Course of Telemedicine

Intrabody communication: a new paradigm for Wireless Body Area Network

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1 Abstract

Intra-body Communication (IBC) is a new way of communicating using human body as transmission medium which is thought to be widely used in the future Wireless Body Area Network. This paper deals with this thematic explaining the physical principles behind this new paradigm and underling the main features and physical layer specifics in terms of communication systems using the results presented so far in the literature.

2 Introduction

Continuous remote monitoring can be considered one of the most important milestone of the current health-care paradigm generally referred as mHealth. The possibility of monitoring health status of a patient without direct human intervention may enhance the current health care practices as well as coping with the costs of the health care system. Over the last few decades new wearable sensors and actuators have been designed to allow a precise measurement of some of the most important clinical parameters as for example the glucose monitors for diabetic people or ECG sensors. These sensors need to be communicating in order send their data to an external medical server where it can be analyzed and stored. At this aim, the old concept of Wireless Local Area Network (WLAN) have been extended with the concept of Wireless Body Area Network (WBAN) requiring the design of new protocols and standards in relation to the specific needs of this kind of communications. As specified in [5], the main concerns of these kind of communications can be summarized as following: **energy constraint**, due to their small form factor, the devices have limited energy resources available; **physical layer problems**: owing to the high number of devices implanted or wore, interference could jeopardize the performances of the entire system requiring a small transmit power per node. On the other hand propagation of the waves takes place in lossy medium, the human body, resulting very attenuated before reaching the receiver and fair trade-off on transmit power has to be found. **Security problems**: health related data are very important and confidential; WBANs have to ensure very high security standards. In 2012, in order to fulfill these requirements, the standard IEEE 802.15.6 has been released defining various specifics for physical layer of so-called *Short-range Communications*. Following the subdivision made in [13], it is possible divide WBAN into two kind of communication: *intra-body communication* and *extra-body communication*. The first one allows information exchange on the body, between sensors (or actuators) and personal devices (e.g. Smartphone) while the second one ensures communications between personal devices and an external network as reported in the figure 1. Differently from other standards presented in the past for Wireless Sensor Network, the challenges of WBANs involve a radically change of paradigm. If in extra-body communications, the usual signal transmission through radio-frequency waves seems to be yet a valid solution, in intra-body communications this choice could not be the best owing to some draw-backs as the high-power consumption and body-shadowing. To overcome these issues an alternative solution could consist in using human body as transmitting medium. This new novel of communication is general referred as Human Body Communication (HBC) or more generally Intra-body Communication (IBC) and can be considered an hot topic of the current research in Telemedicine. This paper can be seen as state of art of HBC analyzing the thematic from different point of views. In 3, the physical principles exploited in these kind of communications are presented and putted in relation with signal propagation models and channel characteristic. In 4, the design of the main HBC systems proposed in the literature is analyzed in terms of different modulation schemes, carrier frequency and hardware, underling the applications in biosignal transmission; then 5 deals with HBC physical layer standard presented in 802.12.6 and in 6 the conclusions are given in relation to future works and development.

3 Physical principles and body channel characteristics

Physical principles: Galvanic and Capacitive coupling The physical principles behind transmission through human body can be mainly referred as *signal coupling method*. Coupling can be simply define as transfer of energy from one medium, such as a metallic wire or an optical fiber, to another medium, in this case human body. So far two coupling methods have been proposed: Capacitive Coupling and Galvanic Coupling. Capacitive Coupling was introduced for the first time in 1995 by Zimmerman in his famous work *Personal Area Networks (PAN): Near-Field Intra-Body Communication*, [23]. In this case electric fields are induced using a certain configuration of electrodes. As shown in figure 3 there are two pairs of electrodes, one pair for the transmitter and one for the receiver, each composed by a "body electrode" attached on the skin and a "environmental electrode" floating on in the air. As possible to notice from the figure, generating a d.d.p. between the transmitter electrodes (1-30V) an electric field E_t is introduced on the body via signal electrode transmitter. The body behave as a perfect conductor [23] acting like a large plate of a capacitor, being charged and discharged by the transmitter. With this configuration the body generate an electric field with the earth ground (E_e) and with the "environment electrode" of the transmitter (E_a,E_c) as well as with the body electrode of the receiver (E_r). The receiver environment electrode ,re "sees" the environment better than the body and inversely receiver body electrode rb sees the body better than the environment. This asymmetry creates a difference of potential between the two electrodes of the receiver caused by the potential difference between

