Enabling Communication Technologies for Medical Wireless Body-Area Networks

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***Abstract*—The increasing percentage of aging population and chronic diseases on one hand, and the advances in the development of integrated short range wireless technologies on the other hand, have created a growing interest in the development of medical telemonitoring and telecare systems through the use of medical on-body sensor networks, also known as medical wireless body area networks (WBANs). This paper provides an overview of the main wireless technologies that can be used for WBANs in the medical domain and discusses the major requirements in such applications. While radio frequency technologies are well established solutions for interconnecting WBANs, the high risk of interference in such networks motivates the use of alternative or complementary technologies including optical wireless communications.**

***Index Terms*—Wireless sensor networks; body area networks; medical on-body networks; optical wireless communications.**

I. INTRODUCTION

According to the World Health Organization (WHO), Life expectancy is consistently increasing and this trend will continue thanks to more efficient medical follow-up of the newborns and a better epidemics prevention and control [1], [2]. At the same time, the changing lifestyle is resulting in an increased mortality rate due to cardiovascular diseases [3] as well as an increased number of chronic diseases such as diabetes [4]. These trends will put more and more pressure on the health-care systems, increasing the treatment costs for both health centers and patients.

With the advances made in the different fields of engineering, smart solutions can be developed to endorse traditional health-care methods. In particular, the advances in very-large-scale integration (VLSI) had made possible the integration of diverse sensors and micro-electro-mechanical systems (MEMS) in millimeter-size chips [5]–[7]. Furthermore, with the development of low-power short-range communication technologies, wireless connection of these sensors and actuators can be readily done, giving rise to wireless sensor networks (WSNs), which are considered as the building blocks of the near-future Internet-of-things (IoT) networks [8]. Indeed, the progress made in cloud computing and machine learning has made computing power and data analysis available at very low costs [9], which has, in turn, allowed removing the processing load from these WSNs.

The application of WSN technology to health-care has given birth to body sensor networks (BSNs) or wireless body-area networks (WBANs), which consist of networks of medical sensors located inside, on, or outside the human body. By the aid of such networks, early detection of health emergencies can be made possible. They can also be used for remote monitoring of vital signs of patients such as ECG, EEG, and temperature, as well as for remote drug delivery such as by insulin pumps. The obvious benefit of using such networks is in saving lives by more efficient and reactive monitoring and treatment of patients with chronic conditions and cost reduction. Compared with general WSNs, WBANs have specific characteristics including: smaller number of network nodes, necessity of a very small delay latency; non-stationary nature of the networks due to the movement of the patients; and heterogeneity of the type of transmitted signals (a mixture of continuous-time signals like ECG and event-based signals like temperature) [10].

A number of relatively recent works have studied different aspects of radio-frequency (RF) based WBANs. In [10], a survey of a few WBAN-related projects and enabling technologies at hardware and connectivity levels was presented. In [11], WBAN physical and data link layers were investigated, whereas the corresponding media-access control (MAC) and network layer protocols were discussed in [12] together with cross layer design. In [13], Movassaghi *et al.* presented in particular the different layers of the IEEE 802.15.6 standard dedicated to WBANs. Also, the requirements for wireless technologies that can be used for these networks were discussed in [14], and a survey on the related textile-based sensors was presented in [15].

Our aim in this paper is to present a general overview of the wireless technologies that are suitable for use in WBANs and to complement the previous works on these networks by considering other non-RF technologies including such ultrasound and optical wireless communications. After introducing the general applications of WBANs in Section II we discuss the architecture of these networks in Section III. The major requirements of WBANs for medical applications are specified in Section IV. We then focus on the wireless technologies for WBANs in Section V including RF, ultrasonic and optical wireless, with a special focus on the latter, and specify some related recent works. Lastly, Section VI concludes the paper.

II. WBANs FOR MEDICAL APPLICATIONS

The use of WBANs has been considered for different applications including medical, military, sport, interactive gaming, etc. Here we focus on the main applications of these networks in the medical domain.

A. Vital sign monitoring

WBANs can be used for continuous monitoring of vital signs such as electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), blood glucose level, blood pressure, heart rate, body temperature, motion, etc. The related physiological signals can be used to monitor or diagnose diseases such as cardiovascular disease, diabetes, epilepsy, as well as for monitoring, sleep, stress, activity, etc. Some typical relevant physiological sensors include: ECG sensors to record the heart electrical activity, i.e., the electrical changes that arise from the pattern of polarizing and depolarizing of the heart muscle; EEG sensors to record the brain electrical activity using several electrodes placed along the scalp to measure voltage fluctuations resulting from ionic currents within the neurons; EMG sensors to record the electrical activity produced by skeletal muscles by measuring the electric potential generated by muscle cells when electrically or neurologically activated; and pulse oximetry (or SO2) sensor to measure the blood oxygen saturation based on the changing absorbance of two wavelengths of light passing through the body and determining the absorbance corresponding to the pulsing arterial blood.

