IMPROVING IN-BODY ULTRA WIDEBAND COMMUNICATION USING NEAR-FIELD COUPLING OF THE IMPLANTED ANTENNA

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ABSTRACT: Ultra wideband (UWB) signal transmission from in-body implanted antenna to on-body or outside body is considered for biomedical applications. The received energy density of the UWB signal in terms of the distance from the body surface of a human anatomy model is computed. Time-domain finite integral equation (FIE) and frequency-dependent body tissue properties are used for field calculations. Path loss factors of the UWB channel for different distances from the body surface and different implanted antenna depths are derived. It is shown that the energy coupling because of the nonradiative near-field of the body implanted antenna is dominant for the signal transmission. The communication link quality can be significantly improved in the range of 14.5–18 dB by exploiting the near-field components. As a result, we propose to use the nonradiative near-field region of the implanted antenna for improving the communication link quality by designing and placing the receiving antenna close to the body surface and then by relaying the signal to the off-body communication device. © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 585–589, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24126

Key words: human tissue model; implanted antenna; near-field coupling; ultra wideband

1. INTRODUCTION

The antennas implanted deep inside human body are used to facilitate the communication links between medical sensors and exterior instruments for short-range biotelemetry applications [1, 2]. The body implantable device needs low complexity, small size, and low power consumption because of low energy autonomy of the battery powered device. Ultra wideband (UWB) communication for implanted devices is a new topic and can be an interesting candidate for providing higher data rate warranted to the forthcoming implantable technologies. Using UWB, the most of complexity is in the receiver that allows the realization of an ultra low power, low complexity transmitter in the uplink (from implanted sensor to the master). Moreover, the very little hardware complexity of UWB transmitter offers the potential for low cost and highly integrated solutions.

Because of the high loss medium of the body tissues and the low transmitted power, the signal strength at the receiver becomes important to achieve high data rate transmission. Thus, the strategies to optimize the UWB communication link quality have to be known. Therefore, for the first time in this context, we perform the simulation of the UWB channel between an in-body implanted antenna and on-body or off-body receiving device. First, an implanted UWB antenna is designed and optimized for using at the chest of a human anatomy model. The model is analyzed using numerical electromagnetic (EM) code, which uses time-domain finite integral equation (FIE) method to solve the Maxwell’s equations. For this analysis, high-resolution anatomy model HUGO [3] based on the data provided by the Visible Human Project of National Library of Medicine [4] and the wideband electric characteristic data of human biological tissues [5] are used. A frequency dispersive model associated to the tissue materials and a total of 15 different human tissues at the selected simulation region of the human torso are considered. We show that because of the high relative permittivity of the body organs that surround the implanted antenna and the fact that the body performs as a part of the radiation source, the near-field region of the implanted antenna extends. The UWB path loss factor is used as a parameter to measure the strength of the near-field region of the implanted antenna. The effect of the implanted antenna’s depth on the path loss factor is investigated as well.

The article is organized as follows: Section 2 presents UWB antenna design and implementation inside human body; Section 3 presents the human anatomy model (HUGO) and associates a simplified model to the frequency dispersive property of the body organs; Section 4 provides the estimated path loss factor for UWB channel and the importance of the nonradiative near-field on the signal energy density. Section 5 discusses about the computation errors that occur using nondispersive materials or limited simulation volume; Section 6 concludes this article.

2. ULTRA WIDEBAND ANTENNA

Different UWB antennas [6 – 8] can be considered for modeling the communication link from the in-body implanted antenna to outside body. Here, we consider an UWB elliptic disc dipole antenna. The antenna is used to simulate the transmission channel between this antenna and on-body or off-body receiving device. A center feed elliptic disc dipole antenna in free-space, with a major axis of 16 mm and a minor axis of 14 mm, provides 50 Ω impedance matching with return loss less than −5 dB for the frequency range of 3–10 GHz. To prevent the direct current flow from the disc dipole to the conductive body tissues and to consider a realistic condition for biocompatibility, the antenna is embedded in a lossless dielectric case of 24 × 40 × 4 mm³ with the relative permittivity, εr = 9. Figure 1 shows the embedded antenna model.

The impedance characteristics of the embedded antenna are different from the original dipole and cover the frequency range of 2.3–10 GHz with RL < −5 dB (see Fig. 2). If the embedded antenna is implanted inside human torso close to the heart of the human anatomy model (see Fig. 4 and Section 4), the impedance characteristics are influenced by the high dielectric permittivity

![Image](https://via.placeholder.com/150)

Figure 1 Embedded elliptic disc dipole antenna in a dielectric slab
and conductivity of the surrounding tissues. The operating frequency of the antenna modifies and the impedance matching for the RL \(< -5\) dB is obtained at the frequency range of 1–6 GHz. Figure 2 shows the simulated RL versus frequency. Different implanted antenna depths (\(d_0\) from the body surface) are considered as well. As shown, similar impedance characteristics are resulted for the implant depth at \(d_0 = 15, 45, 55\) mm.

