In Vivo WBAN Communication: Design and Implementation

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The emerging in vivo communication and networking system is a prospective component in advancing healthcare delivery and empowering the development of new applications and services. In vivo communications is based on networked cyber-physical systems of embedded devices to allow rapid, correct and cost-effective responses under various conditions. This chapter presents the existing research which investigates the state of art of the in vivo communication. It focuses on characterizing and modeling the in vivo wireless channel and contrasting it with the other familiar channels. MIMO in vivo is also of concern in this chapter since it significantly enhances the performance gain and data rates. Furthermore, this chapter addresses in vivo nano-communication which is presented for medical applications to provide fast and accurate disease diagnosis and treatment. Such communication paradigm is capable of operating inside the human body in real time and will be of great benefit for medical monitoring and medical implant communications. Consequently, propagation at the Terahertz (THz) frequency must be well understood as it is considered the most promising band for electromagnetic nano-communication models.

\textbf{Keywords}— In vivo communication, MIMO in vivo, nano-communication, THz frequency, WBAN.

1 Introduction

Wireless Body Area Networks (WBANs) are a new generation of Wireless Sensor Networks (WSNs) dedicated for healthcare monitoring applications. The aim of these applications is to ensure continuous monitoring of the patients’ vital parameters, while giving them the freedom of moving thereby resulting in
an enhanced quality of healthcare [1]. In fact, a WBAN is a network of wearable computing devices operating on, in, or around the body. It consists of a group of tiny nodes that are equipped with biomedical sensors, motion detectors, and wireless communication devices which incorporates techniques similar to those implemented in wireless systems [2–14]. Actually, advanced healthcare delivery relies on both body surface and internal sensors since they reduce the invasiveness of a number of medical procedures [15]. Electrocardiogram (ECG), electroencephalography (EEG), body temperature, pulse oximetry (SpO2), and blood pressure are evolving as long-term monitoring sensors for emergency and risk patients [16].

One attractive feature of the emerging Internet of Things is to consider \textit{in vivo} networking for WBANs as an important application platform that facilitates continuous wirelessly-enabled healthcare [17]. Internal health monitoring [18], internal drug administration [19], and minimally invasive surgery [20] are examples of the pool of applications that require communication from \textit{in vivo} sensors to body surface nodes. However, the study of \textit{in vivo} wireless transmission, from inside the body to external transceivers is still at its early stages.

Fig. 1 shows a modified network organization for interconnecting the biomedical sensors. The data is basically not directly transferred from the biomedical sensors to the hospital infrastructure. Indeed, sensors send their data via a suitable low-power and low-rate \textit{in vivo} communication link to the central link sensor (located on the body like all other sensors). Any of the sensors may act as a relay between the desired and the central link sensor if a direct connection is limited. An external wireless link enables the data exchange between the central link sensor and the external hospital infrastructure [16].

![Figure 1: Simplified overview of the \textit{in vivo} communication network.](image)

Wireless \textit{in vivo} communication creates a wirelessly-networked cyber-physical system of embedded devices. Such systems utilize real-time data to enable rapid, correct as well as cost-conscious responses for surgical, diagnostic, and emergency circumstances [15]. The crucial element that should be carefully regarded when referring to \textit{in vivo} communications is modeling the \textit{in vivo} wireless channel. The ability to understand the characteristics of the \textit{in vivo} channel is fundamental to achieve optimum processing and design effective protocols that enable the arrangement of WBANs inside the human body [15].
This chapter surveys the existing research which investigates the state-of-art of the *in vivo* communication. It also focuses on characterizing and modeling the *in vivo* wireless channel and contrasting this channel with the other familiar ones. MIMO *in vivo* is also of interest since it significantly enhances the performance gain and data rates. Finally, this chapter introduces *in vivo* nano-communication as a novel communication paradigm. The rest of the chapter is organized as follows. In Section II, we present the state-of-art of *in vivo* communication. Conducted research on *in vivo* channel characterization is provided in Section III. The MIMO *in vivo* system is described in Section IV. *In vivo* nano-communication is addressed in Section V. Finally, we draw our conclusions and summarize the paper in Section VI.