Continuous monitoring of these vital signs helps also to detect health emergencies and to alarm physicians and health practitioners for early interventions, especially in the case of elderly people and disabled persons.

B. Therapeutic stimulation

Another important application of WBANs is to deliver therapeutic treatments via actuators that work through electrical stimulation or biochemical injections. Typical examples are: pacemakers that deliver electrical impulses through electrodes to regulate the electrical conduction of the heart; cochlear implants that is used to capture sound using a microphone and to convert it to an electrical signal to stimulate directly the auditory nerve; neuromuscular stimulators that deliver electrical impulses muscles, mimicking the action of the central nervous system; and insulin pump used for administering the delivery of insulin based on the blood glucose level. Some other examples include defibrillator, brain stimulator, artificial retina, etc.

III. Architecture of a WBAN

The general architecture of a WBAN consists of three different tiers: intra-WBAN with a typical transmission range one meter or so, extra-WBAN, and beyond-WBAN communications [13], as illustrated in Fig. 1. For the first, i.e., intra-WBAN tier, communication is between sensor nodes on or inside the body on one hand, and a coordinator node on the other hand. Sensor nodes can be either sensors that measure physiological data, or actuators that upon feedback information from sensors, conduct an electrical or biochemical stimulation. As concerns extra-WBAN tier, communication takes place between the coordinator node and one or more access points (APs), which can be part of the infrastructure or be placed in an ad-hoc mode. After collecting data from different sensor nodes, the coordinator node transmit it to the AP, probably after data fusion or

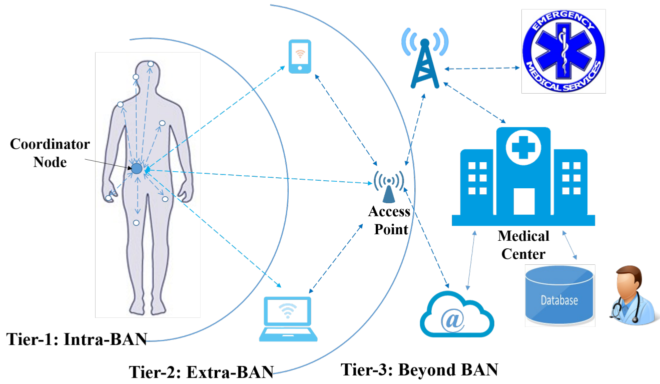

Fig. 1: A typical WBAN with the underlying communication tiers.

compression. The communication between the AP and the medical server concerns the third tier, that is done via Internet or a cellular network. The received data could be stocked in a database and/or used by the medical staff for real-time diagnosis or monitoring.

IV. Specific Requirements of Medical WBANs

As mentioned previously, a WBAN used in medical applications, has special requirements that differentiate it from other networks. We briefly present these considerations in the following.

A. Data rate and link reliability

Based on the targeted application, nodes in a WBAN have different requirement in terms of data rate, which can range from a few bits per second (bps), e.g. for a temperature sensor, to a few Mbps, e.g., for capsule endoscopy. According to the IEEE 802.15.6 standard requirements, WBAN links have to support data rates in the range of 10 Kbps to 10 Mbps [16]. Meanwhile, the network should satisfy requirements in terms of quality-of-service (QoS) to ensure reliable communication, which is usually specified in terms of bit-error-rate (BER). The BER requirement depends on the medical device and can vary from 10^{-3} for deep brain stimulation to 10^{-10} for EEG recording. Also, the required delay latency for medical applications is less than 125 ms [16]. Table 1 presents typical data-rate and BER requirements for some WBAN applications [17].

B. Energy consumption

Obviously, low energy consumption is an important feature of WBANs because it affects the battery lifetime of the medial devices. Battery lifetime is in particular crucial for implant devices where replacing power sources needs a costly surgical operation, although ongoing research considers harvesting techniques to recharge the device batteries remotely [18], [19].

Moreover, a high energy consumption may cause a temperature rise in the tissue that surrounds the sensor. As the human tissue is semi-conductive, it will absorb a part of the radiations emitted at transmission, which can cause severe thermal damage to sensitive organs. The amount of energy absorption is defined by the so-called specific absorption

TABLE I: Requirements on data-rate and BER for some medical applications [20].

