Antenna Independent Path Loss Model for In-Body Communication in Homogeneous Tissue

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Abstract—In this paper we propose for the first time an in-body path loss model for homogeneous human muscle tissue that is independent of the antennas for in-body communication at 2.45 GHz. The path loss model obtained can be used to design in-body communication systems at 2.45 GHz.

I. INTRODUCTION

A wireless body area network (WBAN) consists of nodes that communicate wirelessly and are located on or in the body of a person. A good understanding of propagation loss within human body is required for the development of WBAN for implants within human body. The human body is a lossy medium hence a considerable attenuation of the waves traveling from the transmitter (Tx) to the receiver (Rx) takes place. By understanding the path loss (PL) within human body optimum communication can be established between the nodes placed within the body. In literature various PL models have been proposed for in-body propagation but they do not extract the gain of the antenna and are thus antenna dependent [1]. In this paper, we develop an in-body PL independent of the antenna by extracting the antenna gains from the PL for two different types of antennas within homogeneous lossy human muscle tissue.

II. METHOD

Wave propagation is investigated in human muscle tissue (relative permittivity $\epsilon_r = 50.8$ and conductivity $\sigma = 2.01$ S/m [2]) using two pairs of insulated antennas at 2.45 GHz. Insulated antennas are selected instead of bare antennas because the insulated antenna prevents the leakage of conducting charges from the antenna and also reduces the sensitivity of the entire distribution of current to the electrical properties of the ambient medium. This property makes insulated antennas valuable for in-body communication [3].

The first pair of antennas consist of two identical insulated dipoles where the dipole arms are perfect electric conductors (PEC) surrounded by an insulation made of polytetrafluoroethylene (PTFE) ($\epsilon_r = 2.07$ and $\sigma = 0$ S/m). The length of the dipole arms is chosen to be $\ell_1 = 3.9$ cm (henceforth addressed as $antenna_{(\lambda/2)}$) such that the antenna resonates at 2.45 GHz. The resonance appears when the antenna is equal to half the wavelength in a homogeneous medium equivalent to the combination of the insulation and the muscle tissue medium. Hence, $\lambda_{res} = 7.8$ cm (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.

The second pair of antennas are also dipole antennas insulated with the same insulation of PTFE. The length of the dipole arms $\ell_2 = 7.8$ cm (henceforth addressed as $antenna_{(\lambda)}$).

A. Simulation

Simulations are carried out for the setup of the insulated antennas in human muscle tissue medium for a separation of 30 cm between the Tx and the Rx using FEKO, a method of moments (MoM) program. For accurate modelling in the MoM tool, segmentation rules are adhered (segment length = $\lambda_{res}/12$, edge length = $\lambda_{res}/12$). The source used is a current source.

III. RESULTS

A. Gain of the antenna in conductive medium

The gain of the antenna in free space is defined as the ratio of radiation intensity in a particular direction to the radiation intensity of an isotropic antenna [4]. However, the radiation intensity becomes distance dependent in a conducting medium. To make the antenna gain distance independent in a conducting medium, it can be expressed as follows [4]:

$$G = \left(4\pi R g^2\right)/R_r \qquad (1)$$

where, G is the gain of the antenna in the conductive medium and g is a function involving the parameters of the medium, R is the intrinsic resistance and is equal to $\sqrt{\omega\mu/2\sigma}$ and R_r is the radiation resistance. Also, $\omega = 2\cdot\pi\cdot f$ = angular frequency [rad/sec], f = frequency = 2.45 GHz, μ = permeability of the lossy medium, and σ = conductivity of the lossy medium [S/m].

Further, g is defined [4] as follows:

$$g = (|H|d\ e^{d/\delta})/I_i \qquad (2)$$

where, $|H|$ is the magnitude of the magnetic field in [A/m] taken in the maximum field direction of the antenna under consideration at distance d, δ is the skin depth in [m], I_i is the input current in [A] and d is the distance in [m].
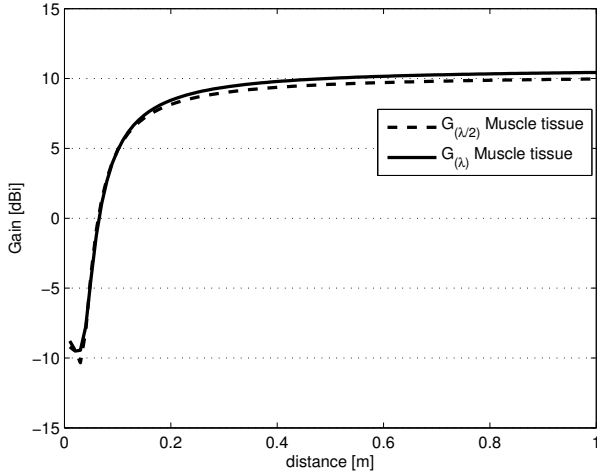
Fig. 1. Gain of the insulated dipole antennas in muscle tissue.

1) Gain of $antenna_{(\lambda/2)}$ and $antenna_{(\lambda)}$ in muscle tissue: The gain of the $antenna_{(\lambda/2)}$ and $antenna_{(\lambda)}$, henceforth referred to as $G_{(\lambda/2)}$ and $G_{(\lambda)}$ respectively, in the muscle tissue is obtained using (1) and is shown in Fig. 1. $G_{(\lambda)}$ and $G_{(\lambda/2)}$ are 10.7 dBi and 8.7 dBi in the muscle tissue, repectively. The values of the gain selected are the asymptotic values obtained at large distance where it is more or less constant. Fig. 1 shows that $G_{(\lambda/2)}$ and $G_{(\lambda)}$ are independent of distance after 80 cm. $|H|$ is obtained from the simulations, $I_i = 1$ A, δ is 7.2 mm.