# 2 State-of-art of *In Vivo* Communication

*In vivo* communication is a genuine signal transmission field which utilizes the human body as a transmission medium for electrical signals [21–23]. The body becomes a vital component of the transmission system. Electrical current induction into the human tissue is enabled through sophisticated transceivers while smart data transmission is provided by advanced encoding and compression. Fig. 2 shows the main components of an *in vivo* communication link.

![Figure 2: *In vivo* communication for data transmission between sensors enabled by transmitter and receiver units.](image)

A transmitter unit permits sensor data to be compressed and encoded. It then conveys the data by a current-controlled coupler unit. The human body acts as the transmission channel. Electrical signals are coupled into the human tissue and distributed over multiple body regions. On the other hand, the receiver unit is composed of an analog detector unit that amplifies the induced signal and digital entities for data demodulation, decoding, and extraction [16].

Developing body transmission systems have shown the viability of transmitting electrical signals through the human body. Nonetheless, detailed characteristics of the human body are lacking so far. Not a lot is known about the
impact of human tissue on electrical signal transmission. Actually, for advanced transceiver designs, the effects and limits of the tissue have to be cautiously taken into consideration [16] [24]. The main requirements of an in vivo system include low power, low latency, less complexity, robustness to jamming, reliability, and size compactness [25]. In vivo communication is involved in a wide array of practical medical usages. For instance, in vivo sensors are utilized in health monitoring applications in order to keep track of glucose and blood pressure levels. In vivo actuators are also important for implanted insulin pumps as well as bladder controllers. Moreover, in vivo technology is involved in both medical nanorobotic device communication and in therapeutic nanoparticles employed in malignant tumor elimination processes. Such distinctive communication can add an effective contribution in the development of Prosthetics including artificial retina, cochlear implants and brain pacemakers for patients with Parkinsons disease.

2.1 Human Body Model

Research into in vivo communications primarily used the ANSYS HFSS [26] Human Body Model software to conduct the simulations. This software is a high-performance full-wave electromagnetic (EM) field simulator which enables the complete electromagnetic fields prediction and visualization. Hence, important parameters such as S-Parameters, resonant frequency, and radiation characteristics of antennas can be computed and plotted. The human body is modeled as an adult male body with more than 300 parts of muscles, bones and organs, having a geometric accuracy of 1 mm and realistic frequency dependent material parameters. The original body model only has the parameters from 10 Hz to 10 GHz. However, the maximum operating frequency is increased to 100 GHz by manually adding the values of the parameters to the datasets [27].

2.2 System Level Setup

To evaluate the Bit Error Rate (BER) performance of the in vivo communication, an OFDM-based (IEEE 802.11n) wireless transceiver model operating at 2.4 GHz is setup. This model implies varying different Modulation and Coding Schemes (MCS) index values as well as bit rates in Agilent SystemVue for various in vivo channel setups in HFSS. The system block diagram is shown in Fig. 3 [28].

![Figure 3: Block diagram of system level simulation with HFSS in vivo channel model](image-url)
3 \textbf{In Vivo} Channel Modeling and Characterization

The \textit{in vivo} channel is a novel paradigm in the field of wireless propagation; thus, it is very different when compared to other frequently analyzed wireless environments such as cellular, Wireless Local Area Network (WLAN), and deep space \cite{2}. Fig. 4 illustrates the classic multi-path channel and the \textit{in vivo} multipath channel.

![Figure 4: Classic multi-path channel vs. \textit{in vivo} multi-path channel \cite{15}.](image)

Basically, in an \textit{in vivo} channel, the electromagnetic wave passes through various dissimilar media that have different electrical properties, as depicted in Fig. 4. This leads to the reduction in the wave propagation speed in some organs and the stimulation of significant time dispersion that differs with each organ and body tissue \cite{28}. This is coupled with attenuation due absorption by the different layers result in the degradation of the quality of the transmitted signal in the \textit{in vivo} channel.