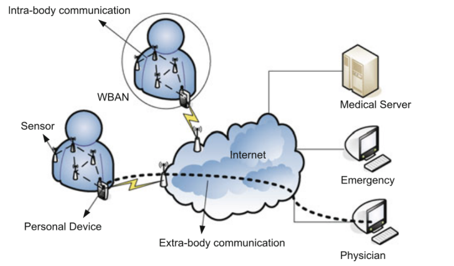

Figure 1: Intra body communications in WBANs

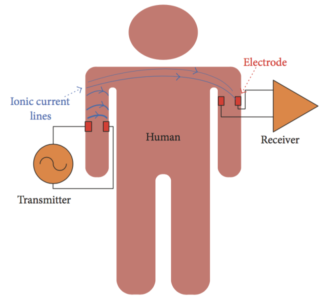

Figure 2: Illustration of galvanic coupling propagation signal [7]

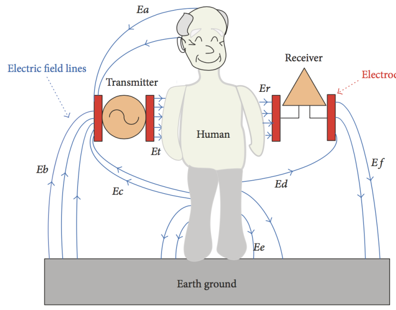

Figure 3: Illustration of capacitive coupling propagation signal [7]

the body and the ground, resulting in a small current measured by the receiver circuit. The oscillating potential of the body electrode rb produce an electric field E_f to the environment return path of the external ground.
Differently from Capacitive Coupling, in Galvanic Coupling a low electric current around 1-2 mA is injected into the body through a pair of electrodes attached to the skin. This weak current generates a low voltage drop that can be detected by an instrumentation amplifier. Most of the current density flows through the direct path between the electrode pairs, however, other weaker currents are induced inside the conductive tissues of the human body. Compared with capacitive coupling HBC, galvanic coupling is less in influenced by the environment, which makes the signal transmission much more stable and reliable for data transmission between devices located on very short distance. On the other hand Capacitive Coupling can operate at higher frequencies ($< 150Mhz$) achieving an higher data rate.

3.1 Body-Channel Characteristics

The development of Human Body Communication is strongly related to the properties of the medium in which they occur: Human Body. A deep investigation in this sense allows the construction of signal propagation models and assessment of important physical parameters as channel gain, path-loss and dispersion, necessary for a correct design of the physical layer specifics as modulation schemes and coding.

Electrical properties of Tissues Biological tissues behave as conductors of electric current depending on their composition. The main dielectric characteristics of tissues as a function of frequency are well known and were studied by Foster and Schwan in 1989, who experimentally showed that the dielectric spectrum of a tissue is characterized by three (dispersion) regions in which the permittivity decreases as frequency increases ((4): α, from 10 Hz to 10 kHz, mainly due to ion diffusion effects in the cell membrane; β, between 10 kHz and 30 MHz, caused by polarization of cell membranes and proteins, γ, above 1 GHz, owing to the polarization of water molecules. Based on this study and on many experimental measurements done on several tissues, it has been possible to establish a proper parametric model which describe the change of dielectric properties of a tissue over a broad frequency range: the Cole-Cole Equation.

$$\epsilon(\omega) = \epsilon(\infty) + \sum_n \frac{\epsilon(s) - \epsilon(\infty)}{1 + (j\omega\tau_n)^{1-\sigma_n}} + \frac{\sigma_i}{j\omega\epsilon_0} \tag{1}$$

$$\sigma = j\omega\epsilon_0\epsilon \tag{2}$$

where the parameters are defined as following: τ_n is the relaxation time constant of the polarization mechanism for the tissue, $\epsilon(\infty)$ and ϵ are the permittivity at $w\tau >> 1$ and $w\tau << 1$ respectively and σ_i is the ionic conductivity of the tissue. In the equation a degree of freedom is represented by the the n which can be different according to the number of dispersion regions of the tissue considered. Gabriel in [10] proposed $n = [1, 5]$, but for the skin it can be simplified to $n = [1, 2]$.

