance of cognitive radio WBANs in Section VI. Medium access control protocols for WBANs with cognitive radio capability are investigated in Section VII. Major challenges and future research directions for enabling WBANs with spectrum sharing capability are summarized in Section VIII. Finally, the conclusions are contained in Section IX. Table 1 contains the notation and abbreviations used throughout this paper. Figure 2 shows the taxonomy chart related to the technologies and challenges of CR-based MWBANs.

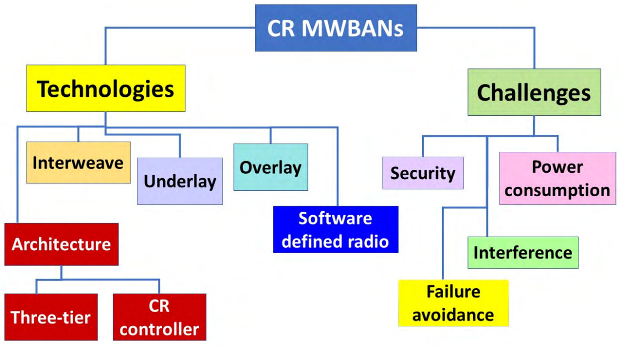

FIGURE 2. Taxonomy chart of technologies and challenges of CR-enabled MWBANs.

A. OPERATION BANDS OF MWBANS

Table 2 presents different regulations for industrial, scientific and medical (ISM) allocations in the USA and Europe. In the US, the ISM band is further divided into three subbands. Table 3 provides a list of different frequency bands for medical WBANs, according to the Federal Communications Commission (FCC). These frequency bands can further be categorized into two groups based on whether the sensors' locations are in-body or on-body.

The medical devices operating in ISM band in the 2.360–2.400 GHz range have been exposed to less interference compared to 2400–2483 MHz band [8].

In [1], based on the presence or the absence of the spectrum license holder or primary user (PU), the ISM band is classified into 2360–2390 MHz (band I) and 2390–2400 MHz (band II). In this classification, MWBANs only get access to band I with maximum 1 milliwatt (mW) transmit power if they are geographically outside of the protection zone of aeronautical mobile telemetry (AMT) as the PU. Band II contains the unlicensed spectrum, hence it is claimed that MWBANs can use this band everywhere, and with a higher maximum transmit power of 20 mW. However, this proposed classification has some drawbacks as it does not consider the degree of the priority of access to the unlicensed spectrum as well as the coexistence with other wireless communication systems. Next, we present the main elements of cognitive radio-enabled WBANs.

II. BUILDING BLOCKS FOR COGNITIVE RADIO ENABLED WBANS

Due to the spectrum scarcity, the surge in WBANs' utilization raises interference issues. However, spectrum scarcity is not the sole problem that needs to be solved for CR-enabled WBANs. In addition to the spectrum scarcity, other major challenges must be overcome, especially across medical sectors. One of these challenges is the sensitivity of biomedical devices to electromagnetic interference (EMI). There are some devices such as incubators, infusion pumps, and anesthesia machines in a hospital, which do not necessarily include a wireless transmission system; however, these devices can be negatively affected by EMI [14]. Moreover, many technical requirements and parameters, such as power consumption and sensor size must be considered in the design of WBANs to make them safe and comfortable to be worn [13]. It is worth noting that medical devices in a hospital can fall into one of these categories: WBANs, telemedicine systems, biomedical devices, and mobile hospital information systems. Unlike WBANs, biomedical devices may not be designed to transmit data through wireless systems; however, they can malfunction due to EMI. Telemedicine systems can be used for remote patient monitoring and diagnosis by forwarding the data collected by WBANs. Mobile hospital information systems store, retrieve, and process patients medical health records [15].

In the unlicensed bands, the concept of priority is not clear and there is no specific boundary to distinguish the

TABLE 1. Abbreviations.

PU	Primary user
SU	Secondary user
WBANs	Wireless body area networks
MWBANs	Medical wireless body area networks
CR	Cognitive radio
ECG	Electrocardiogram
SAR	Specific absorption rate
RF	Radio frequency
FCC	Federal Communications Commission
MedRadio	Medical device radio
HBC	Human body communications
MICS	Medical implant communication service spectrum
WMTS	Wireless medical telemetry service
ISM	Industrial, scientific and medical
AMT	Aeronautical mobile telemetry
SAP/SAB	Services ancillary to programme making/services ancillary to broadcasting
ENG/OB	Electronic news gathering/outside broadcasting
EMI	Electromagnetic interference
CRN	Cognitive radio network
AP	Access point
AWGN	Additive white gaussian noise
SNR	Signal-to-noise ratio
QoS	Quality-of-service
UWB	Ultra wideband
RSSI	Received signal strength indicator
SDR	Software defined radio
ICU	Intensive care unit
RFID	Radio frequency identification
MAC	Medium access control
DCC	Dedicated control channel
RTS/CTS	Request-to-send/clear-to-send
IR-UWB	Impulse radio-ultra wideband
MB-OFDM	Multiband-orthogonal frequency division multiplexing
CSMA/CA	Carrier sense multiple access/collision avoidance
TDMA	Time division multiple access

secondary and primary users [14]. However, in a real medical scenario, the cruciality of the transmitted signal can determine the order of priority to get access to the electromagnetic spectrum in unlicensed bands. The priority of users can be dynamically updated, depending on the importance of data. For instance, since the interference can cause the EMI-sensitive medical devices to malfunction, the EMI-sensitive biomedical devices have a higher priority than non-EMI sensitive devices [16]. Although both the telemedicine and mobile hospital information systems contain crucial data, which are sensitive to the packet loss rate and delay, the telemedicine system has a higher priority and is selected as PU. In the case that two users have equal priority, one has to switch to a different frequency. In cognitive radio enabled WBANs in a medical environment, possible interference scenarios are: interference among WBANs and other medical devices, interference among SU WBANs and PUs, and intra-WBANs interference. Some example interference scenarios in medical applications involving WBANs are depicted in Figure 3. For instance, MWBANs opportunistic usage of the spectrum allocated to AMT, as the PU, may cause interference to the primary user [8], other MWBANs located in the proximity, and other EMI-sensitive devices.

TABLE 2. Comparison of ISM allocations in USA and Europe.

	ISM frequency band		Allocation
USA [8]	2360–2400 MHz	2360–2385 MHz	Fixed, mobile, and radar services
		2385–2390 MHz	Mobile and fixed services
		2390–2400 MHz	Secondary radio services
Europe [8]	2360–2400 MHz		Secondary radio user, Aeronautical mobile telemetry (AMT), Land mobile, Services ancillary to programme making/services ancillary to broadcasting (SAP/SAB), Electronic news gathering/outside broadcasting (ENG/OB)

TABLE 3. Medical body area networks operation bands.

Operation bands	Frequency range		Disadvantages	Application
Medical device radio communications (MedRadio) [9]	401–406, 413–419, 426–432, 438–444, 451–457 MHz		Limited bandwidth [1]	In-body and on-body
Human body communications (HBC)	5–50 MHz		Affected by the human posture and surroundings [10]	In-body [11] and on-body [4]
Medical implant communication service spectrum (MICS) [1]	402–405 MHz		Limited bandwidth	In-body [4]
Wireless medical telemetry service (WMTS) [9]	608–614, 1395–1400, 1427–1432 MHz		• Limited bandwidth [1] • Not harmonized globally or regionally [12]	On-body
Industrial, scientific and medical (ISM)	2360–2500 MHz	2360–2390 MHz	Not suitable for critical life situations due to coexistence with aeronautical mobile telemetry as primary user [1]	On-body
		2390–2400 MHz	Limited bandwidth	On-body
		2400–2500 MHz	Unlicensed band, occupied by IEEE 802.15.6, WiFi, Bluetooth, ZigBee	On-body
Ultra wideband (UWB)	3.1–10.6 GHz		Incomplete spectrum monitoring campaign [13]	On-body

A. CR-BASED ARCHITECTURES FOR MEDICAL APPLICATIONS

There are two types of CR-based WBANs structures, namely three-tier WBAN architecture and central CR controller-based architecture [14]. Three tiers of the former WBANs structure are intra, inter, and beyond-WBAN communication, respectively [13].

The intra-WBAN tier is formed of several WBAN sensors in, or around the body, which communicate within a range of 2 meters with a CR controller, which is also a part of the inter-WBAN model.

