A Radio Channel Model for In-body Wireless Communications

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Abstract. Propagation model plays a very important role in designing wireless communication systems. Transmitting and receiving data from/to inside the body from tissue implanted medical devices are of great interest for wireless medical applications due to the promising of different clinical usage to promote a patient healthcare and comfort from one side and the most effective treatment for medical conditions from other side. The number of available electronic implantable devices is increasing every year. The complexity and functionality of these devices are also increasing at a significant rate. Hence, a reliable and efficient communication link is necessary to guarantee the best connection from/to an implanted device. In this paper we present a radio channel model for body implanted device over Medical Implant Communications Service (MICS) band in the frequency range of 402-405 MHz.

Keywords: Implant communication, radio channel model, electromagnetic wave, thermal effect.

1 Introduction

The use of implantable wireless communication device is growing at a remarkable rate, because the Medical Implant Communications Service (MICS) is replacing inductive communication for radio frequency implanted device. Therefore everybody can benefits of the best healthcare service irrespective of their geographic location.

Using MICS, a healthcare provider can set up a wireless link between an implanted device and a base station, allowing physicians to establish high-speed, easy-to-use, reliable, short-range access to the patient health data in real-time. Innovation in wireless communications aligned with the MICS band of frequencies is fueling the growth. The frequency band for MICS operations is 402-405 MHz [1], [2].

The 402-405 MHz band is well suited for in-body communication networks due to its international availability and compatibility with the incumbent users of the band (weather balloons). The maximum permitted output power for MICS devices is 25 μW EIRP (Effective Isotropic Radiated Power). The EIRP for an implanted device is defined as the signal power measured on external surface of human body and not at closed contact to the implanted device [1], [2].

K.S. Nikita et al. (Eds.): MobiHealth 2011, LNICST 83, pp. 88–95, 2012.

The use of implanted medical device is not without many significant challenges, particularly, the increasing of propagation losses in biological tissue. Therefore, to ensure the efficient performance of body implanted wireless communication the channel model need to be characterized and modeled for reliable communication system with respect to environment and antenna.

The paper discusses a radio propagation modeling, their characteristics, and human body as a medium for radio frequency propagation for medical implant communication service. The rest of this paper is as follows. The radio frequency and human body are discussed in section 2. Section 3 will describe the thermal effects of implant device. Then, description of the tissue interface and intrinsic impedance are provided in Section 4. Propagation model is discussed in section 5. Finally discussion and conclusion are expressed in Section 6.

2 Human Body and RF Wave

The human is partially conductive and consists of materials of different dielectric constants, thickness, and characteristic impedance. Therefore depending on the frequency of operation, the human body can lead to high losses caused by power absorption, central frequency shift, and radiation pattern destruction. The absorption effects vary in magnitude with both frequency of applied field and the characteristics of the tissue, which is largely based on water and ionic content. It is very difficult to determine the absorption of electromagnetic power radiated from an implanted source by the human body. Although quite a few investigations have been done to determine the effect of human body on radiated field [3], [4], and almost all of these studies have been based on external sources.

Prior to taking into consideration any in-body data communication, the effect of the human body on the RF signal must be understood. In order to construct a reliable wireless communication link from/to the human body, the electrical properties of the body tissues should be known for the frequency of interest. Table 1 shows the electrical properties of muscle, fat, and skin at frequency of 403.5 MHz [5]-[7]. Where ε is the dielectric constant, σ is the conductivity, δ is the penetration depth.

Table 1. The electrical properties of the body tissues at 403.5 MHz

Tissue	ε	σ[S/m]	δ[m]
Muscle	57.100	0.797	0.052
Fat	5.578	0.041	0.308
Skin	46.706	0.689	0.055

3 Thermal Effects

The Specific Absorption Rate (SAR) is a standard measure of how much power is absorbed in the tissue. It will determine the amount of power lost due to heat dissipation, which depends upon E and H-fields strength.

The electromagnetic coupling into and/or out of the human body usually requires an antenna to transmit a signal into a body or pick up a signal from a body. The antenna operating environment for the implanted antenna is different from the traditional free-space communications, which is lossy environment. The implanted antennas may be classified in to two main groups: Electrical antennas, such as dipole antennas, and Magnetic antenna, for instance loop antennas.

