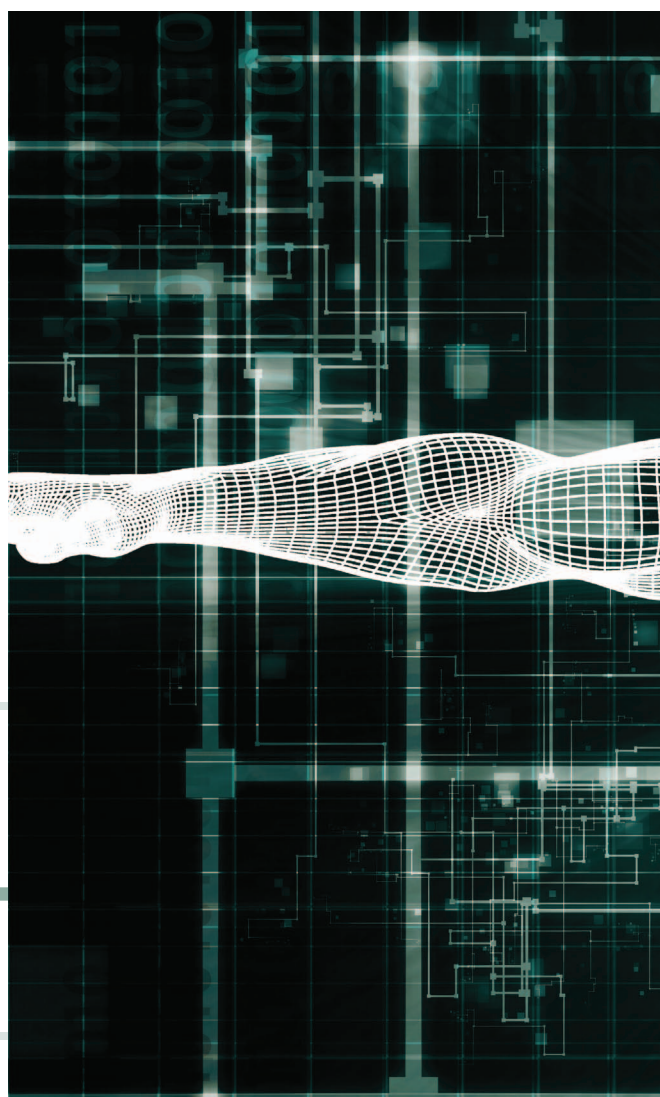# In Vivo Communications

Steps Toward the Next Generation of Implantable Devices

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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, such as pacemakers, internal drug delivery devices, nerve stimulators, and wireless capsule endoscopes (WCEs). 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, patient information can be collected over a longer 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 further increase the potential of WBANs for practical applications, it is necessary to accurately assess 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 models are necessary for achieving high data rates, targeting 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 for obtaining 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 article 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, the in vivo channel exhibits different characteristics than those of the more familiar wireless cellular and Wi-Fi environments. In this article, 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. We review EM modeling of the human body, which is essential for in vivo wireless

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communication channel characterization; discuss EM wave propagation through human tissues; present the choice of operational frequencies based on current standards and examine their effects on communication system performance; discuss the challenges of in vivo antenna design, as the antenna is generally considered to be an integral part of the in vivo channel; review the propagation models for the in vivo wireless communication channel and discuss the main differences relative to the ex vivo channel; and address several open research problems and future research directions. We hope to provide a more complete picture of this fascinating communications medium and stimulate more research in this important area.

