State of the Art of *In Vivo* Wireless Communication Channels

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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. This model will have a significant role in improving the communications performance of embedded medical devices in terms of power and spectral efficiency. In this paper, the state of the art in this field is presented to provide a comprehensive understanding of current models, considering various 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 life expectancy. One component of such advanced technology is wireless *in vivo* sensors and actuators, *e.g.*, glucose sensors, pacemakers, 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 by providing a reliable, continuous monitoring system of patients' vital signs, such as heart rate, body temperature, and blood pressure. These vital signs can be collected over a large period of time and physicians are able to perform more reliable analysis using this *big data* [2] rather than relying on the data recorded in short hospital visits. Furthermore, *in vivo*-WBAN devices provide patients greater mobility as well as reducing their hospital visits [3]–[5].

In order to continue to advance and fully exploit the potential of WBANs, it is necessary to enhance the knowledge of electromagnetic (EM) wave propagation in an *in vivo* communication environment and obtain accurate channel models that are necessary for optimizing the system parameters and building a reliable, high-performance communication system. In particular, such a model is necessary for achieving high data rates, target link budgets, determining optimal operating frequencies, and design of efficient antennas and transceivers including digital baseband transmitter/receiver algorithms [6]. Therefore, investigation of *in vivo* wireless communication channel is crucial to obtain a better performance for *in vivo*-WBAN devices. Although, on-body wireless communication channel characteristics have been well investigated [7], there are relatively few studies for *in vivo* wireless communication channels.

While there are other approaches to *in vivo* communications, such as molecular communications [10], in this paper we will focus on EM communications. Since the EM wave propagates through a very lossy environment inside the body and main scatterers are in the near-field region of the antenna, *in vivo* channel characteristics are different than the more familiar wireless cellular and Wi-Fi environments. In this paper, we present the state-of-the-art of *in vivo* channel characterization as well as several research challenges are presented considering various communication methods, op-

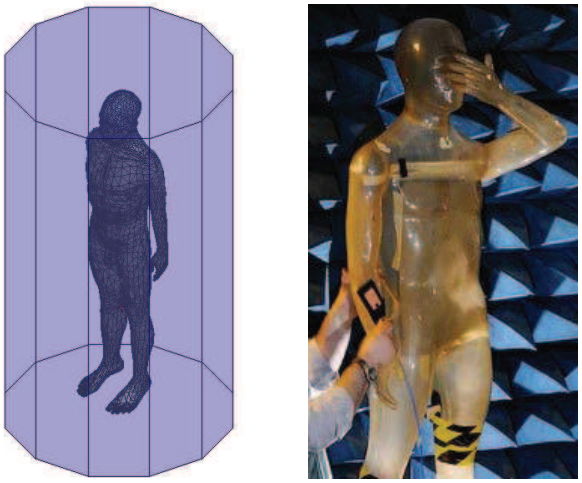

Fig. 1: Heterogeneous numerical human body models: (a) HFSS model [8] (b) physical phantom [9].

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erational frequencies, and antenna design to provide a more complete picture of this fascinating communications media.

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 provides the operational frequencies based on current standards and discusses their effects on the communication system. In section V, 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 *in vivo* wireless communication channel and discusses the main differences from the *ex vivo* channel. In section VII, open research areas and future directions are addressed and 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 [11]. Human autopsy materials and animal tissues have been measured over a frequency range 10 Hz to 20 GHz [12] and frequency dependent dielectric properties of the tissues modeled based on the summation of 4-Cole-Cole equation, given as:

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

where ϵ_∞ is the body material permittivity at terahertz frequency, ϵ_0 is the free-space permittivity, σ_j is the ionic conductivity and ϵ_m, τ_m, α_m are the body material parameters for each anatomical region. The parameters for anatomical regions are provided in [13] and electromagnetic properties such as, conductivity, relative permittivity, loss tangent, penetration depth can be derived using these parameters and 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 [9]. They 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 EM wave radiation characteristics for different anatomical regions. Figure 1 shows examples of heterogeneous physical and numerical phantoms.

