Coexistence of Wireless Systems for Remote Monitoring of Vital Functions in the Unlicensed ISM Band

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Keywords: Wireless Body Sensor, Hospital, Telemedicine, Remote Monitoring, Coexistence.

Abstract: A recent trend in medical practice is the use of wearable wireless body sensors (WBS) to improve mobility of patients and medical personnel during surgery and other procedures, accelerate patients' recovery, and facilitate remote monitoring of patients suffering from chronic diseases. Currently, Wireless Body Area Networks (WBANs) are being introduced in already crowded unlicensed frequency bands, such as the ISM band. This essentially leads to high interference with other electronic devices, low signal-to-noise ratio and links with high bit-error rate. This paper discusses the requirements, benefits and issues related to a WBS in a medical WBAN system for remote health monitoring, operating in the shared ISM frequency band. We investigate the applicability of the concepts of cognitive communications in such environment to enhance the coexistence, robustness, scalability, and utility of medical WBAN systems in heterogeneous wireless networks environment.

1 INTRODUCTION

The health of hospitalized patients is regularly assessed by periodic measurements of vital functions' indicators, such as respiratory rate, heart rate, blood pressure and body temperature. With close monitoring and dynamic change detection of these patient's parameters, necessary medical assistance can be provided. If the patient's condition deteriorates and continuous monitoring is needed, the patient is transferred to the intensive care unit. However, the intensive care units have a limited number of beds. In addition to the issue of intermittent monitoring of vital functions in non-intensive wards, there are other weaknesses in the current health care system.

The interpretation of the patient's condition and the subsequent measures most often depend on the medical personnel, who could be, in certain conditions, overwhelmed with work or busy with other patients. The measured indicators can also be inaccurate, sometimes being biased by the inexperience of the medical personnel or patient's stress, and therefore unreliable. The subsequent interpretation of the documented measurements can be difficult because they may be based on insufficient or unreliable data.

The introduction of contemporary information and communication technologies (ICT), as a support to medical procedures and activities, is one of the possibilities to increase the efficiency of the health care system and to decrease its costs. This basic premise is included in all strategic plans of the EU and the rest of the world (European Union, 2004; Dzenowagis & Kernen, 2005; World Health Organization, 2006). Numerous studies have confirmed the benefits of the development of Telemedicine/Telecare systems (Chaboyer, et al., 2008; Ekeland, et al., 2010). In this respect, wireless communication technologies are increasingly used in various medical applications, significantly enhancing patients' mobility after surgical procedures and interventions, which can potentially lead to earlier patients' discharge from hospitals. Additionally, wireless communications allow remote monitoring of chronic patients and the elderly at home. More specifically, the trends in recent years are towards wireless body area networks (WBANs) applied for patient monitoring (Coronel, et al., 2004).

Although WBANs offer many benefits for monitoring and telecare, their introduction in hospital environments creates additional interference problems that need to be carefully assessed and mitigated. Namely, most of the WBANs include medical sensors operating in the unlicensed

Rashkovska A., Trobec R. and Mohorčič M..
Coexistence of Wireless Systems for Remote Monitoring of Vital Functions in the Unlicensed ISM Band.
DOI: 10.5220/0005284306280633
In *Proceedings of the International Conference on Health Informatics* (HEALTHINF-2015), pages 628-633
ISBN: 978-989-758-068-0

frequency band at 2.4 GHz (referred to as ISM band - industrial, scientific and medical radio band). Moreover, the ISM band is regularly used for transmissions in the operating rooms where surgical procedures are routinely assisted by electronic devices that potentially can interfere with the wireless sensors or vice versa. Also, there are a number of other medical devices that transmit critical information wirelessly, as well as ubiquitous consumer devices with Bluetooth and Wi-Fi access.

In this paper, we consider applying transceivers in wireless medical equipment that are capable of dynamically adjusting parameters like frequency, bandwidth/data-rate, and transmitter power level, based on awareness of the environment in which they operate, and thus avoid or minimize mutual interference. More precisely, we propose the use of the concepts of cognitive communications - a challenging area with many approaches, various development trends, and future directions still being in the research focus (Fortuna & Mohorčič, 2009; Steenkiste, et al., 2009). In this paper, we do not focus on the operational aspects of cognitive communications, but rather on their applicability to improve the coexistence of wireless systems for remote monitoring of vital functions with other systems operating in the same frequency band.

The rest of the paper is organized as follows. In Section 2, we discuss the requirements for a body sensor to be considered in a WBAN for telemedicine purposes. This section also includes the description of a custom developed multifunctional wireless body sensor. Section 3 describes the architecture of the proposed telemedicine system, discusses the issues in such operating environments and outlines the applicability of cognitive communications approaches to improve the coexistence in the ISM band. Finally, Section 4 briefly summarizes the paper.

