

In Vivo Communications: Steps Toward the Next Generation of Implantable Devices

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Abstract—*In vivo* wireless medical devices have the potential to play a vital role in future healthcare technologies by improving the quality of human life. In order to fully exploit the capabilities of such devices, it is necessary to characterize and model the *in vivo* wireless communication channel. Utilization of this model will have a significant role in improving the communication performance of embedded medical devices in terms of power, reliability and spectral efficiency. In this paper, the state of the art in this field is presented to provide a comprehensive understanding of current models. Such knowledge will be used to optimize the design and selection of various *in vivo* wireless communication methods, operational frequencies, and antenna design. Finally, open research areas are discussed for the future studies.

Index Terms—*In vivo* channel characterization, in/on-body communication, wireless body area networks (WBAN), wireless implantable medical devices.

I. INTRODUCTION

Technological advances in biomedical engineering have significantly improved the quality of life and increased the life expectancy of many people. One component of such advanced technologies is represented by wireless *in vivo* sensors and actuators, e.g., pacemakers, internal drug delivery devices, nerve stimulators, wireless capsule endoscopes (WCEs), etc. *In vivo*-wireless body area networks (WBANs) [1] and their associated technologies are the next step in this evolution and offer a cost efficient and scalable solution along with the integration of wearable devices. *In vivo* WBAN devices are capable of providing continuous health monitoring and reducing the invasiveness of surgery. Furthermore, the patient information can be collected over a larger period of time and physicians are able to perform more reliable analysis by exploiting this *big data* rather than relying on the data recorded in short hospital visits [2], [3].

To fully exploit and increase further the potential of WBANs for practical applications, it is necessary to accurately assess

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the propagation of electromagnetic (EM) waveforms in an *in vivo* communication environment (implant-to-implant and implant-to-external device) and obtain accurate channel models that are necessary to optimize the system parameters and build reliable, efficient, and high-performance communication systems. In particular, creating and assessing such a model is necessary for achieving high data rates, target link budgets, determining optimal operating frequencies, and designing efficient antennas and transceivers including digital baseband transmitter/receiver algorithms. Therefore, investigation of the *in vivo* wireless communication channel is crucial to obtain a better performance for *in vivo*-WBAN devices and systems. Although, on-body wireless communication channel characteristics have been well investigated [3], there are relatively few studies of *in vivo* wireless communication channels.

While there exist multiple approaches to *in vivo* communications, in this paper we will focus on EM communications. Since the EM wave propagates through a very lossy environment inside the body and predominant scatterers are present in the near-field region of the antenna, *in vivo* channel exhibits different characteristics than those of the more familiar wireless cellular and Wi-Fi environments. In this paper, we present the state-of-the-art of *in vivo* channel characterization and discuss several research challenges by considering various communication methods, operational frequencies, and antenna designs.

The rest of the paper is organized as follows. In Section II, EM modeling of the human body is reviewed, which is essential for *in vivo* wireless communication channel characterization. Section III discusses EM wave propagation through human tissues. Section IV presents the choice of operational frequencies based on current standards and discusses their effects on the communication system performance. In Section V, the challenges of *in vivo* antenna design are briefly discussed as the antenna is generally considered to be an integral part of the *in vivo* channel. Section VI reviews the propagation models for the *in vivo* wireless communication channel and discusses the main differences relative to the *ex vivo* channel. In Section VII, several open research problems and future research directions are addressed. The last section summarizes our observations and conclusions.

II. EM MODELING OF THE HUMAN BODY

In order to investigate the *in vivo* wireless communication channel, accurate body models and knowledge of the electromagnetic properties of the tissues are crucial. Human autopsy

materials and animal tissues have been measured over the frequency range from 10 Hz to 20 GHz [4] and the frequency-dependent dielectric properties of the tissues are modeled by four-pole Cole-Cole equation, which is expressed as:

$$\epsilon(\omega) = \epsilon_{\infty} + \sum_{m=1}^4 \frac{\Delta\epsilon_m}{1 + (j\omega\tau_m)^{(1-\alpha_m)}} + \frac{\sigma}{j\omega\epsilon_0} \quad (1)$$

where ϵ_{∞} stands for the body material permittivity at terahertz frequency, ϵ_0 denotes the free-space permittivity, σ represents the ionic conductivity and ϵ_m , τ_m , α_m are the body material parameters for each anatomical region. The electromagnetic properties such as conductivity, relative permittivity, loss tangent, and penetration depth can be derived using these parameters in Eq. 1.