Propagation Models Modeling the conductivity with the Cole equation it is possible to characterize the tissue impedance ($z = 1/\sigma$) and study the propagation of the signal. In this sense there is a quite large variety of such models and they can be grouped in four main classes: *Circuit Models*, *Computation Models* and *Electromagnetic Models* and *Empirical models*. **Circuit Models** are mostly used for very short path communication as for example when TX and RX are positioned on the same arm. Being a single impedance described with equation 1, it is possible to model the whole body between TX and RX as circuit of several impedances. Reference works in this direction have been published by Wegmuller [21], which has a elaborated four terminal circuit with 10 impedance for low-frequency Galvanic Coupling, and Callejòn who elaborate in 2012 an equivalent circuit model of the skin both for Galvanic and Capacitive Coupling [3]; in the this case skin is seen as a repetitive lossy transmission line composed of impedance (Z) and admittance (Y) without inductive elements (reported in the figure 4). For what concern **Computational Models** three different methods have been investigated. The first one is FDTD , Finite Difference Time Domain method, used to calculate electric field distribution inside and outside complex geometries such as human body [9].

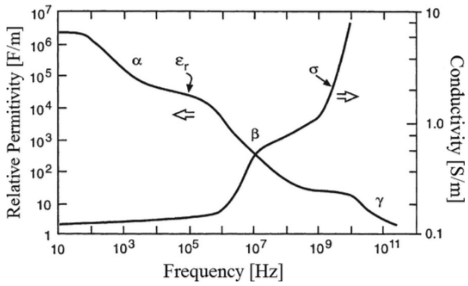

Figure 4: Permittivity change over the frequency

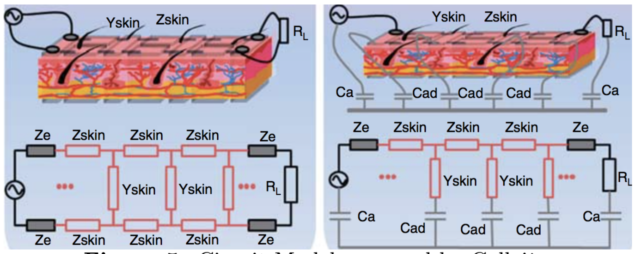

Figure 5: Circuit Model proposed by Callejòn

The second method is FEM (Finite Element Method) which is based on numerical solutions of partial differential equations and has been proposed by Xu ([22]) to simulate the behavior of capacitive coupled IBC and reconstruct the potential distributions caused by induced current into the human tissue; in this case human body has been considered as circuit of lumped resistors paralleled with lumped capacitors and part of the body as harm has been approximated with geometrical shapes as cylinder. Using the same method for galvanic coupling, Callejòn in [4] has studied signal propagation in human harm founding a channel attenuation up to 20 dB with TX-RX distance of 5 cm which remain stable if the distance is greater. The last method concern **Electromagnetic Magnetic Models** which have been developed by solving analytically Maxwell's Equation on tissues modeled with Cole equation and specifics boundary conditions [1]. It is fair to mention that all the simulations models describe the real behavior of the channel (experimentally measured) only for some range of frequencies or distance TX-RX and we are far from a complete description as underlined in [16] In this sense, most of the studies just cited have underlined a pass-band behavior of the human body in range [0.2/1 - 100 MHz] for capacitive coupling based communications, and in range [0.2 - 10 MHz] for galvanic coupling. Moreover many researches agree in modeling the noise as additive Gaussian mainly caused only by the electronic component and electrode-skin interface with an AWGN body channel. Being the simulation models not reliable, most of the HBC systems realized so far are designed following **empirical models** for a specific experimental setup. In this direction Linsdey [15] has tried to estimate the channel attenuation in human body through repetitive direct measurements using a galvanic configuration with $1 - 3mA$ generator with frequencies ranging from 2-160 KHz. In this condition the body channel attenuation is resulted within 37-47 dB. Always considering galvanic coupling another main important result is reported in [20] where it is shown that body behavior such as walking, sitting, flexion has a small influence on communication performances changing gain only of 2-5 dB. On the other hand it has also been shown that channel parameters as gain, path loss vary from subject to subject with different anthropometric features. So far many studies in the literature have proposed different outcomes considering their own configuration with a specific kind of electrodes, specific location of measurements and experimental setup. This heterogeneity makes very difficult to furnish uniform and representative results and future works will have to address this problem (see better 6).

