Review On Intra-Body Communication Using Galvanic Coupling for Wearable Devices

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Abstract— *In recent years, wearable devices have witnessed remarkable advancements, offering numerous possibilities for healthcare monitoring, human-computer interaction, and personalized applications. Intra-body communication (IBC) has emerged as a promising communication technique for wearable devices, enabling seamless and secure data transmission within the human body. This review paper presents an in-depth analysis of IBC using galvanic coupling, a prominent method for establishing reliable and efficient communication channels between wearable devices and the human body. The primary objective of this review is to provide a comprehensive understanding of the principles, applications, and technologies of IBC utilizing galvanic coupling. Firstly, we present an overview of IBC, emphasizing its advantages, such as low power consumption, electromagnetic interference immunity, and miniaturization potential. Next, the fundamental concepts and working principles of galvanic coupling are discussed, including using electrodes, modulation schemes, and signal processing techniques. The paper further explores the wide range of applications for IBC using galvanic coupling as we go through the aspects of an IBC system. Furthermore, we discuss recent advancements in IBC technology, including novel electrode designs, signal processing algorithms, and integration with other wireless communication technologies. By exploring its principles, applications, challenges, and prospects, this review aims to advance this exciting field, facilitating the development of more efficient and reliable wearable devices for diverse applications in healthcare and beyond.*

Keywords— **Intra-Body Communication, Galvanic Coupling, Wearable, Healthcare Monitoring.**

Abbreviations and specific symbols

IBC – Intra-Body Communication
GC- Galvanic Coupling
CC- Capacitive Coupling
CMOS- Complementary Metal-Oxide Semiconductor
WBS- Wideband Signalling
CDR- Clock and Data Recovery
DCO- Digitally Controlled Oscillator
FPGA- Field-programmable gate array
FSK- Frequency Shift Keying
ASK- Amplitude Shift Keying
QAM- quadrature amplitude modulation
DDS- direct signal synthesiser

I. INTRODUCTION

In recent years, the rapid advancement of technology has led to the widespread adoption of wearable devices, revolutionizing various aspects of our daily lives. These devices, from smartwatches and fitness trackers to health monitoring systems, have become integral components of the ever-expanding Internet of Things (IoT) ecosystem. One of the key challenges in designing wearable devices is achieving efficient and reliable communication between the devices and the human body they are worn on. Intra-body communication (IBC) has emerged as a promising solution to address this challenge, firing seamless and secure data transmission within the human body.

IBC has garnered significant attention due to its ability to leverage the body's conductivity to facilitate communication. Unlike conventional wireless communication techniques, galvanic coupling utilizes the electrical properties of the human body, enabling low-power and short-range communication. This method involves the transmission of electrical signals through the body's tissues, primarily using the human skin as a medium.

This research paper aims to provide a comprehensive review of the state-of-the-art intra-body communication using galvanic coupling for wearable devices. By examining the existing literature, this review aims to shed light on the technological advancements, challenges, and potential applications of galvanic coupling in the context of wearable devices.

Section II will consist of the methodology and the Section III of the review will include these sections as below,

A. Intrabody communication physics
B. IBC channel modelling
C. Intrabody communication safety and regulation
D. IBC electrodes for wearables
E. IBC transceivers for wearables
F. IBC protocols
G. Data modulation and power consumption

Finally, section IV will conclude with a summary of the key findings from the reviewed literature and outline potential future research directions in intra-body communication using galvanic coupling.

By providing a comprehensive review of the existing knowledge and advancements, this research paper aims to contribute to the growing literature on galvanic coupling-based wearable devices. This review will inspire researchers, engineers, and practitioners to explore further the potential of galvanic coupling in developing innovative wearable devices that enhance human-machine interaction, improve healthcare monitoring, and foster advancements in the field of personalized medicine.