Various physical and numerical phantoms have been designed in order to simulate the dielectric properties of the tissues for experimental and numerical investigation. These can be classified as homogeneous, multi-layered and heterogeneous phantom models. Although, heterogeneous models provide more realistic approximation to the human body, design of physical heterogeneous phantoms is quite difficult and performing numerical experiments on these models is very complex and resource intensive. On the other hand, homogeneous or multi-layer models cannot differentiate the EM wave radiation characteristics for different anatomical regions. Fig. 1 shows examples of heterogeneous physical and numerical phantoms.

Analytical methods are generally viewed as infeasible and require extreme simplifications. Therefore, numerical methods are used for characterizing the *in vivo* wireless communication channel. Numerical methods provide less complex and appropriate approximations to Maxwell's equations via various techniques, such as uniform theory of diffraction (UTD), finite

integration technique (FIT), method of moments (MoM), finite element method (FEM) and finite-difference time-domain method (FDTD). Each method has its own pros and cons and should be selected based on the simulation model and size, operational frequency, available computational resources and interested characteristics such as power delay profile (PDP), specific absorption rate (SAR), etc. A detailed comparison for these methods is available in [4] and [6].

It may be preferable that numerical experiments should be confirmed with real measurements. However, performing experiments on a living human is carefully regulated. Therefore, anesthetized animals [7], [8] or physical phantoms, allowing repeatability of measurement results, [5], [9] are often used for experimental investigation. In addition, the first study conducted on a human cadaver was reported in [10].

III. EM WAVE PROPAGATION THROUGH HUMAN TISSUES

Propagation in a lossy medium, such as human tissues, results in a high absorption of EM energy. The absorption effect varies with the frequency dependent electrical characteristics of the tissues, which mostly consist of water and ionic content [11]. The specific absorption rate (SAR) provides a metric for the absorbed power amount in the tissue and is expressed as follows:

$$SAR = \frac{\sigma|E|^2}{\rho} \quad (2)$$

where σ , E and ρ represent the conductivity of the material, the RMS magnitude of the electric field and the mass density of the material, respectively. The Federal Communications Commission (FCC) recommends the SAR to be less than 1.6 W/kg taken over a volume having 1 gram of tissue [12].

When an EM plane wave propagates through the interface of two media having different electrical properties, its energy is partially reflected and the remaining portion is transmitted through the boundary of these mediums. Superposition of the incident and the reflected wave can cause a standing wave effect that may increase the SAR values [11]. A multi-layer tissue model at 403 MHz, where each layer extends to infinity (much larger than the wavelength of EM waves) is illustrated in Fig. 2. The dielectric values and power transmission factors of this model were calculated in [13]. If there is a high contrast in the dielectric values of mediums/tissues, wave reflection at the boundary increases and transmitted power decreases. The limitations on communications performance imposed by the SAR limit have been investigated in [12].

In addition to the absorption and reflection losses, EM waves also suffers from expansion of the wave fronts (which assume an ever-increasing sphere shape from an isotropic source in free space), diffraction and scattering (which depend on the EM wavelength). Section VI discusses *in vivo* propagation models by considering these effects in detail.

IV. FREQUENCY OF OPERATION

Since EM waves propagate through the frequency dependent materials inside the body, the operating frequency has an important effect on the communication channel. Accordingly,

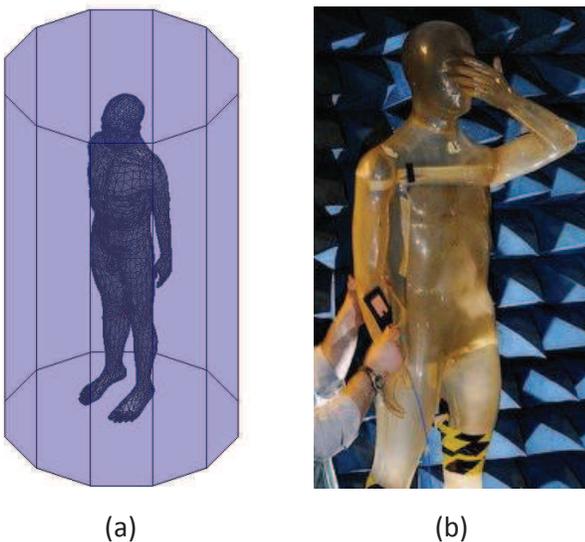


Fig. 1. Heterogeneous human body models: (a) HFSS[®] model, (b) physical phantom [5].

