Voltage and power transfer functions for the path loss of a 402 MHz body area network with multiple small dipole antennas have been reviewed. It has been shown that FDTD simulations for a homogeneous body model implemented in MATLAB® agree quite well with the advanced FEM solver for an inhomogeneous accurate human body model. Both methods model a voltage transfer function (path loss) for out-of-body dipole antennas at 402 MHz at different antenna locations. The reason for the good agreement is that the propagation path is mostly determined by adiffractio around the body, not by the propagation through the (inhomogeneous) body. Such an observation makes it possible to use various homogeneous body meshes in order to study the effect of different body types and positions for out-of-body antennas. A method of creating meshes using a 3D body scanner is described. For a number of body meshes, the magnitudes of the received voltages match exceptionally well when the antenna positions are measured from the top of the head.

Keywords: Body Area Networks, Finite Difference Time Domain Methods, Path Loss
Introduction

As the number of Wireless Body Area Network (WBAN) applications rise, the need for fully understanding antenna characteristics and propagation losses in the presence of the human body becomes paramount. Critical systems in military, medical and commercial fields are reliant on dependable communications within the networks of wireless sensors and communication devices located in or near a human body. Experimental characterization of all the combinations of frequency ranges, environments and antenna configurations is not practical and necessitates modeling and simulation tools that are well understood. In particular, the simple yet versatile Finite Difference Time Domain (FDTD) method has been shown to be well suited for simulation in the time domain of WBANs at a variety of frequencies using either a single homogeneous material (e.g. muscle tissue) or a heterogeneous body model. This method is particularly attractive as a variety of dielectric material/conductivity values can be fully represented by changing the properties of a single FDTD cell.

For example, the FDTD method has been used to identify the path loss of half wavelength dipoles located on or close to the body surface operating at 900 MHz [1]; create radiation patterns of λ/4 wavelength monopole antennas in cell phones with the human head [2] at 1.8 GHz; show the degree of interference between mobile communication systems and in-vivo sensors [3] at 900 MHz; and portray capacitive loading on electrically small antennas due to body proximity at 418 MHz, 916 MHz, and 2.45 GHz [4]. In addition, results from FDTD simulations have been successfully coupled to experimental measurements in the 2-6 GHz band [5]; used for comparison of real human body and ‘body-like’ cylinder geometries [6] (400 MHz and 2.45 GHz); and have been integral in establishing a relationship between radio channel characteristics and body type at 2.4 GHz [7]. In addition to this validation, the FDTD method has been verified against results obtained via Green’s function and Prony Analysis [8] and the Method of Moments [9-10], a simulation routine that has also found use in WBAN applications [11] at 280 MHz. The High Frequency Structure Simulator (HFSS), which is a commercially available frequency-domain and most recently time-domain simulation tool created by Hewlett Packard/Ansoft/ANSYS (USA), has also been used for human body path loss simulations with good comparisons to results obtained via the FDTD method and experimental measurement in the range 2.4 to 6 GHz [12-13]. Other major relevant commercial software packages include CST Microwave Studio (Germany), Remcom (USA), Semcad X (Switzerland), etc.

Experimental characterization of WBAN systems can provide a wealth of validation data with studies conducted for implantable sensors at 403 MHz and 2.4 GHz [14], body posture affect on received signal strength [15] at 2.4 GHz and signal path loss of a pair of dipole antennas at 2.4 GHz [16]. Several statistical models for path loss have been presented for the 2.4 GHz band and beyond [17-19]. Antennas embedded in textiles [20] at 4 to 9 GHz and small monopole antennas [21] at 3.1 to 10.6 GHz present still more applications of WBANs.
This work considers the development and simulation of an antenna-to-antenna link between two arbitrarily sized (and generally non-matched) blade dipole antennas in a variety of configurations in free space and around the human body at 402 MHz. This frequency is particularly relevant given that on March 20, 2009, the Federal Communications Commission (FCC) established a new Medical Device Radiocommunication Service and adopted technical and service rules for advanced wireless medical radiocommunication devices used for diagnostic and therapeutic purposes in humans at 401-406 MHz. Also, the FCC has proposed to allocate up to 24 megahertz of spectrum in the 413-457 MHz band for implantable micro-stimulation devices using wireless technologies.

