A Simulation Study of Capacitive Body-Coupled Communication along Human Limbs

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***Abstract*—Capacitive Body-Coupled Communication (C-BCC) is a promising technique for efficient on-body, RF-EMF communication. C-BCC along the limbs is studied here using numerical simulations between 0.1-1 GHz. C-BCC is modeled as an emitting parallel-plate coupler (PPC) placed on a cylindrical or anatomical human-body phantom. The simulations show that there is an increase in propagation efficiency along the limbs in the studied frequency range, in comparison to propagation in free space, and that this efficiency is frequency dependent. There is a very good agreement between the cylindrical and the anatomical model in terms of propagation trend.**

I. Introduction

There exist several wireless, wearable sensors that use radio-frequency electromagnetic fields (RF-EMFs) to communicate data along the human limbs [1]. Capacitive Body-Coupled Communication (C-BCC) is a technique to establish this communication [2,3]. In this approach, a parallel-plate coupler (PPC) is placed on the skin and emits RF-EMFs that are received by a PPC on another location on the body. This technique is in general applied at frequencies < 200 MHz, where near-field and quasi-static coupling between two PPC is possible over the full body [2]. This comes with the disadvantages of limited band width and coupling to the environment [3]. In [3], it was shown that C-BCC can operate relatively efficient in the 420-510 MHz range, using numerical simulations with a cylindric phantom and on-body measurements. The aim of this study was to extend this study of C-BCC on the cylindrical model to the 0.1-1 GHz frequency range and compare the cylindrical model to an anatomical human body model.

II. Materials and Methods

This section is organized as follows: first the settings of the simulations using a cylindrical and an adult male anatomical phantom, the virtual family male (VFM) [4], are presented. Then the post-processing of the simulations is discussed.

A. Simulation Settings

All simulations in this study were executed using the finite-difference time-domain (FDTD) solver in the commercial software Sim4life (ZMT, Zurich, Switzerland). The transducing element for C-BCC is modeled as a PPC. This is the same one as used in [3], which is a rectangular piece of FR4 with equal width and length of 2 cm and a thickness of 2 mm. All simulations were harmonic, single-frequency simulations in which the PPC was center fed with a sinusoidal voltage source of 1 V and impedance 50 Ω, operating at frequencies 100-1000 MHz in steps of 50 MHz.

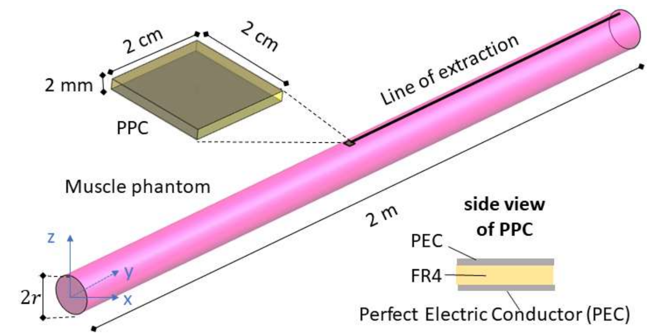

Figure 1. Cylindrical muscle phantom and PPC model.

The simulated cylindrical model is illustrated in Fig. 1. The PPC was placed on the mantle of a homogeneous cylinder with length 2 m and varying radius, $r \in [0,80mm]$ in steps of 5 mm. This corresponds to most humans' limbs' radii [1]. The cylinder was terminated at both ends using perfectly matched layers (PML) and was assigned frequency-dependent muscle properties from the IT'IS tissue database [6]. Each simulation ran until a steady state was reached in terms of electric field amplitude in the simulation domain. This was validated using edge sensors in the simulations.

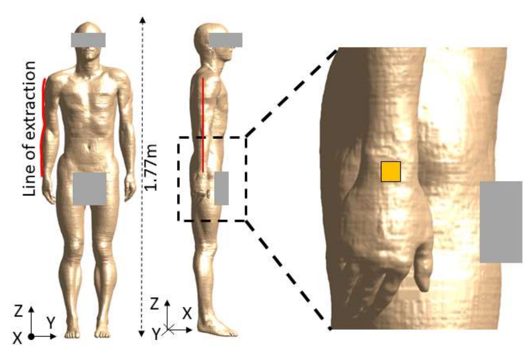

Figure 2. The Duke phantom with PPC placed on the right wrist (yellow) and line of extraction along the right arm (red).

The VFM is shown in Fig. 2, which also shows the placement of the PPC on the wrist to emulate RF-EMFs emitted by a wrist-worn sensor. The phantom (Duke v3) consists out of 74 tissues which were all assigned the corresponding frequency-dependent dielectric parameters from the IT'IS tissue database [6] and was discretized on a rectilinear grid with steps of 2 mm. The simulations ran for 10 (100 MHz) up to 30 (1 GHz) periods and reached a steady-state in terms of RF-EMF distribution in the simulation domain.