4 Intra-Body Communication Systems design

Communication Design of HBC systems Considering what stated in the last paragraph, many investigations have been done to properly design HBC systems. The main parameters to tune are frequency band, modulation schemes and circuit design. It is fair to mention that in this direction many works have been proposed over the last twenty years and, for these reasons, in this paper only the main studies have been reported in the table at the end of the paper 1. It is possible to notice that Capacitive Coupling works usually at higher frequencies compared to Galvanic Coupling, supporting an higher Data rate. For Capacitive Coupling, Zimmerman in his initial configuration [23] used a on-off keying (OOK) modulation and direct sequence spread spectrum (DSSS) to support its HBC system prototype supporting low data-rate (2.4 Kb/s) with an high coupling amplitude (30 V). More advanced configurations have been designed in [18] by Partridge et al. . They extended Zimmerman's original IBC system by improving the filters and amplifiers used in the transceiver circuit. Two different micro-controllers were used in the circuit to generate and modulate the input digital signals exploiting a more complex modulation as frequency-shift keying (FSK). Another important work has been done by Bae in 2012 [2] where, for the first time, a capacitive coupling IBC transceiver was able to fulfill the requirements of the WBAN standard, such as network coexistence and quality of service (QoS) scalability, supporting 10 Mb/s data rate in the operating frequency range of 40–120 MHz. In this case also the BER has been reported: 10^{-5} with a datarate of 10 Mb/s and 10^{-12} with a datarate of 10 Kb/s. An higher datarate is supported in the system proposed by Lin, [14], where a small size system-on-a-chip (SOC) for biomedical applications was implemented for the first time; in this setup an high frequency carrier of 200 MHz has been used with data rates up to 2 Mb/s exploiting OOK modulation. One of the most recent IBC systems based on capacitive coupling is the one proposed by Chung et. al [6] which support a very high datarate from 1 Mb/s to 40 Mb/s with tested

in a frequency ranging from 1 MHz to 40 MHz with a bit error rate 10^{-8} (considering 40 Mb/s). For what concern Galvanic Coupling, Oberle [17] in 2002 has designed a single-chip low-power biomedical system using a continuous phase frequency shift keying (CPFSK). In this case very low transmission rate has been supported using low frequency carrier. Another HBC galvanic system is the one proposed by Wegmuller in 2007 [21] which support a data rate of 64 kbps in a very short range (10-15 cm).
In respect to the hardware design, each of the studies just cited has implemented its own configuration adapted to the experimental setup. Nevertheless there is a basic structure of reference which is recurrent among the studies. The transmitter is usually composed by FPGA (Field Programmable Gate Array) module which contains the modulator and the amplifier directly connected with the electrostatic coupling electrodes (inversely for the receiver). From point of view of the micro-technology the challenge concern the miniaturization of this hardware preserving at the same time the efficiency and security [8]. Despite the devices presented so far have been designed only for experimental purposes some HBC prototypes have been just design for the health-care data transmission. For instance, Handa et al. [11] developed a galvanic coupling HBC prototype to transmit the ECG signal from chest to limb (through the arm). The system uses PWD modulation with a carrier frequency of 70kHz. Later, in 2003, a galvanic coupling HBC has been applied to transmit the heart rate and SpO2 signal to a receiver positioned on the wrist. More recently in 2011 a SOC chip was developed by Lin et al. [14] to directly transferring the ECG signals to a receiver on the wrist (also reported before and in table 1).
Beyond pure technological considerations Intra-Body Communications systems have to take into account very strict safety guidelines due to the potential health risks deriving from the energy injection on internal tissues. At this regard IEEE Std. C95.1 2005 establish some thresholds for electric field within localized human body is between 100 KHz and 3 GHz while the maximum harmless induced current in HBC should be lower than 20 mA at frequency range of 100 KHz and 110 MHz [12].