Sensor nodes	Target data rate	Target BER
ECG	72 Kbps	$< 10^{-10}$
EEG	86.4 Kbps	$< 10^{-10}$
EMG	1.536 Mbps	$< 10^{-10}$
SPO2	32 bps	$< 10^{-10}$
Temperature, glucose level, pH	20 bps	$< 10^{-10}$
Cochlear implant	~ 200 Kbps	$< 10^{-10}$
Deep brain stimulation	$128 - 320$ Kbps	$< 10^{-3}$
Accelerometer, blood pressure	< 10 Kbps	$< 10^{-10}$
Endoscope capsule	1 Mbps	$< 10^{-10}$

rate (SAR) that needs to be minimized for WBAN sensors. The upper limit of SAR exposure is fixed to 2 W/Kg over 10 g of tissue in the European Union countries and Japan, and 1.6 W/Kg over 1 g of tissue in the United States and Australia, which are equivalent to maximum transmit powers of 20 and 1 m, respectively [16].

C. Security and privacy

Security is of high concern in medical WBANs since medical data is considered as sensitive, private, and confidential. As such, data should be encrypted to ensure user's privacy, and authentication mechanisms should be used to verify data integrity and to ensure that data is being sent from a trusted node. This is an important issue in RF-based networks where data-carrying signals can be intercepted and jammed relatively easily, as we will discuss later.

V. Existing Wireless Technologies for WBANs and Related Works

A. RF technologies

Most of the current realizations of WBAN systems are based on the rather well-known wireless personal-area network (WPAN) technologies (IEEE 802.15) operating in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band. Bluetooth as a popular short-range communication system [21] with two main modes of basic rate / enhanced data-rate (BR/EDR) and low-energy (LE), has received particular attention. It is especially the case for the fourth version, known as Bluetooth low-energy (BLE), designed for device-to-device communications with low complexity, low cost, and low power consumption, offering data rates up to 2 Mbps. The most recent (i.e., the fifth) version of Bluetooth, specially developed for IoT device connectivity, has different power classes that can serve different ranges of 100, 10, and 1 m, with a maximum transmit power of 100, 2.5, and 1 mW, respectively.

Another solution is the IEEE 802.15.4 standard [22], which was developed for low-cost wireless connectivity for applications with limited power and relaxed throughput requirements. With a simple and flexible protocol, it offers data rates from 20 to 250 Kbps within a typical range of 10 m and a transmit power limited to 10 mW. The popular Zigbee [23] is a low-cost and low-power technology built on the top of IEEE 802.15.4 standard by modifying the network and application layers.

Lastly, the short-range low-power IEEE 802.15.6 standard [24] was specifically designed for WBANs, offering up to 15 Mbps data-rate with a transmit power between 0.1 and 1 mW. It has been developed to overcome the limitations of the other existing WPANs to meet the requirements of medical applications discussed in Section IV. This standard defines narrow-band transmission in the ISM, WMTS (Wireless Medical Telemetry Service), and MICS (Medical Implant Communication Service) bands, as well as ultra-wideband (UWB) and human body communication (HBC), with data-rates in the range of $57.5 - 971.4$ Kbps for narrow-band transmission, $0.487 - 15.6$ Mbps for UWB, and 164 Kbps – 1.3 Mbps for HBC (operating at 21 MHz).

Although Bluetooth and Zigbee do not meet the requirements in terms of data-rate, reliability, and SAR of certain medical applications (e.g., in hospital environments) [20], most of the reported WBAN implementations rely on these standards [25]–[30]. However, to the best of the authors' knowledge, no realization of WBANs has been reported based on IEEE 802.15.6, which can be explained by the availability of Bluetooth and Zigbee transceivers and their ease of use compared to the former. For instance, a system for monitoring temperature and heart rate was proposed in [27] based on Power-Class 2 (with a maximum emitted power of 2.5 mW) EDR Bluetooth module. In [26] a 3-lead ECG system was designed to measure the respiration rate, based on a Power-Class 2 BLE module. A similar device was used in [31] for a wearable WBAN with solar energy harvesting to measure body temperature, heart rate, and fall detection.

Concerning Zigbee applications, a wearable system was designed in [30] comprising of an accelerometer and temperature and humidity sensors, using an IEEE 802.15.4 compatible transceiver capable of implementing Zigbee protocols and transmitting at 2 mW. Also, a wearable system equipped with GPS and 3-lead ECG was proposed in [32] for the purpose of fall detection and assisting elderly people. A health monitoring system equipped with a 1-lead ECG, a pulse sensor, and a body weight sensor was also designed in [33] where a Zigbee transceiver module with 6.3 mW was used to interconnect sensors with a coordinator node, and a Bluetooth v.2 module with 2.5 mW to connect this latter to an AP.

