Applications of Software-Defined Radio (SDR) Technology in Hospital Environments

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Abstract—A software-defined radio (SDR) is a radio communication system where the major part of its functionality is implemented by means of software in a personal computer or embedded system. Such a design paradigm has the major advantage of producing devices that can receive and transmit widely different radio protocols based solely on the software used. This flexibility opens several application opportunities in hospital environments, where a large number of wired and wireless electronic devices must coexist in confined areas like operating rooms and intensive care units. This paper outlines some possible applications in the 2360–2500 MHz frequency band. These applications include the integration of wireless medical devices in a common communication platform for seamless interoperability, and cognitive radio (CR) for body area networks (BANs) and wireless sensor networks (WSNs) for medical environmental surveillance. The description of a proof-of-concept CR prototype is also presented.

I. INTRODUCTION

A software-defined radio (SDR) is a radio communication system where the major part of its functionality is implemented by means of software in a personal computer or embedded system. The term "software radio" was first used in 1984 by a team at the Garland Texas Division of E-Systems Inc. [1] to refer to a digital receiver; years later, J. Mitola independently invented the term and described some of its architecture principles [2].

In a SDR, significant amounts of signal processing are handed over to a general-purpose processor, rather than being done in special-purpose hardware. Hence, in principle a SDR can receive and transmit widely different radio protocols, commonly referred to as waveforms, based solely on the software used. A main issue for the implementation of SDR is deciding how flexibly the waveform can be changed through changing software without modifying the SDR Platform, i.e, the combination of hardware and operating environment where the waveform application is running. Although the ideal goal is to be able to communicate at any desirable frequency, bandwidth, modulation, transmit power, and data rate by simply loading the appropriate software, this is unrealizable with current platforms, and thus more practical approaches are generally adopted [3]. Usually, large parts of the waveform are defined in software, giving the flexibility to change the waveform within certain bounds as given by the actual system. Figure 1 shows the generic block representation of a digital communication transceiver and the parts that can be implemented in software.

The aforementioned waveform flexibility, together with other practical characteristics, makes SDR an attractive solution for a number of communication issues in hospital environments. The increasing use of wireless sensor networks (WSNs) in medical practice is creating challenging problems for the interoperability of medical devices [4], [5]. When there is a need for medical data to flow from a device to another vendor's automated system, SDR can help to bridge more seamlessly the different communication protocols. Additionally, SDR can be exploited for the implementation of cognitive radio (CR) systems in hospital environments [6]–[8]. A CR system can automatically detect available channels in the electromagnetic spectrum and accordingly change its transmission/reception parameters thereby facilitating the coexistence of various wireless communication systems in a given frequency band at a place. This can be achieved in a SDR platform by instantly changing parts of the waveform processing through loading different software modules.

In light of the most recent technological advances that enable the implementation of SDR system prototypes [9], this paper outlines the applications of this technology for medical communication systems. The benefits that SDR can potentially bring to the healthcare sector are thoroughly discussed. The rest of the paper is organized as follows: in Section II we discuss the use of SDR technology for alleviating the problem of interoperability of medical devices. Section III is devoted to the application of SDR as the enabler of CR solutions for medical wireless systems and a proof-of-concept prototype is described. Finally, Section IV summarizes our conclusions.

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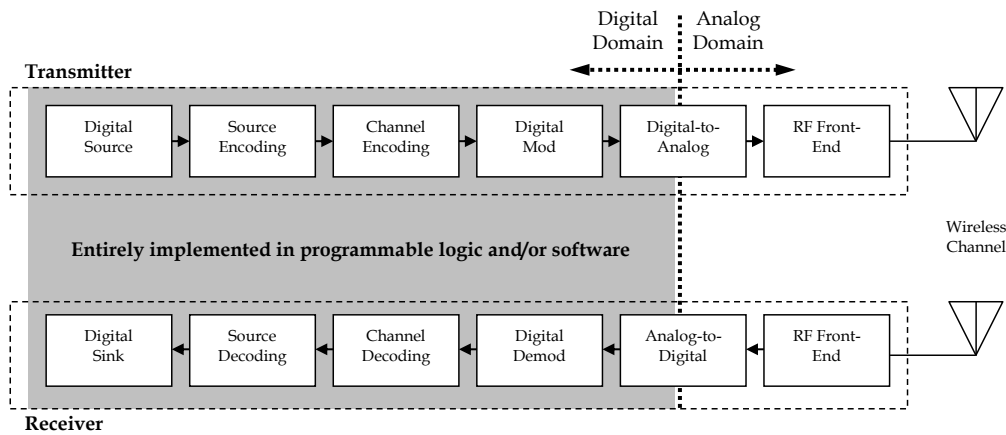
Figure 1. Generic representation of a digital communication transceiver [9]. The blocks that can be implemented in a SDR platform are indicated.