EM Modeling of the Human Body

To investigate the in vivo wireless communication channel, accurate body models and knowledge of the EM 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 using the four-pole Cole-Cole equation, which is expressed as:

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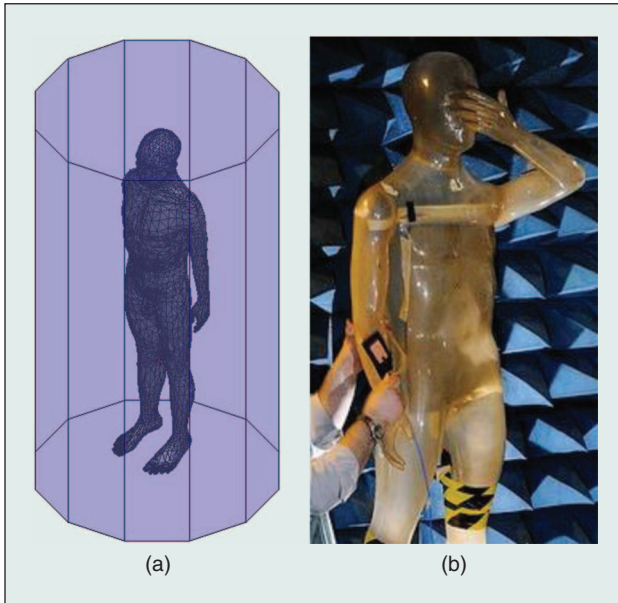

(a)   (b)

FIGURE 1 Heterogeneous human body models: (a) and HFSS model and (b) a physical phantom [8].

where ϵ_∞ stands for the body material permittivity at terahertz frequency, ϵ_0 denotes the free-space permittivity, σ represents the ionic conductivity, and $\epsilon_m, \tau_m, \alpha_m$ are the body material parameters for each anatomical region. The EM properties such as conductivity, relative permittivity, loss tangent, and penetration depth can be derived using these parameters in (1).

Various physical and numerical phantoms have been designed to simulate the dielectric properties of the tissues for experimental and numerical investigation. These can be classified as homogeneous, multilayered, and heterogeneous phantom models. Although heterogeneous models provide a 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 multilayer models cannot differentiate the EM wave radiation characteristics for different anatomical regions. Figure 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 the uniform theory of diffraction, finite integration technique, method of moments (MoM), finite element method (FEM), and finite-difference time-domain (FDTD) method. 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 characteristics of interest, such as power delay profile (PDP) and specific absorption rate (SAR). A detailed comparison of these methods is available in [4] and [5].

It may be preferable that numerical experiments be confirmed by real measurements. However, performing experiments on a living human is carefully regulated. Therefore, anesthetized animals [6], [7] or physical phantoms [8], [9], allowing repeatability of measurement results, are often used for experimental investigation. In addition, the first study conducted on a human cadaver was reported in [10].

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 SAR provides a metric for the absorbed power amount in the tissue and is expressed as follows:

$$\text{SAR} = \frac{\sigma |E|^2}{\rho}, \qquad (2)$$

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 U.S. Federal Communications Commission (FCC) recommends that the SAR be less than 1.6 W/kg taken over a volume having 1 g 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 media. Superposition of the incident and reflected waves can cause a standing-wave effect that may increase the SAR values [11]. A multilayer tissue model at 403 MHz, where each layer extends to infinity (much larger than the wavelength of EM waves), is illustrated in Figure 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 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 absorption and reflection losses, EM waves suffer from expansion of the wave fronts (which assume an ever-increasing sphere shape from an isotropic source in free space) and from diffraction and scattering (which depend on the EM wavelength). In the section "Frequency of Operation," we provide a discussion on in vivo propagation models, by considering these effects in detail.

