Analysis of Magnetically-Coupled Human Body Communications

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Abstract: In this paper magnetically-coupled human body communications (MHBC) is investigated. In human body communications (HBC) the human body is the transmission medium through which wireless sensors and actuators in, on or in close proximity to the human body exchange information. MHBC, unlike the more common galvanic and capacitive coupled HBC, is less affected by the proximity to the surrounding environment, with the exception of materials with high permeability. Therefore, MHBC offers tremendous potential for the implementation of personalised healthcare systems. In this work MHBC is investigated using finite element analysis through COMSOL. A communications scenario involving the human arm is explored for investigating transmission parameters. COMSOL simulation results demonstrate the MHBC technique and highlight the importance of finite element analysis as a powerful tool for investigating the performance of MHBC systems.

Keywords: Body area networks, human body communications, magnetic coupling

1. Introduction

Human body communications (HBC) uses the human body as a transmission medium to connect sensors and actuators in, on or in close proximity to the human body. The HBC approach offers tremendous potential for the design and implementation of emerging personalized healthcare systems, as well as security, and multimedia communications applications [1]. Currently two HBC mechanisms have been extensively explored and are included in HBC standardization initiatives: galvanic and capacitive coupled HBC which rely upon quasi-static electric field mechanisms to enable information transmission using low-power, low-frequency voltages and currents in the human body [2]. However the performance of galvanic and capacitive coupled HBC systems depends upon the surrounding environment. The quasi-static electric field mechanisms, can arbitrarily change the transfer function of the communications channel in many scenarios such as when in close proximity to metallic objects [3].

Magnetically-coupled HBC (MHBC) was proposed in response to challenges of this changing transfer function when using the galvanic and capacitive HBC mechanisms [3, 4]. The magnetic permeability of most surrounding materials, like that of the human body is roughly the same, provided the materials are not highly permeable. Thus, unlike the electric-field based approach used by capacitive and galvanic human body communications mechanisms, the magnetic field is less likely to be affected by the proximity of conductors in the environment, provided they are not materials with high permeability. Thus, in MHBC the communication quality is less affected by the proximity to the surrounding environment, particularly at low frequencies, under the material constraint.

However, the performance of the magnetic coupling mechanism relies upon effective coupling, in which the human body acts as one part of the magnetic loop. Therefore effective system analysis and design would rely heavily upon the investigation and characterization of transmission parameters for scenarios which leverage MHBC. There is still much work to be done to characterize the influence of magnetic coupling parameters including electrode configurations, human tissues and the surrounding environment.

In this work, MHBC is explored using 3D finite element analysis through COMSOL. Various communication scenarios using the human arm are investigated. COMSOL simulation results demonstrate the MHBC technique and highlight the importance of finite element analysis as a powerful tool for performance analysis and design of MHBC systems.

2. Magnetically-coupled Human Body Communications

Figure 1 illustrates the MHBC mechanism. The transmitter outputs an alternating current, I_{Tx}, into the transmitting coil. The resulting current density, $J(t)$, generates a quasi-static magnetic field according to,

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A(t)\right) = \left(J(t) + \frac{\epsilon}{\sigma} \frac{\partial J(t)}{\partial t}\right) \quad (1)$$

which in turn couples to the loop created in part by the conductive human body and in part by the receiver terminals. This induces a received current, I_{Rx}, which is then processed by the receiver device.

