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A Phenomenological Path Loss Model of the *In Vivo* Wireless Channel

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***Abstract* — Channel modeling is of fundamental importance for *in vivo* wireless communication, since it is essential in order to optimize transmitter and receiver signal processing. In this paper, we build a phenomenological model for the distance and frequency dependent path loss of the *in vivo* wireless channel. Measured data is produced through HFSS simulations in the range of 0.4−6 GHz for frequency and λ/50−3λ for distance. Based on the measurements, we produce mathematical models for in body, on body and out of body regions. The results show that our proposed models fit well with the measured data.**

***Keywords* — *In vivo* channel modeling; phenomenological model; distance dependent, frequency dependent**

I. Introduction

Wireless communication for biomedical applications and technologies is a research area that has seen a significant increase in attention in recent years. Channel modeling is of fundamental importance for *in vivo* wireless communication, since it is essential in order to optimize transmitter and receiver signal processing. With an understanding of the *in vivo* channel, optimized physical layer signal processing techniques that will enable optimal performance can be realized.

In characterizing the *in vivo* channel, we need to consider the inhomogeneous and very lossy nature of the *in vivo* medium. Furthermore, additional factors need to be taken into account, such as near-field effects and highly variable propagation speeds through different organs and tissues.

Since the *in vivo* channel is significantly different from the classic wireless channel, it may be necessary to build a novel model to characterize the channel. Prior literature can be found in [2]–[4]. In [2], the authors determined a statistical path loss model for medical implant communication system by observing RF propagation at 402-405 MHz from an immersive visualization environment. In-body path loss models for different homogenous human tissues and the influence of the dielectric properties on path loss were investigated and modeled in [3]. Using ingested wireless implants, the author of [4] performed numerical and experimental investigations for biotelemetry radio channels and wave attenuation in human subjects.

In our previous work on *in vivo* channel characterization [5], [6], we investigated the distance and angular dependency of the *in vivo* path loss. The differences between *in vivo* and *ex vivo* channels are summarized in the table in [6]. However, in those papers we have not explored a wide frequency range or come up with a mathematical model of the *in vivo* channel, which is the focus of this paper.

The rest of this paper is organized as follows. First we describe the simulation tool and our measurement approach in Section II. In Sections III, we present the results for the *in vivo* channel characterization and then fit the measured data into a phenomenological path loss model. Finally, we conclude the paper in Section IV.

II. Measurement Setup

A. Human Body Model

We use the Human Body Model in ANSYS HFSS (High Frequency Structural Simulator) for our measurements. The Human Body Model contains an adult male body with more than 300 parts of organs, muscles and bones modeled to the precision of 1 mm. In its operating frequency range (from 10 Hz to 100 GHz), each part has its realistic frequency dependent material parameters, such as relative permittivity ϵ_r and conductivity σ [7].

B. Measurement Approach

With the Human Body Model and HFSS simulation platform, the measured data can be obtained from scattering parameters (S-parameters). Our simulation setup is shown in Fig. 1. In the Cartesian coordinate system, the *in vivo* transmit antenna is fixed at (35mm, 0, 0), which is located behind the small intestine. The receive antenna is moving along the X-axis and it has the same size as the transmit antenna when it is inside the body. When the receive antenna is outside the body, it equals to the size of the free space dipole antenna, which is as 4−6 times as large as the *in vivo* antenna, since the wavelength in free space is as 4−6 times longer than inside the body.

The frequency range we are investigating is from 0.4 GHz to 6 GHz. Since a dipole is not a wideband antenna, we

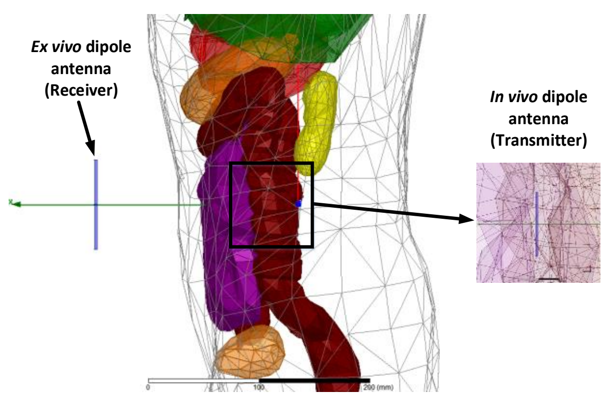

Fig.1. HFSS simulation setup by using dipole antennas.