5 Human Body Communication in WBANs: standard 802.15.6

As stated in the introduction, in 2012 the standard 802.15.6 has been introduced and Human Body Communications have been identified as one of the three type of physical layer. The other ones was Narrow Band Communications (NB), Ultra Wide Band Communications (UWB) which are based on radio waves propagation (RF) and are suitable for extra-body communications. Specifically NB communications operate at lower frequency region in respect to UWB and are thought both for implantable and wearable devices which do not require an high data rate: frequency bands in 402–405 MHz, 863–956 MHz and 2360–2400 region with a datarate between 10 to 1000 kb/s [19]. Meanwhile, UWB PHY operates in the higher frequency regions, particularly the 3–5 GHz and the 6–10 GHz bands with channel bandwidth of 499.2 MHz with a data rate ranging from 395 kb/s–12.636 Mb/s.
For what concern HBC, the standard centers the operating frequency $f_c = 21MHz$ with a bandwidth $f_{BW} = 5.25MHz$ with scalable data rates of 164–1312.5 kb/s. Beyond this, the standard proposes reference HBC transmitter and receiver block diagram the interface between the circuitry (micro-controllers) and the electrodes, very important for a future standardization of the hardware.

6 Conclusion and Future works

In this paper the theme of Intrabody Communication have been surveyed from different point of views. Starting from the IBC coupling methods and related signal propagation models, the main features of human body channels have been presented. In the second part HBC communication systems have been analyzed summarizing the main design specifics presented so far in the literature from a point of view of modulation schemes and performances underling the main application for bio-signals transmission. Finally HBC physical layer of 802.12.6 has been described.
Despite Intra-Body Communication is not a new technology many challenges are still present and future studies are required to be addressed. As underlined by Nikita in [16], one of the main issue related to IBC is the experimental characterization of the human body as a transmission medium. As stated before there is still a mismatch from the simulations models and the experimental results and experimental results can vary from person to person, models shall be personalized with the aim of addressing different subjects' bioelectric properties and characteristics. Moreover, most of the systems published before 2012 did not follow no standard design specifics considering very different experimental setup and measurements of performances. In this direction a new standard should be released in the future to delineate a set of metrics of performances to be measured in specifics experimental conditions (distance TX-RX, dynamic of the body ecc..). In this respect most of the works cover consider a single channel communication but multi-channel applications have not been investigated yet. From the point of view of the performances and system design, the current systems are sufficient to support most of the required rate for biosignal transmission in WBAN (EEG=192 kbps, ECG=86.4 kbps , EMG=1.536 Mbps [5]) and capacitive coupling seems to be the most suitable technique to achieve this goal also in respect to 802.15.6 standard. Despite this further works have to be done to characterize properly QoS in term of BER and time delays. Finally in order to make Intra-body communication applicable in

WBANs two main steps have to be realized: at first investigating HBC performances to support point-to-multipoint communications (MAC layer design) and secondly investigating the reliability of IBC in term of security.

Table 1: Summary of the specifics of the main IBC systems proposed since 1995

Author	Year	Coupling Method	Coupling Amplitude	Carrier Frequency	Modulation Techinque	Data Rate	Overall Power Consumption	Distance TX-RX
Zimmerman	1995	Capacitive	30 V	330 KHz	OOK	2.4 Kb/s	400mW	-
Partridge	2001	Capacitive	22 V	160 KHz	FSK	38 Kb/s	-	200 cm
Bae	2012	Capacitive	1 V	40-120 MHz	Double-FSK	10 Mb/s	4.4 mW	-
Lin	2011	Capacitive	0.5 V	200 MHz	OOK	2 Mb/s	-	-
Chung	2016	Capacitive	1 V	1-40 MHz	Wideband	1 Mb/s-40 Mb/s	1.21 mW	140 cm
Oberle	2002	Galvanic	4 mA	60 KHz	CPFSK	4.8 Kb/s	-	-
Wegmuller	2007	Galvanic	1mA	256 KHz	BPSK	64 Kb/s	726mW	10-25 cm

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