The antenna-to-antenna link is established in frequency and time domains. In the frequency domain, we use an accurate impedance matrix approach to the antenna-to-antenna transfer function due to Silver and Collin [22-23]. This approach allows us to avoid somewhat questionable equivalent circuit models of the receiving antenna [22-25] and proceed with the impedance and scattering parameters of the corresponding two-port network, which could be directly measured.

Then, we compare basic FDTD simulations for the path loss around the human body implemented entirely in MATLAB® with accurate FEM modeling of the inhomogeneous human body in Ansoft/ANSYS HFSS v.12.1. In FEM, we routinely study body meshes with more than 1,000,000 tetrahedra and investigate the convergence accuracy at different mesh sizes.

When the FDTD method is applied, the body has the same shape but a homogeneous composition, with an average value of the relative dielectric constant (50) and material conductivity (0.5S/m). The question of material homogeneity is thus addressed, as the higher fidelity FEM technique uses a geometry that is constructed of separate models with dielectric properties consistent with those experimentally measured [26-27] for organs, bone, blood and skin while the FDTD geometry is entirely homogeneous.

We will show that even the basic the FDTD analysis still yields very convincing results even if it uses a homogeneous body model and simple boundary conditions. The reason for this observation, generally known in the EM community for a long time, is explained and quantified. Furthermore, the FDTD simulations run many times faster than the FEM simulations, with greater ease of implementation.

Finally, we generate a number of our own proprietary human body surface (triangular) and volume (brick, homogeneous) meshes using Cyberware’s WB4 whole body color 3D scanner and post-processing software MeshLab. Those human body models are exported to MATLAB®. We further apply the FDTD algorithm to those models in order to study the effect of different body types on path loss between two antennas close to the human body.
1. Voltage and power transfer functions in the near- and far-field

1.1 Impedance matrix approach

In this section, we describe an accurate impedance matrix approach to the antenna-to-antenna transfer function that originates from Silver and Collin [22-23]. This approach is valid in both the near- and far-field, which is especially important for the 402 MHz link. A direct “conduction” path between the transmitting (TX) and receiving (RX) antennas and the equivalent circuits is established using a two-port linear network concept. This path indeed implies antenna radiation and reception. In that way, a wireless link is represented in the circuit form. Such a model works in both the frequency and time domains as shown in Fig. 1. The only real voltage source in the circuit is the generator voltage.

Fig. 1. A path between the transmitting and receiving antennas in the form of a two-port network. The time-domain version is shown.

The model in Fig. 1 becomes especially inviting in the frequency domain – see Fig. 2 that follows. Of primary interest to us is the received load phasor voltage \( V_{\text{load}} \) as a function of the generator voltage \( V_g \). This approach provides us with the voltage transfer function \( T_V \), which is given in phasor form by

\[
T_V = \frac{V_{\text{load}}}{V_g}
\]  

(1)

For a system with two lumped ports (TX and RX antenna terminals), one can use a 2×2 impedance matrix \( \hat{Z} \). For example, such an impedance matrix is readily available as “solution data” in Ansoft/ANSYS HFSS at a given frequency. The impedance matrix is invariant to port impedances specified. The TX-RX antenna network shown in Fig. 2a is replaced by an equivalent two-port microwave network described by an impedance matrix \( \hat{Z} \), given by Eq. (2) and shown in Fig. 2b.
\[
\hat{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}
\]

Fig. 2. Transformations of the two-port antenna network in frequency domain.

The impedance approach is somewhat more appealing in this problem than the S-matrix approach since the S-matrix approach always requires an extra transmission line at the port. Furthermore, the impedance approach explicitly relates the antenna link to the circuit parameters and to antenna input impedances (in the far-field only), and allows us to directly employ the well-known analytical results for dipole and loop antennas when necessary. For reciprocal antennas, the mutual impedances are identical, i.e. \( Z_{12} = Z_{21} \). In the far-field, self impedances \( Z_{11}, Z_{22} \) coincide with the input impedances \( Z_{TX}, Z_{RX} \) to the transmitting and receiving antennas in free space, respectively.