II. METHODOLOGY

To write this paper, various research papers regarding the relevant topics were collected from 1989- 2021 and the sources of those research papers are from IEEE, PubMed, ResearchGate, Google Scholar, and other internet sources. The keywords that used in accruing these papers were "intra-body communication, communication protocols for IBC, power consumption in IBC systems, IBC physics, data modulation, IBC wearables". The papers were analyzed and summarized the critical points that are useful and relevant for an IBC system using galvanic coupling for wearables. The past findings of IBC wearables that use galvanic coupling as its primary technology were comprehensively reviewed in section III.

III. RESULTS

In this section, a comprehensive overview of the IBC methodologies was summarized in the literature. These methodologies were categorized into several parts, as mentioned in section I.

A. Intrabody Communication Physics

Definitions and a comparison between the two main IBC techniques, galvanic coupling and capacitive coupling were provided by in this section. Furthermore, bioelectric properties were included in this segment.

1) Galvanic Coupling

This method was based on a differential configuration scheme, in which an electric current is applied to the skin, causing two distinct current pathways to form: a primary flow through the TX electrodes and a secondary flow through the inner tissues and towards the RX electrodes (Naranjo-Hernández et al., 2018). By modulating the applied current, data could be encoded and transmitted through variations in the electrical signals. These signals could be represented various types of information, such as sensor readings, commands, or audio signals, depending on the specific application. In (Roa et al., 2014), the experimental findings confirm that the galvanic coupling technique was well-suited for transmitting signals between devices positioned on the chest or nearly on the limbs. This effective transmission was occurred within the frequency range of 10 kHz to 1 MHz for the above experiment.

2) Capacitive Coupling

In capacitive coupling, the electrodes were positioned near the skin surface without direct contact. An alternating current (AC) signal was applied to the TX electrode, creating an electric field around it. This electric field induces an AC voltage on the RX electrode, which was detected and processed to extract the transmitted data (Xu et al., 2019). The primary signal channel predominantly relies on the capacitive return path, which was established through the air. However, this method was highly influenced by external environmental conditions. Furthermore, as the frequency increases, the amount of signal radiation into the air was became significant and could not be ignored (Xu et al., 2012).

Table 1 shows the comparison between the main two IBC techniques.

Table 1. Comparison between GC and CC

Properties	**Galvanic coupling**	**Capacitive coupling**
Physical connection	Direct physical connection	Indirect connection
Signal transfer	Electrical current flowing through the body	Voltage or electric field through the human body
Isolation	Better signal isolation	Limiter electrical isolation
Frequency response	Low and high frequencies	High frequencies
Noice immunity	Higher immunity	Lower immunity
Signal integrity	Higher integrity, low distortion	Higher distortion compared to GC
Data transfer rates	Low data rates	High data rates
Power consumption	Higher	Lower

Bioelectric Properties Corresponding to IBC, the bioelectric characteristics of the human body play a vital role in understanding and implementing IBC methods. These characteristics encompass the electrical properties of various body tissues, such as skin, muscles, and organs. Factors like conductivity, impedance, and capacitance of these tissues need to be accounted for when designing IBC systems. By recognizing the bioelectric properties of the body, researchers and engineers can develop accurate theoretical frameworks and practical setups for IBC. This understanding aids in optimizing the transmission and reception of electrical signals through the body, enabling efficient and reliable communication.

Foster and Schwan published the first study on the primary dielectric properties of biological tissues in 1989(Foster and Schwan, 1989) It has been demonstrated that variations and inconsistencies can be observed in the properties of living tissues. Below is the Debye equation (1), which Foster uses in his research.

$$\epsilon_r^* = \epsilon_r'(\omega) - j\epsilon_r''(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + j\omega\tau} \quad (1)$$

