# In-Body Sensor Communication: Trends and Challenges

Marshed Mohamed, Baraka J. Maiseli, Yun Ai, Khadija Mkocha, and Ahmed Al-Saman

***Abstract*—Wireless body area networks (WBANs) consist of interconnected devices that monitor the human body functions and the surrounding environment. Of these sensors, implants encounter multiple challenges due to their invasive nature. In addition, the transmission channel of the implants involves living tissues that pose practical challenges in channel modeling. Despite several promising applications of implants in the healthcare industry, there have been insufficient comprehensive reviews that extensively describe trends, and challenges of this technology. This work reviews in-body WBANs and presents critical challenges that hinder advancement and application of the technology. We also discuss possible solutions that may be useful to realize in-body WBANs practically.**

***Index Terms*—Communication technologies, implant, WBAN, wireless body area network.**

## I. Introduction

WIRELESS body area networks (WBANs) consist of a collection of low-power, miniaturized, and lightweight devices with wireless communication capabilities operating in the proximity of a human body (Fig. 1). These devices can be placed at different locations of the human body to monitor its functions and characteristics of the surrounding environment. Typical body locations that WBAN devices can occupy include inside (in-body sensor or implant), outside (on-body sensor), and around the human body. Thanks to their capabilities to monitor vital body signs, WBANs find a wide range of biomedical applications in the healthcare industry.

WBAN devices provide critical medical information that requires immediate intervention, and also facilitates analysis of long-term diagnostic information over time. They facilitate disease diagnosis through measurement of body health conditions, including glucose level, oxygen saturation, and acidity. Other WBAN devices such as pacemakers, electrical muscle stimulation machines, and neurostimulators can be used as therapeutic tools to provide required stimulation and interventions. Another group of WBAN devices, such as cochlear and bionic vision implants, help to improve the anatomical and physiological functions of the human body.

For decades, scholars have been reviewing WBAN in the context of performance, routing protocols, applications, network technologies, energy, and communication technologies [1]–[4]. However, implant communication in WBAN has received little attention, hence limiting further advancement of the WBAN technology. In essence, this communication modality poses relatively more complex challenges different from those discussed in the literature. Firstly, the transmission channel of the implants (in-body WBANs devices) contains living tissues that bear high attenuation to the electromagnetic signals. Furthermore, the simulation of communication through such a channel takes a long time and consumes large power as the channel contains several layers with different electromagnetic properties. Consequently, during measurements, the available phantom models lack versatility for multi-frequency applications [5].

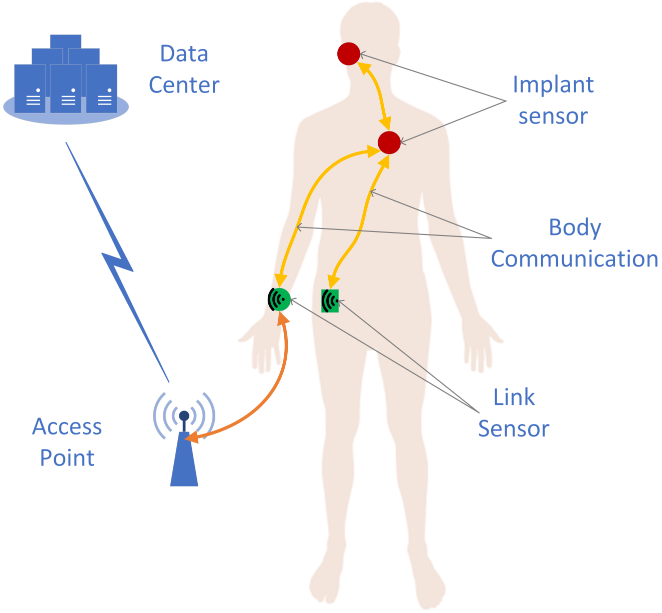

Fig. 1. Wireless body area network.

In addition, the invasive nature of implantation surgeries poses additional challenges to the in-body sensor communication design. The sensors should be miniaturized and should operate under a sustainable power-saving mode to minimize the number of surgeries required to replace the batteries. The feasibility of the sustainable powering regime depends on the data rate requirements of a particular application, which also dictates the bandwidth and the implant communication mechanism.