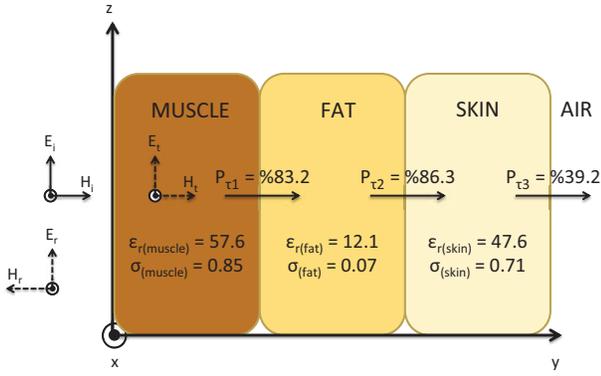


Fig. 2. Multi-layer human tissue model at 403 MHz (ϵ_r : Permittivity, σ : Conductivity, P_T : Power transmission factor).

we summarize the allocated and recommended frequencies including their effects for *the in vivo* wireless communications in this section.

The IEEE 802.15.6 standard [1] was released in 2012 to regulate short-range wireless communications inside or in the vicinity of the human body, and are classified as human-body communications (HBC) [14], narrow band (NB) communications, and ultra-wide band communications (UWB). The frequency bands and channel bandwidths (BW) allocated for these communication methods are summarized in Table I. An IEEE 802.15.6 compliant *in vivo*-WBAN device must operate in at least one of these frequency bands.

NB communications operates at lower frequencies compared to UWB communications and hence suffer less from absorption. This can be appreciated by considering Eq. 1 and Eq. 2 that describe the absorption as a function of frequency. The medical device radio communications service (MedRadio uses discrete bands within the 401-457 MHz spectrum including international medical implant communication service (MICS) band) and medical body area network (MBAN, 2360-2400 MHz) are allocated by the FCC for medical devices usage.

TABLE I
FREQUENCY BANDS AND BANDWIDTHS FOR THE THREE DIFFERENT PROPAGATION METHODS IN IEEE 802.15.6

Propagation Method	IEEE 802.15.6 Operating Freq. Bands		Selected References
	Frequency Band	BW	
Narrow Band Communications	402 - 405 MHz	300 kHz	[8], [11], [16], [17], [20], [24]
	420 - 450 MHz	300 kHz	
	863 - 870 MHz	400 kHz	[8], [16], [20], [24]
	902 - 928 MHz	500 kHz	
	950 - 956 MHz	400 kHz	
	UWB Communications	2360 - 2400 MHz	1 MHz
2400 - 2438.5 MHz		1 MHz	
Human - Body Communications	3.2 - 4.7 GHz	499 MHz	[7], [15], [20], [28]
	6.2 - 10.3 GHz	499 MHz	
Human - Body Communications	16 MHz	4 MHz	[14]
	27 MHz	4 MHz	

Therefore, co-user interference problems are less severe in these frequency bands. However, NB communications are only allocated small bandwidths (1 MHz at most) in the standard as shown in Table I. The IEEE 802.15.6 standard does not define a maximum transmit power and the local regulatory bodies limit it. The maximum power is restricted to 25 μ W EIRP (Equivalent Isotropic Radiated Power) by FCC, whereas it is set to 25 μ W ERP (Equivalent Radiated Power) by ETSI (European Telecommunication Standards Institute) for the 402-405 MHz band.

UWB communications is a promising technology to deploy inside the body due to its inherent features including high data rate capability, low power, improved penetration (propagation) abilities through tissues and low probability of intercept. The large bandwidths for UWB (499 MHz) enable high data rate communications and applications. Also, UWB signals are inherently robust against detection and smart jamming attacks because of their extremely low maximum EIRP spectral density, which is -41.3 dBm/MHz [15]. On the other hand, UWB communications inside the body suffer from pulse distortion caused by frequency dependent tissue absorption and the limitations imposed by compact antenna design.

V. *In Vivo* ANTENNA DESIGN CONSIDERATIONS

Unlike free-space communications, *in vivo* antennas are often considered to be an integral part of the channel and they generally require different specifications than the *ex vivo* antennas [4], [16]–[18]. In this section, we will describe their salient differences as compared to *ex vivo* antennas.