3. HUMAN BODY MODELING

The EM properties of human tissues depend largely on the frequency \([5, 9]\). Thus, the propagation characteristics of UWB signals differ greatly from those obtained for the frequency-independent model. Precise frequency-dependent permittivity and conductivity for human body tissues have been made available by Gabriel and Gabriel based on four-pole Cole-Cole equations \([5]\). To implement the frequency dispersion into EM simulation codes, as for example, finite difference time domain (FDTD) or FIE using simplified models is more effective than by the Cole-Cole model. This is due to the complexity of Cole-Cole model, which causes an extremely long computational time \([10]\). Furthermore, the Cole-Cole model is not integrated at the current EM simulation tools.

Two-pole Debye dispersion and a conductive loss term were proposed to model dielectric dispersion of human tissues for the frequency range of 100 MHz–6 GHz \([11]\). Other dispersion model \([10]\) uses four-pole Debye equation to approximate the frequency dispersion from 1 to 10 GHz. Here, we use a simpler equation by considering the frequency range of 1–6 GHz, where the frequency dispersion model of the complex relative permittivity is described in the form of a general second-order polynomial as given,

\[
\varepsilon_i(\omega) = \varepsilon'_i + j\varepsilon''_i = \varepsilon_\infty + \frac{\beta_0 + j\omega\beta_1}{\alpha_0 + j\omega\alpha_1 - \omega^2}
\]  

where \(\varepsilon'_i\) and \(\varepsilon''_i\) are defined as the real part and the imaginary part of \(\varepsilon_i(\omega)\), respectively, \(\omega\) is the angular frequency (rad/s), \(\varepsilon_\infty\) is the permittivity at infinite frequency, \(\alpha_0, \beta_0, \alpha_1, \beta_1\) are the parameters that are derived by fitting to the Gabriel-based four-pole Cole-Cole data using Newton method and least square fitting. We have obtained the fitting parameters for 15 tissues materials (bloods, liver, lung, marrow, muscles, skin, stomach, and ventricles) available at the simulation region at the human torso. The fitting result for one selected tissue (lung) is plotted in Figure 3; it is clearly demonstrated that the second-order polynomial exhibits good approximation to Gabriel’s data for the given frequency range. However, for the frequencies smaller than 1 GHz, the second-order equation cannot satisfy the data fitting. Therefore, other complicated solutions must be used \([11]\). The given second-order equation can be incorporated in FIE code within CST EM simulation tool.

4. ENERGY DENSITY OF THE IMPLANTED ANTENNA AND THE NEAR-FIELD EFFECTS

The anatomical voxel model of human torso is used to simulate the UWB signal energy density at the near-field region of the implanted antenna. For this simulation, the voxel model with \(2 \times 2 \times 2\) mm\(^3\) resolution is considered and the Gabriel’s frequency dispersive tissue properties are associated to the model using Eq. (1). The cell size of the FIE body model is the same as the voxel size (2 mm) of the torso file. Figure 4 shows the three-dimensional FIE torso model and the sectional FIE torso model, which consists of different tissues represented by relative permittivity, ranging from 1 to 50 at a frequency range of 1–6 GHz. The embedded elliptic disc dipole (see Fig. 1) is placed inside the chest close to heart with the depth of \(d_0\) (mm) from the skin (see Fig. 4). The antenna is oriented horizontally with the major axis of the ellipse at the x-direction. The antenna is directly surrounded with different tissue materials: blood, fats, cartilages, bones, lung, and muscle. The torso model is bounded with perfectly matched layer (PML) boundary and the boundary is extended at the front direction, where \(E\) and \(H\) field probes are used to measure the field intensity.

For the simulations, the antenna prototype is deduced from the surrounding material to include one material property at a given space. This can be conducted by defining the meshing priority using the EM tool. The EM simulation with exciting the antenna with UWB Gaussian pulse is conducted using time-domain solver. The Gaussian pulse with a pulse width of 400 ps and a \(-6\) dB bandwidth of 6 GHz is used. The time-domain electric fields \(E_{x,y,z}(t)\) and magnetic fields \(H_{x,y,z}(t)\) components are calculated at different distances away from the body surface, on a straight line.