B. Ultrasonic technologies

Ultrasonic communications are enabled by the propagation of acoustic waves inside the human body at frequencies higher than 20 KHz. They have the potential to complement or replace RF technologies for implant communications thanks to their low attenuation in the human tissues. Transceivers used for ultrasonic communications are mainly piezoelectric transducers. In [34], an implantable pressure sensor was tested with a data-rate of 40 Kbps and a transmit power of 100 μW through a 12 cm tick castor oil. Also, in [35] an ultrasonic wideband system communicating through a human kidney phantom at 10 cm was demonstrated with a data-rate of 700 Kbps and a power consumption of 40 μW at a BER of 10^{-6}.

C. Optical wireless technologies

Optical wireless communications (OWC) in the infrared (IR), visible, or ultra-violet parts of the spectrum are a potential alternative or complement to RF technologies for medical WBANs thanks to their high immunity to external interference and their inherent security due to confinement in indoor spaces. In addition, the transmit power in OWC systems is not constrained by SAR regulations like for RF counterparts. The interest of the optical wireless technologies has been investigated in several works for on-body, extra-body, and in-body medical applications.

The use of OWC for on-body WBAN links was investigated in [17], where their practical feasibility was demonstrated. Characterizing the communication channel using ray-tracing based numerical simulations, the authors evaluated the theoretical performance of an optical link using on-off-keying modulation and code-division multiple-access for connecting several sensors for the case of purely diffuse links (i.e., without a line-of-sight). They showed a BER of 10^{-10} for data-rates from 10 to 890 Kbps, with a power consumption of 17 mW for 10 Kbps data-rate, which is much lower than the maximum permitted emitted power for IR communications (based on eye safety regulations) [17]. Lower power consumption would be attainable using more efficient transmission schemes, however.

Concerning extra-body links, a bidirectional OWC system was studied in [36] for connecting a WBAN coordinator node with an AP, where visible-light communication (VLC) was used for downlink (the AP being integrated into a LED luminary, for instance) and IR transmission for uplink. It was shown that for most medical sensors, it is possible to satisfy QoS and data-rate requirements with a low radiated power for both IR and VLC links. Moreover, the use of OWC for transmitting accelerometer data for indoor physical activity monitoring was investigated in [37] where its efficacy was demonstrated through experimental measurements using a designed wearable system. On the other hand, in-body communication in the optical domain has attracted increasing attention in the past few years as it provides a better performance in terms of data rate and interference level, as compared to RF technologies [38]–[40]. For instance, a transdermal optical link operating at 1 Mbps through porcine skin was reported in [38] using a 860 nm LED at the transmitter and a PIN photo-diode at the receiver. Also, a telemetry system based on a laser diode was studied in [41] with a data rate of 16 Mbps through a skin thickness of 4 mm and a power consumption of less than 10 mW. Experimental results were also presented in [42] for data transmission through a 1 mm thick chicken derma, where a data rate of 20 Kbps at a BER of 10^{-6} was reported with both direct and retroflection links with a power consumption of 4 mW and $0.4\,\mu$W, respectively. Using a VCSEL laser, a transmission link through a 4 mm tissue was demonstrated in [43], achieving 50 Mbps data rate at BER of 10^{-5} with a power consumption of 4.1 mW. An extension of this study was done in [44], where a data rate of 100 Mbps at a BER of 2×10^{-7} was achieved with a power consumption of 2.1 mW through a tissue of an anesthetized sheep of 2.5 mm thickness. These results were further extended in [45] to a bidirectional link through a 2 mm porcine skin, achieving 1 Mbps with a power consumption of $290\,\mu$W in downlink and 100 Mbps with 3.2 mW in uplink.

VI. Conclusions

In this paper, we have provided a review of WBANs for medical applications, the typical medical sensors that can be used in such networks, the particular requirements that distinguish WBANs from other personal networks, and more importantly, the enabling wireless technologies with a special focus on the OWC-based techniques. With the increasing demand for medical telemonitoring and telecare as well as more efficient hospital systems, the use of WBANs attracts more and more attention. The optical wireless technology appears to be a promising solution in such applications thanks to its immunity to RF interference and inherent security, in particular. We reviewed several proofs-of-concept based on optical wireless data transmission with high data-rate and low power consumption.

Acknowledgment

This work is supported by VisIoN, a European project funded by the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Grant Agreement No. 764461.

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