B. Path Loss

PL between a pair of antennas is the ratio of transmitted power to the received power in decibels [5]:

$$PL|_{dB} = 10 \cdot \log(P_T G_T G_R / P_R L_T L_R) , \qquad (3)$$

where P_T = transmit power , P_R = received power, G_T = transmitter antenna gain, G_R = receiver antenna gain, L_T = feeder loss at transmitter, L_R = feeder loss at receiver. (3) can be written as follows when $L_T = L_R = 0$:

$$PL_{excl}|_{dB} = -|S_{21}|_{dB} + G_T|_{dBi} + G_R|_{dBi} , \qquad (4)$$

where, $|S_{21}|_{dB}$ is the forward transmission coefficient. Current literature [1] defines the in-body path loss (PL_{incl}), which includes the gain and is thus antenna dependent, 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 to regard the setup as a two-port circuit for which we determine $|S_{21}|_{dB}$ with reference impedances of 50 Ω at both ports. PL_{incl} is defined as follows:

$$PL_{incl}|_{dB} = (P_T/P_R) = -10 \log_{10}|S_{21}|^2 = -|S_{21}|_{dB} , \qquad (5)$$

where, P_T = input power at port 1 and P_R = power received at port 2 in a two-port setup.

PL_{excl} is now defined as the actual PL, i.e. excluding the gains and thus antennas independent [5]. The Tx and the Rx

here are identical (Section II) hence the gain of the Tx and Rx are the same. PL_{excl} is then calculated as follows from (4):

$$PL_{excl}|_{dB} = PL_{incl}|_{dB} + 2G_{dBi}, \qquad (6)$$

where G is the gain of the Tx and Rx antenna in dBi in the conductive medium according to (1).

Fig. 2 shows clearly that the PL_{excl} for both the antennas agree well thus showing that an antenna independent PL model can be developed by determining the gain of the antenna. The gain obtained at larger separation i.e., 26 cm (Fig. 1, Section. III-A) is excluded from the path loss using (6). By excluding the gain, PL becomes antenna independent: mean deviation between PL_{excl} of $antenna_{(\lambda)}$ and PL_{excl} of $antenna_{(\lambda/2)}$ is only 1.53 dB. Figs. 2 clearly shows that PL_{incl} as used previously in literature, is antenna dependent with deviations up to 7-8 dB in the muscle tissue. The deviation in PL_{excl} between $antenna_{(\lambda/2)}$ and $antenna_{(\lambda)}$ exists only up to a certain distance (around 26 cm) after which the PL merges because of the gain application at larger distance. We show here that using (1) and (6) we are able to define PL as it should be, namely antenna independent.
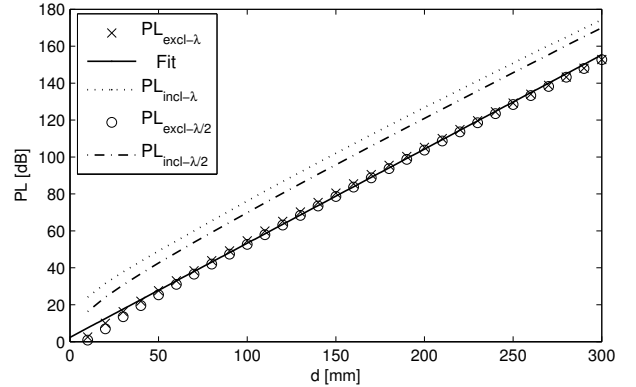

Fig. 2. PL of the insulated dipole including and excluding the gain in muscle tissue.

C. Model for PL

In this section, we propose a generalized model based on the simulation results for both the antennas in muscle tissue. The PL model as a function of distance in human muscle at 2.45 GHz is as follows:

$$PL_{excl}|_{dB} \equiv PL|_{dB} = (10 \log_{10} e^2) \, \alpha \, d + C|_{dB} \qquad (7)$$

where the parameters α is the attenuation constant [$\frac{1}{cm}$], $C|_{dB}$ is the constant, and d is in cm. $(10 \log_{10} e^2)$ equals 8.68 dB and shows the exponential behaviour of the PL. The parameter values for antenna independent PL are $\alpha = 0.58$ [$\frac{1}{cm}$] and $C|_{dB} = 1$ and are obtained by using a least square-error method. The attenuation constant obtained for the muscle tissue agrees well with the attenuation constant for plane wave which is 0.52 [$\frac{1}{cm}$]. In Figs 2 the PL_{excl} in muscle tissue (for

$antenna_{(\lambda/2)}$ and $antenna_{(\lambda)}$) are fitted to the PL model of (7) with a mean deviation lower than 1.5 dB. Thus, the proposed PL model is an excellent fit and can be used for any antenna in link budget calculations by introducing the antenna gain in tissue.

D. Conclusions

The path loss between different types of insulated dipole antennas is investigated at 2.45 GHz in homogeneous human muscle tissue and for the first time an in-body path loss model independent of the antennas is derived by excluding the gain of the antennas. The PL model can thus be used to design any in-body communication system in muscle tissue and head tissue.

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