The authors in \cite{16} compare the characteristics of wireless technologies including the WLAN, Bluetooth, Zig-bee, and active Radio Frequency Identification (RFID) as shown in Table 1. Their aim is to seek a novel transmission technique for \textit{in vivo} communication which focuses on transmission power below 1mW, data rates of 64 kbit/s, and the possibility for miniaturization to integrate the transceiver modules into band-aids and implantable pills.

| Technology       | Frequency       | Data Rate    | Transmission Power | Size          |
|------------------|-----------------|--------------|--------------------|---------------|
| WLAN             | 2.4/5.1 GHz     | 54 Mbit/s    | 100 mW             | PC card       |
| Bluetooth        | 2.4 GHz         | 723.1 kbit/s | 1 mW               | PCB module    |
| Zigbee           | 864 MHz         | 20 kbit/s    | 10 mW              | PCB module    |
| Active RFID      | 134 kHz         | 128 bit/s    | <1 mW              | pill          |
| \textit{In vivo} communication | <1 MHz | >64 kbit/s | <1 mW | band-aid/pill |

In addition, since the \textit{in vivo} antennas are radiating into a complex lossy medium, the radiating near fields will strongly couple to the lossy environment. This signifies that the radiated power relies on both the radial and angular
positions; hence, the near field effect has to be always taken into account when functioning in an \textit{in vivo} environment \cite{29}. The electric and magnetic fields behave differently in the radiating near field compared to the far field. Therefore, the wireless channel inside the body necessitates different link equations \cite{30}. It must be noted as well that both the delay spread and multi-path scattering of a cellular network are not directly applicable to near-field channels inside the body. The reason behind this is the fact that the wavelength of the signal is much longer than the propagation environment in the near field \cite{31}.

The authors in \cite{15} used an accurate human body to investigate the variation in signal loss at different radio frequencies as a function of position around the body. They noticed significant variations in the Received Signal Strength (RSS) which occur with changing positions of the external receive antenna at a fixed position from the internal antenna \cite{15}. Nevertheless, their research did not take into account the basic characterization of the \textit{in vivo} channel. In \cite{25}, the authors used an immersive visualization environment to characterize RF propagation from medical implants. Based on 3-D electromagnetic simulations, an empirical path loss (PL) model is developed in \cite{32} to identify losses in homogeneous human tissues. In \cite{33,34,35,36}, the authors carried out numerical and experimental investigations of biotelemetry radio channels and wave attenuation in human subjects with ingested wireless implants.

Modeling the \textit{in vivo} wireless channel including building a phenomenological path loss model is one of the major research goals in this field. A profound understanding of the channel characteristics is required for defining the channel constraints and the subsequent systems’ constraints of a transceiver design \cite{16}.

\subsection{Path Loss}

Path loss in \textit{in vivo} channels can be investigated using either a Hertzian dipole antenna or a monopole antenna. The authors in \cite{31} carried out their study based on Hertzian dipole in which path loss is examined with minimal antenna effects. The length of the Hertzian dipole is so small resulting in little interaction with its surrounding environment. The path loss can be calculated as

\begin{equation}
\text{Path Loss}(r, \theta, \phi) = 20 \log_{10}\left(\frac{|E|_{r=0}}{|E|_{r,\theta,\phi}}\right)
\end{equation}

where \(r\) represents the distance from the origin, i.e. the radius in spherical coordinates, \(\theta\) is the azimuth angle and \(\phi\) is the polar angle. \(|E|_{r,\theta,\phi}\) is the the magnitude of the electric field at the measuring point and \(|E|_{r=0}\) is the magnitude of electric field at the origin.