2 MEDICAL WIRELESS BODY SENSORS

The main requirements for a wireless body sensor (WBS) in a medical environment include comfort, lightweight, low cost, low power signal, operation under various environmental conditions and interference avoidance (Ikehara, et al., 2007). Having a comfortable WBS that the user voluntarily wears is one of the main criteria that a WBS should fulfil. Light-weighted WBS furthermore improves user comfort and allows for multiple sensors to be comfortably worn at the same time. Low cost WBS would make the WBAN system suitable for mass manufactured health sensor networks.

Two aspects should be considered regarding the transmit power of the WBS signal. First, since the sensor is placed on the human skin for medical use, the radiation caused by the large wireless transmission power may have negative impact on the human health. Second, in order to extend the life of the sensor's battery, the power consumption for the transmitting signal should be minimized. Both aspects set limitations on the power of the signal in a WBAN system (Drude, 2007). Moreover, it is necessary and important for the WBAN system to be capable of detecting and receiving a very low power signal from large background noise. In such scenarios, alternative power sources making use of energy harvesting can be considered, for example, a Peltier device to convert body heat into electricity or a piezoelectric device to convert body motion into electricity (Baard, 2001). Moreover, studies have shown that higher bit-rates actually help preserve power (Rohde & Toftegaard, 2011).

The physical environment of WBAN also provides great challenges that include body effects and surrounding environment. The movement and position of the human body can have a significant impact on the propagation of the signal. One of the most known phenomena of body effect is the body shadowing effect (Cotton & Scanlon, 2007). Another important impact comes from the surrounding environment. The wireless signal transmitted by the sensor will be reflected by the floor, walls and surrounding object, which may lead to the multi-path effect that can impose interference on the original signal. Interference avoidance from nearby users with a similar sensor system or other electronic devices is accomplished by using low power devices (also reducing energy consumption) and by operating them in a frequency range where they are unlikely to interfere.

Other characteristics required from a medical WBAN include also: (i) On-board memory and basic signal processing to extract relevant data, (ii) Data compression to reduce the amount of data to be transmitted and stored if re-transmission is required; the last also implies time stamping of the data, (iii) WBAN should easily interface with standard computer and other medical equipment, (iv) There must be a compromise between the communication and the processing tasks, and furthermore with the WBAN lifetime and the energy supplied by the batteries.

2.1 Multifunctional Wireless Body Sensor

In this section, we discuss the initial, current and future design of our custom developed multifunctional wireless body sensor (MWBS) guided by the requirements for WBAN.

2.1.1 Initial Design

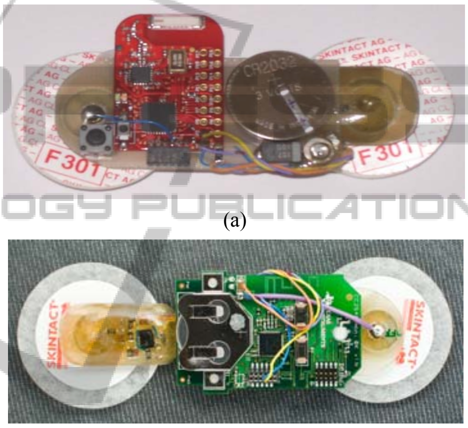
As an initial design, we prototyped a differential wireless bio-electrode (WBE) for measuring ECG and EEG (Trobec, et al., 2010). An example of the prototype electrode is shown in Fig. 1a. The WBE consists of two self-adhesive electrodes (which need to be positioned at a distance of 5 cm when performing measurements), a signal amplifier, a microcontroller and a low-power 2.4 GHz radio (Texas Instruments CC2500). It enables minimal use of wires on the body and consequently maximal wearing comfort. A coin battery powers the WBE. When placed on the body surface near the heart, the WBE measures the potential difference between the electrodes and records a raw ECG signal. Triggered by an internal clock, the WBE performs sampling of the analogue signal and conversion of each sample to a 10 bit digital signal. Seven consecutive samples are collected into a buffer, labelled with a source timestamp and then transmitted via SimpliciTI wireless transmission protocol (http://www.ti.com/simpliciti).

Other relevant data can be extracted from the raw ECG signal using additional signal processing. First, the WBE provides an alternative that resolves the standard 12-lead ECG devices imperfections. The measurements from three WBEs can form a lead system that can potentially be used for reconstruction of the 12-lead ECG (Tomašić, et al., 2013; Trobec & Tomašić, 2011). Next, the ECG-Derived Respiration (EDR) techniques are based on the observation that the positions of the ECG electrodes on the chest surface move relative to the heart. We have confirmed that EDR is a viable option for monitoring of the respiration frequency and for rough classification of the breathing types (Trobec, et al., 2012).