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, in this section we summarize the allocated
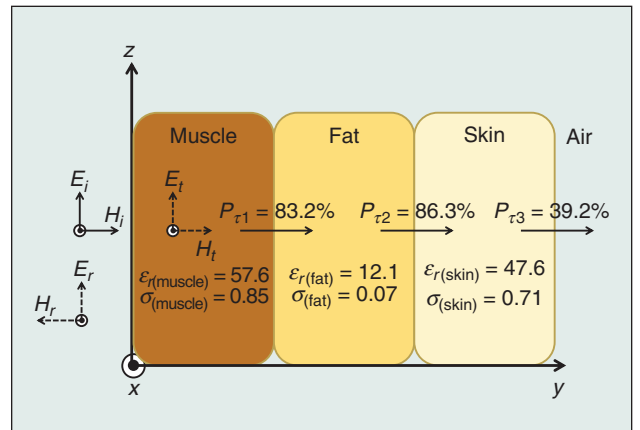

FIGURE 2 Multilayer human tissue model at 403 MHz (ϵ_r: permittivity; σ: conductivity; P_τ: power transmission factor; E_i-H_i: incident waves; E_r-H_r: reflected waves; E_t-H_t: transmitted waves).

and recommended frequencies, including their effects for in vivo wireless communications channel.

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 [14], narrow band (NB) communications, and ultrawide band (UWB) communications. The frequency bands and channel bandwidths (BWs) allocated for these communication methods are summarized in Table 1. An IEEE 802.15.6-compliant in vivo WBAN device must operate in at least one of these frequency bands.

NB communications operate at lower frequencies compared to UWB communications and hence suffer less from absorption. This can be appreciated by considering (1) and (2), which describe the absorption as a function of frequency. The medical device radio communications service [(MedRadio); MedRadio uses discrete

TABLE 1 *Frequency bands and BWs for the three different propagation methods in IEEE 802.15.6.*

Propagation Method	IEEE 802.15.6 Operating Frequency Bands		
	Frequency Band	BW	Selected References
NB communications	402–405 MHz	300 kHz	[8], [11], [16], [17], [20], [27]
	420–450 MHz	300 kHz	
	863–870 MHz	400 kHz	[8], [16], [20], [27]
	902–928 MHz	500 kHz	
	950–956 MHz	400 kHz	
	2,360–2,400 MHz	1 MHz	[8], [20], [25], [27]
	2,400–2,438.5 MHz	1 MHz	
UWB communications	3.2–4.7 GHz	499 MHz	[7], [15], [20], [25]
	6.2–10.3 GHz	499 MHz	
Human body communications	16 MHz	4 MHz	[14]
	27 MHz	4 MHz	

bands within the 401–457 MHz spectrum, including the international medical implant communication service (MICS) band] and the medical body area network [(MBAN) 2360–2400 MHz] are allocated by the FCC for medical devices usage. Therefore, couser interference problems are less severe in these frequency bands. However, NB communications are only allocated small BWs (1 MHz at most) in the standard, as shown in Table 1. 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 μW equivalent isotropic radiated power (EIRP) by the FCC, whereas it is set to 25 μW equivalent radiated power (ERP) by the European Telecommunication Standards Institute (ETSI) for the 402–405 MHz band.

UWB communications are a promising technology to deploy inside the body due to inherent features that include high-data-rate capability, low power, improved penetration (propagation) abilities through tissues, and low probability of intercept. The large BWs for UWB (499 MHz) enable high-data-rate communications and applications. Also, UWB signals are inherently resistant to 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.

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

FIGURE 3 EM propagation through tissue interface (μ: permeability; E: electric field; D: electric displacement field).

the ex vivo antennas [4], [16]–[18]. In this section, we will describe their salient differences as compared to the ex vivo antennas.

In vivo antennas are subject to strict size constraints, and they need to be biocompatible. 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 gain 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 layer (usually subcutaneous fat) to increase the antenna gain. This placement also provides less absorption loss due to a shorter propagation path. However, the antenna size becomes larger in this case. 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 the curvature of the body surface, losses, and dielectric loading from the human body. Therefore, this increased directivity also should be taken into account so as not to harm the tissues in the vicinity of the antenna.