This article intends to provide a general understanding of implant communications' trend and challenges for the average readers within and outside the specialty of this article. Section

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TABLE I
IN-BODY COMMUNICATION TECHNOLOGIES

| Technology | Propagation | Range | Frequency | Standard |
|---|---|---|---|---|
| Radio Frequency (RF) | Radio waves | 2 m | 400 - 406 MHz<br>2.36 - 2.4 GHz | MedRadio<br>ISM |
| Inductive coupled | Magnetic field | < 40 mm | 1, 2, 3, 10, 24, 49 MHz | None |
| Galvanic coupled | Electric field | < 100 mm | < 10 MHz | 802.15.6 |
| Ultrasonic | Ultrasonic | 100 mm | 1 - 3 MHz | none |
| Optical | Infrared | < 4 mm | 300 GHz - 430 THz | none |

II will discuss different communication technology used in implant communication, together with their corresponding advantages and disadvantages, while Section III will sum up their common challenges and Section IV will conclude the article.

## II. COMMUNICATION TECHNOLOGIES

The communication modalities of the in-body devices can be divided into two categories, namely implant-to-surface communication and implant-to-implant communication. The implant-to-surface communication involves communication between in-body and on-body devices. This type of communication is suitable for applications involving transmission of sensed quantities from inside the body to on-body devices for processing or further data forwarding to the control and diagnostic centers. On the other hand, the implant-to-implant communication deals with communication between pairs of in-body devices. Typical applications that utilize implant-to-implant communication include the implants that operate in closed-loop control settings [6]. In this work, we present different enabling techniques for in-body communications and introduce latest developments of the techniques. Summary of the in-body communication technologies are shown in Table I.

### A. *Radio frequency*

This method allows implants and external transceivers to establish communication by radiating and intercepting radio frequency (RF) waves through antennas. The external transceivers could be located on or around the body surface. Radio frequency has been standardized in the Medical Devices Radiocommunication Service (MedRadio) for use within a range of 401 - 406 MHz frequency band. The MedRadio standard specifies the bandwidth of 300 kHz for full-duplex communication with maximum equivalent radiated power (EIRP) of 25 $\mu$W. Furthermore, to minimize energy consumption, the implants can only transmit after receiving a request from the network controllers.

MedRadio endures some shortcomings, including limited bandwidth (300 KHz) that can hardly meet the demands of high speed and large data rate transmission. Additionally, MedRadio and meteorological aids services share the same frequency band (401 - 406 MHz), hence generating possible impulsive interference with other radio networks. Despite the existence of several interference mitigation techniques, the practical implementation of those techniques generally lead to complex transceiver structures that occupy larger space and consume more power. Therefore, simple transceivers limited to indoor usage with long polling intervals are preferred.

To address the low-bandwidth issue, the specific unlicensed industrial, scientific, and medical (ISM) frequency band (2.4 - 2.5 GHz) has been used for implants communication. This band is shared with other communication services, such as WiFi and Bluetooth—hence providing possibilities for interference that may affect the quality of communication between WBAN devices. The Federal Communication Commission (FCC) and the European Telecommunication Standard Institute (ETSI) address the issue of interference by dedicating the frequency band of 2.36 - 2.40 GHz for medical communication applications: maximum bandwidth of 5 MHz and maximum EIRP of 100 $\mu$W.

RF transmission of implant communication suffers from high path loss caused by the lossy dielectric nature of the body tissues. In principle, the loss at 1000 mm in free space translates to 40 mm in in-body to in-body communication and subsequently translates to only 20 mm in variable tissue layers, such as in in-body to on-body communication. These transmission distances imply that such (in-body to on-body) communication can only cover relatively shorter distances corresponding to larger energy consumption [7].

The high path loss of RF transmission in implant communication channel requires highly-efficient RF antenna design. The traditional half-wave dipole antenna can occupy up to 60 mm length at 2.4 GHz—a relatively longer length that should be optimized. For implant applications, different techniques have been proposed to design antennas with acceptable sizes. There are mainly two technical approaches to reduce the antenna size, namely construction-based approach (e.g. use of high-permittivity dielectric materials) and shape-based approach (meandering or spiraling with multiple radiating patches stacked vertically) [8].