In vivo antennas are subject to strict size constraints and in addition, they need to be bio-compatible. Although, copper antennas have better performance, only specific types of materials such as titanium or platinum should be used for *in vivo* communications due to their noncorrosive chemistry [3]. The standard definition of the gain is not valid for *in vivo* antennas since it includes body effects [19]. As noted above, the gain of the *in vivo* antennas cannot be separated from the body effects as the antennas are considered to be an integral part of the channel. Hence, the *in vivo* antennas should be designed and placed carefully. When the antennas are placed inside the human body, their electrical dimensions and gains decrease due to the high dielectric permittivity and high conductivity of the tissues, respectively [20]. For instance, fat has a lower conductivity than skin and muscle. Therefore, *in vivo* antennas are usually placed in a fat (usually subcutaneous fat) layer to increase the antenna gain. This placement also provides less absorption losses due to shorter propagation path. However, the antenna size becomes larger in this case. In order to reduce high losses inside the tissues, a high permittivity, low loss coating layer can be used. As the coating thickness increases, the antenna becomes less sensitive to the surrounding material [20].

Lossy materials covering the *in vivo* antenna change the electrical current distribution in the antenna and radiation pattern. It is reported in [16] that directivity of *in vivo* antennas increases due to curvature of body surface, losses and dielectric loading from the human body. Therefore, this

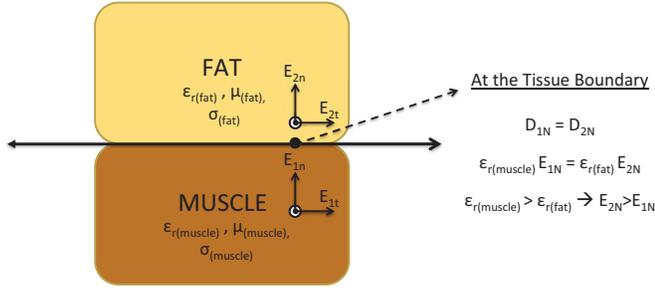


Fig. 3. EM propagation through tissue interface.

increased directivity should be taken into account as well in order not to harm the tissues in the vicinity of the antenna.

In vivo antennas can be classified into two main groups as electrical and magnetic antennas. Electrical antennas, e.g., dipole antennas, generate electric fields (E-field) normal to the tissues, while magnetic antennas, e.g., loop antennas produce E-fields tangential to the human tissues [11]. Normal E-field components at the medium interfaces overheat the tissues due to the boundary condition requirements as illustrated in Fig. 3. The muscle layer has a larger permittivity value than the fat layer and hence, the E-field increases in the fat layer. Therefore, magnetic antennas allow higher transmission power for *in vivo*-WBAN devices as can be understood from Eq. 2. In practice, magnetic loop antennas require large sizes, which is a challenge to fit inside the body. Accordingly, smaller size spiral antennas having a similar current distribution as loop antennas can be used for *in vivo* devices [7]. Representative antennas designed for *in vivo* communications are shown in Fig. 4.

VI. *In Vivo* EM WAVE PROPAGATION MODELS

Up to this point, important factors for *in vivo* wireless communication channel characterization, such as EM mod-

eling of the human body, propagation through the tissues, selection of the operational frequencies, and *in vivo* antenna design considerations have been reviewed. In this section, we will focus on EM wave propagation inside the human body considering the anatomical features of organs and tissues. Then, the analytical and statistical path loss models will be presented. Since the EM wave propagates through a very lossy environment inside the body and predominant scatterers are present in the near-field region of the antenna, *in vivo* channel exhibits different characteristics than those of the more familiar wireless cellular and Wi-Fi environments.

EM wave propagation inside the body is subject-specific and strongly related to the location of antenna as demonstrated in [9], [16], [24] and [25]. Therefore, channel characterization is mostly investigated for a specific part of the human body. Fig. 5 shows several investigated anatomical regions for various *in vivo*-WBAN applications and Table II provides further details about these studies. For example, the heart area has been studied for implantable cardioverter defibrillator and pacemakers, while the gastrointestinal tract (GI) including esophagus, stomach and intestine has been investigated for WCE applications. The bladder region is studied for wirelessly controlled valves in the urinary tract and the brain is investigated for neural implants [18], [26]. Also, clavicle, arm and hands are specifically studied as they are affected less by the *in vivo* medium.