Due to the fact that the \textit{in vivo} environment is an inhomogeneous medium, it is mandatory to measure the path loss in the spherical coordinate system \cite{31}. The setup of this approach is depicted in Fig. 5 which includes the truncated human body, the Hertzian dipole, and the spherical coordinate system.

The authors in \cite{15} carried out their study based on monopole antenna. Actually, monopoles are good choice of practical antennas since they are small.
in size, simple and omnidirectional. The path loss can be measured by scattering parameters (S parameters) that describe the input-output relationship between ports (or terminals) in an electrical system [15]. According to Fig. 6, if we set Port 1 on transmit antenna and Port 2 on receive antenna, then $S_{21}$ represents the power gain of Port 1 to Port 2, that is

$$|S_{21}|^2 = \frac{P_r}{P_t}$$

(2)

where $P_r$ is the received power and $P_t$ is the transmitted power. Therefore, we calculate the path loss by the formula below

$$Path \ Loss(dB) = 20 \log_{10}|S_{21}|$$

(3)

Based on the simulations presented in [31], it can be observed that there is a substantial difference in the behaviors of the path loss between the in vivo and free space environment. In fact, significant attenuation occurs inside the body.
resulting in an *in vivo* path loss that can be up to 45 dB greater than the free space path loss. Fluctuations in the out-of-body region is experienced by the *in vivo* path loss. On the other hand, free space path loss increases smoothly. The inhomogeneous medium results as well in angular dependent path loss [31].

### 3.2 Comparison of Ex Vivo and In Vivo Channels

The different characteristics between *ex vivo* and *in vivo* channels are summarized in [31] as shown in Table 2.

**Table 2: Comparison of Ex vivo and In vivo Channel [28]**

| Features                      | Ex vivo                              | In vivo                              |
|-------------------------------|--------------------------------------|--------------------------------------|
| Physical Wave Propagation     | Constant speed                       | Variable speed                       |
|                               | Multipath - reflection, scattering,  | Multipath and penetration             |
|                               | and diffraction                      |                                      |
| Attenuation and Path Loss     | Lossless medium                      | Very lossy medium                    |
|                               | Decrease inversely with distance     | Angular (directional) dependent      |
| Dispersion                    | Multipath delays-time dispersion     | Multipath delays of variable speed   |
|                               |                                      | frequency dependency                 |
| Directionality                | Propagation essentially uniform      | Propagation varies with speed        |
|                               |                                      | frequency dependency                 |
|                               |                                      | time dispersion                      |
| Near Field Communication      | Deterministic near-field region around the antenna | Inhomogeneous medium - near field region changes with angles and position inside the body |
| Power Limitations             | Average and Peak                     | Plus specific absorption rate (SAR)  |
| Shadowing                     | Follows a log normal distribution    | To be determined                      |
| Multipath Fading              | Flat fading and frequency selective fading | To be determined                      |
| Antenna Gains                 | Constant                             | Angular and positional dependent     |
|                               |                                      | Gains highly attenuated              |
| Wavelength                    | The speed of light in free space     | at 2.4GHz, average dielectric constant  
|                               | divided by frequency                 | $c_r = 35$, which is roughly 6 times smaller than the wavelength in free space. |

### 4 MIMO In Vivo

Due to the lossy nature of the *in vivo* medium, attaining high data rates with reliable performance is considered a challenge [17]. The reason behind this is that the *in vivo* antenna performance may be affected by near-field coupling as mentioned earlier and the signals level will be limited by a specified Specific Absorption Rate (SAR) levels. The SAR is a measurement of how much power is absorbed per unit mass of conductive material, in our case, the human organs [37]. This measurement is limited by the Federal Communications Commission (FCC) which in turns limits the transmission power [37].

#### 4.1 Capacity of MIMO In Vivo

The MIMO *in vivo* system capacity is the upper theoretical performance limit that can be achieved in practical systems, and can provide insight into how
well the system can perform theoretically and give guidance on how to optimize the MIMO in vivo system \cite{28}. The achievable transmission rates in the in vivo environment have been simulated using a model based on the IEEE 802.11n standard \cite{38} because this OFDM-based standard supports up to 4 spatial streams (4x4 MIMO). Owing to the form factor constraint inside the human body, current studies are restricted to 2x2 MIMO.