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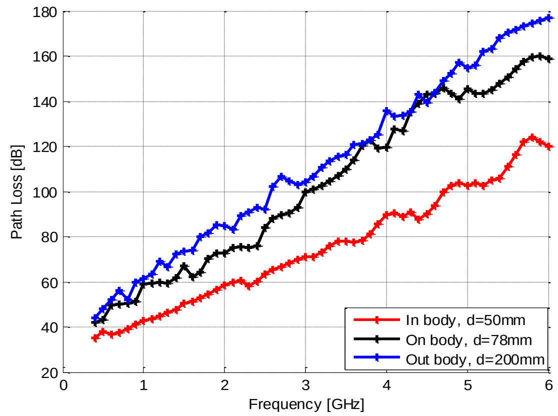

Fig.2. Frequency dependent path loss at different locations.

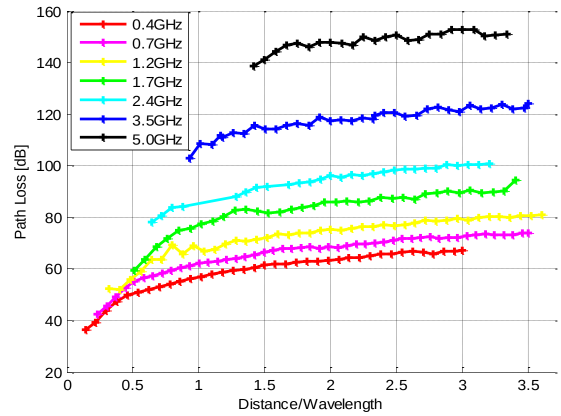

Fig.4. Out of body distance dependent path loss.

choose seven dipoles that operating at different frequencies (0.4, 0.7, 1.2, 1.7, 2.4, 3.5 and 5.0 GHz) to cover this frequency range. The measuring distance ranges from $\lambda/50$ to 3λ, where λ is the free space wavelength.

Considering the return loss of the antenna is not constant at each measuring frequency and even at different positions, we develop the following formula to calculate the path loss and remove the effects on antenna gains from different return losses:

$$Path\ Loss\ (dB) = -S_{21} + 10 * \log_{10}\left(1 - 10^{\frac{S_{11}}{10}}\right) + 10 * \log_{10}\left(1 - 10^{\frac{S_{22}}{10}}\right) \quad (2.1)$$

where S_{11} and S_{22} are the return losses of the transmit and receive antennas, respectively. The parameter S_{21} represents the power gain between these two antennas and all S-parameters are expressed in dB.

III. Results and Data Analysis

A. Frequency and Distance Dependent Path Loss

We denote the distance between transmit and receive antennas as d in mm and the frequency as f in GHz. The skin boundary of the body is at $d = 78mm$. From the measured data, we plot the frequency dependent path loss in Fig. 2 for three different positions: $d = 50mm$ (in body), $d = 78mm$ (on body), $d = 200mm$ (out of body). From the results, we observe that the frequency dependent path loss [in dB] increases linearly at different locations. Therefore, the frequency dependent *in vivo* path loss [in ratio] increases exponentially, which is faster than that in free space.

In Fig. 3 and Fig. 4, the distance dependent path loss at different frequencies is shown. We measured the path loss from 0.4 GHz to 6 GHz in 0.1 GHz increment. In the figures, we only display the optimal operating frequencies for all the seven dipoles. We observe that the path loss [in dB] increases linearly inside the body and then grows logarithmically outside the body.

B. Data Fitting

The observations in Part A provides us with important guidance for fitting the measured data into a phenomenological model. We use the Curve Fitting Toolbox in MATLAB to perform the data fitting. The procedure is as follows:

1) Curve fitting for on body path loss: For both regions inside and outside the body, we will choose the on body location as the reference point. Consequently, we first fit the on body path loss data as a straight line shown in Fig. 5. The fitted line is

$$PL_{on\ body} = 22.4 * f + 31.4 \quad (3.1)$$

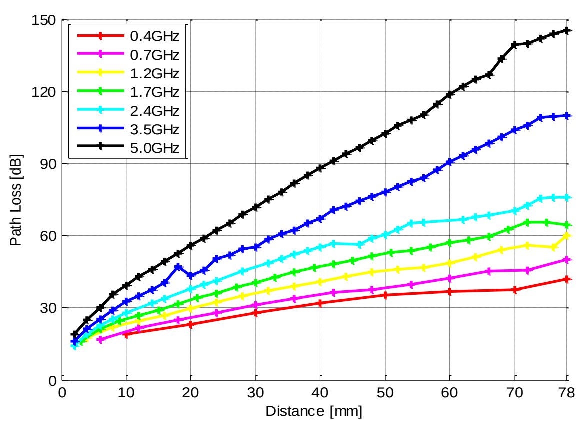

Fig.3. In body distance dependent path loss.