When the *in vivo* antenna is placed in an anatomically complex region, path loss, a measure of average signal power attenuation, increases [24]. This is the case with the intestine which presents a complex structure with repetitive, curvy-shaped, dissimilar tissue layers, while the stomach has a smoother structure. As a result, the path loss is greater in the intestine than in the stomach even at equal *in vivo* antenna depths.

Various analytical and statistical path loss formulas have been proposed for the *in vivo* channel in the literature as listed in Table III. These formulas have been derived considering different shadowing phenomena for the *in vivo* medium. The initial three models are functions of the Friis transmission equation [4], return loss and absorption in the tissues. These models are valid, when either the far field conditions are fulfilled or few scattering objects exist between the transmitter and receiver antennas.

The free space path loss (FSPL) is expressed by the Friis transmission equation in the first model in Table III. The FSPL mainly depends on gain of antennas, distance, and operating frequency. Its dependency on distance is a result of expansion of the wave fronts as explained in Section III. Additionally, FSPL is frequency dependent due to the relationship between the effective area of the receiver antenna and wavelength. The two equations of the FSPL model in Table III are derived including the antenna return loss and absorption in the tissues. Another analytical model, PMBA [27], calculates the SAR over the entire human body for the far and near fields, and gives the received power using the calculated absorption. Although, these analytical expressions provide intuition about each component of the propagation models, they are not practical for link budget design as similar

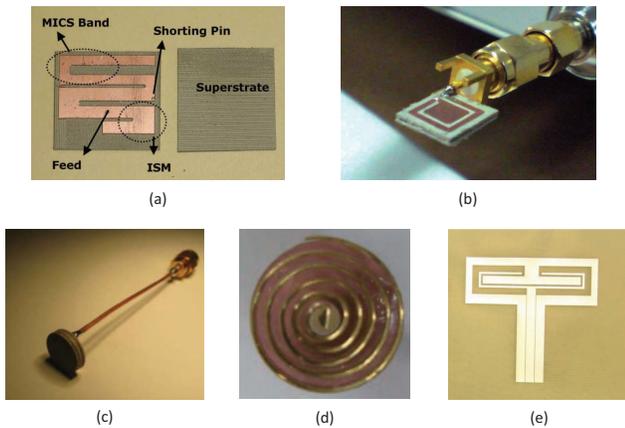


Fig. 4. Selected *in vivo* antenna samples: a) A dual-band implantable antenna [21], b) A miniaturized implantable broadband stacked planar inverted-F antenna (PIFA) [22], c) A miniature scalp-implantable [2], d) A wideband spiral antenna for WCE [7], e) An implantable folded slot dipole antenna [23].

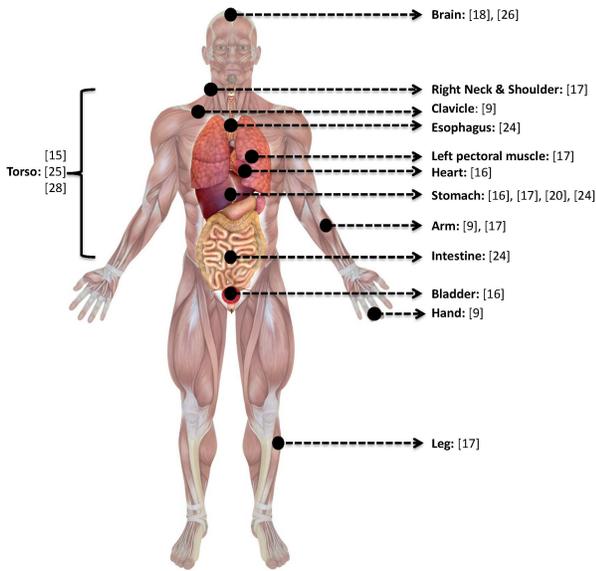


Fig. 5. Investigated anatomical human body regions.

to the wireless cellular communication environment.

