In-body Path Loss Model for Homogeneous Human Muscle, Brain, Fat and Skin

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***Abstract*—In this paper, we study the wave propagation within various lossy homogeneous human tissues such as the muscle tissue, brain, skin, and the fat layer at 2.4 GHz using insulated dipole antennas. Path loss (PL) in these tissues is determined by means of measurements and simulations, based on which suitable path loss models are proposed. By understanding the path loss within the human body one can establish optimal communication between the antennas embedded within it. We further investigate the influence of the insulation thickness of the insulated dipoles on the antenna resonance frequency.**

I. Introduction

A Wireless Body Area Network (WBAN) consists of a wireless network with devices placed close to, attached on or implanted into the human body. Wireless communication within human body experiences loss in the form of attenuation and absorption. A path loss model is necessary to understand these losses. This paper proposes an in-body path loss model for $insulated\ dipole\ antennas$ for different homogeneous human tissues (muscle tissue, brain, skin and the fat layer) at 2.45 GHz with application to implants in a human body. The model is validated for muscle tissue by both measurements and 3D electromagnetic simulations. Simulation are performed for brain, skin and fat layer at 2.45 GHz and the influence of the dielectric properties on path loss is investigated. This model is valid for insulated dipole antennas up to a distance of 8 cm. Finally, the influence of the thickness of insulation of the insulated dipoles on the antenna resonance frequency is investigated in muscle tissue and fat layer.

II. Setup and configuration

We first investigate wave propagation at 2.457 GHz in human muscle tissue (relative permittivity $\epsilon_r = 50.8$ and conductivity $\sigma = 2.01$ [1]) using the insulated dipoles with simulations and measurements. In order to carry out measurements we use a homogeneous medium representing human muscle tissue. Next, we validate the measurements by performing simulations. Simulations are carried out for human muscle tissue and also for brain, skin and fat layer. We select insulated dipoles for our study instead of bare dipoles because the insulation prevents the leakage of conducting charges from the dipole and reduces the sensitivity of the entire distribution of current to the electrical properties of the ambient medium. This property makes insulated dipoles valuable for communication [2], [3]. We design two identical insulated dipoles where the dipole arms are perfect electric conductors (PEC) surrounded with an insulation made of polytetrafluoroethylene ($\epsilon_r = 2.07$ and $\sigma = 0$ S/m). At a length, ℓ_1 = 3.9 cm resonance is obtained for the frequency of 2.457 GHz. The resonance appears when the antenna is equal to half wavelength in a homogeneous medium equivalent to the combination of the insulation and the muscle tissue medium. Hence λ_{res} = 7.8 cm for muscle tissue (where λ_{res} is the wavelength at which resonance occurs) and we can derive the equivalent permittivity $\epsilon_{r,equiv} = 2.45$ which is closer to the permittivity of the insulation than to the muscle tissue. The dipole arms have a diameter t_1 = 1 mm with the overall thickness of the insulation t_2 = 5 mm. Using these same dimensions we carry out all the simulations.

A. Measurements

Measurements are executed using a vector network analyzer NWA (Rohde and Schwarz ZVR) to determine the scattering parameters $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ (with respect to 50Ω) between transmitter (Tx) and receiver (Rx) for the different separations. We measure path loss which is calculated from $|S_{21}|_{dB}$. The two insulated dipoles are immersed in the muscle tissue medium and placed parallel and lined up for maximal power transfer at 5 cm above the bottom of the flat phantom. The flat phantom represents the trunk of a human body and is recommended by CENELEC standard EN50383 [4] (dimensions 80x50x20 cm3). It is filled with muscle tissue simulating fluid (relative permittivity $\epsilon_r = 50.8$ and conductivity $\sigma = 2.01$ S/m at 2.45 GHz). A robot (3D-positioning Phytron IXEα-C-T) with an accuracy of 0.025 mm is used to position the Tx and the Rx in the human muscle tissue simulating fluid. The Tx is fixed inside the fluid and the Rx is moved by means of the robot arm. The measurements are performed at every 2 mm starting from 6 mm up to 8 cm. We start from 6 mm as this is the closest distance at which we could place both the antennas using the robotic arm.