In the second layer, CR controller communicates with access points (APs) implemented in personal devices, such as notebooks. This tier has two subcategories; infrastructure

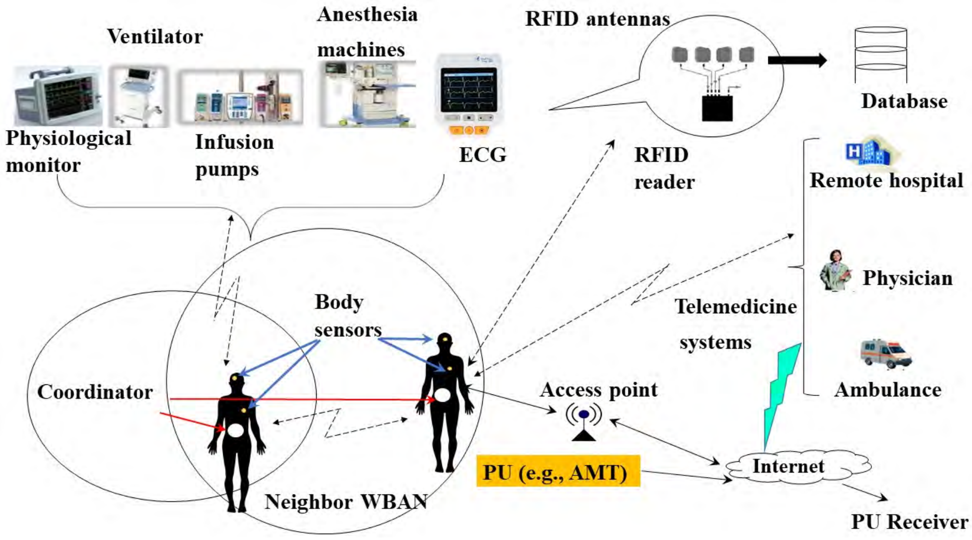

FIGURE 3. Interference scenarios related to WBANs with cognitive radio capability connected to telemedicine terminals and patient monitors in a hospital environment.

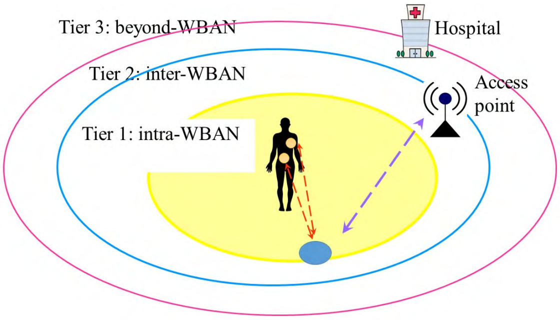

FIGURE 4. A three-tier architecture for the transmission of medical WBAN data (based on [17], [18]).

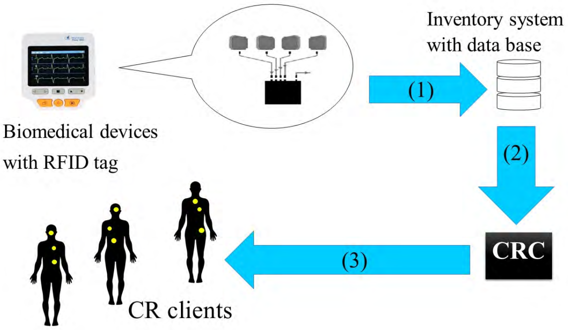

FIGURE 5. A central CR controller-based architecture (based on [16]).

based and *ad-hoc* [17]. In the infrastructure-based category, APs have a centralized structure and the coverage area range is limited, for example, to a room in a hospital. In the *ad-hoc* paradigm, the APs form a mesh structure with a higher coverage space to support patient mobility. In the beyond-WBAN tier, the APs communicate with base stations, connected to a medical team or medical databases. In fact, APs bridge the gap between intra and beyond tiers [4]. The three-tier architecture is a common design of a telemedicine system in a busy medical environment. In other words, the WBAN sensors in the first tier have been presumed as PU trying to transfer biological information to the third tier while many medical devices operate as SUs in same frequency band.

In the central CR controller-based architecture, as shown in Figure 5, the CR system consists of three components: an inventory system, the CR controller, and CR clients [14]. The inventory system maintains medical devices' information and sends it to the CR controller. Later, the CR controller adjusts the power of CR clients. The three-tier architecture lacks an inventory system; hence, it has no access to the location of non-wireless EMI-sensitive devices. Therefore, central CR controller-based architecture might be a more viable option in real hospital scenarios.

III. SPECTRUM SENSING AND SPECTRUM ACCESS IN CR-ENABLED WBANS

Based on the network side information along with the regulatory constraints, the CR network paradigm is classified into underlay, overlay, or interweave [6]. In the interweave CR, the secondary users sense the spectrum in either frequency or time domain to detect the presence of primary users and only broadcast a signal if there is no primary signal. In other words, the secondary user searches for white spaces to fill in. Underlay CR can be sophisticated as it adjusts the SU power by evaluating the level of interference between primary and secondary users and comparing it with an acceptable interference level determined by the PU Quality-of-Service (QoS) constraints. In this case, primary and secondary users can transmit concurrently, and the secondary signal appears to be noise for the PU. Therefore, UWB radio technology can be a prospective candidate for the underlay CR due to its low-powered transmissions [19]. Finally, the overlay paradigm, like underlay, allows concurrent primary and secondary signals. In this paradigm, the primary users share their data sequence and/or codebook with the secondary transmitter. For instance, consider a case where the information for telemedicine and in-hospital patient monitoring data originate from the coordinator of the same WBAN. In this case, since both applications have side information about each other's messages, the overlay CR paradigm can be used to send the MWBAN data to two different destinations on the same frequency band. In this scheme, the telemedicine transmitter is the PU and the in-hospital patient information is the SU [20]. This priority selection is based on the higher importance of reliable and real-time communications for telemedicine than for the in-hospital patient record.

The next step is spectrum access. Spectrum sensing involves collecting information about the occupancy of spectrum bands and using this information to decide whether the PU channel is idle for SU transmission. The spectrum access function coordinates the channel sharing between SUs and PUs to keep the SU interference on the PU receiver at an acceptable level. In Figure 6, the main features of the CR cycles of spectrum sensing and spectrum access are shown. Below, we describe the element of Figure 6 in more details.

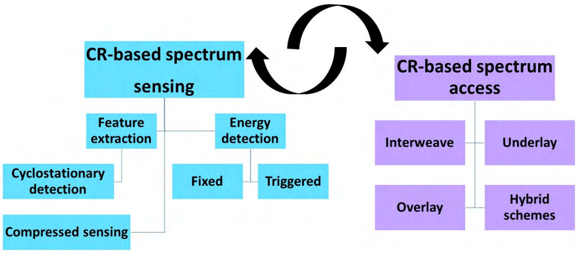

FIGURE 6. Interrelation of CR cycles of spectrum sensing and spectrum access.

A. SPECTRUM SENSING FOR WBANS WITH CR CAPABILITY

A major challenge in CRNs is the spectrum sensing phase. Spectrum sensing is modeled as two hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$, where $\mathcal{H}_0$ defines the channel in the absence of the primary user and $\mathcal{H}_1$ defines the channel as occupied. In energy detection-based spectrum sensing, with the assumption of Additive White Gaussian Noise (AWGN) on the channel, a certain threshold λ is set on the sensed power to decide whether the channel is vacant or not. Two performance metrics of spectrum sensing are P_d and P_f, the detection probability of the channel and the probability of false alarm, respectively. A desirable sensing algorithm should reach maximum P_d for an acceptable P_f. In the energy detection method, the CR has the knowledge of received energy from the PU and decides about the channel vacancy by comparing the energy with a predefined threshold. For example, the energy detection methods in both [21] and [22] are based on received signal strength indicator (RSSI) measurement during channel sensing period. Two possible timings for the energy detection method are fixed and triggered sensing times [23]. In fixed timing, the channel sensing time is deterministic and cannot be updated. In triggered timing, the sensing time is initially preset to a value that can be increased or decreased later according to some criteria, which are considered in different studies discussed later.

Another spectrum sensing algorithm for CR-based WBAN systems is cyclostationary based detection [24]. The cyclic term is used because of the periodicities in modulated signals. Generally, some statistics of modulated signals, such as autocorrelation show periodicity. In the cyclostationary spectrum sensing algorithm, the cyclostationary properties of PU modulated signals are exploited. For instance, the received signal can be decomposed into sinewave components. Then, the products of pairs of sinewave components are averaged to produce spectral correlation. If the correlation factor is greater than a predefined threshold, a primary user is active over the frequency channel [25]. Generally, the cyclostationary spectrum sensing method requires more processing than energy detection. Also, in general, cyclostationary detection requires some knowledge of PU signal characteristics, such as cyclic frequencies. Nevertheless, some blind methods are also proposed that do not need information about PU signal attributes [26].