The electrical antenna typically generates large components of E-field normal to the tissues interface, which overheat the fat tissue. This is because boundary conditions require the normal E-field at the interface to be discontinuous by the ratio of the permittivities, and since fat has a lower permittivity than muscle, the E-field in the fat tissue is higher [8].

SAR in the near field of the transmitting antenna depends on the H-field, whereas the SAR in the far field of the transmitting antenna depends mainly on the E-field. An important factor on the absorption characteristics of human body tissue layers is due to standing wave or impedance matching of the tissue types with high and low water content. The reflections of the propagation waves at different tissue layer interfaces, as shown in Fig. 1, can give rise to standing wave effect, which can increase the amount of local SAR.

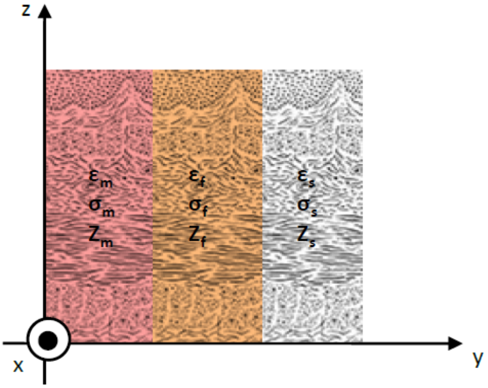

Fig. 1. Model of body tissues; muscle (m), fat (f), and skin (s)

The transmission from an antenna embedded in biological tissue is subject to a number of different electromagnetic phenomena including wavelength shortening due to dielectric loading, reflections from material transitions and absorption losses. The relationship between radiation and SAR is given by

$$\mathrm{SAR} = \frac{\sigma |E|^2}{\rho} \; (\mathrm{W/Kg}) \tag{1}$$

where E is the induced electric field and ρ is the density of tissue. For safety reason, in-body radiation is restricted to certain level. The Federal Communication Commission (FCC) regulations limit the Maximum Permissible Exposure (MPE) to non-ionizing radiation based on the amount of temperature rise that will occur. The regulation limits the temperature rise to 1 degree of Celsius. This limit being is determined by the specific heat of the tissue. The IEEE C95.1 [9] is defined that, the body exposure to radiation from implanted medical device is considered as partial body exposure in an uncontrolled environment. In such a case, the general provisions of the standard should not be violated, which is whole-body averaged SAR during localized exposure. The SAR averaged over the whole body is to be lower than 0.08 W/Kg and the spatial peak value of the SAR averaged over any 1 g of tissue (define as a tissue volume in the shape of cube) is to be less than 1.6 W/Kg. The spatial peak SAR shall not exceed 4 W/Kg over any 10 g of tissue in wrists, ankle, hands and feet. Experiments show exposure to an SAR of 8 W/Kg in any gram of tissue in the head or torso for 15 min may have a significant risk of tissue damage [10].

4 Tissues Interface

The reflections of propagation waves at different tissue layer interfaces can give rise to standing wave effects and impedance matching, which can, lead to local SAR increase. The intrinsic impedance (η) of a dielectric medium can be calculated from the material parameters by [11]:

$$\eta = \frac{\sqrt{\dfrac{\mu}{\varepsilon'}}}{\left[1+\left(\dfrac{\sigma_{\mathrm{eff}}}{\varpi\varepsilon'}\right)^{2}\right]^{1/4}} e^{j(1/2)\tan^{-1}(\sigma_{\mathrm{eff}}/\omega\varepsilon')} \tag{2}$$

where μ is the permeability, σ_{eff} is the effective conductivity, ω is the radian frequency, and $\acute{\varepsilon}$ is the real part of the complex relative permittivity. The intrinsic impedance of human tissues at 403.5 MHz is shown in Table 2 [11].