The channel modeling subgroup (Task Group 15.6), which worked on developing of IEEE 802.15.6 standard, submitted their final report on body area network (BAN) channel models in November 2010. In this report, it is determined that Friis transmission equation can be used for *in vivo* scenarios by adding a random variation term and the path loss was modeled statistically with a log-normal distributed random shadowing S and path loss exponent n [15]. The path loss exponent (n) heavily depends on environment and is obtained by performing extensive simulations and measurements. In addition, the shadowing term (S) depends on the different body materials (e.g. bone, muscle, fat, etc.) and the antenna gain in different directions [17]. The research efforts on assessing the statistical properties of the *in vivo* propagation channel are not finalized, and there are still many open research efforts dedicated to

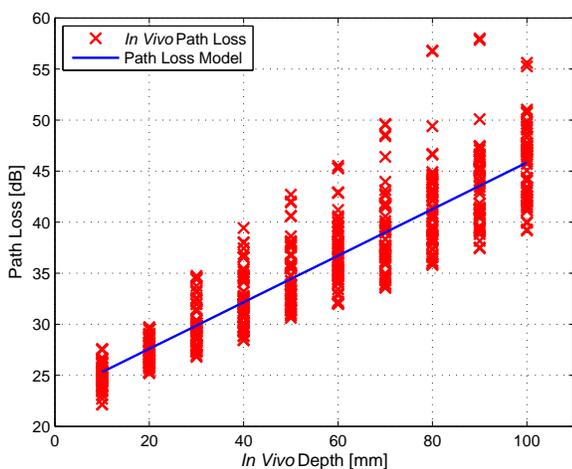


Fig. 6. Scatter plot of path loss versus *in vivo* depth at 915 MHz [25].

TABLE II
FURTHER DETAILS OF THE STUDIES PRESENTED IN FIG. 5.

Ref.	Freq.	Antenna	Investigation Method
[9]	2.45 GHz	Dipole Antennas	FDTD on human body model. Experiment on three-layered model.
[16]	402 and 868 MHz	Point sources	FDTD on human body model.
[17]	402 - 405 MHz	Novel implant antennas	FEM on human body model.
[18]	3.1 - 10.6 GHz	Monopole antennas	FEM on multi-layer model.
[20]	433, 915, 2450 and 5800 MHz	Dipole antennas	MoM on homogenous and three-layer models.
[28]	1 - 6 GHz	Electric Field probes (Ideal Isotropic Antennas)	FIT on human body model.
[25]	915 MHz	Dipole Antennas	FEM on human body model.
[24]	100 - 2450 MHz	Waveguide Ports	FIT on human body model.
[26]	402 - 405 MHz	Loop Antennas	FDTD on human body model. Experiment on homogeneous model.

building analytical models for different body parts and operational frequencies [5], [16], [17], [25], [28].

A recent work investigates the *in vivo* channel for the human male torso at 915 MHz [25]. Fig. 6 shows the scatter plot of path loss versus *in vivo* depth in the simulation environment. The *in vivo* antenna is placed at various locations (stomach area, intestine area, etc.) and various depths (10 mm to 100 mm) inside the body and the *ex vivo* antenna is placed 5 cm away from the body surface. The path loss is modeled as a function of depth by a linear equation in dB. The shadowing presents a normal distribution for a fixed distance and its variance becomes larger due to the increase in number of scattering objects as the *in vivo* antenna is placed deeper. The location-specific statistical *in vivo* path loss model parameters and a power delay profile are provided in this study. The results confirm that the *in vivo* channel exhibits different characteristics than the classical communication channels and location dependency is very critical for link budget calculations.

VII. OPEN RESEARCH

In vivo-WBAN devices are expected to provide substantial flexibility and improvement in remote healthcare by managing more diseases and disabilities and their usage will likely increase in time. Therefore, *in vivo* channel characterization for a huge variety of body parts is an obvious requirement for their future deployment scenarios. With such models, wireless communication techniques can be optimized for this environment and efficiently implemented. However, research into solutions to satisfy emerging requirements for *in vivo*-WBAN devices such as high data rates, power efficiency, low complexity, and safety should continue and continuous improvement of channel characterization is necessary to optimize performance.

Some of the most important open research topics for efficient *in vivo* wireless communications are given as follows:

TABLE III
A REVIEW OF SELECTED STUDIED PATH LOSS MODELS FOR VARIOUS SCENARIOS.