Marbukh and Sayrafian [27] consider energy detection in the IEEE 802.15.6 standard for wireless connectivity of wearable and implantable sensors inside or close to the human body. Their main goal is to avoid interference among co-located WBANs that are using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. To this end, they propose a regret minimization-based algorithm for energy detection threshold adaptation. Their method is applicable to interweave (spectrum sensing) CR-enabled WBANs that operate based on energy detection to avoid interference with PUs.

Compressed sensing is another spectrum sensing approach with the ability of implementation in ultra-low power wireless communication with small memory. WBANs are prospective candidates for such networks, due to the transmission power constraints as well as limited memory space [28]. In this approach, the aim is to recover the signal with sparse sampling. By considering the fact that the original signal has been represented by a linear superposition of various wavelets, only wavelets with high magnitude coefficients are preserved and the rest are omitted. Then, the remaining wavelets are sampled and among all these wavelets fitted to the data, the one with minimum coefficient sum represents the signal. WBANs sensors with limited power supply carry out the sampling step with low processing load, whereas personal devices do the task of minimization, i.e., finding the minimum coefficient sum.

TABLE 4. Overview of common spectrum sensing methods in CR-enabled WBANs.

Spectrum sensing methods	Advantages	Disadvantages
Energy detection	• Low computational complexity • Short delay	• Poor performance in low SNR • Depends on the threshold selection, which is highly affected by noise
Cyclostationary detection	• Higher probability of detection in low SNR • Resistance to disturbance • Lower power consumption	• Higher computational time • Requires prior statistical knowledge (spectral correlation) of PU
Compressed sensing	• Acceptable performance in ultra-low power networks • Requires low memory	High power consumption for the minimization algorithm task

TABLE 5. Typical interference distribution models for WBANs.

	Band	Interference distribution	Locations
[29]	ISM [2.399–2.485] GHz	*t-location* scale/ generalized	Office, Home, Emergency wards
[21]	ISM [2.4–2.4835] GHz	Erlang or exponential distribution	General
[31]		Rician fading channel distribution	General

Overall, an ideal spectrum sensing mechanism should meet these three criteria:

- reliability in low signal-to-noise ratio (SNR);
- low complexity; and
- short processing time for detection.

A performance comparison between the energy detection and the cyclostationary detection methods has been presented in [24]. For simulation parameters used in [24], when the SNR is below -25 dB, there is no meaningful difference in the probability of detection. When the SNR of primary is above −15 dB, the detection probability of energy detection method (with a probability of false alarm of 0.08) is in the range of 10% while this value is almost 100% for the cyclostationary algorithm. Jingling *et al.* [24] state that cyclostationary detection has a better performance than the energy detection approach in a low SNR environment. By referring to the real measurements obtained in [29], SNR in a modern hospital is extremely low, e.g., less than -50 dB. Therefore, medical WBANs fall into the category of low SNR systems and if they are opportunistically accessing the spectrum, as SUs, the spectrum sensing method should be selected accordingly. Detection timing is another important factor in spectrum sensing. The energy detection approach is the most common technique in the literature on CR-based WBANs due to its low complexity and short delay [8], [30], [21], [22]. Table 4 summarizes the advantages and disadvantages of common spectrum sensing methods in WBANs.

Having a model of interference distribution can help with the design of WBAN parameters. In [29], the best fit has been calculated based on real measurements collected from a hospital, a typical room, and an office in Italy. The suggested distribution for a busy channel is *t-location*, which is defined as the distribution of the location of the sample mean of a normal distribution of collected measurements divided by the sample standard deviation; otherwise, a generalized extreme value distribution is applied. Table 5 summarizes some of the proposed interference distribution models for WBANs in the literature.

B. SPECTRUM ACCESS FOR COGNITIVE RADIO ENABLED BODY AREA NETWORKS

Table 6 summarizes the differences among different CR approaches. This table further contains some limitations of applying these CR paradigms for medical purposes without considering the hardware requirements. In addition to the three main paradigms of underlay, overlay, and interweave, hybrid or combination schemes can also bring some advantages to the CR applications [6]. Although energy consumption is a main issue to be considered, the selection of the suitable CR paradigm for CR-enabled MWBANs is based on the medical application. For instance, the interweave scheme can result in a better performance when the PU is rarely using the channel.

Next, we review the issues that arise when implementing CR MWBANs.

IV. IMPLEMENTATION OF CR-ENABLED WBANS

In this section, first we provide an overview of interference management techniques for experimental implementation of CR-enabled WBANs. In the second part of this section,

TABLE 6. Various CR paradigms (outline in [6]) and their deployment for WBANs.

	Interweave	Underlay	Overlay	Hybrid Interweave-Underlay
Simultaneous transmission	Not Permitted	Permitted	Permitted	Permitted
Power consumption limit [6]	Limited by device power and range of sensed frequencies	Limited by device power and allowed interference level	Limited by device power	Limited by device power, allowed interference level, and range of sensed frequencies
Limitations in medical WBANs	Due to broadcasting of the signal only in the idle channel mode, in the case the channel is busy and delay is not tolerable (e.g. remote surgery), it cannot be utilized	Due to limited SU rate and limited transmission power, in the case that the bit error rate (BER) is not tolerable or the receiver is far, it cannot be used	Considering power constraints of MWBANs, the SU transmitters use more processing (power) to encode both PU and SU messages	This approach suffers from both limitations noted for Interweave and Underlay

we proceed to software defined radio (SDR) implementation of WBANs.

A. INTERFERENCE MANAGEMENT IN EXPERIMENTAL CR-BASED WBANS

In general, interference avoidance in CR-based WBANs is implemented by the following approaches:

- Spectrum sensing;
- Prediction and update of WBAN (SU) channel sensing and access times;
- Prediction of PU activities;
- Transmission below PU tolerable interference; and
- Allocation of a portion of SU's power to relay the PU's message

Below, we describe the details of each of the above-mentioned approaches.

1) SPECTRUM SENSING

In [8], the performance of IEEE 802.15.4 physical layer (PHY) with the capability of operating in the 2360–2400 MHz ISM band in the presence of a primary user, here AMT and ENG/OB, is evaluated. The channel sensing and access times are fixed to 0.2 and 1 ms, respectively. When the channel is busy, the spectrum sensing task is halted for a defined time interval. However, channel switching may lead to a lower delay than waiting for the current channel to become idle, although switching the channels may consume more energy than waiting for a channel. In other words, waiting for the channel for an extended amount of time can be either rewarded with finding a better condition with a higher rate to transfer data to compensate for the delay or not. Although this method is protective of the PU, due to inflexibility in varying the channel sensing and access times, a SU WBAN may miss the opportunity of accessing the channel for a longer time in the presence of a PU with low duty cycles. In [12], Chavez-Santiago *et al.* applied a CR framework, including spectrum sensing, spectrum decision, and spectrum handoff, in a laboratory experiment. In this experiment, the presence of IEEE 802.11, which has the role of PU, is actively checked by a spectrum analyzer. Initially, the surveillance data of Sun SPOT,[1] which has the role of SU is transmitted over channel 26 of ZigBee. Whenever the PU is detected on the PU channel, the SU shifts to ZigBee channel 12.

In [32], the wireless medical devices in a hospital are considered to be primary users to protect them from EMI caused by WBANs as secondary users. As soon as the PU returns to the channel, the WBAN (SU) halts its transmission.

2) PREDICTION AND UPDATE OF WBAN (SU) CHANNEL SENSING AND ACCESS TIMES

Earlier, the spectrum sensing and access mechanisms were defined. The trade-off between sensing and access times can be either fixed (e.g., periodic sensing) or triggered. The indicator for updating either the channel access time or the channel sensing time is the collision rate as used in [21] and [22]. More specifically, Han *et al.* [21] implement a WBAN scenario with CR capability and show that cognitive radio can overcome the negative impact of collisions caused by interference. In this regard, they use an interference model with a defined distribution, e.g., exponential or Erlang. At the beginning, the channel access time is predicted according to the known interference distribution. Here, channel sensing time is being updated by estimating the critical collision rate. If the collision rate of the channel becomes higher than this threshold, the channel sensing continues to seek other spectrum parts with lower collision rate. Otherwise, the channel access time is updated according to the collision rate. Clearly, for a higher collision rate, the channel access time decreases.