Table 2. Intrinsic impedance of tissues at 403.5 MHz

Tissue	$\eta(\Omega)$
Muscle	$43.5 \angle 13.0^{\circ}$
Fat	$105.4 \angle 14.1^{\circ}$
Skin	$47.7 \angle 14.4^{\circ}$

Each tissue has own electrical properties which is different from other tissue. Therefore, there will be reflections of the propagation waves at different tissues layer interfaces. When a plane wave traveling in medium 1 strike a medium 2, the fraction that is reflected is given by the reflection coefficient (Γ), and the fraction is transmitted into medium 2 is given by the transmission coefficient (τ). A simplified model to compute the reflection and transmission coefficients are shown in Fig. 2.

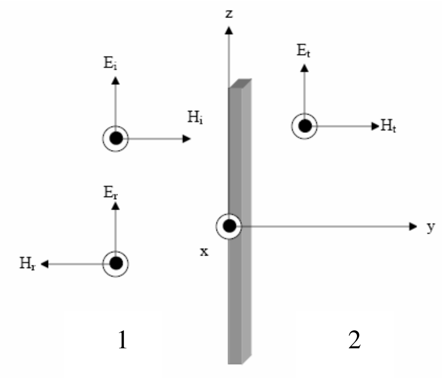

Fig. 2. Simple model to represent the reflection and transmission power by a planer interface

The reflection coefficient (Γ) and transmission coefficient (τ) at the interface are determined by [12]:

$$\Gamma = \frac{E_r}{E_i} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{3}$$

$$\tau = \frac{E_t}{E_i} = \frac{2\eta_2}{\eta_2 + \eta_1} \tag{4}$$

where E_i, E_r, and E_t are incident, reflected, and transmitted waves correspondingly. The reflection coefficient of field and power transmission factor at tissue boundaries at 403 MHz is shown in Table 3 [11].

Table 3. Field reflection coefficient and power transmission factor at tissue boundaries

Interface	Γ	τ (%)
Muscle to Fat	0.41	83.2
Fat to Skin	0.37	86.3
Skin to Air	0.78	39.2

5 Propagation Model

Optimization of the link efficiency and path loss must be quantified for expected radiation performance and link budget calculation due to effect of body tissues on output power and radiation pattern. The output power and radiation pattern are frequency dependent and strongly influenced by the electrical properties of the surrounding tissues. The foundation of any link budget is the Friis transmission equation

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^n \tag{5}$$

where P_r is the received power to the receive antenna, P_t is the transmitted power, G_t and G_r are gains of the transmit and receive antennas respectively, λ is the signal's wavelength, and r is the distance between two antennas.

To model the path loss of an implanted device, the field exited by an antenna can be expressed in terms of reactive wave and propagating wave with E-polarization or H-polarization with respect to the antenna type and body coordinates. This will considers both the near-field of the antenna, where reactive waves will be dominant, and the far-field of the antenna, which are determined by the propagating wave. Therefore the propagation loss between the transmitting and the receiving antenna, where one of them at least is placed inside a human body, as a function of frequency and distance, is dependent to: thermal attenuation due to conductivity, reflection losses at tissue boundaries, near-field losses and, far-field losses.

By determining the average SAR over the entire mass of the tissue between the transmitter and the receiver for near-field and far-field regions, we are able to compute the total power lost for human body part.

5.1 Near-Field

Kuster *et.al* shown in [13] that, SAR in the near-field is proportional to the square of H-field. Also they have shown the peak SAR is related to the antenna current, not to the input power. The SAR in the near field is

$$\mathrm{SAR} = \frac{\sigma}{\rho} \frac{\mu\omega}{\sqrt{\sigma^2 + \varepsilon^2\omega^2}} \left(\frac{Idl \sin\theta}{4\pi} e^{-\alpha R} \left(\frac{1}{R^2} + \frac{|\gamma|}{R} \right) \right)^2 \tag{6}$$

where I is current and R is distance. The power absorbed in the infinitely small volume is $\Delta P = \mathrm{SAR} \times \Delta\mathrm{mass} = \mathrm{SAR} \times \rho \times dV$ where dV is $dV = R^2 \sin\theta dR d\theta d\phi$ The powered absorbed in the near-field (P_{nf}) is

$$P_{nf} = \int_{R=r}^{d_0} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \Delta P = \frac{\sigma}{\rho} \frac{\mu\omega}{\sqrt{\sigma^2 + \varepsilon^2\omega^2}} \left(\frac{Idl \sin\theta}{4\pi} \right)^2 \times \int_{R=r}^{d_0} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} R^2 \sin^3\theta \times e^{-2\alpha R} \left(\frac{1}{R^4} + \frac{|\gamma|^2}{R^2} + \frac{2|\gamma|}{R^3} \right) dR d\theta d\phi \tag{7}$$