![Electric Dispersion Lung](image_url)

**Figure 3** Gabriel’s human tissue data and least squares fitted general second-order equation for lung.

**Figure 2** Return loss (dB) versus frequency (GHz) for embedded elliptical disc dipole antenna at the free-space and implanted inside human body at different depths, \(d_0\) (mm)
between the antenna center and the observation points along the \( y \)-axis. The distance resolution of \( dy = 5 \) mm is considered for EM fields and the first observation point is on the body surface with \( d_0 \) distance from the implanted antenna center. The pointing vector, \( S_{x,y,z}(t) \), describes both the direction of propagation and the power density of the EM wave, which can be written as

\[
S_{x,y,z}(t) = E_{x,y,z}(t) \times H_{x,y,z}(t) \quad \text{W/m}^2
\]  

We note that the calculated \( E \) and \( H \) fields are valid for the frequency range of 1–6 GHz. Thus, the EM simulated results are filtered with a bandpass filter at the given frequency range.

Because of the fact that the dipole antenna is oriented in \( x \)-axis direction, the near-field components at the given distances (greater than \( d_0 \)) are dominant for only \( E_x \) and \( H_z \). Thus, the power flow direction is on the \( y \)-axis. The UWB signal energy density, which is received outside the body in different distances, \( d > d_0 \) from the dipole antenna, is calculated by integrating the power density over the whole observation time, where the time-domain signal is significantly attenuated.

\[
e_y = \int |S_y(t)| \, dt, \quad \tau < t < \tau_{\text{max}} \quad \text{J/m}^2
\]  

\( \text{Figure 4} \) Simulation model of an implanted dipole antenna inside chest of a human torso close to the heart; the field observation points for \( E \) and \( H \) are illustrated. (a) 3D-model, (b) Side-view.
where $\tau_p$ and $\tau_{\text{max}}$ constitute the time window of the received signal energy. The time window can be $\sim 3$ ns for the selected channels.

The effect of the nonradiative near-field on the energy density of the implanted antenna, at the depth of $d_0$, is investigated by modeling the distance dependence of the path loss factor. The energy density at the initial observation point (on the body surface) is considered as the reference (thus the propagation loss because of body tissues is compensated). The energy density with normalized distance ($d/d_0 > 1$, outside body) is calculated. Figure 5 shows the normalized energy density with distance and for different implant depths ($d_0 = 35, 45, 55$ mm). For the sake of comparison, the normalized energy density in free-space (without human body) is depicted. We see that as the distance increases the received signal density decreases, where the path loss because of the presence of the human body becomes dominant.

The UWB path loss is modeled with the known distance dependence formulation [12] given as

$$P(d) = n10 \log(d/d_0) + a_0$$  \hspace{1cm} (4)

where $n$ corresponds to the path loss factor and $a_0$ is a power scaling constant. In the free-space, the loss factor $n$ equals 2. A linear regression line can be fitted to the simulated data points using above equation. However, in this case, the accurate method is to use piecewise fitting where the loss factor is different for the shorter distances than the longer.

As shown in Figure 5, for selected simulated models, the energy density reduces as the distance increases. For the antenna in free-space, the simulated energy density reduces with a loss factor $n = 1.8$ as the normalized distance away from the antenna increases. Note that the minimum distance is greater than 35 mm.

**Figure 5** Normalized signal energy density (dB) with normalized distance ($d/d_0$) for the antenna in free-space and the implanted antenna in different depths ($d_0 = 35, 45, 55$ mm)

| TABLE 1 Path Loss Factor ($n$) and Scaling Constant ($a_0$) for Different Implant Antenna Depth ($d_0$) |
|---|---|---|---|---|
| $d_0 = 55$ mm | $1 < d/d_0 < 2.2$ | $2.2 < d/d_0 < 3$ | $3 < d/d_0 < 4.5$ | $4.5 < d/d_0$ |
| $n = 3$ | $n = 4$ | $n = 3$ | $n = 2.5$ | $a_0$ |
| $d_0 = 45$ mm | $1 < d/d_0 < 2.2$ | $2.2 < d/d_0 < 3$ | $3 < d/d_0 < 6$ | $6 < d/d_0$ |
| $n = 5$ | $n = 4$ | $n = 3$ | $n = 2.5$ | $a_0$ |
| $d_0 = 35$ mm | $1 < d/d_0 < 2.2$ | $2 < d/d_0 < 3.5$ | $3.5 < d/d_0 < 6$ | $6 < d/d_0$ |
| $n = 4.5$ | $n = 3.5$ | $n = 3$ | $n = 2.5$ | $a_0$ |

For the antenna implanted inside the human body, different loss factors for different normalized distances are derived. The fitted loss factors ($n$) are tabulated in Table 1. For close distances, the loss factor is as large as $n = 5$. This large loss factor proves the presence of the nonradiative near-field energy at the near region. This energy is concentrated around the body surface and does not propagate. For distances far away from the body ($d/d_0 > 6$), the loss factor approaches to the corresponding loss factor for free-space, $n = 2$.