### B. *Inductive coupling*

This technology applies the electromagnetic induction principle to facilitate RF energy transfer. The current injected into the transmitting coil (normally placed near the body) produces a time-varying magnetic field that induces an electromotive force (EMF) at the implant receiving coil (Fig. 2). The implant uses the induced EMF as a source of power, and also applies telemetry to send data back to the external device. Inductive coupling uses resonant frequencies of 1 MHz, 5 MHz, 10 MHz, 24 MHz, and 49 MHz, and is only applicable for

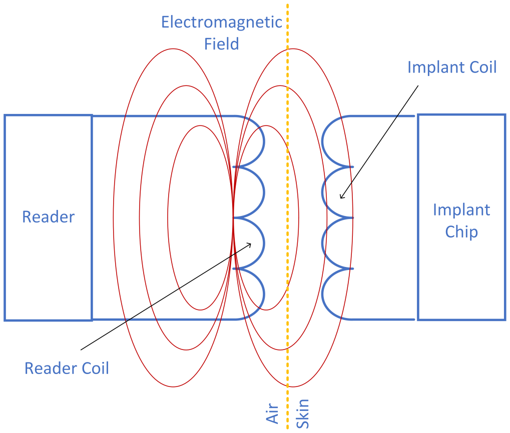

Fig. 2. Inductive coupling.

implants near the surface (< 40 mm), such as retinal and cochlear implants [9].

The in-body sensor transmission by inductive coupling offers a small bandwidth for efficient power transfer. Therefore, researchers have recommended separate coils for power and data transfer as an attempt to increase bandwidth. In other studies, recommendations have been given to increase the number of data coil pairs from single to multiple. With these recommendations, and in conjunction with the current sophisticated modulation techniques, the data rate can be increased significantly [9].

Engineers have been using bandwidth enhancement techniques together with radio frequency identification technology to address problems in implant communication. Using these techniques, implants can be as small as 1.2 mm × 2.0 mm and can consume as little power as 50 $\mu$W. The functioning principle of inductive coupling makes it advantageous in a number of applications [10].

## C. Galvanic coupling

This technique uses the human body as a transmission medium for electrical signals to enable communication between WBAN devices (Fig. 3). Given the type of medium involved, galvanic coupling suits implants and on-body devices, and cannot be applied to off-body devices. The Institute of Electrical and Electronics Engineers (IEEE) 802.15.6 standard designates galvanic coupling as the human body communication with a center frequency of 21 MHz. Galvanic coupling operates as follows: a transmitter injects an electric current using two electrodes attached to the human body; similarly, the receiver uses two electrodes to detect the injected current. This delicate mechanism of operation necessitates strict compliance of the devices with the pre-defined regulations to avoid interference with other biomedical devices and to avoid adverse health problems. Galvanic coupling, as a mode of communication, allows devices to be confined within the human body. Devices using the technique cannot be detected by a potential eavesdropper, even at a close distance from the body surface. Galvanic coupling offers physical security and eliminates interference between implants in the body. These advantages become significant with an increased number of people containing the implants [5].

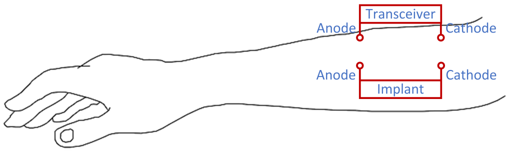

Fig. 3. Galvanic coupling.

Compared with RF communication, galvanic coupling encounters less attenuation in the human tissue. For example, using a 39 mm dipole antenna, communication between implant and on-body device at a frequency of 2.4 GHz and a distance of 40 mm gives a path loss of 55 dB. Conversely, using galvanic coupling at 1 MHz and 5 mm electrode spacing, the same distance gives a path loss of only 35 dB. This significant reduction in attenuation and the size of the interface between the device and the transmission media (39 mm for simple RF antenna and 5 mm for the electrode spacing in galvanic coupling) makes the miniaturization of the devices less challenging [11].

## D. Ultrasonic

Ultrasonic communication is based on principles of mechanical wave propagation (Fig. 4). Since the implants are based on electricity, an ultrasonic transducer is needed to convert electrical energy into mechanical energy, and vise versa. Similar to inductive coupling, ultrasonic transducers can also be used in power scavenging or back-scattering communication [12].

With a speed of 1500 m/s, the ultrasonic waves of frequencies greater than 1.5 MHz result in wavelength of less than 1 mm. Therefore, communication can be established for implants of a size comparable with this wavelength. The small wavelength (of 1 mm) enables beam focusing using multiple transducers, and hence a single transmitter may communicate with multiple implants by sweeping the focus of the beam from one implant to the other. The narrow-focusing spot protects the surrounding tissues from unnecessary temperature rise [13].