5.2 Far-Field

The SAR in the far field of the transmitting antenna depends mainly on the *E*-field.

$$\mathrm{SAR} = \frac{\sigma}{\rho} E_{rms}^2 = \frac{\sigma}{\rho} \left(|\eta||\gamma| \frac{Idl \sin\theta}{4\pi R} e^{-\alpha R} \right)^2 \tag{8}$$

The power absorbed in the infinitely small volume is $\Delta P = \sigma \left(|\eta||\gamma| \frac{Idl}{4\pi} \right)^2 \sin^3\theta e^{-2\alpha R} dR d\theta d\phi$
The powered absorbed in the far-field (P_{ff}) is

$$P_{ff} = \int_{R=d_0}^{d_0} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \Delta P = \sigma |\eta|^2 |\gamma|^2 \frac{I^2 dl^2}{12\pi\alpha} \left(e^{-2\alpha d_0} - e^{-2\alpha d} \right) \tag{9}$$

5.3 Received Power

From (7) and (9), the total power loss in tissue (P_{tl}) is $P_{tl} = P_{nf} + P_{ff}$. Hence the received power is

$$P_r = \frac{(P_t - P_{tl})\lambda_m^{\ 2}}{(4\pi d)^2} G_t G_r \tag{11}$$

where λ_m is the wavelength in the biological tissue.

If one of the device is placed in free space and communicating with implanted one, path loss of free space should be counted for received power. In this case the total power loss is $P_{TI} = P_{tl} + P_{fl}$, where the P_{TI} is the total power loss and P_{fl} is the loss in free space.

6 Discussions and Conclusion

The path loss analysis at 403 MHz between two devices where one of them is placed outside the body at distance of 2 m from the body surface, while other one is implanted to the muscle tissue at 3cm deep inside the body is shown in Fig. 3.

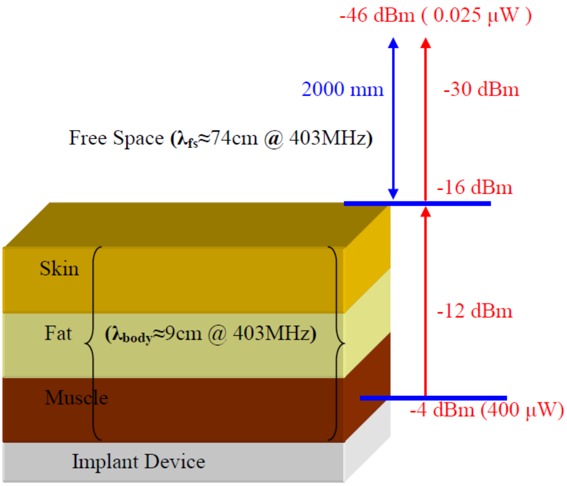

Fig. 3. Path Loss at 403 MHz

The paper presented a possible channel model for in-body communication. The study confirmed the importance of near-field and far-filed attenuation, which can affect not only radiation inside the body but can also determine the optimum distance of which good performance can be achieved in the surrounding environment.

The MICS technology delivers mobility, comfort, and higher levels of patient care. As designers develop new implanted medical devices taking advantage of RF technology to improve the quality of care for patients, propagation model is a key to this new system. Although the propagation models and RF system design is well understood for today's telecommunication systems, their application in medical systems offer unique challenges. A channel model performance assessment for implant device is more complex than for models in the free space, due to the conductivity and permittivity of an environment surrounded the implanted device.

The challenge in understanding of body implanted device is to make a propagation model in the environment which is extremely different from free space.

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