The OFDM system can be modeled as:

\[ Y_k = H_k X_k + W_k, \quad k = 1, 2, ..., \text{N}_{\text{data}} \]  (4)

where \( Y_k, X_k, W_k \in \mathbb{C}^2 \) denote the received signal, transmitted signal, and white Gaussian noise with power density of \( N_0 \) respectively at OFDM subcarrier \( k \). The symbol \( \text{N}_{\text{data}} \) is the total number of subcarriers configured in the system to carry data. The complex frequency channel response matrix at subcarrier \( k \) is denoted by \( H_k \in \mathbb{C}^{2 \times 2} \).

The SVD (Singular Value Decomposition) of \( H_k \) is given as:

\[ H_k = U_k \Sigma_k V_k^H \]  (5)

where \( U_k, V_k^H \in \mathbb{C}^{2 \times 2} \) are unitary matrices, and \( \Sigma_k \) is the nonnegative diagonal matrix whose diagonal elements are singular values of \( \sqrt{\lambda_{k1}}, \sqrt{\lambda_{k2}} \), respectively.

The system capacity for subcarrier \( k \) is \( \cite{39} \):

\[ C_k = E[\sum_{i=1}^{2} \log_2(1 + \frac{\lambda_{ki}P}{2N_0BW})] \]  (6)

where \( P \) is the total transmit signal power of the two transmitter antennas, \( BW \) is the configured system bandwidth in Hz, and \( E \) denotes expectation. In this chapter, only time-invariant Gaussian channels will be considered. Hence, the expectation in the capacity calculation will be ignored.

The total system capacity is calculated as:

\[ C = \frac{1}{T_{\text{sym}}} \sum_{k=1}^{\text{N}_{\text{data}}} C_k = \left( \frac{BW}{N_{\text{total}}} \right) + T_{GI} \sum_{k=1}^{\text{N}_{\text{data}}} C_k \]  (7)

where \( T_{\text{sym}} \) is the duration of each OFDM symbol, \( N_{\text{total}} \) is the total number of subcarriers available in bandwidth \( BW \), and \( T_{GI} \) is the guard interval.

4.2 Results of MIMO In Vivo

The authors in \cite{28} analyzed the Bit Error Rate for a MIMO in vivo system. By comparing their results to a 2 × 2 SISO in vivo, it was evident that significant performance gains can be achieved when using a 2 × 2 MIMO in vivo. This setup allows maximum SAR levels to be met which results in the possibility of achieving target data rates up to 100 Mbps if the distance between the transmit (Tx) and receive (Rx) antennas is within 9.5 cm \cite{37}. Fig. 7 below demonstrates
the simulation setup that shows the locations of the MIMO antennas. Two Tx antennas are placed inside the abdomen while two Rx antennas are placed at different locations inside the body at the same planar height [28].

![Simulation setup showing locations of MIMO antennas.](image)

Figure 7: Simulation setup showing locations of MIMO antenna [28].

The antennas used in Fig. 7 are monopole antennas designed to operate at the 2.4 GHz ISM band in their respective medium which is either free space for the \textit{ex vivo} antennas or the internal body for the \textit{in vivo} antennas [28]. For the \textit{in vivo} case, the monopole’s performance and radiation pattern varies with position and orientation inside the body; therefore, the performance of the \textit{in vivo} antenna is strongly dependent on the antenna type [15] [29].

Further, in [17], it was proved that not only MIMO \textit{in vivo} can achieve better performance in comparison to SISO systems but also considerably better system capacity can be observed when Rx antennas are placed at the side of the body. Fig. 8 compares the \textit{in vivo} system capacity for front, right side, left side, and back of the body. In addition, it was noticed that in order to meet high data rate requirements of up to 100 Mbps with a distance between the Tx and Rx antennas greater than 12 cm for a 20 MHz channel, relay or other similar cooperative networked communications are necessary to be introduced into the WBAN network [17].