In vivo antennas can be classified into two main groups: 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 media interfaces overheat the tissues due to the boundary condition requirements, as illustrated in Figure 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 (2). In practice, magnetic loop antennas must be large in size and are 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 [6]. Representative antennas designed for in vivo communications are shown in Figure 4.
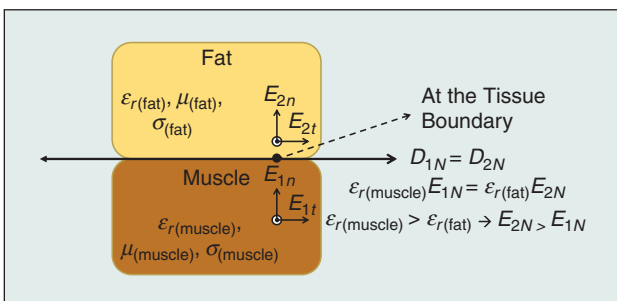
In Vivo EM Wave Propagation Models

Up to this point, we have reviewed important factors for in vivo wireless communication channel characterization, such as EM modeling of the human body, propagation through the tissues, selection of the operational frequencies, and in vivo antenna design considerations. In this section, we will focus on EM wave propagation inside the human body, considering the

EM WAVE PROPAGATION INSIDE THE BODY IS SUBJECT SPECIFIC AND STRONGLY RELATED TO THE LOCATION OF THE ANTENNA.

anatomical features of organs and tissues. Then we will present the analytical and statistical path loss models. The in vivo channel exhibits different characteristics
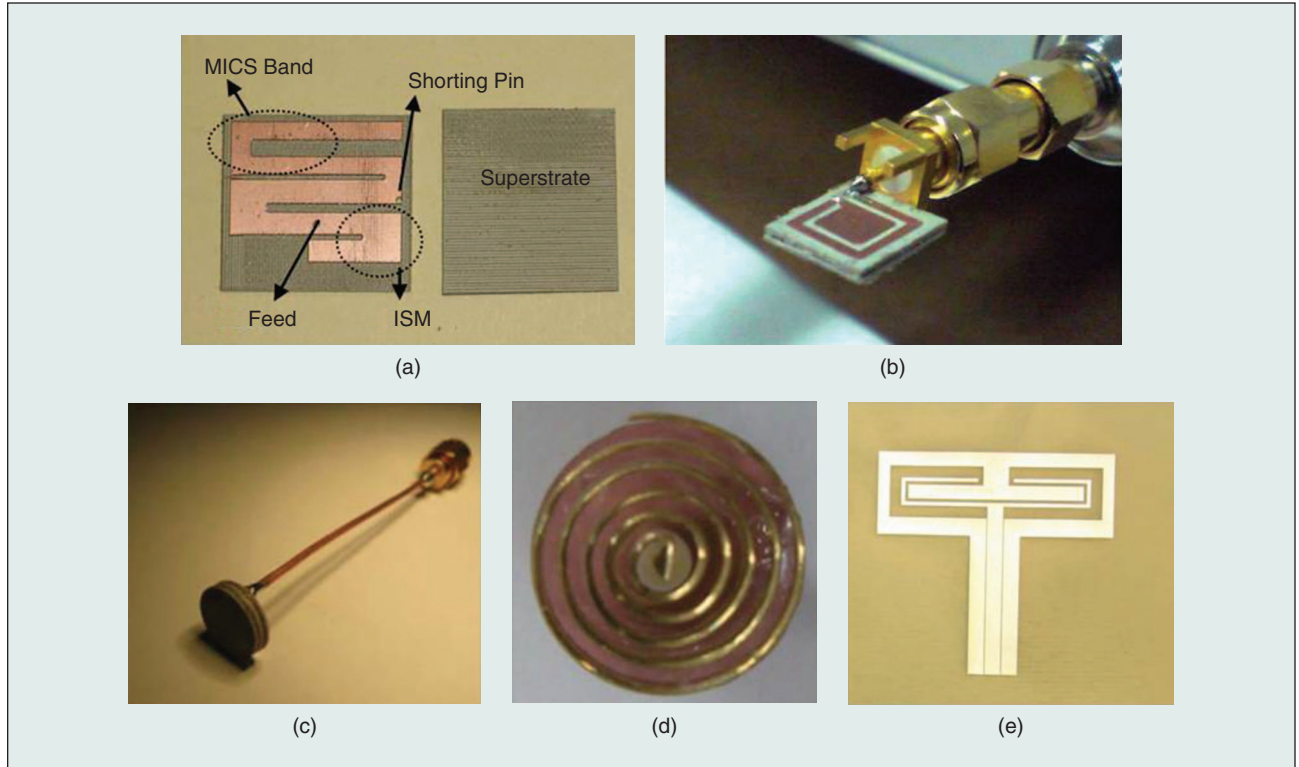