Moreover, in [22], WiFi is mentioned as a major source of interference on WBANs. An advantage of cognitive radio in WBANs is minimizing the effects of interference in coexistence of WiFi and WBANs. To this end, a dynamic cognitive

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[1] http://www.sunspotdev.org/

TABLE 7. Summary of cognitive radio features for existing interweave (spectrum sensing) WBANs.

	Frequency band	Channel sensing method	Channel sensing time	Channel access time	Advantages	Disadvantages
[8]	ISM 2360–2400 MHz	Energy detection	Fixed time intervals	Fixed time intervals	Protection of PU	Reduced SU WBAN access time for a PU with low duty cycle (due to fixed sensing time)
[21]	ISM 2405 MHz	Energy detection	Fixed time intervals	Variable	Controlled collision rate	Reduced chanel access time due to larger sensing time
[22]	ISM 2.4 GHz	Energy detection	Triggered	Variable	Enhanced channel utilization with interference control	Complexity

radio algorithm to stagger the spectrum access time is used in [22]. The sensing time is initially set to 1 ms. Here, both the channel sensing time as well as the channel access time are updated. To update the timing, the collision rate of the channel is compared with the critical collision rate, i.e., collision threshold. When the difference between the collision rate and the threshold is small, the timing decreases. The time intervals in the spectrum sensing are chosen to be 3, 5, or 10 ms according to the calculated difference between the average packets collision rate and an acceptable collision limit for the system. The time interval for spectrum access is also relevant to the calculated difference between the collision rate and the critical threshold for acceptable collision. This method enhances the channel utilization while controlling the collision caused by interference. However, variable selection of channel sensing time costs more complexity.

Table 7, presents a summary of the features, advantages, and disadvantages of some existing interweave (spectrum sensing) WBANs.

3) PREDICTION OF PU ACTIVITIES

To alleviate the effects of interference in spectrum sensing CR-enabled WBANs, a predictor is used in [33] to forecast the arrival of PU signals on the band. This spectrum occupancy predictor is a faster variant of the hidden Markov model. In other words, the PU channel usage is a hidden stochastic process from the viewpoint of SU WBANs. However, this stochastic process is observable through sensing. Therefore, a CR-based WBAN can use past observations to predict most probable observation in the next sensing slot. This hardware-based predictor can be implemented on Vertex-6 processor.

4) TRANSMISSION BELOW PU TOLERABLE INTERFERENCE

This mode of operation relates to underlay CR-based WBANs. Using IR-UWB signals for WBANs is an implementation of this scheme [13], [19], [34]. UWB signals use very low transmission powers. As such, they appear as noise to the PU and do not cause interference.

5) ALLOCATION OF A PORTION OF SU’S POWER TO RELAY THE PU’S MESSAGE

This scheme is used in overlay CR-enabled WBANs, where the SU has knowledge of PU’s message or codebook [20]. For example, in the coexistence of telemedicine (PU) and in-hospital patient data transfer (SU), since the messages of both PU and SU originate from the coordinator of the same WBAN, SU has knowledge of PU’s message. To alleviate the interference on the PU (telemedicine), the SU (in-hospital patient data transmitter) can use this knowledge to relay the PU’s message to the destination. The SU allocates a fraction of its power for this purpose, in exchange for spectrum sharing with the PU.

Table 8 summarizes the main features and advantages obtained by applying CR methods to WBANs. It also outlines the drawback of each method.

B. SOFTWARE DEFINED RADIO IMPLEMENTATION OF CR-ENABLED WBANS

A software defined radio (SDR) is a radio communication system, which can transmit and receive based on different communication protocols and frequencies, using programmable radios [12]. Table 9 presents a list of some existing works on the implementation of CR-based WBANs

TABLE 8. Main advantages of CR systems in WBANs.

Reference	Advantage of using cognitive radio in WBANs	Performance metrics	Drawbacks
[12]	Coexistence of all medical and non-medical devices in a hospital	Spectrum occupancy	Low rate and low accuracy in conversion between digital and analog domains
[13]	Reduction of interference in hospitals	Interference	• Needs collection of statistics of spectrum in 2.4 –10.6 GHz • Needs knowledge of the location of EMI-sensitive medical devices • Two critical medical applications with equal priority cannot transmit simultaneously
[8]	Decreasing the probability of packet errors	• Packet error rate • Probability of detection • Probability of false alarm	Due to power constraints of WBANs, spectrum sensing methods more complicated than energy detection cannot be used
[16]	• Prioritizing wireless channel access • Reducing interference to passive EMI-sensitive medical devices • Increasing the patient mobility by embedding CR into medical devices	• QoS of e-health systems (data loss, delay)	• Needs to track the location of EMI-sensitive medical devices • Needs knowlege of nodes' priorities
[30]	• Increasing the possibility of continuous communication by calculating the power required to reach APs • Saving energy by using CRs with controllable transmission power	• Transmission power • Battery consumption • Percentage of successful transmissions	Needs knowledge of propagation loss and materials in the environment
[21]	• Reducing the interference from other same frequency users • Improving the WBAN throughput in comparison with non-CR enabled WBANs	• Throughput • Collision rate • Energy efficiency	Nodes have to wait until suitable communication slots are sensed by the coordinator
[32]	• Maximizing bandwidth • Protecting medical devices by considering them as PUs	• Bandwidth • Adjacent channel interference	Channel bonding requires finding consecutive non-overlapping idle bands
[35]	• Minimizing the concentrated transmission power and consequently heat on the body by use of a cooperative CR scheme	• Capacity • Power gain	Relaying needs knowledge of channel gains
[36]	Minimizing co-channel interference (e.g., among IEEE 802.11 based devices and IEEE 802.15.6 devices)	• Probability of channel availability • Energy consumption	Extended size of superframes

on SDR platforms. The safe integration of medical devices for wireless clinical monitoring using SDR is feasible if all the devices use the same communication protocols [12].

Overall Insights: There are several SDR platforms for implementation of WBANs. SoC CC2510 implementation consumes less energy than using field programmable gate arrays (FPGAs) [21], [22]. Energy efficiency is an important factor for battery powered WBANs. The majority of underlay CR-enabled WBANs are implemented using IR-UWB. For implementation of spectrum sensing (interweave) WBANs, SDR platforms with sensing capability are used, e.g., USRP, mote Zigbee nodes, WARP boards, *etc.*. The choice of each platform depends on the application, the cost, and the range of frequencies that are supported. For example, some WARP devices may cost more than some USRP devices [40].

Once CR-based MWBANs are implemented, they should be maintained such that they do not fail to operate. To this end, in the next section, we present failure avoidance solutions for CR MWBANs.

V. FAILURE AVOIDANCE IN SPECTRUM SHARING WIRELESS BODY AREA NETWORKS

Sometimes communication failure of vital biological signs may lead to the death of a patient. This possibility is the motivation for considering a backup plan for cases when the patients' vital data cannot make their way to the

TABLE 9. SDR platforms for CR-based WBANs.

	Transmitter	Receiver	Source of interference	CR paradigm
[13]	Multiband orthogonal frequency division multiplexing (MB-OFDM) with IFFT/FFT engine and impulse radio ultra wideband (IR-UWB) with on-off keying modulation	MB-OFDM with IFFT/FFT engine	Licensed wireless medical telemetry service (WMTS), medical implant communications service (MICS), and other WBANs	Underlay
[8]	Universal Software Radio Peripheral 2 (USRP2)/RFX2400 daughter board	Commercial TI development kit/Chipcon CC2520	ENG/OB and AMT generated by Agilent's MXG 5182A and Agilent's digital video studio N7623B	Interweave
[21], [22]	SoC CC2510 integrated with RF transceiver	SoC CC2510 integrated with RF transceiver	A transceiver pair on the same band (e.g., WiFi)	Interweave
[37]	Agilent N5182A signal generator	SP Devices ADC development board	Other WBANs operating on MICS, ISM, WMTS	Underlay
[38]	Wireless Open Access Research Platform (WARP) v2 board (compressed ECG)	WARP v3 board	Other transceivers in unlicensed or under-utilized licensed bands	Interweave
[34]	Altera Stratix II FPGA	IR-UWB	Transmitters in the 3.5–4.5 GHz band	Underlay
[39]	TMote Sky nodes (mote Zigbee devices)	TMote Sky node	WiFi device on the same band, i.e., Microsoft Research Software Radio (SORA) with USRP XCVR2450 daughter board	Interweave

CR controller. This may happen when a SU MWBAN cannot find an idle channel. In this regard, MWBANs can be equipped with spectrum sensing capability in addition to a few dedicated channels. Whenever the inter-MWBAN interference causes the packet loss over dedicated channels to exceed a tolerable limit, MWBANs switch to idle PU channels. However, channel sensing and channel switching consume some energy. Hence, there is an energy-efficiency vs. packet loss tradeoff between either switching the channels or continuing to use the same channel [41]. In [1], a solution is proposed for hospital transmissions on 2360–2390 MHz. In the first step, the WBAN should register with a coordinator. The coordinator decides if a registered hospital is within protection zones of PUs, e.g., AMT sites. For WBANs outside this protection zones, the coordinator allocates an electronic key specifically for that hospital to enable WBANs in that hospital to use PU spectrum. Without this key WBANs are only allowed to use the 2390–2400 MHz band.