### 4.3 Applications of MIMO \textit{In Vivo}

One prospective application for MIMO \textit{in vivo} communications is the MARVEL (Miniature Anchored Remote Videoscope for Expedited Laparoscopy) [40]. MARVEL is a wireless research platform for advancing MIS (Minimally Invasive Surgery) that necessitates high bit rates (\( \sim 80 - 100 \) Mbps) for high-definition video transmission with low latency during surgery [41].
In vivo Nano-communication

Nanotechnology opens the door towards a new communication paradigm that introduces a variety of novel tools. This technology enables engineers to design and manufacture nanoscale electronic devices and systems with substantially new properties [42]. These devices cover radio frequencies in the Terahertz (THz) range and beyond, up to optical frequencies. The interconnections of nanodevices build up into nanonetworks enabling a plethora of potential applications in the biomedical, industrial, environmental and military fields.

In vivo nanosensing systems [43], which can operate inside the human body in real time, have been recently proposed as a way to provide faster and more accurate disease diagnosis and treatment than traditional technologies based on in vitro medical devices. However, the sensing range of each nanosensor is limited to its close nano-environment; thus, many nanosensors are needed to cover significant regions or volumes. Moreover, an external device and user interaction are necessary to read the actual measurement. By means of such communication, nanosensors will be able to overcome their limitations and expand their applications [44]. Indeed, nanosensors will be able to transmit their information in a multi-hop fashion to a gateway or sink, react to instructions from a command center, or coordinate between them in case that a joint response to an event or remote command is needed. For instance, Fig. 9 shows several in vivo nanosensors that communicate as they travel through a blood vessel.

A number of challenges exist in the creation of in vivo nanosensor networks, which range from the development of nano-antennas for in vivo operation to the characterization of the intra-body channel environment from the nanosensor perspective [45].

In order to develop in vivo wireless nanosensor networks (iWNSNs), plasmonic nano-antennas for intra-body communication must be utilized [46]. In addition, a new view on intra-body channel modeling must be presented. In
traditional channel models, the human body is modeled as a layered material with different permeabilities and permittivities. However, from the nanosensor perspective, and when operating at very high frequencies, the body is a collection of different elements (cells, organelles and proteins, among others), with different geometry and arrangement, as well as different electrical and optical properties. Further, coupling and interference effects among multiple nanosensors must be investigated and utilized at the basis of novel protocols for iWNSNs. The very high density of nanosensors in the envisioned applications results in non-negligible interference effects as well as electromagnetic coupling among nano-devices.

The future vision of in vivo networks entails the distribution of nano-machines that will patrol in the body, take measurements wherever necessary, and send collected data to the outside. As a result, the development process and the operation of these devices invoke careful measures and high requirements. Moreover, it is important to understand in-body propagation at THz, since it is regarded as the most promising band for electromagnetic paradigm of nano-communication. Actually, the THz Band (0.1-10 THz) is envisioned as a key technology that satisfies the increasing demand for higher speed wireless communication. THz communication alleviates the spectrum scarcity and capacity limitations of current wireless systems, and hence enables new applications both in classical networking domains as well as in novel nanoscale communication paradigms. Nevertheless, a number communication challenges exist when operating at the THz frequency such as propagation modeling, capacity analysis, modulation schemes, and other physical and link layer design metrics.

6 Conclusion

This chapter provided an overview of the in vivo communication and networking. The overview focuses on the state of art of the in vivo communication, the in vivo channel modeling and characterization, and the concept of MIMO in vivo. The chapter also addresses in vivo nano communication which is considered a novel communication paradigm that is going to revolutionize the concept of wireless body area networks. However, several challenges exist which open
the door towards further research in this genuine field.

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