FIGURE 4 Selected in vivo antenna samples: (a) A dual-band implantable antenna [21], (b) a miniaturized implantable broadband stacked planar inverted-F antenna (PIFA) [22], (c) a miniature scalp-implantable antenna [2], (d) a wideband spiral antenna for a WCE [6], and (e) an implantable folded slot dipole antenna [23].

TABLE 2 *Further details on the numerical phantom-based studies presented in Figure 5.*

Reference	Frequency	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 multilayer model
[20]	433, 915, 2,450, and 5,800 MHz	Dipole antennas	MoM on homogeneous and three-layer models
[25]	1–6 GHz	Electric field probes (ideal isotropic antennas)	FIT on human body model
[26]	915 MHz	Dipole antennas	FEM on human body model
[27]	100–2,450 MHz	Waveguide ports	FIT on human body model
[28]	402–405 MHz	Loop antennas	FDTD on human body model; experiment on homogeneous model

than those of the more familiar wireless cellular and Wi-Fi environments since the EM wave propagates through a very lossy environment inside the body and the predominant scatterers are present in the vicinity of the antenna.

EM wave propagation inside the body is subject specific and strongly related to the location of the antenna, as demonstrated in [9], [16], [26], and [27].

Therefore, channel characterization is mostly investigated for a specific part of the human body. Figure 5 shows several investigated anatomical regions for various in vivo WBAN applications, and Table 2 provides further details about these studies. For example, the heart area has been studied for implantable cardioverter defibrillators and pacemakers, while the gastrointestinal tract, including the esophagus, stomach, and intestines, 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], [28]. Also, the 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, there is an increase in path loss, which is a measure of average signal power attenuation [27]. This is the case with the intestine, which presents a complex structure, with repetitive, curvy, 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 3. These formulas have been derived
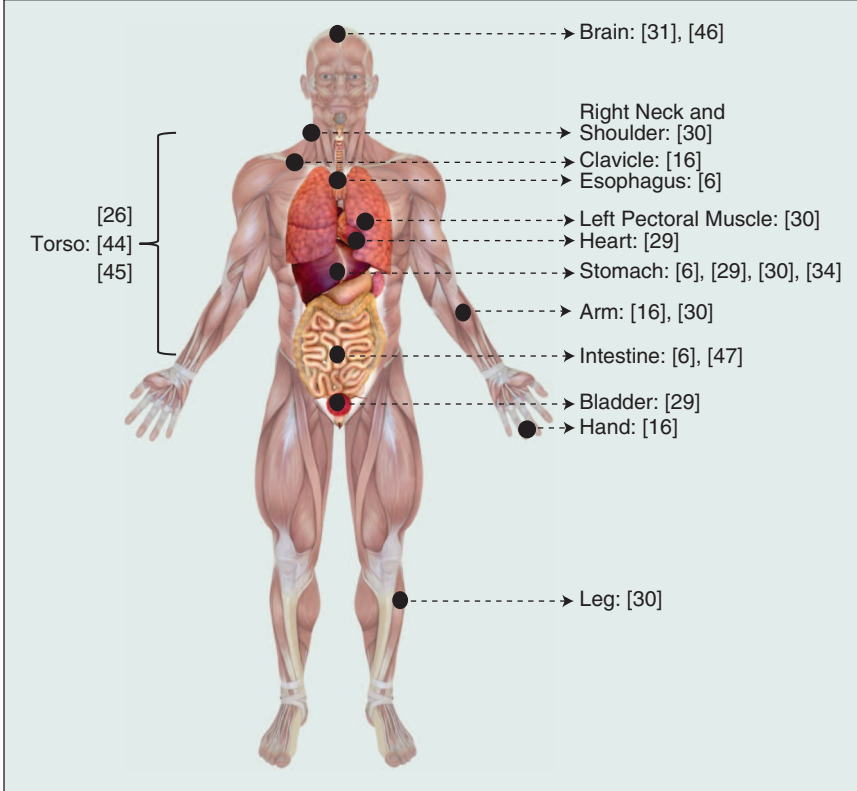