B. *Post Processing*

Following each simulation using the cylindrical phantom, the electric fields along the line indicated in Fig. 1 on a cylinder's mantle with radius r ($\bar{E}(f,d,r)$) were extracted. We have shown previously that this quantity can be used as a good proxy for RF-EMF communication using PPCs on dielectric cylinders [5] and using C-BCC [3]. After each simulation using the VFM, the electric fields ($\bar{E}(f,d)$) were extracted along the surface of the phantom's arm along a line that is the intersection between the plane parallel to the YZ plane containing the voltage source of the PPC and the boundary of the phantom, as illustrated in Fig. 2 in red. In order to compare the cylindrical model to the VFM, the circumference of the VFM's right arm was determined in each horizontal slice from wrist to shoulder. This resulted in a median circumference of 0.27 m (p_{25}=0.22 m, p_{75}=0.28 m). The VFM results were then compared to a cylinder with radius of 40 mm.

III. Results & Discussion

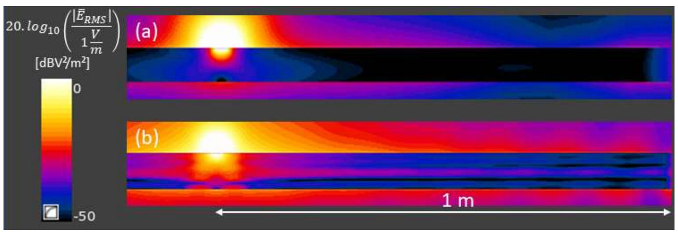

Figure 3. Root-mean-squared electric field strength ($|\bar{E}_{RMS}|$) around the cylindrical phantom with r = 40 mm normalized to 1 V/m at (a) 200 MHz, (b) 1 GHz, (c) 200 MHz, and (d) 1 GHz.

Fig. 3 shows $|\bar{E}_{RMS}|$ at 200 MHz and 1 GHz for the cylindrical phantom with r= 40mm. Propagation along the cylinder is more efficient at 1 GHz, e.g. at a distance of 30 cm $|\bar{E}_{RMS}|^2$ is 20 dB higher at 1 GHz in comparison to 200 MHz (corrected for mismatch efficiency). In the transverse direction (Y), the field profile fits that of a Hertzian dipole (see Fig. 5) at both frequencies. At all studied frequencies, E fields decay slower as function of distance in the longitudinal direction along the phantom than in the transverse direction into free space. This is also true for the VFM. Fig. 4 shows $|\bar{E}_{RMS}|$ at 200 MHz and 1 GHz around the right arm of the VFM.

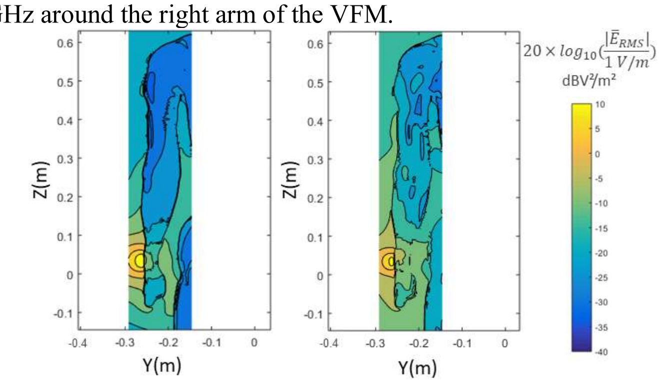

Figure 4.$|\bar{E}_{RMS}|$ around VFM's arm at 200(left) and 1000 MHz (right).

Fig. 5 compares the results obtained on the VFM and the cylindrical phantom. $|\bar{E}_{RMS}|$ is normalized to its maximum in each simulation. In order to compare the propagation, rather than absolute differences in field strengths, the results for the VFM were scaled by an antenna aperture, AA = 1/300. The cylinder results were scaled by AA=1. Fig. 5 shows that for $d > 3cm$, the cylindrical model is an excellent predictor of the propagation along the arm of the anatomical model. The results presented here are in line with previous results, where we showed that PPCs can be used to excite propagating modes along dielectric cylinders [5] and that they can be used for BCC communication around 450 MHz [3].

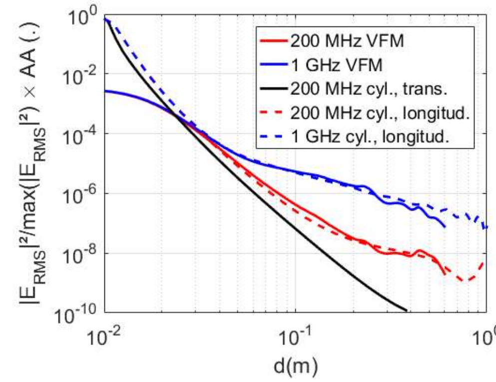

Figure 5. $|\bar{E}_{RMS}|$ relative to its maximum as a function of d for the VFM (solid) and a cylinder (dashed) with r= 40 mm at 200 MHz and 1 GHz.

IV. Conclusions

PPCs can excite enhanced propagation along a human limb in comparison to free space. This propagation is frequency dependent and for the VFM's arm it is more efficient at 1 GHz than at lower frequencies in the 100 – 1000 MHz range. The trend in propagation along a real human arm can be predicted accurately using a cylindrical model. Since propagation along a cylindrical, lossy waveguide can be described analytically [1,5], this opens up the possibility of a theoretical analysis of this frequency dependent propagation. Using modal analysis of the cylindrical model, we aim to show that also in this configuration this effect is due to surface waves which are tied to propagating modes along the arm.

Acknowledgment

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