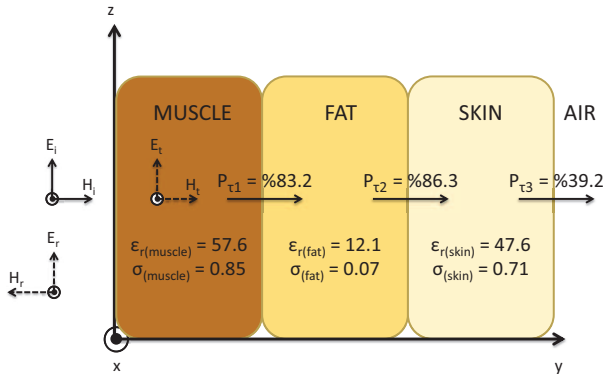

Fig. 2: Multi-layer human tissue model at 403 MHz (ϵ_r: Permittivity, σ: Conductivity, P_τ: Power transmission factor).

Analytical methods are generally viewed as infeasible and require extreme simplifications; hence numerical methods are used for characterizing the *in vivo* wireless communication channel. Numerical methods provide less complex and appropriate approximations to Maxwell's equations with various techniques, such as uniform theory of diffraction (UTD), method of moments (MoM), finite element method (FEM), finite-difference time-domain method (FDTD) [11].

One may claim that such numerical experiments should be confirmed with real measurements. However, performing experiments on a living human is carefully regulated. Therefore, anesthetized animals [14], [15] under anesthesia or physical phantoms [9], [16] are often used for experimental investigation.

III. EM Wave Propagation Through the Human Tissues

Propagation in a lossy medium, such as human tissues, results in a high absorption of EM energy [17]. The absorption effect varies with the frequency dependent electrical characteristics of the tissues, which mostly consist of water and ionic content [18]. The specific absorption rate (SAR) provides a metric for absorbed power amount in the tissue and expressed as [19]:

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

where σ, E and ρ are the conductivity of the material, the RMS magnitude of the electric field and the mass density of the material, respectively. Federal Communications Commission (FCC) recommends SAR to be less than 1.6 kg/W taken over the volume having 1 gram of tissue [20].

When a plane EM wave propagates through the interface of two media having different electrical properties, its energy is partially reflected and the remaining portion is transmitted at 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 [18]. A multi-layer tissue model at 403 MHz, where the dielectric values are calculated in [21], is illustrated in Fig. 2. If there is a high contrast in the dielectric values of mediums/tissues, wave reflection at the boundary increases and transmitted power decreases.

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, we summarize the allocated and recommended frequencies including their effects for *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 that are classified as narrow band (NB) communications, ultra-wide band communications (UWB) and human-body communications (HBC) [22], [23]. 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 should be able to 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 which describes the absorption as a function of relationship with frequency. The medical implant communication service (MICS, 402-405 MHz) and medical body area network (MBAN, 2360-2400 MHz) are allocated by the FCC for medical device usage. Therefore, co-user interference problems are less severe in these frequency bands. However, NB communications can only provide small bandwidths (1 MHz at most) in the standard as shown in Table I.

UWB communications is a promising technology to deploy inside the body due its inherent features including high data rate capability, low power 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 with their extremely low maximum effective isotropic radiated power (EIRP) spectral density of -41.3 dBm/MHz

Propagation Method	IEEE 802.15.6 Operating Freq. Bands		Selected References
	Frequency Band	BW	
Narrow Band Communications	402 - 405 MHz	300 kHz	[6], [9] , [18], [27], [28], [30], [39]
	420 - 450 MHz	300 kHz	
	863 - 870 MHz	400 kHz	[6], [9], [27], [30], [39]
	902 - 928 MHz	500 kHz	
	950 - 956 MHz	400 kHz	
	2360 - 2400 MHz	1 MHz	[6], [9], [30], [41]
	2400 - 2438.5 MHz	1 MHz	
UWB Communications	3.2 - 4.7 GHz	499 MHz	[15], [24], [30], [41]
	6.2 - 10.3 GHz	499 MHz	
Human - Body Communications	16 MHz	4 MHz	[22], [23]
	27 MHz	4 MHz	

Table I: Frequency bands and bandwidths for the three different propagation methods in IEEE 802.15.6.