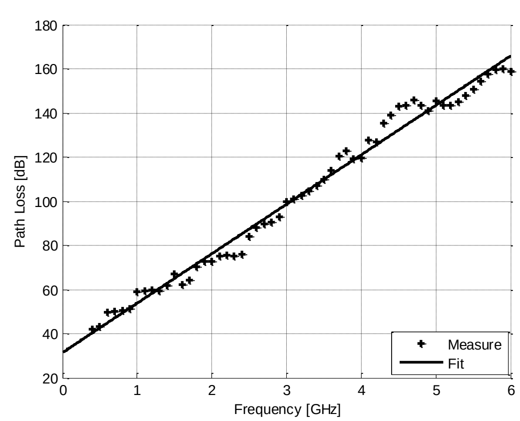

Fig.5. On body path loss fitting.

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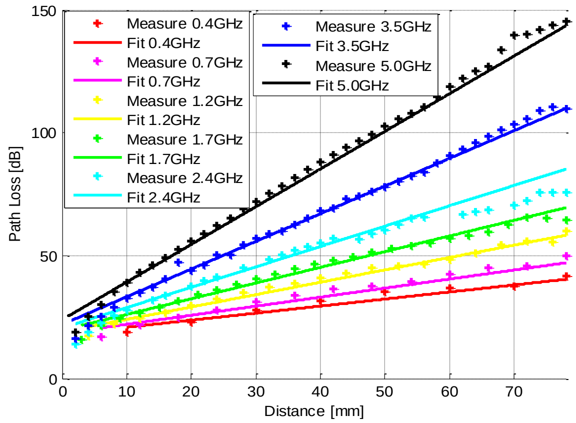

Fig.6. In body path loss fitting.

2) Curve fitting for in body path loss: As we observed in Fig. 3, the in body path loss increases linearly and we choose the reference point on the body and fit the data at all frequencies. The fitted results are:

$$PL_{in\ body} = PL_{on\ body} + k * (d - 78) \qquad (3.2)$$

The parameter k is the slope for the path loss at each frequency and it can be fitted as $k = 0.271 * f + 0.1782$. In Fig. 6, we compare the measured data with the fitted lines. This model indicates that the in body path loss increases exponentially with distance, which is faster than the free space path loss.

3) Curve fitting for out of body path loss: The operation is similar to last step. The fitted formula is:

$$PL_{out\ of\ body} = PL_{on\ body} + 10 * \log_{10}\left(\frac{d}{78}\right)^{n} \qquad (3.3)$$

where $n = 1.71 - 2.37$ is the exponent for the path loss at each frequency. In our measured data, the exponent has an average value of $n = 2.04$. So the out of body path loss is similar to the free space path loss. We plot the measured data versus the fitted data in Fig. 7.

From Fig. 5 to Fig. 7, we can see that our proposed models (3.1)−(3.3) generally fit well with the measured data, except for two regions: one is the near field region of the in body antenna and the other is the out of body region closer to the body-air interface. It can be seen that the measured path loss slightly drops when the receiver just gets out of the medium. We assume that slight miscalculations by HFSS occur at the body-air interface because of multiple reflections and refractions.

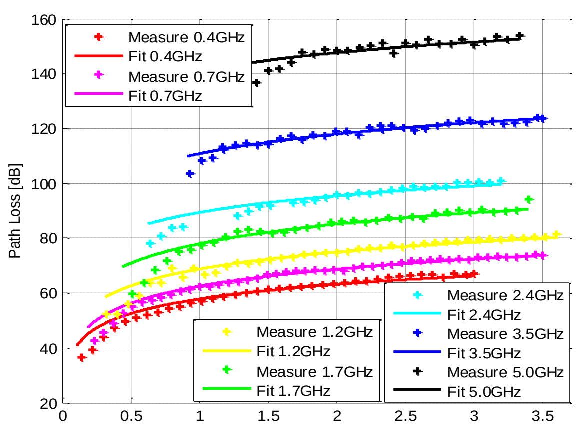

Fig.7. Out of body path loss fitting.

IV. Conclusions

In this paper, we proposed a phenomenological *in vivo* path loss model based on the measured data obtained by HFSS simulations. First we found some important characteristics for the *in vivo* path loss. The path loss increases linearly with frequency at different locations. Inside the body, the path loss also increases linearly in dB with distance except for the near field region. Outside the body, the path loss grows logarithmically with distance similar to free space. These characteristics enable us to fit the model for three different regions: on body, in body and out of body. The on body path loss is modeled as a straight line [in dB] versus frequency and it acts as the reference point for the other two regions. The in body path loss is also modeled as a straight line with both frequency and distance as the parameters. The out of body path loss is modeled as a logarithmical curve with an exponent of 1.71−2.37 on the distance, which is similar to the exponent of 2 on the distance for the free space path loss.

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