The loss factor for different implant antenna depths ($d_0$) shows different values, which was also confirmed in Figure 5. The loss factor for deeper implants is more than the loss factor for the superficial implants, thus the energy density rapidly reduces. This shows stronger nonradiative near-field of the deeper implant around the body. Consequently, we propose to use the receiving UWB antenna as close as possible to the body surface to exploit the nonradiative energy to improve the link quality. The more the implant is deeper inside the body, the receiving antenna must be designed and placed closer to the body surface, i.e., the receiving antenna impedance should be satisfied at the near distances of the body.

The improvement of the link quality because of exploiting near-field region can be explained through Figure 5. At far distances (for example: $d/d_0 = 4.5$), an additional loss of 14.5 dB for the superficial implant ($d_0 = 35$ mm) and 18 dB for the deeper implant ($d_0 = 55$ mm) are observed compared with the free-space curve. This loss is related to the nonradiative part of the near-field because the material loss is compensated with the energy normalization at $d_0$. Therefore, the link quality of a UWB communication can be improved with the given factors if the near-field is exploited.

The energy scaling constant, $a_0$, is tabulated in Table 1. As listed, for the deeper implants the initial energy density is less than the superficial implant because of the higher losses in tissues. The comparison of the scaling constant with the related value for the antenna in free-space as listed in Table 2 gives the absorption in the body tissues. For example, the energy loss because of the tissue’s absorption for the implant depth at $d_0 = 55$ mm is 15 dB and for $d_0 = 35$ mm is 9.4 dB.

**5. EFFECTS OF FREQUENCY DISPERSIVE MATERIAL AND SIMULATION VOLUME**

Numerical simulation of antennas operating in high frequency and anatomy model of human body with high resolution requires large computing facility and adequate memory in the computer. It becomes further difficult if the simulation should constitute the entire body. Furthermore, using the nondispersive model for wideband
transmission can reduce the computation time. Here, we assess the effects of the frequency dispersive material and the computation volume on the above simulation results.

The simulation of the implanted antenna at the torso of human voxel model is conducted by considering nondispersive material. The human tissues are loaded with the frequency characteristics at 2450 MHz. The UWB signal energy density with distance is calculated for the implanted antenna at \( d_0 = 45 \text{ mm} \). Figure 6 shows the energy density with normalized distance. As shown, by considering the nondispersive material, the loss factor \((n)\) is slightly increased and the energy density curve with distance is reduced. The scaling factor, \( \alpha_n \), is increased from 13.69 for the dispersive material to 14.15 dB for nondispersive materials. This shows an increase in loss for the model with frequency dispersive material.

The choice of the modeling volume is important and defines the total number of EM cells that affects the simulation time and the memory. To evaluate the volume influence, a smaller part of the human torso is selected. The antenna is located at the same place for the whole torso but the body volume is limited inside the box with \( 5 \times 20 \times 11.2 \text{ cm}^3 \). The frequency dispersive material properties are considered. The energy density with distance is evaluated and the results are shown in Figure 6. The energy density at the normalized distance \( d/d_0 > 1.5 \) is over estimated compared with whole torso. This can be explained as whole torso model has larger energy absorption than a small part of it. This means simulations that require higher accuracy, the entire volume must be considered.

6. CONCLUSIONS

EM simulation of an implanted UWB antenna inside the chest of an anatomical voxel model of the human torso is considered. The signal energy transmission from the antenna to on-body and off-body is assessed at the frequency range of 1–6 GHz, by considering frequency dispersive dielectric material properties. The frequency dispersion model is described in the form of a second-order polynomial. Time-domain solver using FIE code is used and the UWB signal energy density at different distances from the body surface is evaluated. Nonradiative near-field is distinguished as the dominant energy transmission way from the implanted antenna to a receiver outside the body. A high loss factor \((n = 5)\) is measured at close distances to the body. Our results show that by exploiting the nonradiative near-field region of the antenna, we can improve the UWB link quality by 14.5 and 18 dB for an implant depth of 35 and 55 mm, respectively. Furthermore, the calculated energy losses because of the body tissues are 15 and 9.4 dB for an implanted antenna at a depth of 55 and 35 mm, respectively.

The influence of the frequency dispersive materials is evaluated by simulating similar model using nondispersive material at a center frequency, \( f_0 = 2450 \text{ MHz} \). The simulated energy density in distance is under estimated by 1 dB. Furthermore, our simulations for the signal energy density show that high precision results can be obtained if the whole volume of the human torso is considered.

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