In [35] and [31], the aim is to increase the patient's safety even when the transmission is lost. This goal is achieved by applying a cooperative relaying technique.

In [35], the focus is on game theory, where relays, known as supportive networks, receive the WBAN sensors signals during the transmission. In this method, source nodes and the relays are buyers and sellers, respectively. Relays charge a price to sell the bandwidth to the sensor nodes with regard to the cooperation cost and the utility function, which take into account parameters, such as throughput, transmission power level, SNR, and channel gain. In [31], some of the secondary nodes act as relays and others only as secondary nodes. First, the secondary transmitter broadcasts its data to both the relay nodes and the secondary receivers. Then, if the SNR of the received signal at the relay is greater than a predefined threshold, the relay transmits the signal to the secondary receiver. Otherwise, the secondary user transmits directly to the destination. Here, the interference threshold is a deterministic interference temperature constraint.

The above-mentioned methods rely more or less on some level of cooperation among MWBANs. However, cooperation may not always be a practical assumption. In this case, the SU MWBANs need a distributed failure avoidance scheme. For example, once a set of idle PU channels become available to a group of SU MWBANs, the coordinator of each MWBAN (SU) starts sensing the channels one after the other to detect the level of activity of other peer SU MWBANs. Whenever a SU MWBAN finds the first channel for which the interference level is less than the threshold for the MWBAN (i.e., achievable data rate is more than SU's threshold), the SU does not continue sensing the remaining channels and starts transmitting over that channel [42]. This scheme is different from listen-before-talk in which a channel is used by only one MWBAN at any given time. In other words, in this scheme, multiple SU MWBANs can use the same channel, provided that the amount of interference on each SU MWBAN is below a threshold.

Age of information is another parameter for avoiding failure in CR MWBANs. To this end, for time-sensitive cognitive MWBANs, Valehi and Razi [43] investigate the impact of packet length on power consumption and the age of information. In this scheme, the MWBAN is the SU in an interweave CR paradigm. The goal is to derive the best packet length of the SU based on factors, such as the number of bits per sample, the number of bits on the header of the packet, spectrum sensing rate, and channel utilization by the PU. Accordingly, longer packets are shown to reduce the power consumption in error-free channels, whereas shorter packets are preferred for erroneous channels.

Next, we consider the practical aspects of CR technology in hospital environments.

A. PRACTICAL SCENARIO OF CR IMPLEMENTATION ON ISM BAND IN A HOSPITAL

CR implementation in a practical hospital scenario must avoid EMI to protect users as well as to maintain an acceptable QoS. Hospital intensive care units (ICUs) and operating rooms contain non-communication electronic devices that can be interrupted by EMI from wireless devices. The solution of stopping secondary transmission in the presence of PU signal protects the PU, but cannot protect the non-wireless communication medical devices. A solution to guaranteeing electromagnetic compatibility for all medical devices is to estimate the user's location and to track the user during the operation time of the wireless devices. Two common approaches are using either radio frequency identification (RFID) tags attached to medical devices [14] or measuring time of flight of electromagnetic waves operating in upper UWB by using an active echo engine [13]. As RFIDs can cause interference to EMI-sensitive devices, the latter method seems to cause less interference to other medical devices in the vicinity of WBANs. Dong *et al.* [44] consider measuring the location of biomedical devices based on power consumption and channel coding. In [16], [18], and [45], practical scenarios for hospitals have been presented in which the CR controller uses the information collected in the database to adjust the transmission power. In addition to PU and mobile SUs, other main components for the cognitive radio enabled wearable hospital sensors are the inventory system, CR controller, and fixed non-life supporting and life supporting medical devices [45]. The inventory system is basically a database of all medical devices. Furthermore, the CR controller is a fixed controller to adjust the transmission parameters of mobile and uniformly distributed PUs and SUs.

The main issue of the EMI-aware medium access control (MAC) protocol proposed in [16] is the higher probability of outage compared to the traditional multiple access/collision avoidance protocol [45]. When the number of CR clients in a hospital area increases, the CR clients are not allowed to exceed the permitted transmission power level. This leads to outages as CR clients cannot reach the CR controller by the proposed protocol in [16]. Therefore, Chavez-Santiago *et al.* [45] alleviated the outage problem by using additional lower frequencies when the EMI causes some number of transmissions to get dropped. As depicted in Figure 7, they considered two channels in the ISM 2.4 GHz band, namely dedicated control channel (DCC) and data channel with an additional frequency band known as an emergency band. Candidates for emergency bands can be 2360–2400 MHz and 902–928 MHz bands [46], though the latter band results in reduced outage, compared with the former candidate for emergency band. The two candidates for emergency bands do not overlap with common IEEE 802.11 channels and the DCC and data channels. Also, the emergency bands are at a lower frequency range than ISM 2.4 GHz band to give a transmission chance to the dropped request by the CR controller on the DCC channel. By using a lower frequency band in the indoor environment, the CR clients, i.e., SUs can reach the CR controller with a lower power, lower outage probability, and can transmit their signals over a larger area.

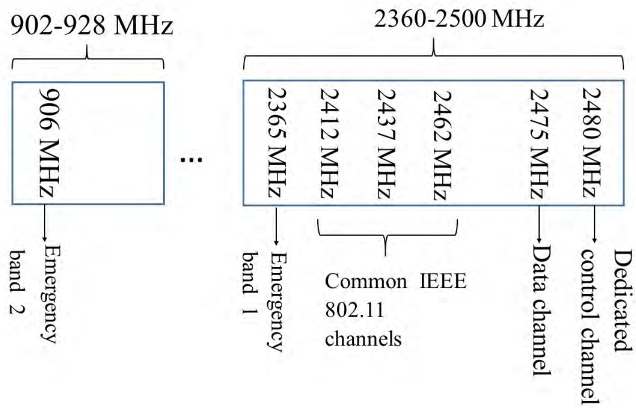

FIGURE 7. Two candidate emergency band frequencies used to decrease outage probability for WBANs without overlapping with IEEE 802.11 channels (based on [45]).

The mechanism of request-to-send/clear-to-send (RTS/CTS) protocol is depicted in Figure 8. If a CR client cannot transmit data on the DCC, it switches to an emergency band [45]. Compared to the EMI-aware RTS/CTS protocol in [16], the proposed protocol in [45] with two additional emergency channels can decrease the outage probability, especially in small spaces, such as ICUs with several medical devices.

B. PRACTICAL HOSPITAL SCENARIO OF UNDERLAY CR IMPLEMENTATION USING UWB

UWB technology offers plenty of opportunities for underlay CR-based WBANs mostly due to its noise like behavior, which is neither harmful to the patients nor to medical devices [18]. Unfortunately, CR-based WBAN implementation on the UWB in the literature for medical scenarios is limited, due to the lack of custom-made commercial transceivers specific to this application [18]. Pros and cons of applying underlay CR using UWB are listed in Table 10.