“Debye's expression” for dielectric properties is insufficient in accurately representing the behaviour of materials across a broad spectrum of frequencies. As a result, the “Cole-Cole” equation was developed as an alternative (equation 2 in (C. Gabriel et al., 1996a)). This equation enables the calculation of the complex electrical permittivity,

$$\epsilon_r^* = \epsilon_\infty + \sum_{n=1}^{4} \frac{\Delta\epsilon_n}{1 + (j\omega\tau)^{1-\alpha_n}} + \frac{\sigma_s}{j\omega\epsilon_0}, \quad (2)$$

In a significant contribution to the field, Gabriel conducted a notable study in 1996, presenting extensive data on the conductivity and permittivity of vital living tissues across a wide frequency range from 10 Hz to 20 GHz (Wegmueller et al., 2010). Additionally, Gabriel provided the corresponding “Cole-Cole” model parameters for these tissues (Tomlinson et al., 2016).

One important factor influencing the behaviour of tissues is the polarization of cell membranes, which can be modelled as capacitance. This polarization is primarily responsible for dispersion. Cell membranes, characterized by low conductivity, act as a barrier between the intracellular and extracellular media, which have higher conductivity. At lower frequencies, the high impedance of the cell membrane limits the current flow through the extracellular fluid surrounding the cells. However, as the frequency increases, the membrane plates charge and discharge rapidly, reducing membrane impedance. This allows a small amount of current to pass through the cell. Consequently, the current traverses the intra and extracellular media directly from frequencies in the tens of MHz range (Naranjo-Hernández et al., 2018), (S. Gabriel et al., 1996), (C. Gabriel et al., 1996b). Figure 1 and 2 shows the permittivity and conductivity of different tissues.

B. *IBC Channel Modelling*

IBC models aid in understanding transmission through biological tissues and designing WBANs. Techniques for modelling human anatomy as communication have been proposed. Bioelectric characteristics understanding is crucial. Three categories of modelling approaches are compared and evaluated in the literature for their contributions.

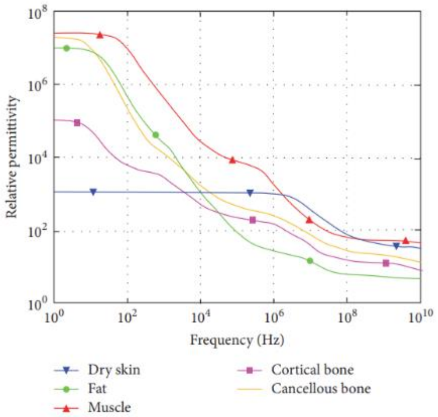

Figure 1: Gabriel’s report on the relative permittivity of cortical and cancellous bone, fat, muscle, and dry skin

Source: C. Gabriel et al., 1996a

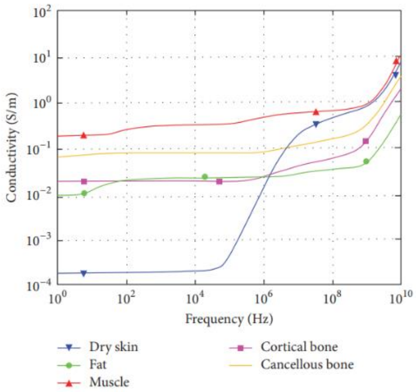

Figure 2: Gabriel's report on the electrical conductivity of cortical and cancellous bone, fat, and dry skin

