Numerical Simulations of On-Body Channel in the Frequency Range of 2.5 MHz to 2.5 GHz

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1. Introduction

In recent years, body-centric wireless communications have become an active area of research due to their various applications such as e-healthcare, support systems for specialized occupations, and personal communications[1]–[6]. Whereas UHF bands are subjects of interest especially in Europe, relatively low frequency bands below several megahertz are also in researchers’ and corporations’ interest especially in Japan [4], [5]. Thus, all of the candidate frequencies are in an extremely wide range. In such range, dielectric properties of the human body tissues, relative dimensions of the human body to wavelength, and the propagation channels around the human body extremely vary with frequencies; therefore, we have to focus on certain frequency bands in most cases. Especially at tens of megahertz, of which wavelength is longer than the human body, the electromagnetic phenomena are often explained by using lumped-parameter equivalent circuit model that the devices and the human body are electrostatically coupled. However, it cannot be stated that the equivalent circuit model is always valid, and experimental results would significantly affected by the presence of measuring instruments and cables. So, we believe that 3-D EM simulations are important to assess the channels accurately. In our previous paper, we calculated the electric field distributions around a human body wearing a small top-loaded monopole antenna in a wide frequency range (2.5 MHz–2.5 GHz) to bring objective and unified idea on the frequency characteristics of body-centric wireless communication channels [6]. In this paper, we newly choose the open voltage of receiving antennas as a gauge, and examined two different postures. In addition, wide-frequency excitation in which the dispersibility of the human body is ignored was conducted for reference. These data would be useful to choose appropriate frequency range for specific applications.

2. Numerical Modeling of Antennas and Human Body

Since extremely wide frequency range is used in this study, an antenna should remain as simple and identical as possible over the range. From this requirement, a typical top-loaded monopole antenna shown in Fig. 1 is used both for transmitting and receiving. The antenna has low-profile dimension (4-mm thick) and has no matching structure (e.g. shorting posts); thus, impedance matching is not considered here. However, its radiation pattern is omnidirectional for any frequency over the range, and its input impedance is always capacitive below the resonant frequency (around 1.5 GHz). Moreover, its ground plane resembles an electrode mounted to megahertz-band devices both in appearance and operation.

Figure 2 shows a 3-D view of whole-body models with the antennas. The model has homogenous dielectric property equal to muscle at each frequency [7], and consists of several elliptical cylinders and spheroids. It has two different postures; one is upright (posture A) and the other reaches forward (posture B). The dimensions are determined by reference to the realistic numerical model of Japanese adult male [8]. A transmitting antenna is positioned at left breast, and three receiving antennas are positioned at left ankle, left wrist, and left ear, respectively. There is a 4-mm separation between the antennas and the body surface. The z-axis is set to center of the torso, and z = 0 at the feed point.
The finite-difference time-domain (FDTD) method is used for the calculation. Selected frequencies are 2.5, 10, 25, 100, 250 MHz, 1 GHz, and 2.5 GHz. In addition, wide-frequency excitations are conducted for two ranges; below and above 1 GHz. In these cases, the dielectric properties of the body are approximated by the 100-MHz value for the range below 1 GHz, and the 1-GHz value for the range above 1 GHz. In order to reduce computation resources, the non-uniform mesh FDTD algorithm is used, and the mesh size and computation domain are selected in accordance with the frequency, as summarized in Table 1. In the case of posture B, the domain is extended toward +x direction. The transmitting antenna is excited by use of 1-V delta gap voltage source with 50-Ω internal resistance. The feed pin is represented by a thin PEC wire, but its radius is not considered because it is not very important in this case. Terminals of receiving antennas are open-ended in order to observe the open voltage. The absorbing boundary condition is 8 layers of perfectly matched layer (PML).