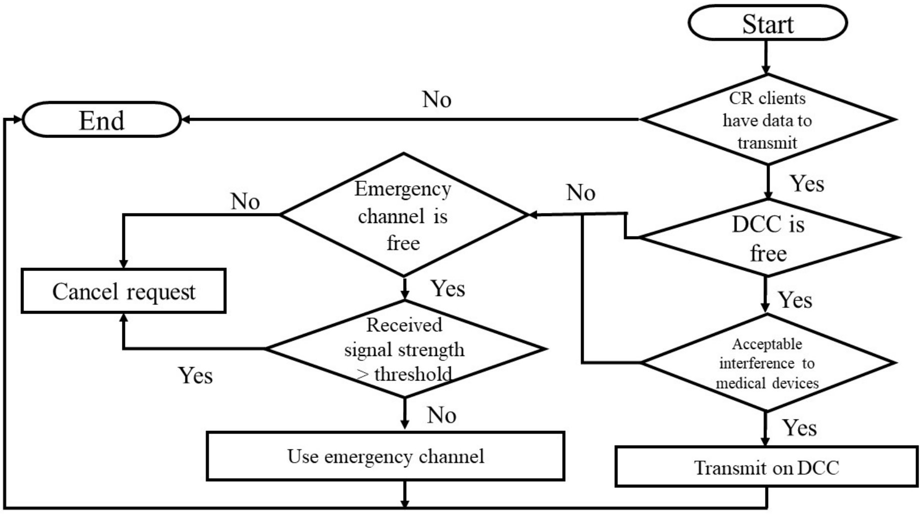

FIGURE 8. RTS/CTS for CR-based body area networks with emergency bands (based on [45]).

TABLE 10. Main features of underlay CR-enabled WBANs Using UWB technology.

	Frequency Ranges	Application	Advantages	Disadvantages
UWB [13]	3.1–3.4 GHz	Radiolocation systems	• Reduced power consumption • Simpler way to implement CR capability in the WBAN network controller • Higher communication rate and reliability • Security of patients' data (robustness against jamming) [18] • Patients' safety due to low-powered transmissions [18] • High processing gain [18] • Coexistence with narrowband systems through spectrum shaping [18]	• Higher complexity of transceivers • Incomplete spectrum monitoring campaign
	3.4–4.2 GHz	Broadband wireless access		
	8.9–9 GHz	Radiolocation systems		

In [18], two UWB modalities for both wearable and implanted transceivers are introduced, namely IR-UWB and MB-OFDM. As the first tier of CR architecture is composed of MWBAN sensors and CR controller on and around patient bodies, the range of communication is short and limited. The transmission in the first tier also consumes less power than the second tier. Therefore, Chavez-Santiago *et al.* [18], propose a solution for the communication within the first tier by tailoring the IEEE 802.15.6 standard. The proposed IR-UWB by IEEE 802.15.6 is based on either the transmission of a single and long pulse or burst of short pulses per symbol that can be used as communication links between MWBAN sensors and the CR controller. IR-UWB is covered by frequency band 3.1–4.8 GHz with three sub-bands due to better propagation characteristics. During the broadcast of signals between the sensors and the CR controller, one of these three sub-bands with the least probability of being occupied is chosen. IR-UWB system cannot be applied for the second tier as it cannot sense at which specific frequencies interference occurs. The transmission in the second tier needs a higher rate and can be achieved by ECMA-368, which is a high-rate UWB wireless standard for portable and fixed electronic devices. In MB-OFDM, modulated data are precisely spaced at mutually orthogonal carriers. As the symbols are interleaved over multiple sub-bands across both time and frequency, the power level is the same as a single band OFDM transmission, whereas the throughput is higher. MB-OFDM is covered by the higher frequency band 4.8–10.6 GHz with 11 sub-bands to achieve rates from 53.3 to 480 Mb/s over distances up to 10 m. This technology can also sense other narrowband or wideband interferences by using power spectral density information on each sub-band. Features of UWB technology for underlay cognitive WBANs, as in [18], are summarized in Figure 9. There is still a need for more rigorous quantitative evaluations of the feasibility of IR-UWB communications in the human body.

VI. DECISIVE PARAMETERS AFFECTING THE PERFORMANCE OF SPECTRUM SHARING WBANS

There is no single ideal model for benchmarking the design of high-performance CR-based WBAN systems. Some major

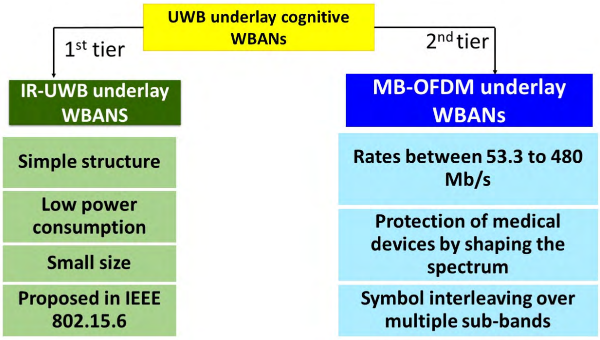

FIGURE 9. **Features of cognitive underlay WBANs using UWB technology (based on [18]).**

parameters that affect the performance of deployment of cognitive radio concepts in WBANs are

- number of APs,
- dynamic vs. fixed channel access time,
- number of secondary WBAN nodes, and
- priority of sensors.

Below, we explain these parameters in more details.

A. NUMBER OF APs

Beic *et al.* [30], obtain electromagnetic properties for a residential area composed of concrete walls, glass windows, wooden doors, tables, and fences to calculate the positions of sensors located on both moving and stationary bodies for the case of different numbers of APs. This radio mapping is updated when there is a difference between the received signal value and the calculation of the most likely propagation path. Here, using a predefined residential area can make the calculation of the required transmitted power easier. Also, it can make it easier to update the radio propagation mapping. Moreover, the results denote that in the case of a transmitter with a fixed constant power, there is no meaningful difference in battery consumption and the percentage of successful packet transmissions for a larger number of access points. However, when the transmitters have power control capability, increasing the number of APs leads to prolonged battery life. For instance, by increasing the number of access points from 1 to 6, the battery consumption decreases 18 times. Moreover, the percentage of successful packet transmissions for a higher number of APs increases as the probability of the data loss decreases owing to a wider coverage. In summary, the lesson learned is that when deciding to increase the number of APs, it is more beneficial to have APs with adaptable transmission power capability, rather than fixed power. This factor results in decreased battery consumption and lower probability of error.

B. DYNAMIC VS. FIXED CHANNEL ACCESS TIME

Although a longer channel access time can enhance the channel utilization, it negatively affects the communication reliability. The tradeoff between the utilization and reliability under dynamic channel access time scenarios clarifies that the channel utilization rises by 50%, while the collision rate stays almost the same as the system tolerance bound [22]. However, there is no trade-off between the utilization and reliability in the fixed channel access time.

As a result, it is beneficial for a CR-enabled WBAN to dynamically update the channel access time, rather than using a fixed value for access time. Particularly, when the channel access time adapts itself to the variations of the average packet collision rate, a secondary WBAN succeeds in utilizing the idle channels more efficiently. On the contrary, when a CR-enabled WBAN sets a fixed time for accessing the channels that are sensed to be idle, the channel utilization efficiency decreases. This may cause more packets to be dropped by the WBAN.

C. EFFECT OF THE NUMBER OF SECONDARY WBAN NODES

In [31] a network of secondary underlay WBANs share the spectrum with a cellular system as the primary user. Since the WBANs are operating in low-power underlay mode, they use cooperative relaying to get their message to the receiver. The results in [31] indicate that in the cooperative method, there is an optimal number for the secondary WBAN nodes acting as relays. After that, the increase in the number of relay nodes will cause performance degradation due to interference. In addition, the density of PU and SU nodes determined by the distance between them is an important factor affecting the performance. In a scenario comprising cellular users as the PU and CR-enabled WBANs as the SU [31], numerical results show that for a larger separation in distance between the cellular users and WBANs, the network capacity of the secondary users increases, owing to smaller interference. Collectively, parameters, such as the number of secondary WBAN nodes and the distance between CR-enabled WBANs and the PU system are determined by the amount of tolerable interference.

D. PRIORITY OF SENSORS

Medical WBAN sensors have different priorities. For example, WBAN sensors for the heart signal are more critical than WBAN sensors on a leg muscle. Based on the application and the priority, sensor nodes need different bandwidths. Finding a selection of the best available channels in terms of the received signal strength, energy efficiency, interference, transmission power, number of users, QoS, and security requirements, gives the SU the chance to transmit on the best channel. In this case, the CR performance improves, but the channel sensing process consumes more time and energy. Due to limited battery life of WBANs, there are tradeoffs for performance and channel selection energy consumption, while trying to serve users with higher priority.