[24], [25]. Recently, the terahertz frequency band has also been a subject of interest for the *in vivo* propagation and it is regarded as one of the most promising band for the EM paradigm of nano-communications [26].

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 *ex vivo* antennas [11], [27]–[29]. In this section, we will describe their salient differences as compared to *ex vivo* antennas.

In vivo antennas have strict size constraints and in addition need to be bio-compatible. Although, copper antennas have better performance, only specific type of materials such as titanium or platinum should be used for *in vivo* communications due to their noncorrosive chemistry [5]. When the antennas are placed inside the human body, their electrical dimensions and gains decrease due to high dielectric permittivity and high conductivity of the tissues, respectively [30]. For instance, fat has a lower conductivity than skin and muscle. Therefore, *in vivo* antennas are usually placed in a fat layer for increasing the antenna gain. However, the antenna size becomes larger in this case. In order to reduce high losses inside the tissues, a coating layer can be used. As the coating thickness increases, the antenna becomes less sensitive to the surrounding material [30].

Lossy materials covering the *in vivo* antenna change the electrical current distribution in the antenna and radiation pattern [16]. It is reported in [27] that, directivity of *in vivo* antennas increases due to curvature of body surface, losses and dielectric loading from the human body. that, directivity of *in vivo* antennas increases due to curvature of body surface, losses and dielectric loading from the human body. Therefore, this increased directivity should be taken into account as well not to harm the tissues in the vicinity of the antenna [19].

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 [35]. Normal E-field components at the medium interfaces overheat the tissues due to the boundary condition requirements [36] as

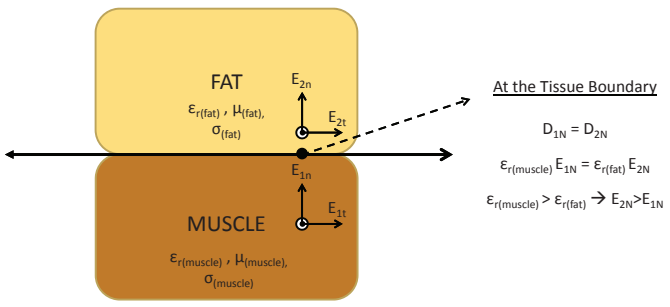

Fig. 3: EM propagation through tissue interface.

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 are more preferable for *in vivo* WBAN devices. 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 [37]. Several selected sample 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 modeling of the human body, propagation through the tissues, and selection of the operational frequency have been reviewed. Moreover, main differences of *in vivo* and *ex vivo* antenna design are discussed since the antenna is considered as an integral part of *in vivo* channel. In this section, we will focus on EM wave propagation inside the human body considering the anatomical features of organs and tissues. Then, analytical and statistical path loss models will be presented. Since the propagation environment is very lossy and the main scatters are often in the near field of the antenna, the *in vivo* wireless communication channel models are different than those proposed for classical indoor and outdoor environments [3].

EM wave propagation inside the body is subject-specific and strongly related to the location of antenna as demonstrated in [6], [16] 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. 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

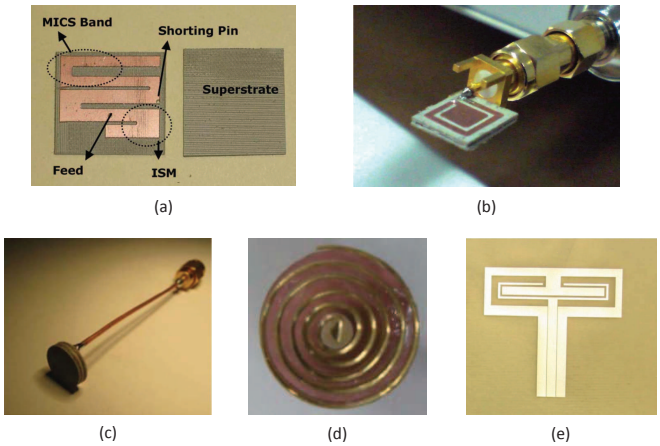

Fig. 4: *In vivo* selected antenna samples taken from [14], [31]–[34].