Source: C. Gabriel et al., 1996a

1) Electromagnetic model

In (Teshome et al., 2016), an analytical electromagnetic model is introduced, designed to capture the effects of tissue layers in a scalable and comprehensive manner applicable to any body part. The model is constructed with simplicity, ensuring analytical solutions can be obtained. Using this geometry-based approach, the researchers derived a mathematical representation of the channel. The authors have analytically resolved the “Maxwell equations under quasi-static assumptions” by simulating the head, torso, and limbs with “Lame's functions” in an ellipsoidal geometry. They investigated the characteristics of the received signal in more detail, considering the size of the transmitter, the tissue layers, the locations of the transmitter and receiver, and the distance between the electrodes. The authors of (Gao et al., 2008) used an electromagnetic model with cylindrical geometry to investigate the flow of electric current through the arm. The model specifically focused on galvanic coupling and considered an overall length of 30 cm and an outer diameter of 5 cm. The muscle and skin layers were modelled as two concentric mediums within a cylindrical structure. The distribution of current density within a cross-sectional plane of the cylinder was investigated. The operating frequency was set below 200 kHz, where the impact of permittivity was considered insignificant. To simplify the problem, it was assumed that the conductivity remained constant throughout the studied frequency range. As a result, “Laplace's equation" was applied through the quasi-static approximation. The analysis revealed that the current density was predominantly concentrated near the electrodes.

2) Body channel electric circuit models

In intra-body communication (IBC), body channel electric circuit models are used to represent the electrical behaviour of the human body as a communication channel. These models aim to capture the characteristics of the body tissues and their response to electrical signals. Several circuit models have been proposed for different aspects of IBC channel modelling. The authors (Wegmueller et al., 2010) propose a four-terminal circuit model for a galvanic IBC system. This model accounts for the impact of electrode, coupling impedance and incorporates ten resistances. It also incorporates aspects of the Cole-Cole model, which characterizes the frequency-dependent dielectric properties of muscles and skin, as well as the bioelectric properties of cell membranes. The goal is to develop a more sophisticated and realistic model for understanding and analysing the behaviour of the IBC system (Wegmueller et al., 2007).

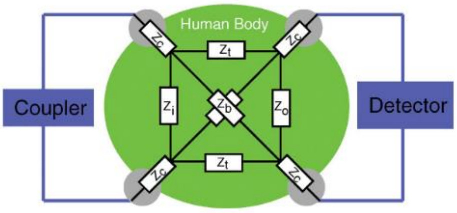

Figure 3: Circuit model of the human body modelling the coupling electrode impedances (Zc), input impedances (Zi), and output impedances (Zo)as well as longitudinal transmit impedances (Zt)and butterfly cross impedances (Zb).

Source: Wegmueller et al., 2010

3) Phantoms models

Phantom models are commonly used in intra-body communication (IBC) channel modelling to simulate the behaviour of the human body and assess the performance of IBC systems. These models replicate the electrical properties of the body tissues and enable experimental evaluation in a controlled environment. In (Fujii et al., 2006) proposed a solid phantom for intra-body communication experiments, while (Wegmueller et al., 2009) used an ellipsoidal phantom filled with MSL27 fluid to model a human torso.

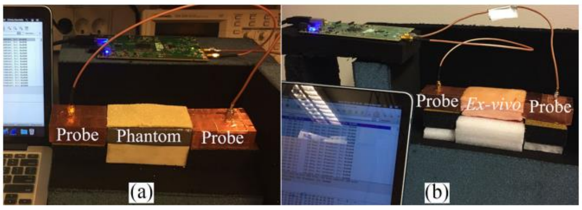

Figure 4 - experimental in-vitro setup

Source: Asan et al., 2017

In (Asan et al., 2017) focused on high data rate microwave communication through adipose tissue, utilizing both a phantom and ex-vivo porcine belly tissue for channel measurements. These studies contribute to the understanding and development of intra-body communication systems.

C. Intra Body Communication Safety and Regulations

The "International Commission on Non-Ionizing Radiation Protection" (ICNIRP) has mentioned in discussions regarding regulations for electromagnetic exposure. The ICNIRP establishes limits based on occupational and public exposure, considering different characteristics of these groups (“Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz),” 2010). Occupational exposure limits are set for individuals who have received training on safety precautions and work in controlled radiation environments. In contrast, the term "general public exposure" refers to the broader population, including people of all ages, genders, and health conditions, including vulnerable groups like the elderly, pregnant women, and young children, who lack formal radiation protection training. The ICNIRP has identified three primary physical quantities as basic limits at various frequency ranges. For frequencies between 1 Hz and 10 MHz, the limiting factor is the current density (j) or electric field (E), while for frequencies between 100 kHz and 10 GHz, the Specific Absorption Rate (SAR) is the key consideration. In evaluating galvanic-coupled weak intra-body communication (IBC) signals that act on the human arm, specific criteria are employed. These include ensuring that the current density remains below f/500, the electric field remains lower than 1.3510(-4) f, and the SAR stays below 4 W/kg.