Admission control is determined by priority. Different patients may have different priorities based on their health conditions. For example, ICU patients should be given higher priority than general care patients [47]. Given that a system can support a maximum number of users, the goal of the admission control procedure is to accommodate as many high-priority users as possible. Consider a system with several MWBANs and one scheduler. Each MWBAN has a coordinator and some sensors. The scheduler schedules intra-MWBAN transmission from sensors to their coordinator. When only one channel is available, the scheduler uses TDMA scheme [47]. Denote a high-priority user (e.g., ICU patient) by i and a low-priority patient by j. A group of users that are far enough can simultaneously transmit without interference. In a frame of length T, denote by t_m the time allocated to the mth group of non-interfering MWBANs. Indicator function $f_{i,m} = 1$ if the ith MWBAN belongs to the non-interfering group m of MWBANs.

Denote by u_i the minimum amount of data required to be transmitted in a frame by MWBAN i. In addition, denote the transmission rate of user i by r_i. Low-priority users are only allowed to transmit if all high-priority users have been served with their minimum requirements, i.e., a minimum transmission time $\tau_i = \frac{u_i}{r_i}$. Consider an indicator x_i such that $x_i = 1$ if user i accesses the system and $x_i = 0$ otherwise. The admission control can be formulated as the following optimization problem:

$$\max \sum_i x_i \tag{1}$$

$$\text{s.t} \sum_m t_m \leq T \tag{2}$$

$$(\sum_m f_{i,m} t_m - \tau_i) \quad x_i \geq 0 \tag{3}$$

$$x_j \leq x_i \tag{4}$$

$$x_{i'} = x_i \tag{5}$$

Constraint (2) implements the TDMA scheduling within a frame of length T. Constraint (3) indicates that a high-priority patient accesses the system ($x_i = 1$) only if its minimum traffic demand is satisfied, i.e., $f_{i,m} t_m \geq \tau_i$. Constraint (4) prevents a low-priority user j from transmission if a higher-priority user i cannot access the system. Finally, constraint (5) implements fairness among high-priority users i' and i. Solving the above optimization problem guarantees that MWBANs of higher priority (e.g., ICU) patients in hospitals are not affected by MWBANs of low-priority patients [47].

Higher priority WBAN packets may be sent with higher transmission power than lower priority WBAN packets [48]. Packets of urgent information experience less collision than lower priority packets. Since, the receiver discards the lower priority packet if it is transmitted at the same slot as the higher priority packet. Cognitive radio entails a PU, which has priority over SU. Therefore, cognitive radio comes to the help of critical WBAN sensors by the mechanism of prioritizing them over non-critical nodes.

To summarize, the results of [48] indicate that when the lower priority WBAN nodes face collision with higher priority nodes, they should not retransmit their packets beyond a certain number of trials. Since, this increases the packet dropping rate and saturates the throughput of lower priority WBANs. On the other side, when the higher priority WBAN sensors collide with each other, they try retransmitting their packets. This retransmission for critical WBAN nodes increases the throughput of higher priority traffic, while having adverse effects on the throughput of lower priority traffic by rejecting non-critical WBAN sensor data. Nevertheless, even the throughput of the high-priority traffic can saturate by too many re-transmissions. Accordingly, the level of priority of WBAN nodes dictates the threshold for the number of trials after collision.

VII. MEDIUM ACCESS CONTROL PROTOCOLS FOR CR-BASED WBANS

There are several MAC protocols proposed for WBANs as well as cognitive radio networks in the literature. Nevertheless, there are quite a few works on MAC protocols for CR-enabled WBANs (e.g., [21], [49], [50]). The MAC protocols presented in various technologies, such as IEEE 802.11 (WiFi), IEEE 802.15.6, and IEEE 802.15.4 (ZigBee) need to be modified specifically for CR-based WBANs. The reason why general MAC protocols for WBANs cannot completely fulfill the requirements of CR-based WBANs is that these protocols only operate on specified spectral bands, while the CR paradigm operates on different channels during the transmission time.

Ignoring the cognitive radio and spectrum sharing, the majority of MAC protocols for WBANs are either contention-based, such as CSMA/CA or reservation-based, such as time-division multiple access (TDMA) [4]. The power consumption in CSMA, which is a result of collisions, is a major shortcoming [51]. Besides, physiological data from WBANs are typically correlated, i.e., a single physiological change triggers sensors at different parts of the body at the same time. This, in turn, generates bursts of traffic that unslotted CSMA/CA protocol cannot handle [52].

The IEEE 802.15.6 standard modifies TDMA by defining exclusive access phases for high-priority emergency patients' signals. The IEEE 802.15.6 standard can be utilized in the first tier, followed by a distributed reservation based MAC protocol, such as ECMA-368 in the second tier [18].

For the most part, to implement CR functionalities in WBANs, the existing general MAC protocols must have devotion to maintain a longer battery life. Longer battery life results in small sized sensor nodes on the body to allow patient's mobility.

A. ENERGY EFFICIENCY IN CR WBAN MAC MECHANISMS

In this part, we present an overview of MAC protocols for CR-based WBANs. Our focus is on how these protocols address energy efficiency between sensor nodes and the CR controller. In CR-enabled WBANS, the emphasis is on decreasing the amount of energy consumed for searching idle channels. Collision of packets, overhearing of data of other sensors, listening to channels to find out whether

TABLE 11. MAC protocols for CR-based WBANs.

Reference	Channel sensing parameter	Channel access method	Energy efficiency solutions	Performance evaluation metric
[21]	RSSI value of collision rate	Interweave	• Low-power programmable SoC • Centralized spectrum sensing	• Collision rate vs. interference traffic • Throughput vs. interference traffic
[18]	Power spectral density	Interweave	• IR-UWB technology	
[49]	RSSI	Underlay	• Two-level transmission power • No SU switching when the time duration of interference is short.	• Delays vs. transmission power • Energy per packet vs. transmission power

other WBAN nodes are using them, and the use of control messages are major factors that waste some of the power in WBANs [51].

For instance, to decrease the energy consumption in CR MAC, C-RICER (Cognitive-Receiver Initiated CyclEd Receiver) design uses a power adaption strategy to make switching decision. By decreasing the amount of channel switching and staying on the occupied channel for a short time, even with a higher power, the energy can be saved [49]. MAC layer designed for cognitive WBANs using HCVP (Hybrid Cognitive Validation Platform) [21] has the advantage of a centralized spectrum sensing scheme to achieve energy efficiency. In this scheme, a coordinator with less energy constraints controls the data exchange and channel access. In the CR-MAC protocol [50], package priority based on the criticality of the health information controls the power level.

A method to tackle the challenge of designing a cognitive MAC protocol for WBANs is to adjust an available MAC protocol for WBANs. In this regard, the C-RICER protocol [49] adds the cognitive functionality to an available energy-efficient MAC protocol. In a traditional MAC protocol from RICER (Receiver Initiated CyclEd Receiver) family, the data exchange starts when the coordinator with less energy constraints receives buzz signals from sensors with data to send. To include the cognitive task into the traditional protocol, transmission power control and channel switching based on the interference level must be considered. At first, the coordinator as the only receiver senses the channel interference level based on the RSSI for a certain time. This protocol deploys two interference threshold levels and two transmission power levels for each transmitter. If the interference is less than the lower threshold level, the coordinator sends wake up beacons to the sensors to enquire about whether sensors have data to send or not. As switching to a different channel when the interference appears for a short time can lead to a higher power consumption, this protocol considers increasing the transmission power for a short time when the interference exceeds the lower threshold but not the upper threshold. The value of the upper threshold is set to a level where the interference starts to affect the packet error rate, yet not affecting the transmission of control packets.

After each channel sensing, if the RSSI of the current channel is less than the lower threshold, the sensor node transmits at the default power level. If the coordinator detects that the interference level of the current channel is greater than the lower threshold, but less than the upper threshold, the transmission power is increased to the second level. Then, the coordinator rescans the channel to find out whether the RSSI of the current channel is reduced to below the lower threshold or not. In the former case, the node can resume transmission at the lower power level. In the latter case, if the RSSI level is still higher than the lower threshold, the coordinator scans the remaining channels and the nodes switch to a new channel that has the lowest interference level. As such, the transmission power can be reduced to the default value. This is the key to energy efficiency of the C-RICER MAC protocol.

In [18], IEEE 802.15.6 MAC and ECMA-368 protocols have been adopted to design a modified MAC protocol for CR-based WBANs in the first and the second tier, respectively. The IR-UWB technology, which is a key factor to energy efficiency was described earlier. Here, ECMA-368 provides a prioritized contention-based channel access as well as reservation-based access mechanism. In [21], an adaptive CR MAC has been proposed, which uses the low-power system on chip (SoC) to achieve energy efficiency. In this protocol, when a suitable channel is found, the coordinator will transmit a beacon signal to inform the WBAN nodes to be prepared for broadcasting the physical data. In Table 11, MAC protocols for CR-based WBANS are compared from the viewpoint of energy efficiency solutions and the applied metrics.