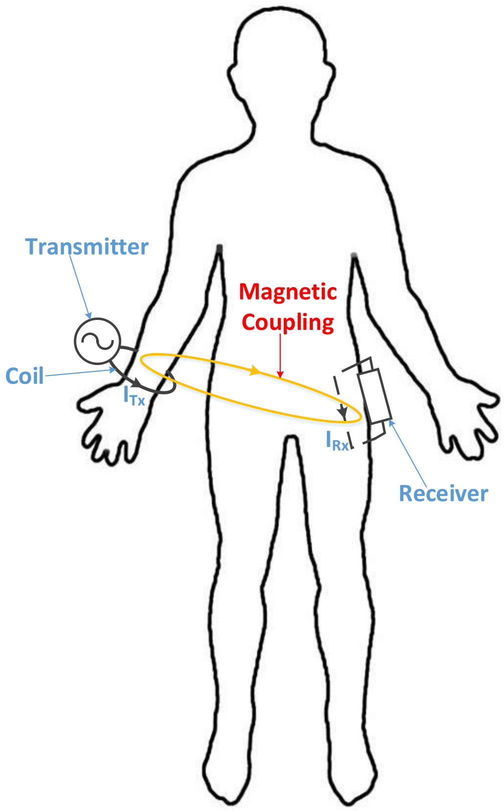

Figure 1. Magnetic human body communications scenario

The interactions can be analysed using the equivalent circuit model [3, 4] in Figure 2. The transmitter is modelled as a voltage source in series with resistance R_{Tx} and the self-inductance of the transmitter coil, L_0. The body channel is modelled by a resistance, R_B, in series with effective loop inductance, L_1. L_1 models the effective loop of the conductive body and receiver's conductive line. M models the mutual inductance between the transmitter coil and effective loop of the receiver:

$$M = \alpha\sqrt{L_0 L_1} \quad (2)$$

where $0 \le \alpha \le 1$. The receiver terminals also model capacitive coupling of the receiver electrodes to the body using C_1 and C_2. Let C_B denote the total series capacitance of C_1 and C_2 in the receiver loop. Using the above, it can be shown that the channel transfer function is given by [4]:

$$H(\omega) = \frac{V_{Tx}}{V_{Rx}} = -\frac{\omega^2 M C_B R_{Rx}}{\{(L_0 + C_B R_{Tx}(R_B + R_{Rx}))\omega + C_B(-L_0 L_1 + M^2)\omega^3 + j\,[C_B(L_0 R_B + L_0 R_{Rx} + L_1 R_{Tx})\omega^2 - R_{Tx}]\}} \quad (3)$$

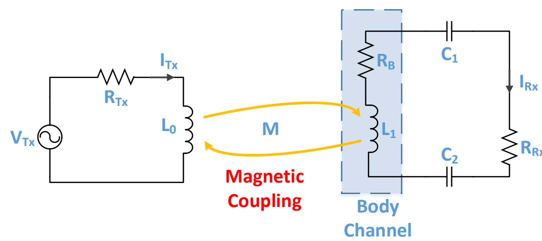

Figure 2. Equivalent circuit model for magnetic human body communications

3. Use of COMSOL Multiphysics®

While analytical models including circuit theory coupled with empirical approaches can be used for analysing MHBC scenarios, many logistic impracticalities prevent the use of these approaches for all possible enumerations of scenarios of interest. For system analysis and performance evaluation, simulation-based investigations offer many advantages. Therefore, COMSOL Multiphysics 4.3b software was used for investigating MHBC in this paper. Specifically, the Magnetic and Electric Fields (mef) and Electric Currents (ec) physics in the AC/DC module were used to perform a Frequency Domain study to investigate the operation of MHBC on a human arm.

The AC/DC module was used for the analysis based upon the range of frequencies of interest (*i.e.*, $f \le 20MHz$) having wavelengths which were sufficiently larger (*i.e.*, approximately, $\lambda \ge 15m$) than the order of magnitude of the body dimensions in the arm model.

4. Model Details

The model used for the study is shown in Figure 2. The arm is modelled as a cylinder with 5 concentric layers to account for the following tissues: skin, fat, muscle, cortical bone and cancellous bone. Surrounding the arm model is a larger cylinder which represents the surrounding medium (i.e. air). (Fig. 1). The dimensional model parameters are listed in Table 1.

Table 1: Dimensional parameters used for the MHBC model (values are in cm)

Parameter	Value	Description
e_r	10	Surrounding radius
e_l	120	Surrounding length
a_r	5	Arm radius
a_l	60	Arm length
d_s	0.15	Skin thickness
d_f	0.85	Fat thickness
d_m	2.75	Muscle thickness
d_{cb}	0.6	Cortical bone thickness
c_l	56	Tx-Rx separation

Geometry parameters were based upon similar parameters used in [5] which are well within the range of typical anatomical proportions. Tissue dielectric properties were modelled to account for frequency dependent behaviour using the 4-parameter Cole-Cole model:

$$\epsilon(\omega) = \epsilon_\infty + \sum_{n=1}^{4} \frac{\Delta\epsilon_n}{1+(j\omega\tau_n)^{1-\alpha_n}} + \frac{\sigma_i}{j\omega\epsilon_0} \qquad (3)$$

where $\epsilon(\omega)$ represents the frequency-dependent complex permittivity, ϵ_∞ represents the high-frequency permittivity, ϵ_s represents the low frequency permittivity, $\Delta\epsilon_n$ represents the magnitude of the n^{th} dispersion, τ_n represents the n^{th} relaxation time constant, α_n represents broadening of the dispersion, σ_i represents the static ionic conductivity and ϵ_0 is the dielectric permittivity of free space. For tissues used in the model, values of the Cole-Cole parameters were obtained from [6]. The transmitting electrode was modelled as a 22mm x 22mm square copper coil with three turns. The receiving electrodes were modelled as copper cuboids with sides of length 20 mm.