2.1.2 Current Design

The initial design has been upgraded to support the newest version of Bluetooth technology – low energy Bluetooth 4.0 (BLE) for transmission of measured data from the MWBS. It enables direct communication between the MWBS and smartphones and devices with incorporated low energy Bluetooth. An example of the current prototype electrode is shown in Fig. 1b.

The Bluetooth low energy protocol is low-cost wireless solution designed to meet special requirements for long-term operation in devices with limited energy capacity (e.g. coin-cell battery). Its ultra-low peak, average and idle mode power consumption and enhanced working range enable the MWBS to operate on a single coin-cell battery for several days while transmitting live stream of raw ECG data (Bregar & Avbelj, 2013). The maximal bit-rate of the data payload is 1 Mb/s, which is sufficient also for high-resolution short-term measurements.



(a)

(b)

Figure 1: (a) A prototype of the WBE with two self-adhesive disposable electrodes, a lithium coin battery and a ceramic chip antenna. (b) A prototype of the MWBS with two self-adhesive disposable electrodes, a lithium coin battery, a microprocessor, a BLE radio, and a printed circuit board antenna.

2.1.3 Future Design

In future, with respect to data collection, more sensors will be incorporated into the final version of the MWBS, including sensors for measuring beat rate, vascular pressure, oxygen saturation, skin resistance, temperature, etc. Furthermore, microphones, accelerometers and video sensors could offer additional contextual data that could contribute to a better estimate of the status of the monitored patient. We envisage the use of advanced signal processing techniques before transmission and cognitive communications techniques to mitigate the interference in the increasingly crowded ISM band.

3 REMOTE HEALTH MONITORING SYSTEM ARCHITECTURE

The scheme of the proposed wireless system for remote monitoring of vital functions is shown in Fig. 2. The system establishes a virtual state of a semi-intensive care unit, which significantly improves the quality of hospital care. Patients are fitted with body sensors for vital functions. The primary concern of the system is reliable transfer of the collected data from the sensors to a computer server that maintains a database and is responsible for processing, presentation, alerting and taking necessary actions. Once the data resides on the server, the users of the systems (patients/physicians/doctors) can access the collected data in the database via a terminal of their choice. The transfer of data from the sensors to the data server is achieved through appropriate gateways equipped with Internet connection. Before reaching such a gateway, the data can be transferred through a multi hop connection between intermediate devices.

We account as gateway not only a wireless static gateway in the traditional sense, but also personal terminals, such as smartphones and tablet PCs with the ability for wireless transmission. Therefore, we can distinguish two modes of operation. In the first mode, more suitable for a home environment, the personal terminal will act as a primary mobile gateway (Pesko, et al., 2014). The data from the sensors is transmitted for representation and/or storing on the personal terminal. This can be achieved with direct communication between the sensor node and the mobile gateway (for example, using a BLE link). The measurements are stored in the personal terminal for preliminary monitoring and processing with automated procedures based on the comparison with threshold values, predetermined rules and automatic learning. Furthermore, the measured data is also sent to the remote data server.

In the second mode, more suitable for a hospital environment, the data from sensors to the server is transferred using fixed wireless infrastructure gateways located in patients' rooms and hospital hallways. By using infrastructure gateways, the coarse indoor location of the patient can be also determined, which is not always the case when using personal terminals. In this scenario, the personal terminals should be considered as a secondary device, serving more for preliminary representation and processing of the data. Increasing the number of redundant low cost wireless nodes can create a more robust communications network. An ad-hoc network with an appropriate multi-hop routing protocol and redundant wireless nodes can provide redundant communication pathways to the nearest wireless gateway node (Biagioni & Chen, 2004; Jingling, et al., 2010).

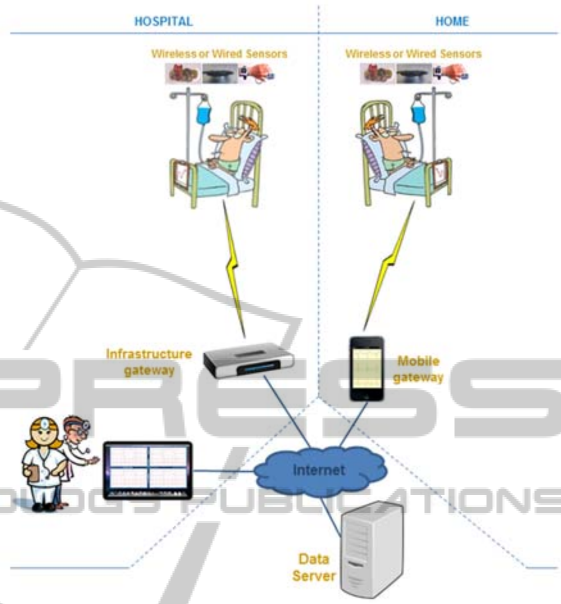


Figure 2: Conceptual scheme of the wireless system for remote monitoring of vital functions.