VIII. MAJOR CHALLENGES OF CR-BASED WBAN DESIGN AND FUTURE RESEARCH DIRECTIONS

Below, we discuss obstacles of full-fledged implementation of cognitive radio enabled WBANs.

A. CHALLENGES IMPOSED ON WBANS BY THE PHYSICAL ENVIRONMENT

Human bodies are sophisticated inhomogeneous communication channels. The movement and posture of the human body can cause shadow effects on signal propagation. The path loss caused by shadow effects may range from 5.6 dB to 15.8 dB [8].

The effect of human body movement with a speed of 5 km/h is considered by Beic *et al.* [30] in cognitive body area networks. They simulated different sensor power requirements for different network topologies in a residential area. The WBAN sensors moved with respect to an AP. Their power control method calculates the transmission power required to reach the receiver, based on the observed characteristics of the environment. Their simulations show that their method provides a higher coverage and packet transmission rate using the lowest amount of battery power, compared with the cases when the transmission power is fixed to 1 mW and 100 mW.

Another challenge in this area is multidirectional reflection due to the surrounding environment. Moreover, the antenna and the body together can cause a coupling effect. Therefore, the positions of the sensor nodes play an important role in both the coupling effect and the reflection. These factors introduce challenges for designing CR-based WBANs as the transmitted signal weakens more than expected. For example, they can negatively affect the accuracy of spectrum sensing in the interweave CR paradigm. Likewise, they cause errors in the underlay CR paradigm when a WBAN must keep its interference to the PU below a certain threshold.

B. POWER CONSUMPTION CONSTRAINTS

To not restrict patients' mobility, sensors must have small batteries and tiny sizes. In addition, as sensors are placed very close to a human body, CR power consumption is not only limited by the implemented CR paradigm (underlay, interweave, or overlay) and the device power, but also by the patients' safety criteria.

The power consumption constraint is an important metric in designing body sensor nodes [53], including the ones with CR capabilities. Specifically, in interweave or overlay CR body area networks, the power consumption constraints of body tissues must be taken into account. The power consumption profile for patient monitoring using wireless intelligent sensors suggested by Jovanov *et al.* [54] is $400\mu A$ in active mode and less than $1\mu A$ in standby mode. Energy harvesting for CR-based WBANs is an area that still needs further investigation [55]. Next, we address the issue of interference among body area networks (BANs).

C. INTER-BAN INTERFERENCE

The interference caused by other physically located WBANs can impact the QoS. As patients carrying these wearable sensors move, there is a high possibility that these operating BANs will come in the proximity of each other [56]. To alleviate the interference problem with growing density of CR MWBANs in an area, a variant of TDMA with flexible rather than fixed slot times can be used. More specifically, when the density of CR MWBANs increases, the number of TDMA slots increases to reduce the inter-BAN interference [57].

In addition, interference is a challenge against the adoption of existing MAC protocols for CR-enabled WBANs. In CR-enabled WBANs, the medical devices or the WBANs with the role of PU have a higher priority over SUs. The issue of PU protection from the SU interference needs to be addressed in the design of MAC schemes for CR-enabled WBANs. The solutions should also consider the CR paradigm that is being used. For example, in the underlay spectrum access paradigm, the SU signal should appear as noise to the PU, whereas in the interweave CR paradigm, SUs consume some of their power to switch to vacant channels to avoid collision with PU packets.

The inter-BAN interference is mostly caused by hidden and exposed nodes [58]. In the case of hidden nodes, the sensor node A can hear its relevant coordinator and the adjacent coordinator B, but it cannot hear sensor node B. This can lead to interference on coordinator B. In the case of an exposed node, a WBAN node A can hear both its own coordinator and node B from another WBAN. Therefore, when node B transmits, node A mistakenly concludes that the channel is taken and refrains from sending the message to its own coordinator.

To solve the inter-BAN issue, RTS/CTS has been suggested to improve the CSMA/CA transmission protocol for the IEEE 802.15.6 standard used in wireless body area networks [58]. With the assumption of perfect synchronization between sensor nodes and the coordinator of each BAN, a backoff counter is used to reduce the percentage of simultaneous transmissions by the sensor nodes. The backoff counter begins from a randomly chosen number related to the priority type of the traffic. If the channel is idle for a pre-determined time duration, the backoff counter is decremented by one for each upcoming idle slot. Data exchanges between the sensor nodes and the coordinator only occur when the counter reaches zero.

However, when the range of the random number selection for the backoff counter is small, more concurrent transmissions by the nodes of the same WBAN become more likely. In light of this, the need still exists for more advanced interference cancellation and interference avoidance schemes for WBANs. Effective parameters causing Inter-BAN interference are depicted in Figure 10.

D. ADJACENT CHANNEL INTERFERENCE PROBLEM

When a SU detects a channel as idle, it proceeds with transmission on that channel. SU transmissions can cause destructive interference to the PU signals located on adjacent channels. A solution to this problem is channel bonding of contiguous non-overlapping channels [32]. Although the resulting aggregated bandwidth increases the packet

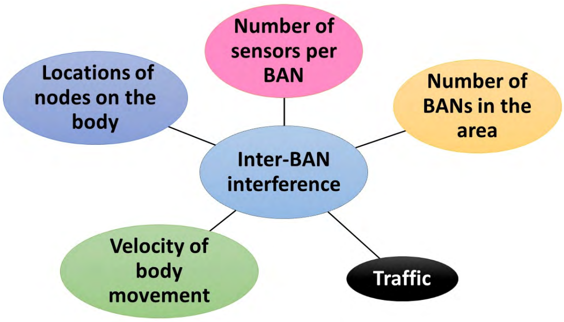

FIGURE 10. Effective parameters causing inter-BAN interference.

transmission rate, it increases the energy consumption as well as the chance of being interrupted by the primary signal. In addition, since separate modulators are required for bonded channels at different carrier frequencies, channel bonding can be challenging due to hardware and software changes at the transmitter and receiver [59].

E. SECURITY

The health information parameters collected by WBANs are highly confidential. Hence, traditionally, the transmitted medical information is being encrypted for protection against intrusions. Addressing security in WBANs, despite resource constraints and harsh environment conditions, brings additional challenges to the design of WBANs [60].

In CR-based WBANs the nodes responsible for channel sensing and channel access can also be attacked, and they are even more vulnerable to attacks as the attackers can prevent SUs transmission only by emulating PUs signals [61]. For example, the channel can be sensed as occupied by sending manipulating signals over primary user frequencies [62]. In underlay CR-based WBANs using UWB, to avoid a jamming signal, nodes have access to a wider frequency range, which can increase the security. However, providing security for WBANs requires processing power, which is an energy consuming task for power constrained wireless body area networks. It is noteworthy to mention that the other energy consuming tasks for CR enabled WBANs are channel sensing and transmission [35].

In addition to the above-mentioned challenges, some other future research directions on CR-enabled WBANs are:

- Routing in CR-based WBANs; and
- Broadcasting in CR-based WBANs

IX. CONCLUSION

In this survey, we reviewed existing CR-enabled WBAN schemes discussed in the literature. We tried to present a whole vision of common issues with the deployment of spectrum sharing WBANs in medical environments. Moreover, possible interference scenarios were reviewed to emphasize the importance of cognitive radio as a solution. Then, CR-enabled WBANs were discussed from a variety of viewpoints. A comparison between the common methods of spectrum sensing as well as spectrum access was presented. We also focused on the fixed and triggered sensing and access timing methods. Coming up with a practical scenario to avoid data transmission failure in emergency situations is a challenging task. Although there are several works in the literature on cognitive radio applications in health care environments, there is still the need for the thorough adoption of cognitive radio concepts in medical communication use cases. For example, data prioritization based on the vitality and importance of the medical application still needs further investigation. This prioritization can highly affect the CR controller decision to continue channel sensing or to switch to the emergency bands set aside for time critical medical applications. In addition, another research direction is further investigation of the performance of CR-enabled MWBANs with moving bodies.

ACKNOWLEDGEMENT

The authors would like to thank the anonymous reviewers for their comments to improve the quality of this manuscript. B. Bozorgchami was with the Electrical Engineering Department, California State University, Long Beach, CA, USA.

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