It is important to note that the continuous operation of IBC transceivers can potentially cause thermal effects. According to the "Japan Society of Medical Electronics and Biological Engineering" (JSMEBE), it is considered safe for tissues near an electrical circuit to remain below a temperature of 42.5° C (“HOME | Japanese Society for Medical and Biological Engineering,” n.d.).

D. IBC electrodes for wearables

The authors of (Hachisuka et al., 2005) examined the effects of square electrodes with sizes ranging from 10 to 50 mm. The researchers observed that the gain exhibited a decrease when using electrodes of larger or smaller sizes, with the highest gain achieved when employing square electrodes measuring 25 mm by 25 mm. This peak gain was obtained within a frequency range of around 10 MHz. This may be since as electrodes get bigger, current loss among electrodes of the same pair increases and electrode capacitance declines as electrode size increases.

The Callejon experiment (Callejon et al., 2013) comparing different electrode kinds (pre-gelled Ag/AgCl, aluminium, and copper) revealed that the use of a conductor’s performance of the IBC remains largely unaffected or shows minimal impact. The smaller active area of the Ag/AgCl electrodes, however, did not prevent them from performing better. This is likely because they have been pre-gelled, which enhances their conductive qualities and skin adherence. Due to the application of a higher current and the subsequent amplification of signal levels, the electrode-skin impedance is effectively reduced compared to the impedance of other electrodes, primarily due to the presence of the gel. Additionally, it was discovered that pre-gelled electrodes were more immune to movement artifacts.

A comparison has been made between galvanic coupling and capacitive coupling in terms of their effectiveness, focusing on the perspective of the electrodes. In their study (Alshehab et al., 2008), the authors considered various factors such as the ground circuit board, electrode sizes, the distance between the signal electrode, and the distance to circuit board from them, and the presence or absence of a ground electrode in contact with the skin. These considerations were made to determine the optimal configuration.

E. IBC transceivers for wearables

IBC (Intrabody Communication) transceivers refer to the devices or systems that enable communication within the human body. These transceivers typically consist of a transmitter and a receiver that facilitate the transmission and reception of signals through the body's conductive medium. IBC transceivers are commonly used in applications such as medical implants, wearable devices, and human-machine interfaces, where reliable and low-power communication within the body is required. They employ various modulation and encoding techniques to transmit data efficiently and can operate in different frequency ranges depending on the specific application.

There are two main IBC system development methods used in literature. They are namely,

- Discrete Components method
- CMOS Technology

To be implemented in wearable devices CMOS technology is the best approach compared to discrete component method due to its compactness over the other.

In (Song et al., 2006), the authors demonstrated that their transceiver chip, operating at a 2 Mbps data rate, outperformed a Bluetooth transceiver while consuming only 5 mW of power. The architecture of the transceiver consists of five components: physical medium, interface layer, signaling link layer, transceiver module, and application. The human body's physical medium, with a broadband-pass operational spectrum, can transfer real-time multimedia data streams through the induced weak electric field on the skin. The interface layer establishes connections, allowing digital audio data to be transmitted to wearable input/output devices via a wireless body sensor (WBS) link. The transceiver module facilitates point-to-point transfers and broadcasting between application layers, generating packets of streaming data.

