Proceedings of the 2009 IEEE
International Conference on Robotics and Biomimetics
December 19 -23, 2009, Guilin, China

A Novel Radio Propagation Radiation Model for Location of the Capsule in GI Tract

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***Abstract*—In this paper, we discuss the influence of the antenna orientation radiation pattern in localization algorithm based on Received Signal Strength Indicator (RSSI). We also improve the empirical model of signal propagation by building the path loss function of the human gastro-intestine (GI) tract. The novel model includes information of both the distance and azimuth angle variables. The numerical electromagnetic analysis with the finite-difference time-domain (FDTD) is applied to model the vivo radio propagation channels by using a dipole antenna suitable for the model related to the human body. The proposed propagation model is compared with empirical model, and the simulation results show that the compensated model is more accurate by calculating the azimuth radiation attenuation. It demonstrates that the often overlooked antenna orientation has the dominant effect on the signal strength sensitivity.**

I. INTRODUCTION

VARIOUS technologies have been used to implement wireless localization systems including ultrasound, magnetic and radio frequency identification (RFID) [1]. These localization systems require specialized hardware and infrastructure, which might be very expensive. Consequently, for the medical diagnosis or treatment application, a wireless positioning implementation with non-specialized, relatively inexpensive hardware is desirable. For the tracking of the object in the GI tract, the radio frequency (RF) localization technique based on time or angle measurement methods, i.e. Time of Arrival (TOA), Time Difference of Arrival (TDOA) [2, 3] and Angle of Arrival (AOA), are not feasible due to the absorption characteristics of the digestive organs. Such a localization problem is worsened by non-line-of-sight (NLOS) conditions due to the gastro-intestinal shifting, routing, filling and emptying, resulting in the radio signal loss. Therefore, for easier implementation and more accurate localization in the GI tract [4], the RSSI method is more appropriate.

Received signal strength (RSS) is a measure of the power received by the radio receiver with respect to the radio transmitter, and it can be used to estimate the distance between them. RSS intensity is location dependent as it is affected by the factors such as the transmission distance and the attenuation due to the medium of the propagation and other barriers. The availability of radio signal strength attenuation information of wireless RF signal has received considerable attention as a convenient means for positioning information. Most existed RSSI methods are based on signal propagation empirical model [5], but it is very complicated to build a full sensor location database for the sensor deployment in the tracking environment [6]. The performance of current RSSI methods is not acceptable, so much work has been done to improve its accuracy and robustness [7].

Currently, most of the research on the radio propagation model for medical applications has focused on enhancing the communication performance [8] and verifying the security of the implantable devices radiation with various frequencies [9]. Chirwa et al. numerically investigated the radiation characteristics of implantable sources in the human GI tract at different locations for VHF and UHF bands [10]. They found that radiation intensity outside the body has a Gaussian-like relationship with frequency, and the near and far fields are not directly related because of the presence of reactive fields in the near region of the implantable sources. Scanlon et al. [11] described the body-worn efficiencies of a vaginally implanted 418 and 916.5 MHz sources. The research shows that at higher frequencies, the losses in human tissues increase and lead to reduction in efficiencies and deformation of the power pattern.

Being different from those researches above, to improve the accuracy of RSSI localization algorithm in GI tract, we focus on the antenna radiation pattern in this paper. A detailed analysis of radio propagation in different human tissues has been done by calculating the path loss parameters of various frequencies. Then the path loss is compensated related to both distance and azimuth in the GI parts of human body. The simulation results have verified that the compensated propagation model with the azimuth part is more accurate than the empirical model, especially in the close vicinity of the in-body source.

The paper is organized as follows: in section II the items ignored in signal propagation empirical model and the antenna radiation patterns are analyzed. In section III, a compensated propagation attenuation model is proposed to describe the received biotelemetric RF signal strength, and

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Manuscript received July 31, 2009. This work is supported in part by Chinese National High Technology Research (863) Funds (2007AA01Z308), National Natural Science Foundation of China (60804031), and Sci. Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, and Shenzhen Nanshan Sc. & Tech. Research Funds awarded to Chao Hu.

