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Modeling the Wireless *In vivo* Path Loss

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***Abstract*— Our long-term research goal is to model the *in vivo* wireless channel. As a first step towards this goal, in this paper we performed *in vivo* path loss measurements at 2.4 GHz and make a comparison with free space path loss. We calculate the path loss by using the electric field radiated by a Hertzian-Dipole located inside the abdominal cavity. The simulations quantify and confirm that the path loss falls more rapidly inside the body than outside the body. We also observe fluctuations of the path loss caused by the inhomogeneity of the human body. In comparison with the path loss measured with monopole antennas, we conclude that the significant variations in Received Signal Strength is caused by both the angular dependent path loss and the significantly modified *in vivo* antenna effects.**

***Index Terms*—*In vivo* propagation, *ex vivo* communication, path loss model, Hertzian-Dipole, angular dependent.**

I. Introduction

The wireless body area network (WBAN) [1] IEEE 802.15 Task Group 6 studied the devices and technologies on, in or around the human body for various kinds of applications such as healthcare and entertainment. However, research on *in vivo* models for propagation in the human body is still in the early stages. Understanding the characteristics of the *in vivo* channel is necessary to optimize *in vivo* physical layer signal processing, and designing efficient networking protocols that ultimately will make possible the deployment of wireless body area networks inside the human body.

There are many challenges in characterizing the *in vivo* channel including the inhomogeneous and very lossy nature. Furthermore, additional factors need to be taken into account, such as near-field effects and highly variable propagation speeds through different organs and tissues. These effects are summarized in Table I and illustrated in Fig. 1.

In this paper, we study the path loss for *in vivo* wireless communications. The rest of the paper is organized as follows. In section II, we summarize the prior work on *in vivo* wireless communications and channel modeling in WBANs. Our simulation setup and the approach to obtain the path loss for the *in vivo* channel are described in section III. In Section IV, our simulation results and analysis for *in vivo* path loss are presented. Finally, in Section V we present our conclusions and future research directions.

II. Literature Review

A. *In vivo Wireless Communications*

Understanding the *in vivo* wireless channel is critical to advancing many bio-medical and other procedures. The authors [2] performed signal strength and channel impulse response simulations using an accurate human body model and investigated the variation in signal loss at different radio frequency (RF) frequencies as a function of position around the human body. However, the previous research does not include the fundamental characterization of the *in vivo* channels, is the focus of this paper.

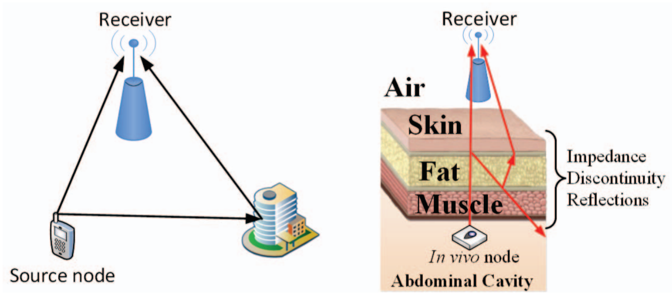

Fig. 1. Classic multi-path channel vs *in vivo* multi-path channel

B. *In vivo Channel Characterization*

For *in vivo* channel modeling, a phantom or a human body model is necessary to be used for measurement. For example, in [3], the authors observed the RF propagation from medical implants inside a human body via a 3D Immersive Platform. An *in vivo* channel model for homogeneous human tissues was developed in [4]. Using ingested wireless implants, the authors in [5] performed numerical and experimental investigations for biotelemetry radio channels and wave attenuation in human subjects.

III. Simulation Setup

A. *Human Body Model*

We use the ANSYS HFSS 15.0.3 Human Body Model software to perform our simulations. This tool contains an adult male body with more than 300 parts of muscles, bones and organs modeled to 1 mm. The antenna we use is the Hertzian-Dipole, which can be treated as an ideal dipole. In this way, we can investigate the path loss when there is little antenna effect. The operating frequency is the 2.4 GHz ISM band.