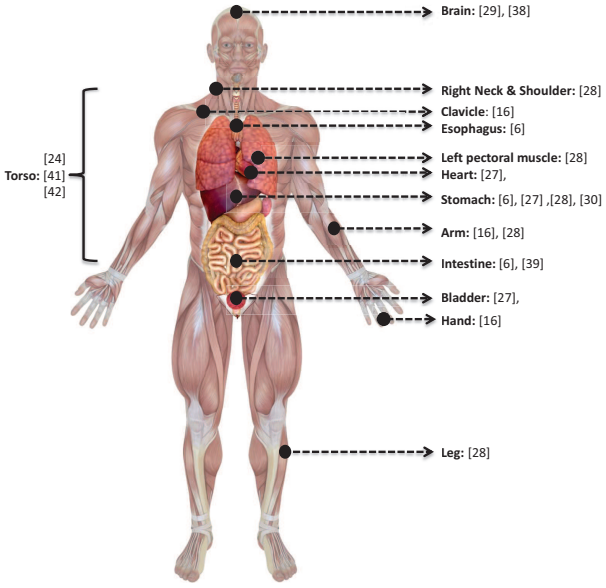

Fig. 5: Investigated anatomical human body regions.

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 [29], [38]. 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 [6]. For example, the intestine has 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 [6]. Also, more radiation occurs in the anterior region than in the posterior region due to the human body structure [27], [39].

Free space path loss (FSPL), which can be expressed by the Friis transmission equation [11], mainly depends on distance and operating frequency. Its dependency on distance is a result of spherical power radiation of EM waves in free space from an isotropic antenna. The received power per unit area on the sphere is inversely proportional to the distance, i.e., radius of the sphere. Additionally, path loss is frequency dependent due to the relationship between the effective area of the receiver antenna and the wavelength.

Various path loss formulas have been proposed for the *in vivo* channel in the literature as listed in Table II. These formulas have been derived considering shadowing different phenomena of *in vivo* medium. Furthermore, the channel modeling subgroup for the IEEE 802.15.6 standard determined that the Friis equation can also be used for some of the WBAN scenarios by adding a random variation term [25].

The initial three path loss equations are functions of the Friis transmission equation, return loss and absorption in the tissues. These formulas are valid, when either the far-field conditions are fulfilled or few scattering objects exist between

Table II: A review of selected studied path loss models for various scenarios.

Channel Type	Model
FSPL [27]	$\mathrm{P}_r = \mathrm{P}_t\mathrm{G}_t\mathrm{G}_r(\frac{\lambda}{4\pi R})^2$
FSPL with RL [27], [30]	$\mathrm{P}_r = \mathrm{P}_t\mathrm{G}_t(1-\lvert S_{11}\rvert^2)\mathrm{G}_r(1-\lvert S_{22}\rvert^2)(\frac{\lambda}{4\pi R})^2$
FSPL with RL and Absorption [37]	$\mathrm{P}_r = \mathrm{P}_t\mathrm{G}_t(1-\lvert S_{11}\rvert^2)\mathrm{G}_r(1-\lvert S_{22}\rvert^2)(\frac{\lambda}{4\pi R})^2(e^{-\alpha R})^2$
PMBA for near field [40]	$\mathrm{P}_r = \frac{16\delta(P_t-P_{NF})}{\pi L^2}A_e$
PMBA for far field [40]	$\mathrm{P}_r = \frac{(P_t-P_{NF}-P_{FF})\lambda^2}{4\pi R^2}\mathrm{G}_t\mathrm{G}_r$
Statistical Model-a [41], [42]	$PL(d) = PL_0 + n(d/d_0) + S \qquad (d_0 \leq d)$
Statistical Model-b [9], [27], [28]	$PL(d) = PL(d_0) + 10n\log_{10}(d/d_0) + S \qquad (d_0 \leq d)$