Ultrasonic waves have a slower absorption rate in the human tissues than the RF electromagnetic waves. Note that, in implant-to-implant communication, MedRadio waves incur 40 dB loss when propagated through 60 mm, and ISM waves incur equally the same loss for a propagation distance of 40 mm; on the contrary, ultrasonic waves can travel as far as 400 mm before encountering the same loss (40 dB) under similar channel conditions. Moreover, ultrasonic waves dissipate lower heat to body tissues, making this communication modality safer compared with radio frequency. Therefore, regulatory authorities (FCC and ETSI) have allowed 72 times more power intensity for ultrasonic waves relative to RF waves [14].

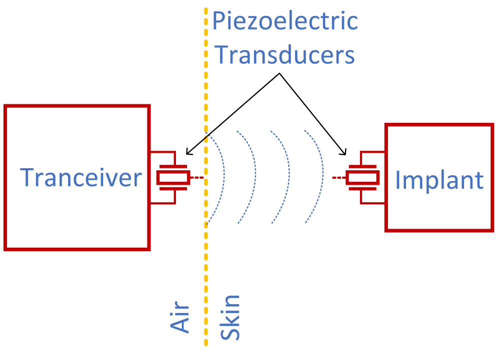

Fig. 4. Ultrasonic communications.

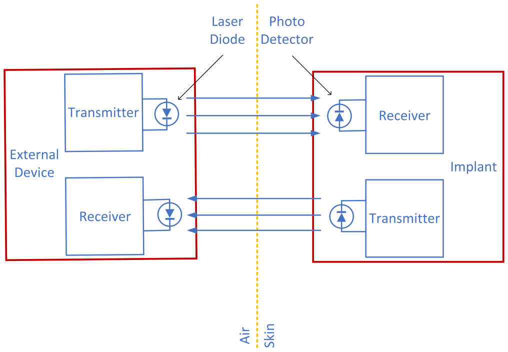

Fig. 5. Optical communications.

### E. Optical

In recent years, the optical communication has caught researchers' interest in the biomedical research community. In optical communication, the optical transmitter uses laser diodes as transducers to convert data (electrical signals) into infrared waves (Fig. 5). At the receiving end, photo detectors convert infrared waves back to an electrical signal and subsequently detect and decipher the transmitted messages. Infrared waves have high operating frequency (300 GHz - 430 THz) and wider bandwidth but suffer from extreme attenuation [15]. The contributing obstacles include spreading losses, reflections caused by multi-layer structures of the human tissues, and skin light absorption. Compared with ultrasonic communication, which gives 40 dB losses at 400 mm, optical communication can only support 4 mm transmission distance for the same loss [16]. Therefore, communication through infrared waves is limited to subcutaneous implants.

Increasing the communication distance for implants has been the biggest challenge in optical communication. To this end, some researchers recently proposed the use of optical communication for very short links, e.g., for communications with nodes under the skin. The communication distance can be increased by a number of means, such as focusing light using nano-antenna arrays and by placing hydro-gel waveguide between the communicating devices to guide light using total internal reflections [17]. By applying these enhancement techniques, the range can be considerably increased to several centimeters, allowing communications with deeply implanted devices as well as between in-body devices.

## III. COMMON CHALLENGES

### A. Energy source and consumption

Implants, usually powered by batteries, undertake delicate and sensitive medical applications, and hence they should operate reliably over an extended period of time. They should, in addition, dissipate minimum energy through sensing, communication, and data processing. To maintain constant energy supply, batteries of the implants should be replaced at specific periods during operation. This non-trivial task, however, should be discouraged. Furthermore, biosensors that collect vital body conditions should receive uninterruptible energy to maintain their effective communication with caregivers and doctors. Data inconsistency, caused by unstable energy consumed by the biosensors, may result into inappropriate treatments or improper decisions by doctors. Despite their energy requirements, there have been designing challenges to manufacture energy-efficient implants with longer operation periods without battery replacement or recharging. A trade-off exists between miniaturization and energy efficiency of the implants: the human body requires a miniature medical device (implant) at the expense of poor battery life.

Due to the limited battery size and their replacement challenges, battery-less techniques becomes more interesting. These are however limited to implant-to-surface communication, using technologies such as inductive coupling, where the implants can communicate back to the surface device using back-scattering modulation. Energy deficiency in implants may also be addressed through energy scavenging techniques such as body biochemical reactions and thermal energy; kinetic energy generated through body movements, or mechanical energy harvested using piezoelectric materials.