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978-1-4244-4775-6/09/$25.00 © 2009 IEEE.

based on the proposed model the numerical electromagnetic analysis method of FDTD [12] is applied to evaluate the attenuation parameters. In section IV, we present the comparison results of the empirical model and the compensated propagation model obtained from simulation experiments, follows by the conclusions in section V.

II. PROPAGATION MODEL AND ANTENNA RADIATION PATTERN

A. *Empirical Signal Propagation Model*

The empirical model [8] of signal propagation is widely used in RF localization by calculating the distance between transmitter and receiver. The RSS is logarithmically with distance shadowing, the model is described as follows:,

$$RSSI\left(d\right)=P_T-PL\left(d_0\right)-10n\log_{10}\frac{d}{d_0}+X_\sigma \qquad (1)$$

where P_T is the transmit power, $PL(d_0)$ is the path loss for a reference distance, n is the path loss exponent, X_σ is a Gaussian random variable with zero mean and σ^2 variance, which models the random variation of the RSSI value.

The empirical model only considers the environment noise and the distance between transmitter and receiver antenna, and it is assumed that the radiation pattern of antennas on transmitters and receivers are omni-directional. Then, its radiation pattern can be depicted in Fig. 1(a), just like a ball in 3D. In addition, it is worth emphasizing that the RSS is also greatly affected by another three factors, i.e. transmitter variability, receiver variability and antenna orientation. These factors have been proved to be more important both in theory and practice, see, for instance [5] [13]. In this paper, the propagation attenuation model is modified by considering the antenna orientation factor which is caused by the antenna radiation pattern.

B. *Radiation Pattern of the Implantable Antenna*

Most sensor nodes applied in localization use a 1/4 monopole antenna, which shows the same radiation pattern of a 1/2 wavelength dipole antenna whose horizontal radiation pattern is omni-directional. However, this omni-directional radiation pattern is distorted when an antenna is in the complicated environment, such as in human body which is shown in Fig. 1(b), we can see that the contour plane likes a tomato, not a ball as assuming in empirical model. Fig. 1(c) gives 2D radiation pattern plane, the blue line, red line and green line represents the tot, phi and theta directivity respectively, and it clearly shows the radiation pattern varies form directions since the posterior side of human body absorbs more electric fields from radiation source in the gastro-intestine than the anterior side.

Fig. 1 demonstrates that the radiation pattern in GI of the human body is totally different from that in free space, it means the antenna radiation pattern is not uniform in various mediums and orientations. Therefore, the empirical propagation model is robust as the RSS measurements are also greatly affected by the medium and orientation. This paper has compensated the empirical model by considering the azimuth into it in next section.