B. *Measurement approach*

Since the *in vivo* environment is an inhomogeneous medium, it is instructive to measure the path loss in the spherical coordinate system. The truncated human body, the Hertzian-Dipole and the spherical coordinate system are shown in Fig. 2. The path loss can be calculated as:

TABLE 1

Comparison of *Ex vivo* and *In vivo* Channel

Features	***Ex vivo***	***In vivo***
Physical Wave Propagation	Constant speed Multipath - reflection, scattering and diffraction	Variable speed Multipath - plus penetration
Attenuation and Path Loss	Lossless medium Decreases inversely with distance	Very lossy medium Angular (directional) dependent
Dispersion	Multipath delays→time dispersion	Multipath delays of variable speed → frequency dependency →time dispersion
Directionality	Propagation essentially uniform	Propagation varies with direction Directionality of antennas changes with position\orientation
Near Field Communications	Deterministic near-field region around the antenna	Inhomogeneous medium→near field region changes with angles and position inside 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 divided by frequency	$\lambda = \frac{c}{\sqrt{\epsilon_r} f}$→At 2.4GHz, average dielectric constant $\epsilon_r = 35$→ roughly 6 times smaller than the wavelength in free space.

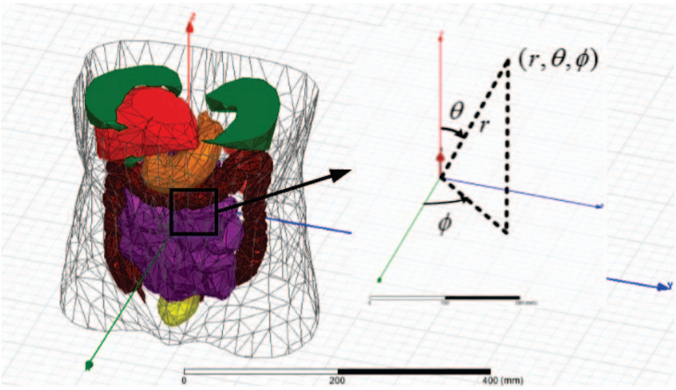

Fig. 2. Truncated human body with Hertzian-Dipole at the origin in spherical coordinate system

$$PathLoss(r,\theta,\phi) = 10 * \log_{10} \frac{|E|^2_{r=0}}{|E|^2_{r,\theta,\phi}}, \qquad (1)$$

where r represents the distance from the origin, i.e. the radius in spherical coordinates, θ is the polar angle and ϕ is the azimuth angle. $|E|^2_{r,\theta,\phi}$ is the square of the magnitude of the electric E field at the measuring point and $|E|^2_{r=0}$ is the square of the magnitude of E at the origin.

IV. Results

A. Path loss vs distance

When we fix the azimuth and polar angles to $0°$ and $90°$, respectively, we obtain the relationship between path loss and distance, as shown in Fig. 3. For the *in vivo* case, the skin boundary is at $r = 108mm$. We can clearly observe the different behavior of the path loss between the *in vivo* and *ex vivo* regions. In the body, the path loss increases rapidly and the curve can be approximately seen as a line with a slope of 0.815 dB/mm. Outside the body, there exist many constructive and deconstructive waves, which come from refractions through the skin. These waves produce path loss fluctuation.

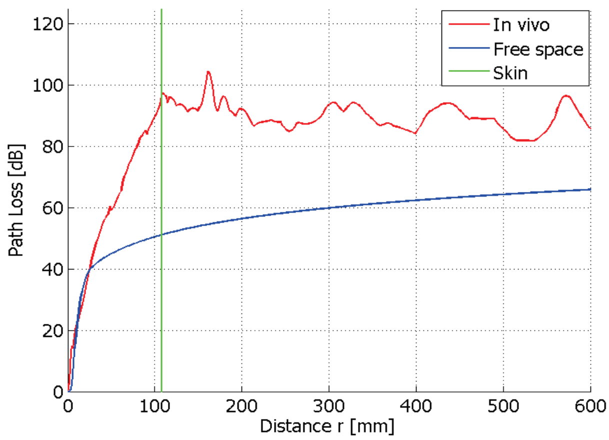

Fig. 3. Path loss vs. distance at azimuth angle $\phi = 0°$ and polar angle $\theta = 90°$. Skin boundary is at $108mm$.

In contrast, at the skin boundary, the *in vivo* path loss is about 45 dB greater than the free space path loss. In the range of $r = 108 - 600mm$, the difference between *in vivo* and free space path loss fluctuates within 18 dB to 50 dB. Both the free space and *in vivo* path losses initially increase rapidly, but the *in vivo* path loss rises rapidly inside the body while free space path loss also does so for $r = 1 - 20mm$, which is exactly the free space near field region. These results are similar to those in [5].