FIGURE 5 The investigated anatomical human body regions.

TABLE 3 *A review of selected studied path loss models for various scenarios.*

Model	Formulation
FSPL [16]	$P_r = P_t\, G_t\, G_r \left(\dfrac{\lambda}{4\pi R}\right)^2$
FSPL with RL [20], [16]	$P_r = P_t\, G_t(1-|S_{11}|^2)\, G_r(1-|S_{22}|^2)\left(\dfrac{\lambda}{4\pi R}\right)^2$
FSPL with RL and absorption [6]	$P_r = P_t\, G_t(1-|S_{11}|^2)\, G_r(1-|S_{22}|^2)\left(\dfrac{\lambda}{4\pi R}\right)^2 (e^{-\alpha R})^2$
PMBA for near and far field [24]	$P_{rn} = \dfrac{16\delta(P_t - P_{NF})}{\pi L^2} A_e,\quad P_{rf} = \dfrac{(P_t - P_{NF} - P_{FF})\lambda^2}{4\pi R^2}\, G_t\, G_r$
Statistical Model-A [25], [26]	$PL(d) = PL_0 + n(d/d_0) + S,\ \text{where}\ (d_0 \le d)$
Statistical Model-B [8,] [16], [17]	$PL(d) = PL(d_0) + 10n\,\log_{10}(d/d_0) + S,\ \text{where}\ (d_0 \le d)$

P_r and P_t stand respectively for the received and transmitted power; G_r and G_t denote respectively the gain of the receiver and transmitter antennas; λ represents the free space wavelength; R is the distance between transmitter and receiver antennas; $|S_{11}|$ and $|S_{22}|$ stand respectively for the reflection coefficients of receiver and transmitter antennas; α is the attenuation constant; P_{NF}/P_{FF} is the loss in the near/far fields; P_{rn} and P_{rf} represent respectively the 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.

considering different shadowing phenomena for the in vivo medium. The initial three models in the table are functions of the Friis transmission equation [4], return loss (RL), and absorption in the tissues. These models are valid when either the far field conditions are fulfilled or when 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 3. 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 the section "EM Wave Propagation Through Human Tissues." 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 3 are derived including the antenna RL and absorption in the tissues. Another analytical model, PMBA [24], 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 insight about each component of the propagation models, they are not practical for link budget design similar to the wireless cellular communication environment.

The channel modeling subgroup (Task Group 15.6) that worked on developing the IEEE 802.15.6 standard submitted its final report on body area network (BAN) channel models in November 2010. In that report, the group determined that the 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, and fat) 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 building analytical models for different body parts and operational frequencies [8], [16], [17], [25], [26].

A recent work investigates the in vivo channel for the human male torso at 915 MHz [26]. Figure 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 (e.g., stomach area and intestine area) and various depths (10–100 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

IN VIVO CHANNEL CHARACTERIZATION FOR A HUGE VARIETY OF BODY PARTS IS AN OBVIOUS REQUIREMENT FOR FUTURE DEPLOYMENT SCENARIOS [FOR IN VIVO WBAN DEVICES].

shadowing presents a normal distribution for a fixed distance, and its variance becomes larger due to the increase in the number of scattering objects as the in vivo antenna is placed deeper. The location-specific statistical in vivo path loss model parameters and a PDP 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.