B. Simulations for different tissues

Simulations are performed using FEKO (EMSS, South Africa), a Method of Moments (MoM) program. For the simulations the flat phantom is modeled according to [4]. Simulations in FEKO also use the exact dimensions of the insulated dipoles placed in different tissues. For accurate modeling in the MoM tool, segmentation rules are adhered (segment length = λ_{res}/12, edge length = λ_{res}/12). The simulations uses a voltage source. Simulations are carried out

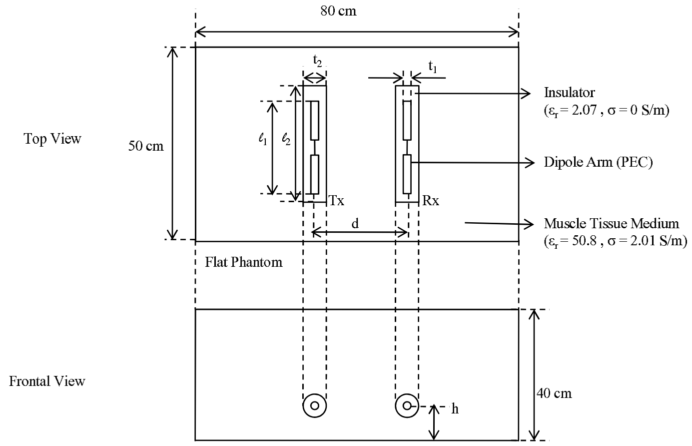

Fig. 1. Setup and configuration

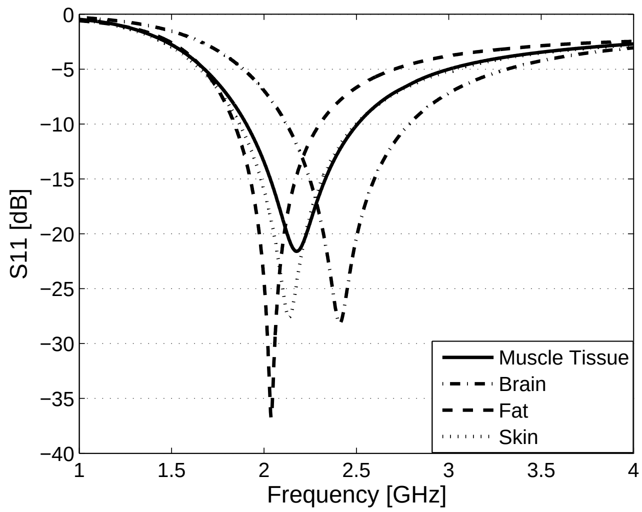

Fig. 2. Return loss for a insulated dipole in different tissues.

starting at d = 6 mm from the transmitting antenna up to a distance of 8 cm. The dielectric parameters of the tissues are provided in Table. I.

TABLE I
DIELECTRIC PROPERTIES OF THE TISSUES

Tissues	ϵ_r**[F/m]**	σ [S/m]
Brain [5]	42.53	1.51
Fat [5]	5.28	0.10
Muscle [1]	50.8	2.01
Skin [5]	38	1.46

III. RESULTS

A. Return loss for a single insulated dipole

Good agreement is obtained between the measured and the simulated insulated dipoles. The simulated and the measured dipoles are efficient radiators in a human muscle tissue as the $|S_{11}|_{\mathrm{dB}}$ is below -10 dB for 2.457 GHz. The $|S_{11}|_{\mathrm{dB}}$ for the insulated dipoles at 2.457 GHz is -13.60 dB and -11.25 dB for the measurements and MoM tool, respectively. Fig. 2 compares $|S_{11}|_{\mathrm{dB}}$ as a function of frequency obtained by simulations for brain, fat, muscle tissue, and skin. The $|S_{11}|_{\mathrm{dB}}$ for the brain, skin, muscle tissue, and the fat layer are -25.09, -10.96, -11.25 and -7.36 respectively at 2.457 GHz. Fig. 2 shows a shift in the resonance frequency in each of the human tissues. The antenna is constructed with respect to the muscle tissue (Section II), however when placed in a different human tissue the input impedance of the antenna changes, which leads to change in the resonance frequency. Even though the physical structure of the antenna remains the same for each tissue, the effective permittivity and thus the wavelength changes and hence the variation in $|S_{11}|_{\mathrm{dB}}$ [3].