Model	Formulation
FSPL [16]	$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$
FSPL with RL [16], [20]	$P_r = P_t G_t (1 - S_{11} ^2) G_r (1 - S_{22} ^2) \left(\frac{\lambda}{4\pi R}\right)^2$
FSPL with RL and Absorption [6]	$P_r = P_t G_t (1 - S_{11} ^2) G_r (1 - S_{22} ^2) \left(\frac{\lambda}{4\pi R}\right)^2 (e^{-\alpha R})^2$
PMBA for near and far field [27]	$P_{rn} = \frac{16\delta(P_t - P_{NF})}{\pi L^2} A_e, P_{rf} = \frac{(P_t - P_{NF} - P_{FF})\lambda^2}{4\pi R^2} G_t G_r$
Statistical Model-A [25], [28]	$PL(d) = PL_0 + n(d/d_0) + S \quad (d_0 \leq d)$
Statistical Model-B [8], [16], [17]	$PL(d) = PL(d_0) + 10n\log_{10}(d/d_0) + S \quad (d_0 \leq d)$

P_r/P_t stands for the received/transmitted power; G_r/G_t denotes the gain of the receiver/transmitter antenna; λ represents the free space wavelength; R is the distance between transmitter and receiver antennas; $|S_{11}|$ and $|S_{22}|$ are the reflection coefficients of receiver/transmitter antennas; α is the attenuation constant; P_{NF}/P_{FF} is the loss in the near/far fields; P_{rn} & P_{rf} represents received power for near and far fields; δ is A_e/A where A_e is the effective aperture and A is the physical aperture of the antenna; L is the largest dimension of the antenna; d is the depth distance from the body surface; d_0 is the reference depth distance; n is the path loss exponent; PL_0 is the intersection term in dB; S denotes the random shadowing term. Abbreviations: FSPL represents free space path loss in the far field, RL is the return loss, PMBA is the propagation loss model.

- *Subject-Specific Studies*: It is known that on-body communication channel is subject-specific [4]. Additional studies need to be performed on the subject-specific nature of *in vivo* channels to better understand the communication channel variations with respect to the change of subject. This will help in developing efficient and reliable implantable systems in future.
- *Security*: It is one of the most critical issues in the usage of *in vivo*-WBAN devices as various malicious attacks may result in serious health risks, even death. Therefore, robust security algorithms are essential for confidently using these devices. Physical layer (PHY) security is a promising concept for providing security in wireless communication [29]. Since most of the proposed techniques in this field utilize the mutual channel information between the legitimate transmitter and receiver, *in vivo* channel characterization considering the requirements of PHY-based security methods is very important for implementing such techniques on *in vivo*-WBAN devices.
- *Multiple Input, Multiple Output (MIMO) and Diversity*: To overcome ever increasing data rate demand and fidelity issues, while keeping compactness in consideration for *in vivo* communication, MIMO and diversity based methods are very promising [30]. However, the knowledge of spatial correlation inside the body medium should be investigated for facilitating the implementation of these techniques and understanding the maximum achievable channel capacity.
- *Adaptive Communications*: Although, the *in vivo* medium is not as random as an outdoor channel, natural body motions and physiological variations may lead to some changes in the channel state. Therefore, more specific channel parameters, e.g., coherence time, coherence bandwidth, Doppler spread in *in vivo* medium should also

be investigated for facilitating adaptive communication against physical medium variations to maintain adequate performance for specific scenarios under different circumstances.

- *Interference and co-existence of WBAN devices* : Inter-WBAN interference emerges as another problem for patients having multiple *in vivo*-WBAN sensors and actuators. Energy efficient techniques enabling multiple closely located WBAN devices to co-exist are also crucial for future applications and should be considered as an open research.
- *Nanoscale in vivo wireless communication*: With the increase in demand for compact and efficient implantable devices, nano-communication technologies provide an attractive solution for potential BANs. More studies are needed to better understand the *in vivo* propagation at terahertz frequencies, which is regarded as the most promising future band for the electromagnetic paradigm of nano-communications. In addition, studies are also needed to explore the connection between micro-devices and nano-devices, which will be helpful for the design of future system-level models.

VIII. CONCLUSIONS

In this paper, the state of the art of *in vivo* wireless channel characterization is presented. Various studies have been highlighted from the literature for *in vivo* channel models, considering different parameters and by taking into account various anatomical regions. A complete model is not available and remains as an open research objective. However, considering the expected future growth of implanted technologies and their potential use for the detection and diagnosis of various health related issues in the body, the channel modeling studies

should be extended to enable the development of more efficient communications systems for future *in vivo* systems.

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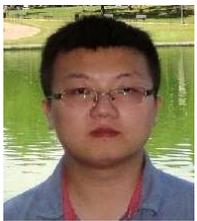


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