Open Research

In vivo WBAN devices are expected to provide substantial flexibility and improvement in remote health care by managing more diseases and disabilities, and their usage will likely increase over time. Therefore, in vivo channel characterization for a huge variety of body parts is an obvious requirement for the devices' 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 in the following subsections.
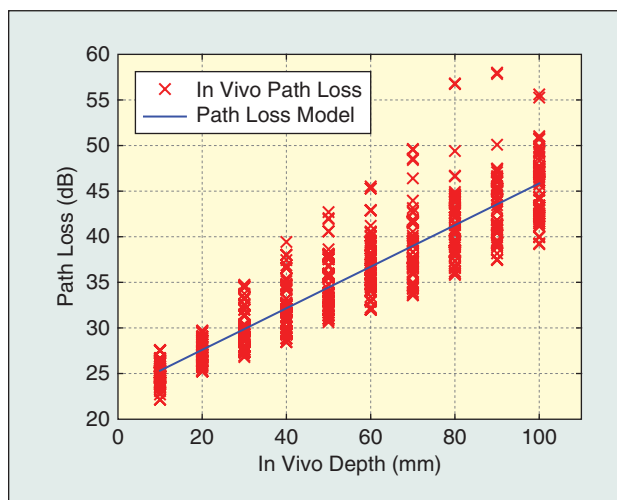

FIGURE 6 A scatter plot of path loss versus in vivo depth at 915 MHz [26].

SINCE EM WAVES PROPAGATE THROUGH THE FREQUENCY-DEPENDENT MATERIALS INSIDE THE BODY, THE OPERATING FREQUENCY HAS AN IMPORTANT EFFECT ON THE COMMUNICATION CHANNEL.

Subject-Specific Studies

On-body communication channels are 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 the future.

Security

Security is one of the most critical issues in the use 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, and Diversity

To overcome ever-increasing data-rate demand and fidelity issues while keeping compactness in consideration for in vivo communication, multiple-input, multiple-output 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—for example, coherence time, coherence BW and Doppler spread in vivo media—should also be investigated for facilitating adaptive communication against physical medium variations to maintain adequate performance for specific scenarios under different circumstances.

Interference and Coexistence 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 coexist are also crucial for future applications and should be considered as an open area of research.

Nanoscale In Vivo Wireless Communication

With the increase in demand for compact and efficient implantable devices, nanocommunication technologies provide an attractive solution for potential BANs. More studies are needed to better understand in vivo propagation at terahertz frequencies, which is regarded as the most promising future band for the EM paradigm of nanocommunications. In addition, studies are also needed to explore the connection between microdevices and nanodevices, which will be helpful for the design of future system-level models.

Conclusions

In this article, we presented the state of the art of in vivo wireless channel characterization. We have highlighted various studies in the literature for the in vivo communications channel that consider different aspects and various anatomical regions. A complete model is not available and remains 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, channel-modeling studies should be further extended to enable the development of more efficient communications systems for future in vivo systems.

Acknowledgment

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Laboratories fellow, and a Charter fellow of the National Academy of Inventors. He was also a corecipient of the 2005 Thomas Alva Edison Patent Award and the 1995 IEEE S.O. Rice prize. He has coauthored a communications text, published more than 100 papers, including three prize-winning papers, and holds 55 U.S. patents. At the University of South Florida, Tampa, his research has focused on the intersection of communications with biomedical engineering, and he has created an interdisciplinary team that is focused on wireless networking in vivo miniature wirelessly controlled devices to advance minimally invasive surgery and other cyberphysical health care systems, as well as on fifth-generation systems.

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