II. INTEROPERABILITY OF WIRELESS MEDICAL DEVICES

In hospitals and other clinical facilities, electronic medical devices are playing an ever-increasing role in healthcare delivery. These devices have the ability to capture critical medical data but, for the most part, they lack interoperability, i.e., the ability to communicate seamlessly with one another. In order for medical data to flow from a device to another vendor's automated system, it is necessary to develop interfacing software and extra processors, which adds expenses and potentially reduces overall system reliability. The current lack of interoperability is one of the most daunting challenges facing the integration of advanced technologies in healthcare and medical practice. This problem may prevent medical staff from having timely access to critical data that would help them provide the safest and most effective patient care. Interoperability has many practical, technical, and commercial implications that have prevented broad implementation and adoption. Nevertheless, governmental institutions, standardization bodies, and vendor-alliance organizations are working toward a vendor-neutral solution to the medical device communication problem. Such a solution could enable the easy integration of new medical sensors and actuators (manufactured by small vendors) with the existing infrastructure as they become available. Currently, "plug-and-play" interoperability for medical devices is, in practical terms, inexistent. SDR technology can greatly help alleviate this problem, particularly in device-to-device communication at point-of-care and personal health settings.

A. The Use of the 2.4 GHz ISM Frequency Band

Wireless medical devices operate in several frequency bands under various national and international rules. The Medical Implant Communication Service (MICS) operates globally in parts of the 401–406 MHz frequency band, including the United States and Europe. Nevertheless, the frequency bands for Wireless Medical Telemetry System (WMTS) are not harmonized globally or regionally [10]. This has motivated many vendors to consider the production of devices operating in the unlicensed industrial, scientific and medical (ISM) bands such as 902–928 MHz and, more

typically, in 2400–2500 MHz (2.4 GHz ISM band). Some commercially available short-range transceivers (motes) utilize communication standards such as Bluetooth (based on IEEE 802.15.1), Bluetooth low energy (BLE), and ZigBee (IEEE 802.15.4). In addition, WiFi (IEEE 802.11) networks in this band are ubiquitous and can be found from acute care clinical settings to home environments where body area networks (BANs) [11], [12] are envisaged to operate. It has been demonstrated that the safe integration of medical devices in a wireless clinical monitoring platform is feasible if the same radio communication protocol (e.g., IEEE 802.15.4) is adopted by all the device manufacturers [13]. When other different radio interfaces are used, plug-and-play interoperability is not possible.

B. The Universal Access Point for Medical Devices

In such scenario, SDR technology can be very useful for the integration of medical devices in operating rooms, emergency rooms, and intensive care units. In a star network topology, the wireless medical devices transmit the information they collect to an access point through a point-to-point radio link. By loading different software modules for each of the waveforms used in the network, a SDR platform can function as a Universal Access Point (UAP) as shown in Fig. 2. A multiplexer (MUX) or a specially designed software application can manage the collected information for display on a patient monitor. This approach can make plug-and-play interoperability possible, even for devices utilizing proprietary waveforms, since vendors can make available the software implementation of their own communication protocols to be loaded in the UAP. In this case, the radio frequency (RF) front end operates in the 2.4 GHz ISM band, which is readily available in commercial SDR platforms (e.g., https://www.ettus.com/product). In the future, when SDR technology is available for implementation in very small devices such as medical sensors, full plug-and-play interoperability will become a reality because then, the UAP will decide what waveform is more convenient to use for certain time and location depending on the spectrum occupancy and interference conditions. Hence, all the transmitting medical devices will homogenize the radio interface used in the medical monitoring platform according to the UAP commands.
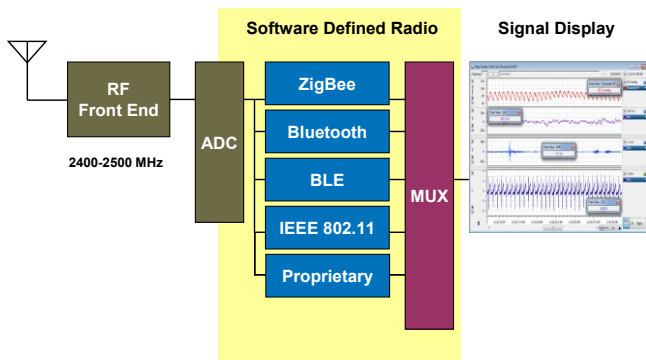
Figure 2. Block diagram of the UAP for wireless medical devices in the 2.4 GHz ISM band.