B. Path Loss for muscle tissue: Measurement vs. Simulations

The PL is defined as $1/|S_{21}|^2$ with respect to 50 Ω when the generator at the Tx has an output impedance of 50 Ω and the Rx is terminated with 50 Ω, this allows us to regard the setup as a two-port circuit for which we determine $|S_{21}|_{\mathrm{dB}}$ with reference impedances of 50 Ω at both ports:

$$PL|_{\mathrm{dB}} = (P_{in}/P_{rec}) = -10\ \log_{10}|S_{21}|^2 = -|S_{21}|_{\mathrm{dB}} \quad (1)$$

where P_{in} is the input power at port 1 and P_{rec} corresponds to power received at port 2 in a two-port setup. Fig. 3 shows the simulated and measured path loss in human muscle tissue as a function of distance d for the insulated dipole. The measured and the simulated values show excellent agreement up to 8 cm. The deviations between the measurements and the simulations of the human muscle tisse are very low with the maximal and average deviation are 3.4 dB and 1.3 dB, respectively. The path loss increases with respect to distance and high path losses are obtained in human muscle tissue.

C. Path Loss

1) PL for different tissues: Fig. 3 compares the PL for the various tissues. The PL for the muscle is the highest, followed by the PL of the skin and brain and the PL of the fat layer is the lowest. The reason will be explained in the next Section III-C2.

2) PL Model for various tissues: In this section we use the simulation results to develop a PL model as a function of distance in brain, muscle tissue, skin and fat at 2.457 GHz. The simulation and the fitted model in the tissues are shown in Fig. 4. The path loss is modeled as follows:

$$PL|_{\mathrm{dB}} = (10\ \log_{10} e^2)\ \alpha_1\ d + C_1|_{\mathrm{dB}} \qquad for\ d \leq d_{bp} \quad (2)$$

$$PL|_{\mathrm{dB}} = (10\ \log_{10} e^2)\ \alpha_2\ d + C_2|_{\mathrm{dB}} \qquad for\ d \geq d_{bp} \quad (3)$$

where the parameters α_1 and α_2 are the attenuation constants $[\frac{1}{cm}]$, $C_1|_{\mathrm{dB}}$ and $C_2|_{\mathrm{dB}}$ are constants, d_{bp} is the breakpoint where the coupling between the transmitter and the receiver ends and is 3 cm, 2.4 cm, 2 cm, and 2.4 cm for muscle tissue, brain, skin and fat layer respectively. d is in cm. $(10\ \log_{10} e^2)$ equals 8.68 dB and is shown here to express the exponential behaviour of the PL. Since the fields behave in an exponential

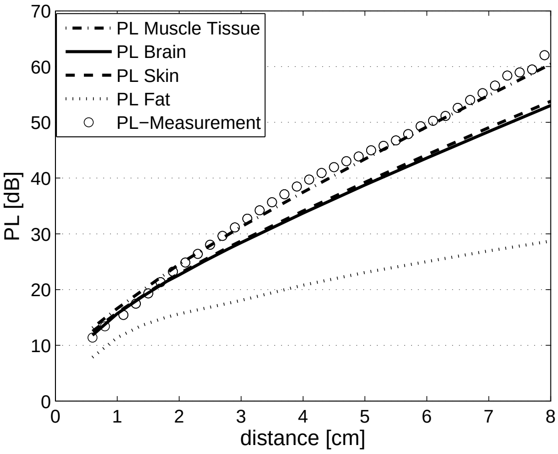

Fig. 3. PL of insulated dipoles in muscle, brain, fat, and skin tissues.