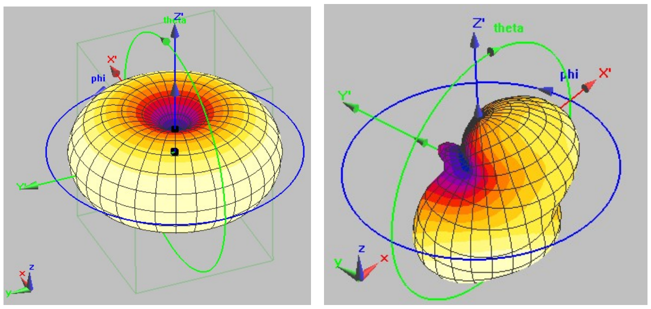

Fig. 1(a) 3D radiation in free space Fig. 1(b) 3D radiation in GI

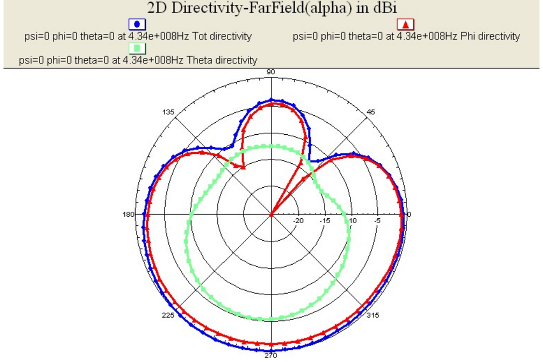

Fig. 1(c) 2D radiation pattern in GI

Fig. 1. Radiation pattern of dipole antenna

III. THE COMPENSATED PROPAGATION MODEL AND ITS PATH LOSS ANALYSIS

A. *Building the Compensated Propagation Model*

The RF signal transmitting and receiving for dipole antennas can be described as Fig. 2 Provided that both the receiver antenna and transmitter antenna is Hertzian diplole. We assume that the receivers are all only influenced by far-zone field (or radiated field), since they are far away enough from the transmitter.

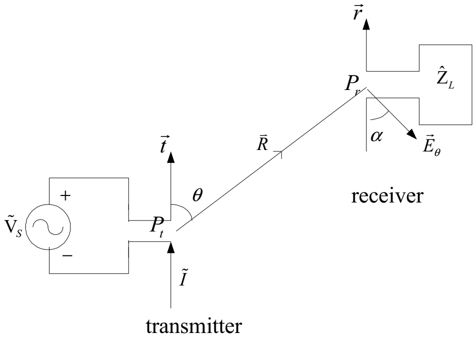

Fig.2. Schematic description of the RF signal transmitting and receiving for dipole antennas

Notations used in Fig.2 are listed as follow: P_t is the middle point of transmitter antenna, P_r is the middle point of receiver antenna, $\vec{t}$, $\vec{r}$ are the orientation vectors of transmitter antenna and receiver antenna respectively , $\vec{R}$ is the vector from P_t to P_r , θ is the angle between $\vec{t}$ and $\vec{R}$, $\vec{E}$ is the vector of electrical field at the receiver antenna which is perpendicular to $\vec{R}$, α is the angle between $\vec{r}$ and $\vec{E}$, $\hat{Z}_L$ is the load impedance of the receiver antenna, I is the effective value of the current going through the transmitter antenna.

The magnitude of electrical field in can be expressed as follows:

$$E = \sin\theta\left(\beta\eta I l_t\right)/\left(4\pi R\right) \tag{2}$$

where l_t is the length of transmitter antenna, R is the magnitude of $\vec{R}$, β is the phase constant, η is the medium intrinsic impedance.

As the relationship between electric field and the power is $\left(E(d,\theta)/E(d_0,\theta)\right)^2 \propto PL(d,\theta)/PL(d,\theta)$, we can deduce the path loss parameter as follows:

$$\begin{aligned} n(d,\theta) &= k\cdot\log\left[\frac{E(d_0,\theta_0)}{E(d,\theta)}\right]\Big/\log\left(\frac{d}{d_0}\right) \\ &= k\cdot\log\left[\frac{\beta\eta I_0 l_t\sin\theta_0}{4\pi d_0}\cdot\frac{4\pi d}{\beta\eta I l_t\sin\theta}\right]\Big/\log\left(\frac{d}{d_0}\right) \end{aligned} \tag{3}$$

where k denotes the path loss parameter that will be discussed in the rest paper.

Through putting $n(d,\theta)$ into equation(1), we can get the following RF propagation attenuation model of received signal, electricity (RSE) as follows:

$$\begin{aligned} RSE(d,\theta) &= RSE(d_0,\theta_0) - 20n_d\log\left(\frac{d}{d_0}\right) \\ &\quad + 20n_\theta\log\left(\frac{\sin\theta}{\sin\theta_0}\right) + S_\sigma \end{aligned} \tag{4}$$

where n_d is the distance path loss parameter, n_θ is the azimuth pass loss parameter, and $\sin\theta$ can be calculated by $\sin\theta = \sqrt{x^2+y^2}\Big/\sqrt{x^2+y^2+z^2}$, S_σ is a Gaussian random variable with zero mean and σ^2 variance, which is called shadowing. Then we need to do some work to fix on the optimal n_d and n_θ in the GI of human body. Selection of the path loss parameter is the key work to regulation the proposed model for adapting special location of the human body.