III. Cognitive Radio in Clinical Settings

Quality of service (QoS) is a key requirement for medical communications, especially when sensor data for clinical decision support in critical care are transmitted. Hence, medical BANs must operate in relatively interference-free conditions. This is difficult to achieve in the 2.4 GHz ISM band. On May 2012, the Federal Communications Commission (FCC) voted to set aside protected broadband spectrum for BANs in the United States. With this ruling, the FCC has allocated 40 MHz of spectrum, i.e., 2360−2400 MHz, for use by BAN devices on a shared, secondary basis. This provides a spectrum band for short-range medical technologies to facilitate reliable low-power operation. However, BAN devices must be equipped with the capability to access the spectrum dynamically in order to protect primary users (PUs). Here, the flexibility of SDR can be exploited for effective implementation of CR for BANs [14]; this approach, combined with the UAP in Fig. 2, can make possible the use of the whole 2360−2500 MHz band without the risk of mutual harmful interference with other radio devices. Besides the use of BAN for the monitoring of physiological signals, other WSNs can be used for ambient surveillance in hospitals collecting data like temperature, humidity, and CO_2 levels. These WSNs can coexist with medical BANs through CR too, as described below.

A. Implementation of Cognitive Radio

The implementation of CR for BAN/WSN requires a dynamic spectrum access (DSA) framework to perform the main CR functionalities, namely spectrum sensing, spectrum decision, and spectrum handoff. The first functionality needs to be implemented in the network nodes since they must gather spectrum occupancy information. By analyzing these data, the nodes make a decision about transmission parameters (channel, transmission power, and/or modulation). Upon deciding on the available channels and transmission parameters, the nodes perform spectrum handoff or spectrum mobility. Depending on the hardware performance, the handoff may cause long delays or buffer overflows that reflect on the application performance.

B. Proof-of-Concept Cognitive Radio Prototype

We implemented a proof-of-concept surveillance WSN on a Sun SPOT platform (http://www.sunspotworld.com/) that demonstrated the DSA flexibility of CR [8]. For this sake, the Sun SPOT surveillance nodes were treated as secondary users (SUs) transmitting on ZigBee links collocated with PU medical IEEE 802.11 or IEEE 802.15.4 transmissions. Figure 3a illustrates the Sun SPOT testbed components. The WSN nodes, i.e., Sun SPOT devices (Fig. 3b), have in-node processors, transceivers that send the data wirelessly to the sink, and they were equipped with environmental sensors. The sink node, also referred to as base station (BS), was connected to a PC and was driven by the host application. The DSA was performed by using energy detection for spectrum sensing, centralized decision making, and spectrum handoff driven by the exchange of control messages between the BS and the nodes. The Sun SPOT devices measured the spectrum occupancy and the centralized decision making host application drove the spectrum handoff aiming to switch the BS and the remote nodes to an unoccupied channel for surveillance data transmission when a PU was detected.

In a laboratory experiment, a spectrum analyzer was used to detect the presence of IEEE 802.11 activity in the 2.4 GHz ISM band (Fig. 4a). Then, the surveillance information (SU data) was initially transmitted on the unoccupied ZigBee channel 26 (Fig. 4b). When medical information (PU data) assumed to be transmitted by a BAN was detected in the same channel, the surveillance data transmission was shifted to ZigBee channel 12 (Fig. 4c).