### B. Miniaturization of implant size

The invasive nature of the implants necessitates their miniaturization to ensure that they compactly fit into body organs and produce insignificant damage to the body tissues. Given the technological advancement in very large scale integration of electronic components, this miniaturization can be achieved at a satisfactory degree. In essence, miniaturization depends on two limiting factors, namely antenna and battery sizes, which should be balanced to produce compact implant devices. In the former factor, antenna size decreases with the transmission frequency at the expense of larger attenuation. This relationship springs a challenge of establishing a trade-off between antenna size and radiated power while maintaining miniaturized implants. Practical scenarios include electrode spacing in galvanic coupling and transducer size reduction in ultrasonic communication. In the later limiting factor, a smaller battery size encourages compact implants at the expense of frequent battery replacements. For on-body devices, this challenge may be tolerated. However, the challenge becomes even serious for the implant because battery replacement could require a surgical intervention. On one hand, the approach to overcome the challenge can be done through inductive coupling that allows battery-less and back-scattering operation of the implant.

### *C. Bio-compatibility and human safety concerns*

The human body has internal defense mechanisms that may be activated upon the introduction of an implant. Bio-compatibility occurs when the body responds positively to the implant, causing insignificant health concerns. However, implants may interact with cells of some human bodies and cause toxic reactions, organ failure, tissue scarring, or inflammation. If left untreated, these undesirable consequences may worsen the patient's quality of life. Therefore, before applying implants to patients, comprehensive studies should be conducted to understand how specific cells of human bodies behave when interacted with the implants. Perhaps human bodies respond differently with specific types of bio-materials, meaning that scholars require a thorough understanding of bio-materials and their interaction mechanisms with body cells.

Furthermore, implants generate electromagnetic radiation that raises health safety concerns. Scholars have invested considerable efforts to design implant antennas with radiation powers that meet the recommended specific absorption rate (degree at which the human body absorbs electromagnetic radiation). Antenna design for implants is an active area of research that intends to provide better communication infrastructure between transmitting and receiving ends while ensuring adherence to health safety guidelines.

### *D. Channel modeling*

Implementation of WBANs requires a detailed mathematical analysis (modeling) showing how wireless signals behave when passing through a communication channel. For the implants, the channel modeling process becomes more challenging because of the involvement of live human subjects. The mere changing of human posture implies changes in the corresponding communication channel. Furthermore, an implant should undergo an invasive procedure to be embedded into the human body. Therefore, getting a sufficient number of volunteers (test subjects) to participate in this procedure may be challenging. Besides, complying with all relevant policies, laws, and regulations from authorities further complicate the matter. Another challenge involves the implant's communication channel as it solely comprises of living tissues with layers exhibiting different electromagnetic properties that should be estimated and incorporated into the channel model. This challenge makes the simulation of the channel, multi-frequency phantom modeling, and model's empirical validation complex.

## IV. CONCLUSION

WBAN devices have found various medical applications due to their capabilities of monitoring the human body functions with respect to the surrounding environment. They provide critical medical information for immediate intervention. Also, WBAN devices can provide tracked historical data for analysis and investigation. Despite the advantages, special attention should be drawn on the inherent challenges of the technology. The implant devices, for instance, pose serious challenges because of their invasive nature that demands living-tissue communication channels—a consequence that unnecessarily adds complexities in the channel modeling.

In WBAN communication, signals suffer from high attenuation during propagation through the environment (e.g. living tissues), and miniaturization of such devices is limited to their antenna and battery sizes. Inductive coupling eliminates the need for batteries because the technique allows communication through back-scattering. However, this advantage may only be feasible for communications between near-the-surface implants and on-body devices. The high attenuation encountered by RF communication can be reduced by using galvanic coupling or ultrasonic communication. Moreover, ultrasonic waves are considered to be safer because they dissipate much less heat in human tissues.

We have further discussed that the limited size of the implants significantly affects their energy source. Large batteries are not recommended, and hence researchers have attempted to optimize energy consumption as a possible solution to extend the implants' battery life. Some researchers propose scavenging techniques to power the implants. But, given their location in the human body, special considerations are required to ensure safety and bio-compatibility during testing, experimentation, and real-world application.

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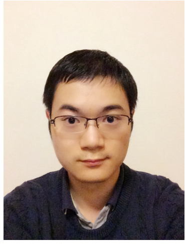

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