B. Numerical Analysis of Propagation Attenuation from Wireless Implantable Antenna

In this paper, the numerical analysis technique FDTD utilized in the SEMCAD [14] is applied for accurate propagation model of implantable radiation source in human body. It is seen as very valuable and convenient method for evaluating radio propagation attenuation inside and outside around the human body. This method is more flexible with respect to modeling various situations in on-body area propagation since a numerical human model can easily simulate various body postures. Akram Alomainy et al. [15] have done some experiments to compare the FDTD simulation with measurement methods, their results are verified with materials measurement in good agreement. Therefore, we use FDTD simulation results as the real measurement value to evaluate the path loss parameter in-body propagation radiation model.

This study covers commonly used frequencies in telemedicine applications: frequencies at 434 MHz, 868 MHz and the industrial, scientific and medical (ISM) band frequency at 2.4GHz. The computational domain has an approximate cell size of $\lambda/15$ with regards to antenna wavelength. The total size of the computational region is $300\times200\times200\text{mm}^3$. Average number of time steps applied is around 50000 to ensure that a steady-state had been achieved. The source is defined as sinusoidal excitation with 1V voltage.

Fig. 3 gives the normalized electric field varies with both distances and frequency. The blue, green and yellow line denotes the field attenuation at 434 MHz, 868 MHz and 2.4 GHz respectively. The curves vividly depict the electric field attenuation with reference to frequencies and tissues. Especially, at 2.4 GHz the attenuation fluctuates greatly than the other two frequencies. In all, the radiation pattern of a dipole antenna at 434MHz is suitable for the detecting an embedded device that is subject to the characteristic of tissue and other related structures. In this frequency, it can guarantee the high effective of communication quality to transmit and receive data for localization and other applications.

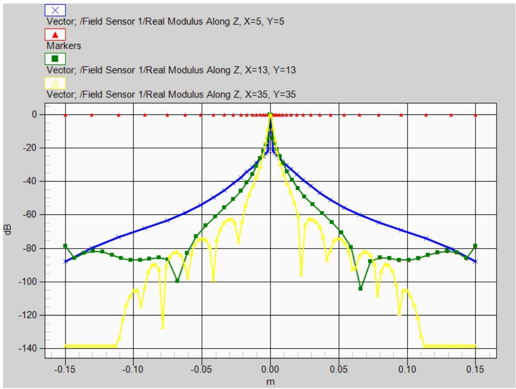

Fig. 3(a) Attenuation in Stomach

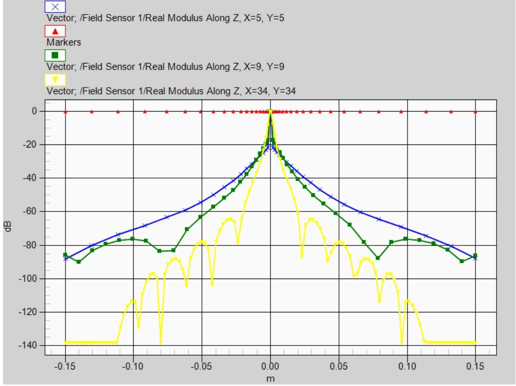

Fig. 3(b) Attenuation in Intestine

Fig. 3 Comparison of the normalized electric field values with different frequencies and tissues

Through the empirical propagation model, we induce the distance path loss parameter as follows:

$$n_d = \frac{P_T - PL(d_0) - RSSI(d) + X_\sigma}{10\log_{10}\dfrac{d}{d_0}} \qquad (5)$$

where the range of d/d_0 is from 6 to 44, and X_σ is not considered here.

In the simulation, source is oriented in the z direction and placed near the backward of the sensing region which is filled in different human body tissues as Fig. 4 and Fig. 5. We get the slice electric field magnitudes by using a steady state field scanner with wireless implantable sensors, then calculate the average value of pass loss exponent as shown in Table Ⅰ.