C. Perspectives

The encouraging results of the aforementioned experiment provided the motivation to consider the implementation of the centralized decision making unit on a more flexible SDR platform. For instance, implementation of an IEEE 802.15.4 physical layer (PHY) on a GNU Radio-based Universal Software Radio Peripheral 2 (USRP2) equipped with the RFX2400 daughterboard was demonstrated in [14] for CR. In this case, an energy detection spectrum sensing engine was implemented on the USRP2.
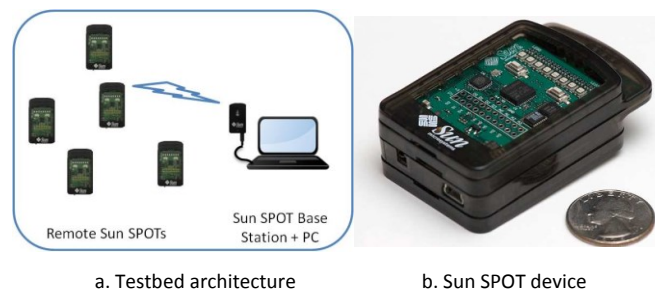

a. Testbed architecture   b. Sun SPOT device

Figure 3. Sun SPOT testbed architecture.

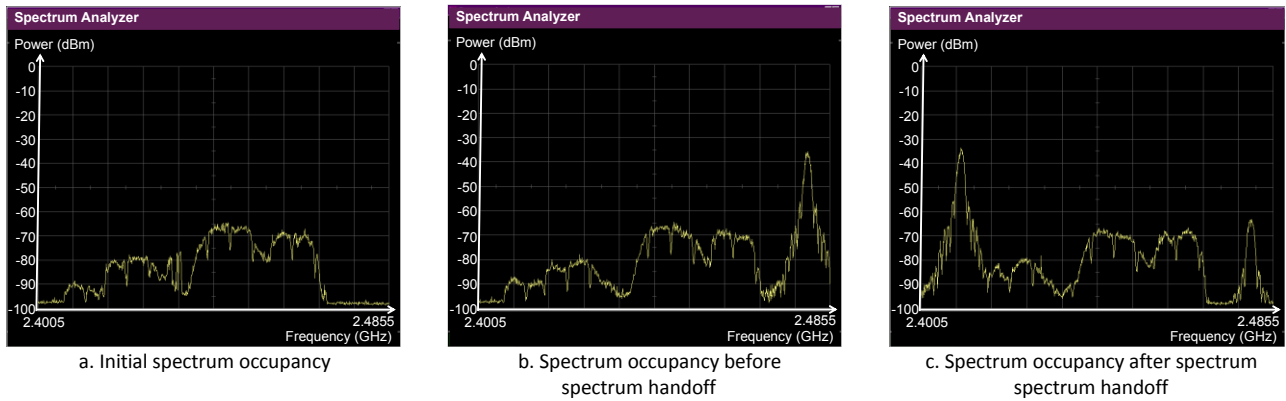| a. Initial spectrum occupancy | b. Spectrum occupancy before spectrum handoff | c. Spectrum occupancy after spectrum handoff |

Figure 4.   Spectrum occupancy measurements in the 2.4 GHz ISM band.

We will implement a similar SDR testbed. The RFX2400 daughterboard allows transmissions in 2300–2900 MHz, which perfectly covers the whole 2360–2500 MHz frequency band for use in clinical settings. In this case, however, we will aim to maintain the spectrum sensing capabilities in the network nodes as in the Sun SPOT demonstrator. Eventually, other PHYs like IEEE 802.11 and Bluetooth might be added. Our ultimate objective is to implement a proof-of-concept prototype for the UAP as suggested in Fig. 2, adding CR capabilities for coexistence of all the medical and nonmedical devices operating in confined places commonly found in hospital environments.

IV.   Conclusion

In this paper we have outlined the different applications that SDR can have in clinical settings. Two major benefits were identified, namely device interoperability and cognitive radio. We proposed the architecture of a Universal Access Point, which can enable "plug-and-play" interoperability of medical devices. Although SDR have significant applicability in hospital environments, the ideal SDR scheme is not completely realizable due to the actual limits of the technology. The main problem in both directions is the difficulty of conversion between the digital and the analog domains at a high enough rate and a high enough accuracy at the same time. Hence, after the planned physical implementation, the SDR system has to be tested with real medical data in a clinical setting like an operating room and its performance must be evaluated. Compliant with safety and reliability requirements for medical communications will be decisive for the adoption of this technology. Clearly, much work remains to be done.

Acknowledgment

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