B. Path loss vs azimuth angle

In this simulation, we vary the distance $r = 150mm, 50mm$ and fix the polar angle at $\theta = 90°$. In this way, we obtain the path loss vs azimuth angle as shown in Fig. 4. Overall, the *in vivo* path loss is about 32-52 dB greater than the free

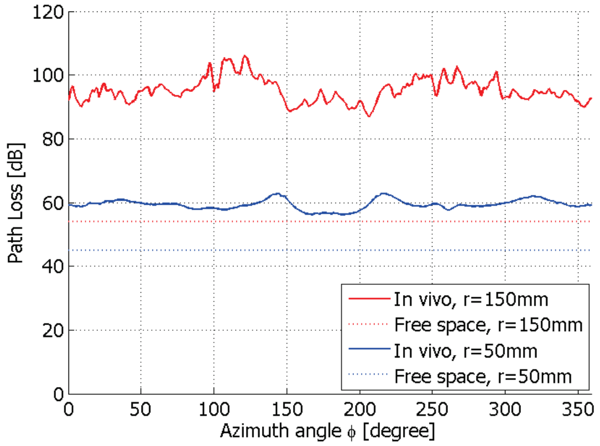

Fig. 4. Path loss vs azimuth angle at polar angle $\theta = 90°$ and distance $r = 150mm, 50mm$

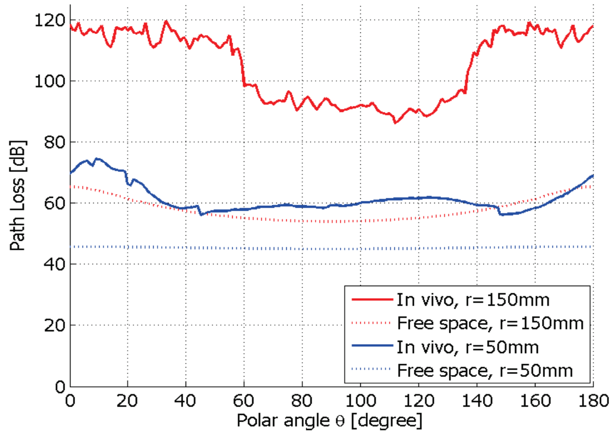

Fig. 5. Path loss vs polar angle at azimuth angle $\phi = 0°$ and distance $r = 150mm, 50mm$

space path loss at $r = 150mm$, which is outside the body. At $r = 50mm$, which is inside the body, the difference between *in vivo* and free space path loss is 11-18 dB. We can see that the free space path loss is flat and the *in vivo* path loss varies with azimuth angle. The variation is larger for the region outside of the body than inside the body. At $r = 150mm$, we note that the path loss is lower at the back of the body, when the azimuth angle is in the range $\phi = 150° - 210°$. These fluctuations show that the human body is inhomogeneous as expected and, consequently, that the path loss is angular dependent. Compared with our another method of measuring the path loss by using monopole [2], we found the path loss measured by using a Hertzian-Dipole has less angular variation than that by using monopole. Therefore, we conclude that the significant variations in Received Signal Strength is caused by both the angular dependent path loss and the significantly modified *in vivo* antenna effects.

C. Path loss vs polar angle

Figure 5 shows the path loss vs polar angle when the distance $r = 150mm, 50mm$ and azimuth angle $\phi = 0°$. For the case of $r = 150mm$, the *in vivo* path loss curve is fluctuating and also is concave within $\phi = 60° - 135°$. The cause of this concavity is that the path is outside the body in this range, which has less attenuation. The reason why the curve of the free space path loss appears as an arch instead of a flat line is that the Hertzian-Dipole has some effects on the path loss in different polar angles because of its donut-shaped antenna pattern. However, when the distance $r = 50mm$, the free space path loss is almost a flat line, which means that there is little antenna effect. For the *in vivo* path loss at $r = 50mm$, we observe that there is an arch at $\phi = 45° - 145°$. This is because the path is through the small intestine, which makes the path loss relatively greater.

V. Conclusion and Future Research

We used HFSS software and Human Body Model to calculate the electric field caused by a Hertzian-Dipole at the origin and obtained the *in vivo* path loss versus different parameters in spherical coordinates. We observed the different behaviors of the path loss between *in vivo* and free space environments. Significant attenuation occurs inside the body and the *in vivo* path loss can be up to 45 dB greater than the free space path loss. The *in vivo* path loss experiences a lot of fluctuations in the out-of-body region, while the free space path loss increases smoothly. Also the inhomogeneous medium results in angular dependent path loss. We also compared the results to the method of using monopole antennas and found that the angular-dependent signal variation was caused by both the angular-based path loss and *in vivo* antenna effects.

This initial research is a first-step in building an *in vivo* channel model and in exploring the different types of *in vivo* antenna effects.

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