TABLE Ⅰ
THE ATTENUATION PARAMETER VERSUS FREQUENCIES AND TISSUES

quency(Hz) Tissue	434M	868M	2.4G
Skin	1.9658	2.0420	2.5848
bone	2.5369	2.7616	2.9674
Fat	2.3772	2.7332	3.8637
Stomach	2.8589	3.0494	4.0885
Lung	2.7076	2.8499	3.5874
Small Intestine	2.9081	3.0857	4.0885
muscle	2.9465	3.8013	4.1664

Results in Table Ⅰ verify that path loss exponent n_d is increased with the frequency, but it is different with reference to various human body tissues. From FDTD simulation results, we can derive that in-body situation is not much like the ideal situation, its attenuation is more complicated and relating to more factors such as boundary effects, reflections and so on. Therefore, the exact attenuation model in human body is particularly challenging due to variable tissues properties and frequencies. In this paper, we select the average value of stomach (2.8589) and intestine (2.9081) in 434 MHz as the path loss parameter n_d of compensated propagation model. The azimuth path loss parameter n_θ will be confirmed by comparing simulation results of compensated model with the FDTD simulation in the experiment.

IV. EXPERIMENT RESULTS AND DISCUSSION

According to the compensated propagation model derived above, we do some experiments to verified its performance in the human model. For this purpose we are using an adult male model from the National Institutes of Health (NIH) Visible Man project [16], which is available in SEMCAD (see Fig. 4). Simulation experiments are performed for sources at the human body location of GI in the 434 MHz. The source is oriented in the z direction and placed near the bottom of the stomach and not far away from intestine in the digital phantom. The sensing region is a green rectangular which is marked by a red circle. The transmit sensor is placed in the close vicinity of abdomen system as Fig. 4. The cell size of computational domain is about $\lambda/15$, the average time step is around 50000.

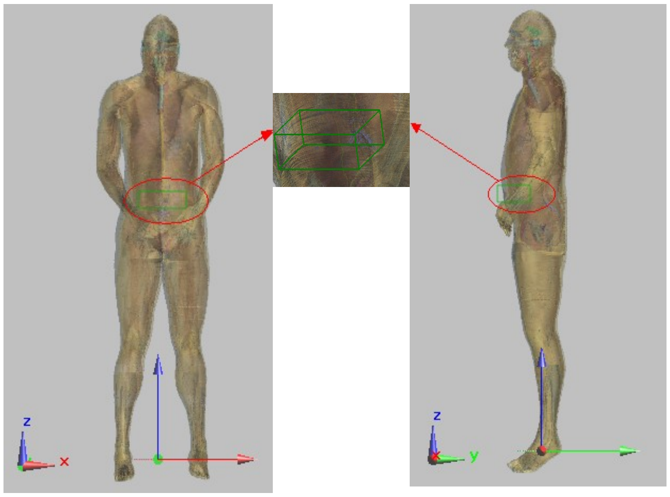

Fig. 4 The human body model

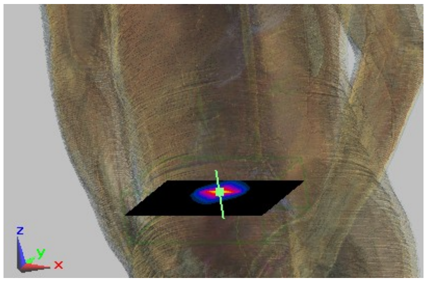

Fig. 5 The maximum z-axis slice field E[x, y, z, f0] in dB

Fig. 5 gives the maximum z-axis slice electric field, the green line denotes the maximum slice field in the plane which demonstrates the radio radiation of electric field, it is not a regular circle because of the absorption of human body tissues.

We regulate the compensated model by selecting various n_θ for modeling an accurate biotelemetric channel of the proposed radio propagation. In Fig. 6, it can be seen that the minimum error is derived when n_θ is 3, so in this paper we choose this value for the propagation model. Fig. 7 shows the relationship between model error and signal noise ratio (SNR), the result demonstrates the optimal SNR must be larger than 20 dB.