3.1 Coexistence Issues in a Remote Health Monitoring Wireless System

In the following, we discuss the applicability of the concept of cognitive communication to the wireless system for remote health monitoring.

3.1.1 Spectrum Sensing and Dynamic Spectrum Access

Because of the requirements for low power consumption in WBAN, a prerequisite for successful operating frequency adaptation in WBAN is energy efficient spectrum sensing. Spectrum sensing is a highly demanding signal processing task, since the radio signals in WBAN are weak and with possible large background noise. Several research activities have been carried out in order to evaluate different approaches for energy-efficient spectrum sensing under various assumptions (Biagioni & Bridges, 2002; Rohde & Toftegaard, 2011). Energy harvesting has been also proposed as a solution to complement the power supply requirements in the context of cognitive sensor nodes (Barroca, et al., 2012).

Since hospitals represent a complex dynamic ISM band radio environment, it is generally not suitable to rely on WBAN devices capable of accurate sensing and independent decision making. A more viable solution is thus to equip the hospital rooms and wards with spectrum sensing nodes, similar as there are Wi-Fi access points, and use the collected information to build an indoor radio environment map (REM) (Atanasovski, et al., 2011). REM can be built and maintained centrally or in a distributed manner, and provides knowledge about radio signal coverage and interference levels to a dynamic spectrum management (DSM) system. Furthermore, such centrally managed system can assist in indoor localization of patients, personnel and even equipment/instruments if equipped with detectable radio devices.

3.1.2 Power and Mobility Management

In the described scenarios, problems can occur when the patient moves with all the sensors attached, which can cause for the sensors to lose their primary point of connection to the gateway. Moreover, while moving, the radio-operating environment can change dynamically as there may be other transmitters causing interference or ambient noise that can cause data loss. Therefore, in a mobility scenario, since nodes frequently change position, also some transmit power level adjustments should be considered. For example, when nodes are close to each other, their transmission power can be lowered. Hence, mobility-aware dynamic spectrum management solutions must be incorporated. This means that in a cognitive WBAN for medical applications in unlicensed bands, depending on the protocol, either the transmitting nodes need to have the capability to perform cognitive functions or the network should incorporate a smart scheduler.

In the search for solutions, it makes perfect sense to base the implementations of cognitive communications on one or more existing standards. Moreover, using existing standards will also provide compatibility with legacy devices already in operation. Typical wireless technologies suitable for use in WBAN are Bluetooth (based on IEEE 802.15.1), ZigBee (based on IEEE 802.15.4) and 802.11/WiFi (Golmie, et al., 2005). Bluetooth is particularly suitable since its 4.0 version, as BLE-supported devices can transmit low power in the 2.4 GHz worldwide ISM band.

Besides optimising to the required range, the transmit power can also be optimised according to the priority of the information from a given sensor node. Sensor nodes can be grouped into nodes with critical traffic and non-critical traffic. Transmission for critical nodes would be prioritized over transmissions for non-critical nodes by using higher transmission power for critical traffic and lower transmission power for non-critical traffic.

3.1.3 Optimal Assignment of Wireless Interfaces

On the end-to-end network level, the transport services should provide service delivery in accordance with specific performance criteria and cost parameters. In a heterogeneous wireless access system, typical for the ISM band operating environment, sensor units as well as mobile and fixed infrastructure gateways may support multiple wireless interfaces and have the ability to optimally switch between them (Fortuna, et al., 2008). In doing so, they may take into account operating parameters (interference level, energy consumption, etc.), transmission parameters (delay, bandwidth, data priority level, etc.), application requirements (presentation on intermediate devices, need for advanced processing, etc.), and others.

4 CONCLUSIONS

In this paper, we addressed the coexistence of medical WBANs for remote health monitoring with other wireless networks operating in the shared ISM frequency band. The trend of this type of networks is towards implementation in already crowded unlicensed frequency bands, characterised by interference that may severely affect the performance and reliability of very low power devices such as WBSs. In order to reduce the interference from other wireless systems and enhance the performance, we discussed the applicability of the concepts of cognitive communications to medical WBAN systems, pointing out dynamic access to temporarily available spectrum, adjusting transmit power to operating conditions and data priority, and setting up most appropriate end-to-end transmission path.

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