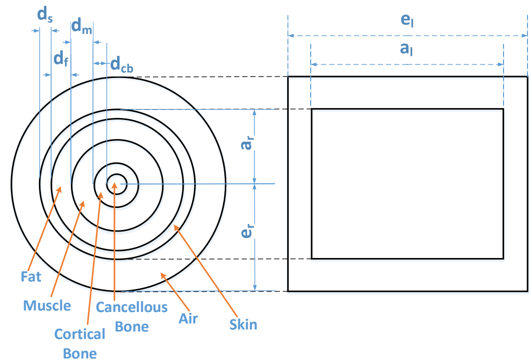

Figure 3. MHBC geometric model

5. Results

Figure 4 illustrates a plot of the electric field magnitude in a plane containing the transmitter and receiver electrodes. Figures 5 and 6 illustrate the resulting electric field magnitudes in planes at the transmitter and receiver respectively. As seen, there is an approximate 50dB drop moving from along the arm. Drops of between 50-70dB were observed across the range of frequencies studied.

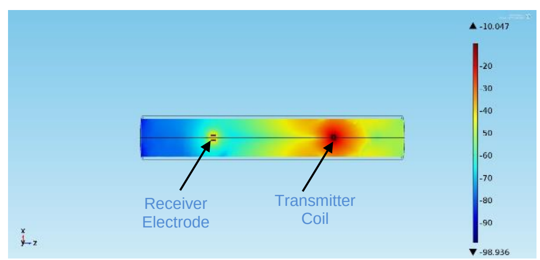

Figure 4. Plot of electric field induced for a plane containing transmitting coil and receiving electrodes.

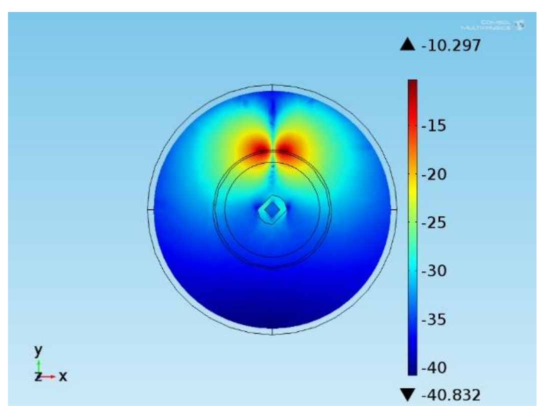

Figure 5. Plot of electric field induced, for plane containing transmitting coil.

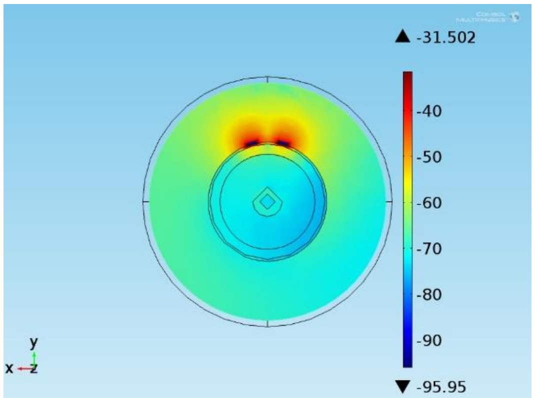

Figure 6. Plot of electric field induced, for plane containing receiving electrodes.

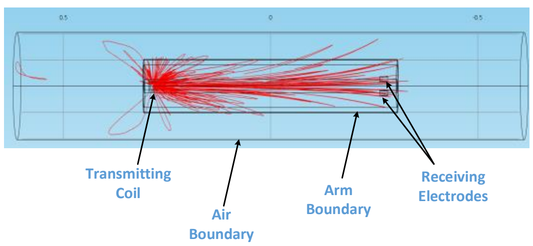

Figure 7. Comsol model showing magnetic streamline plot.