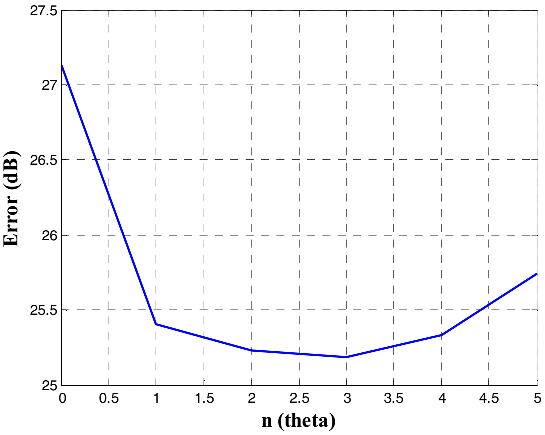

Fig. 6. Compensated model error with various n(theta)

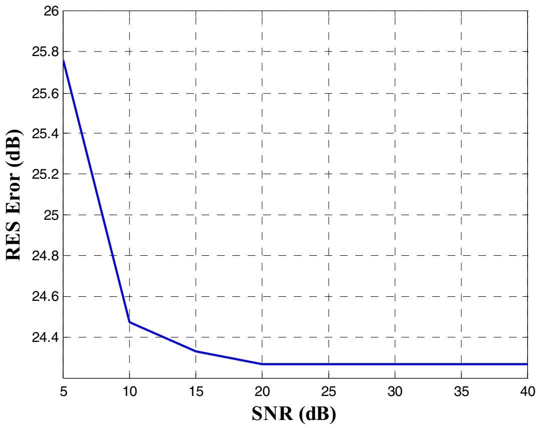

Fig. 7. RSE error vs. SNR

Then we have done some performance analysis of the proposed model. Based on the data from FDTD simulation, Fig. 8 gives the azimuth radiation attenuation part in the first figure and the distance radiation attenuation part in the second figure. It demonstrates the azimuth radiation part compensates the signal electric field in region near the source, which is different from the empirical model which only calculates the distance radiation attenuation. The compensated coordinates are about 60mm to 80mm in x-axis, and 100mm to 120mm in y-axis.

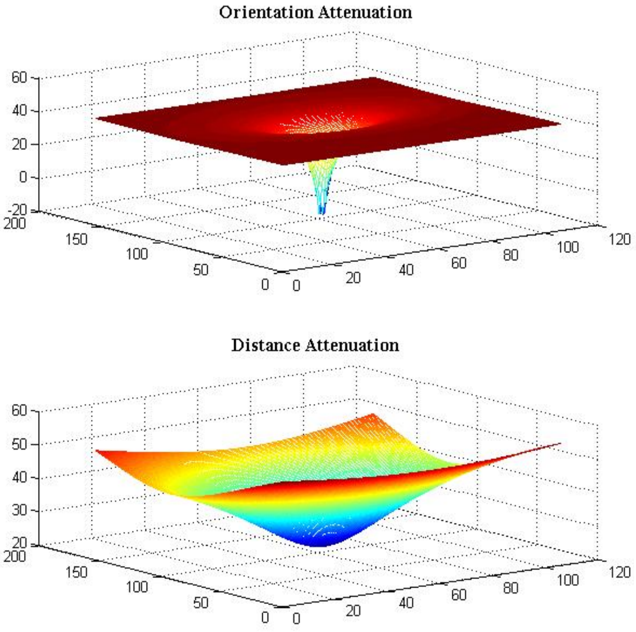

Fig. 8. Orientation and distance attenuation

Fig. 9 is the comparison of the RSE that are computed by FDTD, compensated propagation model and the empirical propagation model. We simulate the real radio radiation attenuation, and use other two models to approximate it. Fig. 8 vividly depicts the RSE propagation attenuation in every coordinate.