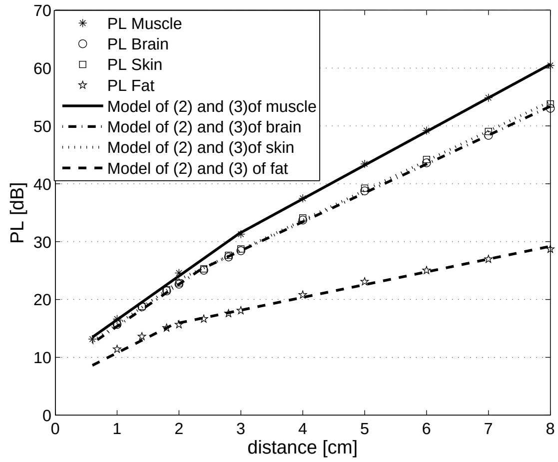

Fig. 4. PL model in brain, muscle tissue, skin and fat.

manner in the medium, the trend of the PL in Fig. 4 shows an exponential behaviour in accordance to the equations (2) and (3).

The model consists of two regions : *Region 1* and *Region 2*. We define here the *Region 1* $d \leq d_{bp}$ as the region which is very close to the Tx dipole and extends from 0 cm to d_{bp}. In this region a coupling appears between the Tx and the Rx. In *Region 2* $d \geq d_{bp}$ the coupling between the Tx and the Rx disappears. The parameters α_1 and α_2 are the attenuation constants of *Region 1* and *Region 2*, respectively.

The parameter values in the equations (2) and (3) are obtained by using a least square-error method and are shown in Table II along with the standard deviation σ, maximum deviation(dev_{max} [dB]) and the average deviation (dev_{avg} [dB]) between the simulated and the fitted models. α_1 in *Region 1* is higher than α_2 due the Tx and Rx being close to each other, hence α_1 depends on both the Tx and the Rx as well as the dielectric properties of the human tissues and of the insulation. α_2 is lower in *Region 2* and depends on

Parameter	α_i	C_i	σ_i	dev_{imax}	dev_{iavg}
Unit	$[1/cm]$	[dB]	[dB]	[dB]	[dB]
$Model\ of\ (2)\ Muscle$	0.87	8.93	0.16	0.52	0.32
$Model\ of\ (3)\ Muscle$	0.67	14.10	0.09	0.28	0.17
$Model\ of\ (2)\ Brain$	0.83	8.06	0.21	0.61	0.36
$Model\ of\ (3)\ Brain$	0.57	13.45	0.15	0.38	0.21
$Model\ of\ (2)\ Skin$	0.85	8.30	0.06	0.20	0.16
$Model\ of\ (3)\ Skin$	0.59	13.15	0.18	0.56	0.28
$Model\ of\ (2)\ Fat$	0.62	5.35	0.28	0.73	0.51
$Model\ of\ (3)\ Fat$	0.25	11.50	0.18	0.50	0.26

TABLE II
PARAMETER VALUES AND STANDARD DEVIATIONS OF THE FITTED MODELS FOR PL_{dB} USING FDTD SIMULATIONS IN HUMAN MUSCLE, BRAIN, SKIN AND FAT (i=1,2).

the dielectric properties of the human tissues. The parameters $C_1|_{\mathrm{dB}}$ and $C_2|_{\mathrm{dB}}$ are constants and depend on the dielectric properties of the medium and insulation. The values of α_1 and α_2 in Table II are highest for the muscle tissue and lowest for the fat layer. This can be explained as follows. From plane waves we have [6]:

$$\alpha = \omega \left[\left(\frac{\mu\epsilon}{2} \right) \left(\sqrt{(1 + \frac{\sigma^2}{\epsilon^2\omega^2}} - 1 \right) \right]^{1/2} \qquad \left[\frac{Nep}{m} \right] \quad (4)$$