$\mathrm{P}_r/\mathrm{P}_t$ is the received/transmitted power; $\mathrm{G}_r/\mathrm{G}_t$ is the gain of the receiver/transmitter antenna; λ is the 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; $\mathrm{P}_{NF}/\mathrm{P}_{FF}$ is the loss in the near/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, the random scattering parameter. The Abbreviations: FSPL represents free space path loss in the far field, RL is the return loss, PMBA is the propagation loss model.

the transmitter and receiver antennas. The next two equations (PMBA) calculate the SAR over the entire human body for the far and near fields, and give the received power using the calculated absorption. The last two statistical equations define path loss with lognormal distributed random shadowing, S and path loss exponent, n. The path loss exponent heavily depends on environment and obtained by performing extensive simulations or measurements. In addition, S is caused by different body materials (e.g. bone, muscle, fat, etc.) and the antenna gain in different directions [28].

Figure 6 shows the scatter plot of path loss vs depth on a human male torso in a simulation environment [42]. The *in vivo* antenna is placed at various depths and the *ex vivo* antenna is placed 5 cm away from the body surface at

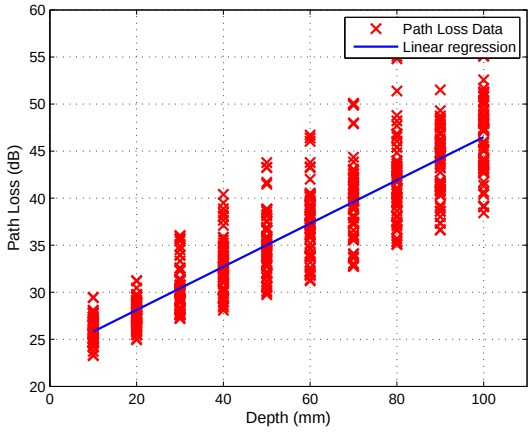

Fig. 6: Scatter plot of path loss versus *in vivo* depth at 915 MHz.

915 MHz. The path loss is modeled as a function of depth by a linear equation in dB. The shadowing has 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.

VII. Open Research

In vivo-WBAN sensors and actuators, also called wireless implantable medical devices (WIMDs), provide substantial flexibility in remote healthcare and their usage will likely increase in the near future. Besides the existing devices mentioned in the earlier sections, new WIMDs are expected to be developed for managing more diseases and disabilities in different parts of the body. Therefore, channel characterization for a huge variety of body parts is an obvious requirement for future WIMDs deployment scenarios. With such models existing wireless communication techniques can be implemented efficiently for these regions. However, solutions to satisfy emerging requirements for WIMDs such as high data rates, power efficiency and safety should also be discussed and different aspects of the channel characterization should be investigated accordingly.

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

- *Subject-Specific Studies*: It is shown in [43], that on-body communication channel is subject-specific. Studies need to 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 usage of WIMDs as various malicious attacks may result in serious health risks, even death. Therefore, robust, security (including authentication and privacy) ensuring algorithms are essential for using these devices confidently. Physical layer (PHY) security is a promising concept for providing security in wireless communication [44]. 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 WIMDs.
- *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 [45]. However, the knowledge of spatial correlation inside the body medium should be investigated for facilitating the implementation of these techniques and understanding maximum achievable channel capacity.
- *Adaptive Communications*: Although, the in body medium is not as random as an outdoor channel, natural body motions and physiological variations may lead to some changes in the channel state. Considering this fact, more specific channel parameters, *e.g.*, coherence time, coherence bandwidth, Doppler spread in body medium should also be investigated for facilitating adaptive communication against physical medium variations to maintain adequate performance under different circumstances.
- *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. A thorough studies are needed to better understand the in-body propagation at terahertz frequencies, which is regarded as the most promising future band for 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 presented in the literature for *in vivo* channel models, considering different parameters by using various anatomical regions. 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, channel-modeling studies should be extended to develop better and efficient communications systems for future *in vivo* systems. Within this context, current and future research thrusts, in this important and emerging research domain were presented.

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