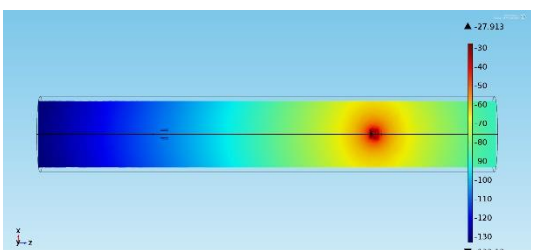

Figure 8. Plot of magnetic flux density for arm model.

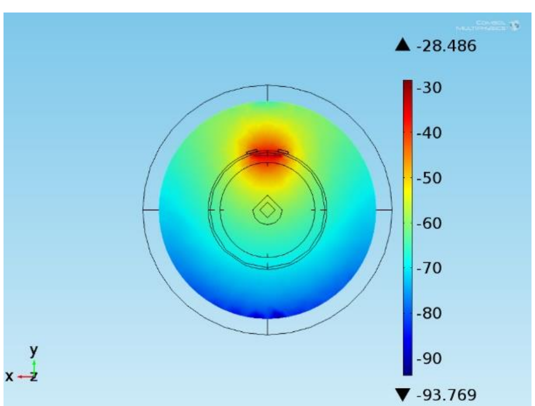

Figure 9. Plot of magnetic flux density for arm model, for plane containing transmitting coil.

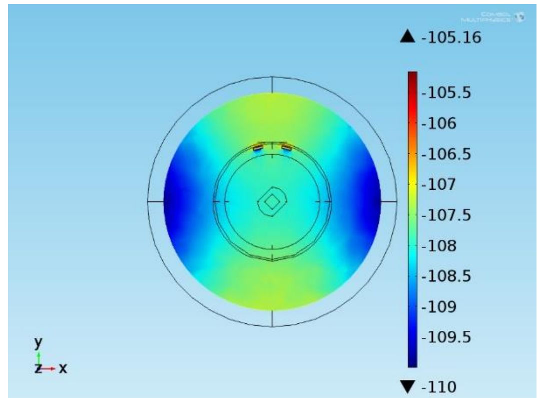

Figure 10. Plot of magnetic flux density for arm model, for plane containing receiver electrodes.

Figure 7 illustrates a streamline plot of the magnetic field generated by the coil, which propagates through the arm towards the electrodes. Figures 8-10 illustrate similar plots to Figures 4-6, but for the magnetic flux density. As for the electric field plots, comparable trends were observed across the range of frequencies studied.

6. Conclusions

In this work, magnetic human body communications were studied. Investigations were carried out to demonstrate the potential use of finite element analysis tools such as COMSOL, for channel analysis and characterization, as well as for design and evaluation of transceiver systems which use MHBC. A baseline was provided as the first step in investigation MHBC using simulation based analysis. In further work, there will be investigations of the impact of different scenarios on the channel model.

7. References

1. Zimmerman, T.G., “Personal Area Networks: Near-field Intrabody Communication,” *IBM Systems Journal*, vol. 35, no.3/4, pp. 609-617, 1996.
2. Seyedi, M. et. al., "A Survey on Intrabody Communications for Body Area Network Applications," *IEEE Transactions on Biomedical Engineering*, vol. 60, no.8, pp.2067-2079, Aug. 2013.
3. Ogasawara, T. et. al., “A Circuit Parameter Identification of Personal Area Networks

under the Magnetic Coupling," *Proceedings of the IEEE Antennas and Propagation Society International Symposium* (APSURSI), pp.1-2, 8-14 July 2012.
4. Ogasawara, T. et. al., "Human Body Communication Based on Magnetic Coupling," *IEEE Transactions on Antennas and Propagation*, vol. 62, no.2, pp.804-813, Feb. 2014.
5. Callejon, M.A., Reina-Tosina, J., Naranjo-Hernandez, D., and Roa, L.M., "Galvanic Coupling Transmission in Intrabody Communication: A Finite Element Approach," *IEEE Transaction in Biomedical Engineering*, vol. 61, no. 3, March 2014.
6. Gabriel, R., Lau, W., and Gabriel, C., "The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues," *Physics in Medicine and Biology*, vol. 41, no. 11, pp. 2271–2293, 1996.