where α = attenuation constant, $\omega = 2{\cdot}\pi{\cdot}f$ = angular frequency [rad/sec], f= frequency = 2.45 GHz, μ = permeability of the lossy medium, ϵ = $\epsilon_r\epsilon_0$, ϵ_r= permittivity of the lossy medium, σ = conductivity of the lossy medium [S/m]. Thus, the attenuation constant depends on the dielectric properties of the medium. The attenuation constant α_2 of the muscle tissue is higher than the other tissues as the σ of the muscle tissue is much higher than the σ of the other tissues. The explanation (Section III-C1) of the PL being the highest in muscle tissue and lowest in fat layer is as follows. Equations (2) and (3) show that PL is dependent on the attenuation constant, α. Since the α for muscle tissue is the highest (Table II) than the other tissues the PL in muscle tissue is maximal. The σ of both the skin and the brain are very close to each other hence here ϵ_r is the deciding factor. The PL in skin is somewhat higher than PL in brain as the α for the skin is slightly higher than that of the brain, PL for the fat layer is the least as α is the lowest for fat layer.

The low values of the maximum deviations (Table II) of 0.52 dB and 0.28 dB for muscle tissue, 0.61 dB and 0.38 dB for brain, 0.20 dB and 0.56 dB for skin and 0.39 dB and 0.50 dB for fat suggest excellent agreement between the FDTD simulations and the derived models.

D. Influence of thickness of insulation of muscle tissue and fat layer on the resonance frequency

In this section the influence of the insulation thickness t_2t on the resonance frequency, f_{res} is studied in muscle tissue and fat layer. We define f_{res} as the frequency where the imaginary part of the input impedance is zero. Fig. 5 shows that increase in thickness of the insulation causes f_{res} to increase. Hence the length of the insulated antenna as well as the thickness of

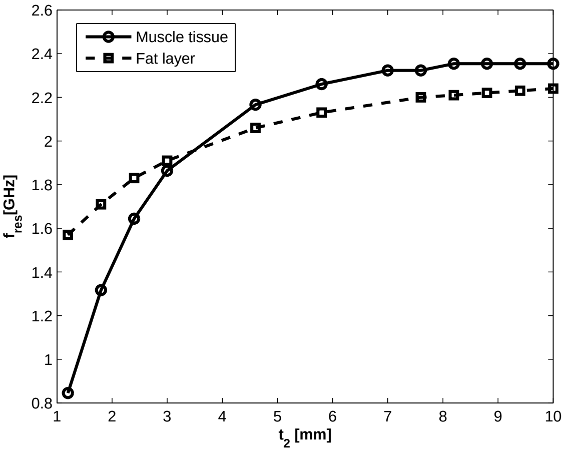

Fig. 5. Resonance frequency vs. insulation thickness.

the insulation has an effect on f_{res} of the antenna. In muscle tissue and fat layer the insulation thickness of 1.8 mm causes the antenna to resonate at frequency of 1.31 GHz and 1.71 GHz respectively. The f_{res} at 1.8 mm for muscle tissue is lower than the fat layer as the ϵ_r for the muscle tissue is higher than the ϵ_r of fat layer. As t_2 increases the $\epsilon_{r,equiv}$ (i.e., equivalent permittivity) of the insulation and the medium reduces and the $\epsilon_{r,equiv}$ will become closer to the value of the permittivity of the insulator. Thus as t_2 increases $\epsilon_{r,equiv}$ decreases and the resonance frequency increases which can be seen in Fig. 5. From a certain thickness of insulation on, f_{res} reaches more or less a constant value: e.g., in muscle tissue from a thickness of the insulation of 7 mm it is observed that the resonance frequency does not change anymore. In order to achieve a certain resonance frequency for the antenna varying the insulation thickness can thus be considered as an option.

E. Conclusion

The PL is investigated in various tissues using measurements and simulations and a PL model is proposed. The measurement and simulations of the muscle tissue show excellent agreement. Low deviations are observed between the PL simulated in various human tissues and the fitted models. PL in muscle is the highest while PL in fat layer is the lowest as the attenuation constant in muscle is the highest and in fat layer is the lowest. Thus PL depends on the dielectric properties of the medium. The insulation thickness vs. resonance frequency is studied and the insulation thickness can be considered as a parameter to achieve certain resonance frequency.

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