In addition, since the ground is considered as something affecting the channel characteristics, the posture-A model standing on an infinite ground is modeled. Here, the ground is unreinforced concrete, and has a complex relative permittivity of $6 - j0.2$. The concrete is extended into the PML so that it represents the infinite earth. There is a 20-mm separation between the sole and the ground plane which simulates shoes.

![Geometry of the antenna](image)

![Whole-body models with the antennas](image)

**Figure 1: Geometry of the antenna.**

**Figure 2: Whole-body models with the antennas.**

**Table 1: Mesh size and computation domain.**

<table>
<thead>
<tr>
<th></th>
<th>Below 1 GHz</th>
<th>Above 1 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh size</td>
<td>2–10 mm</td>
<td>2–5 mm</td>
</tr>
<tr>
<td>Computation domain</td>
<td>1.4 m × 1.4 m × 2.9 m</td>
<td>1 m × 1 m × 2.1 m</td>
</tr>
</tbody>
</table>

### 3. Results and Discussions

In order to grasp the total picture, Fig. 3 shows the calculated electric field distributions inside and around the posture-A model in free space at 10 MHz, 250 MHz, and 2.5 GHz. The observation plane is x-z plane, which includes the feed point. Here the same input power is assumed for visibility. At 10 MHz, the electric field is smoothly distributed over the body surface, and similar results are obtained at 2.5, 25, and 100 MHz. In the case of 250 MHz, null points are found around the neck and the feet. Lastly at 2.5 GHz, radiation from the antenna naturally has a null angle toward +x direction, and there are some standing waves in the other side of the body model due to multipath as is already reported [1]. In addition, relatively similar results are obtained at 1 GHz. Actually, the input power increases with frequency as plotted in Fig. 4; here net voltage is assumed to be 1.0 V, the symbols indicate the results obtained with the sinusoidal excitation, and...
the lines indicate the results with the pulse excitation. The peaked curve around 1.5 GHz corresponds to the resonant frequency of the antenna. It should be noted, however, that the estimated input power includes unignorable computation error especially at low frequency because the input power is extremely reactive and the spectrum of the pulse contains only a little low-frequency component. However, we believe that the accuracy of our computation is enough to grasp the tendencies.

Figures 5–7 plot the frequency dependence of the received open voltage at the ankle, the wrist, and the ear, respectively. The results with the posture A, B, and posture A on the ground are plotted together in each figure. The received voltage is normalized with the value of net voltage at the feed point. In the same manner as Fig. 4, the symbols and the lines indicate the results obtained with the sinusoidal and pulse excitation, respectively, and both results well agree with each other although the dispersibility of the human body is ignored in the pulse excitation. According to these results, the received level is almost flat independently of the frequency below 25 MHz. This tendency is same as the directly plotted electric field [6], and it implies that much less consuming power is needed to generate equal electric field level around the body surface at lower frequencies. According to Figs. 5 and 7, it can be seen that the level at the ankle and the ear can vary only due to movements of the arm below 100 MHz. By contrast, above 100 MHz, the level at the ankle is relatively stable. According to Fig. 6, the level at the wrist considerably varies with posture. In particular, apparent null points are generated at 60 MHz, 200 MHz, and 2.5 GHz. In any figures, it is found that there is only a little effect due to the presence of the ground, except some ripples above hundreds of megahertz, and variation around 100 MHz in Fig. 5 at least in these cases.
4. Conclusions

In the present paper, to bring objective and unified idea on the frequency characteristics of body-centric wireless communication channels, electromagnetic fields around a body wearing a small top-loaded monopole antennas and the received open voltage at the ankle, the wrist, and the ear are numerically calculated in a wide frequency range of 2.5 MHz to 2.5 GHz. Comparing the results obtained with two different body postures, which are upright and reaching forward, the received level at the ankle and the ear can vary only due to movements of the arm below 100 MHz. By contrast, the level at the wrist considerably varies especially at 60 MHz, 200 MHz, and 2.5 GHz. In addition, there is only a little effect due to the presence of the earth ground.

References