Fig. 10 gives the profile of received signal electric field error in a plane, the first figure is the error between compensated model and FDTD simulation result, the second figure is the error of empirical model. The average Error 1 of RSE in empirical propagation logarithm model at 40dB, but the average compensated propagation model's error is lower than 20dB. As there are too many electric field values, we depict the third figure to demonstrate good performance of the compensated model, and results in the third figure show that the compensated model compensates the middle part of the radiation attenuation plane, so it gets better performance than the empirical propagation model.

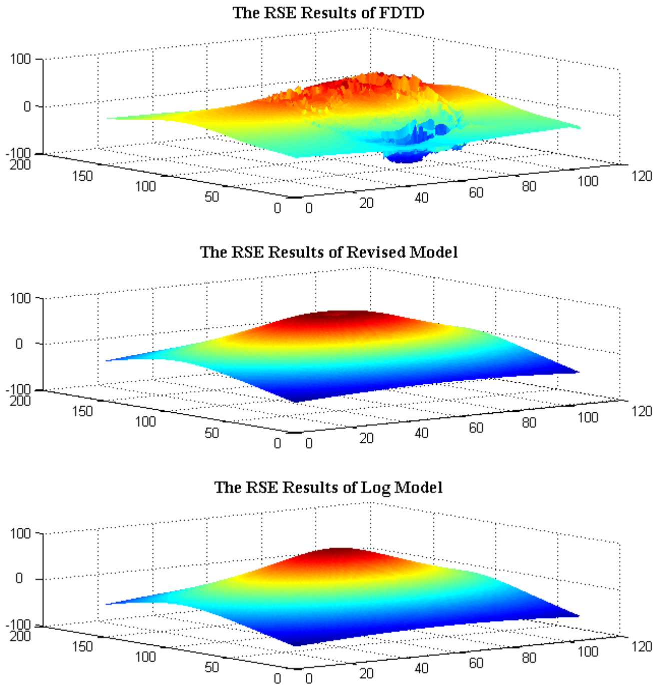

Fig. 9. Comparison of RSE results

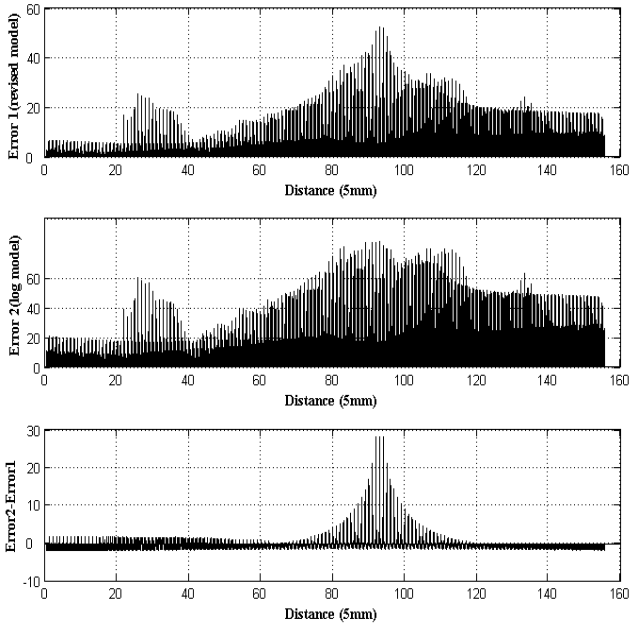

Fig. 10. The received signal electric field error

V. CONCLUSION

We have carried out a detailed study of the radiated properties of implantable sources in the gastro-intestine of human body. This paper proposes a novel propagation model, which includes both orientation attenuation part and distance attenuation part. Based on the data from FDTD simulation, we have selected the optimal parameters which are most suitable for the channel of gastro-intestine. Simulation results show that the novel model has got better performance to model this special channel in GI parts, and the orientation is really an important factor greatly influence the signal propagation attenuation. At last it should be noted that some of these results only serve as guideline, since humans vary significantly in location, posture, morphology, size and weight.

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