In study (Chen et al., 2017), a novel receiver utilizing Golay Complementary Binary Code (GC-BCC) is introduced, operating at 200 kHz. It incorporates an all-digital Gaussian Frequency Shift Keying (GFSK) demodulator and Clock and Data Recovery (CDR) module. The receiver design can tolerate frequency misalignments, and a carrier tracking method is proposed to address significant carrier frequency misalignment. The CDR employs a circle-index approach to mitigate clock drift or inaccuracy. The all-digital design reduces power consumption, and the receiver chip, fabricated using 180 nm CMOS technology, includes a Butterworth Bandpass Filter (BPF) to filter out unwanted interferences. The compact CMOS design occupies a pad-limited area of 1.1 mm by 1.1 mm.

F. IBC protocol

In an Intra-Body Communication (IBC) system, a communicational protocol defines the rules and procedures for the exchange of data and control information between different components within the system. It ensures reliable and efficient communication while addressing issues such as data synchronization, error detection and correction, addressing, and protocol overhead. Understanding of the communicational protocol provides a significant advantage in building the communicational structure of an IBC system.

The IBC protocol implemented on a wearable device needs to fulfill several requirements.

In (Asan et al., 2017), LP-WPANs protocols based on the IEEE 802.15.4 standard were employed for experiments using the O-QPSK modulation method. The aim was to achieve high data rate microwave communication through fat tissue for intra-body area networks. As in (Tomlinson et al., 2016) utilized the USRP N210 SDR platform to emulate a single implanted sensor and develop the GC-IBC testbed. (Wei et al., 2020) focused on developing galvanic coupling IBC transceiver systems with low coupling amplitude and high data rate. It used an all-digital DPSK modulation and demodulation implemented on an FPGA. The transmitter employed DDS and shaping filter technologies for signal quality, while the receiver used a Costas loop coherent demodulation scheme for reliable demodulation. The modulator unit in (Wang et al., 2014) utilized a QPSK modulation technique where the carrier signal's phase was adjusted based on the transmitted symbol. The DDS method was employed to generate the sine and cosine carriers using a phase-to-amplitude converter and an N-bit accumulator. The Carrier recovery, required for coherent demodulation, was achieved through the use of the Costas Loop in reference. The Costas Loop consisted of mixers, low pass filters, a loop filter, a phase detector, and a DDS.

G. Data modulation and power consumption

The authors of (Seyedi et al., 2014) suggest developing a new IBC transmitter that uses an impulse radio-based pulse position modulation (PPM) scheme. The carrier free PPM transmission's architecture is implemented using an FPGA. Results show that the 1.56 Mb/s data rate is appropriate for the galvanic coupling IBC method. With a 3.3 V supply voltage, the PPM transmitter's power consumption is 2.0 mW. A better option is offered for body area network-based portable biomedical applications by having energy efficiency as low as 1.28 nJ/bit. The human body is used as a data transmission medium in (Song et al., 2007) to propose and implement a novel Human-Body-Communication scheme for energy-efficient data communications. The WBS digital transceiver operates at 2-Mb/s with a power consumption of 0.2 mW from a 1-V supply thanks to four low-power techniques: direct digital transmission, all-digital CDR architecture, low-voltage DCO, and quadratic sampling technique.

IV. CONCLUSION

In this review paper, a comprehensive analysis of intra-body communication (IBC) was provided using galvanic coupling for wearable devices. Through the exploration of the principles, applications, challenges, and prospects of this communication technique, several key insights have emerged. Firstly, IBC using galvanic coupling offers significant advantages for wearable devices, including low power consumption, immunity to electromagnetic interference, and potential for miniaturization. These features make it an attractive option for various applications, particularly in healthcare monitoring, human-computer interaction, and personalized devices. Moreover, this paper has highlighted the main aspects of a IBC system and expressed the key features that are crucial for a wearable IBC system. However, it is important to acknowledge the challenges associated with IBC. Signal attenuation, interference from surrounding tissues, and establishing reliable connections in varying physiological conditions remain significant hurdles. These challenges warrant further research and development to optimize the performance of IBC systems and overcome these limitations.

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