Next, the two-port network in Fig. 2b with the impedance matrix given by Eq. (2) is replaced by an equivalent T-network (the \( \Pi \)-equivalent is also possible but it is not
considered here). The resulting circuit is given in Fig. 2c. The solution for the receiver voltage in Fig. 2c then becomes an exercise in basic circuit analysis. One has

\[ V_{\text{load}} = \frac{R_{\text{load}}Z_{21}}{(R_g + Z_{11})(R_{\text{load}} + Z_{22}) - Z_{21}^2} V_g = T_T V_g \]  

(3)

for the voltage transfer function. The result for a power transfer function may be obtained in the same way. The component \( Z_{21} \) – the mutual impedance – contains all the information about the path between the TX and RX, and must be either calculated numerically or estimated analytically.

For two antennas separated by a large distance, \( Z_{21} \) is small. When the separation distance tends to infinity, \( Z_{21} \to 0 \). In that case the transmitter in Fig. 2c is shorted out and the receiver gets no signal. Thus, at large separation distances, \( |Z_{21}| < \min(|Z_{\text{TX}}|, |Z_{\text{RX}}|) \), and one has from Eq. (3)

\[ V_{\text{load}} = \frac{R_{\text{load}}Z_{21}}{(R_g + Z_{11})(R_{\text{load}} + Z_{22})} V_g = T_T V_g \]  

(4)

1.2 Transfer function in terms of voltage across the TX antenna

Quite often, we normalize the received voltage not by the generator voltage, \( V_g \), but by the voltage, \( V_1 \), across the TX antenna - see Fig. 2b. The voltage transfer function so defined is denoted by \( T \). With reference to Fig. 2b,

\[ T = \frac{V_{\text{load}}}{V_1} \]  

(5)

Solving the circuit in Fig. 2c once again, one has

\[ V_{\text{load}} = \frac{R_{\text{load}}Z_{21}}{Z_{11}(R_{\text{load}} + Z_{22}) - Z_{21}^2} V_1 = TV_1 \]  

(6)

Eq. (6) is none other than a truncated version of Eq. (3) when \( R_g = 0 \).

1.3 Scattering matrix approach

Although the transfer functions given in Eqs. (3) and (6) may be (and have been) directly programmed in Ansoft/ANSYS HFSS and in other software packages, it is instructive to define the transfer function in terms of \( S \)-parameters (measurable scattering parameters) of the two-port network in Fig. 1 or Fig. 2a.
In Fig. 3, the Z-matrix network is replaced by the S-matrix network. We assume that the characteristic transmission line impedance, $Z_0$, is equal to generator and load resistances for both the transmitter and receiver, i.e.

$$Z_0 = R_g = R_{\text{load}}$$  \hspace{1cm} (7)

![Fig. 3. Network transformation of the antenna-to-antenna link – S-matrix approach.](image)

The straightforward way to rewrite Eqs. (3) and (6) in terms of scattering parameters is to use two identities for a two-port network [32]:

$$S_{21} = \frac{2Z_{21}Z_0}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{21}^2}$$  \hspace{1cm} (8)

$$1 + S_{11} = 2 \frac{Z_{11}(Z_{22} + Z_0) - Z_{21}^2}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{21}^2}$$  \hspace{1cm} (9)

In view of this and taking into account Eq. (7), one obtains

$$T_V = \frac{1}{2} S_{21}$$  \hspace{1cm} (10)

$$T = \frac{S_{21}}{1 + S_{11}}$$  \hspace{1cm} (11)

Eq. (10) is the definition of the scattering coefficient, $S_{21}$. The factor of $\frac{1}{2}$ appears due to voltage division between the source resistance, $R_g$, and the TX antenna.

1.4 Power transfer function
The power transfer function, $T_p$, may be defined in a number of ways. The most common way [1], [9], [10], [16] is to assign

$$T_p \equiv |S_{21}|^2$$  \hspace{1cm} (12)
We again assume that $R_g = R_{load}$. In this case, the transfer function $T_p$ would give us the received load power – the power delivered to the load resistance in Fig. 2 or 3,

$$P_{load} = \frac{1}{2} \left| \frac{V_{load}}{R_{load}} \right|^2$$  \hspace{1cm} (13a)

versus the power delivered to a transmitting antenna, $P_a$, if and only if the transmitter antenna is *perfectly matched* to the generator resistance [29], that is

$$P_a = \frac{1}{8} \left| \frac{V_g}{R_g} \right|^2$$  \hspace{1cm} (13b)

### 2. FEM and FDTD solvers

As two competitors to the same problem, we apply an FEM solver and an FDTD solver, respectively. We study various body phantoms including homogeneous and inhomogeneous models. The FEM method in frequency domain has a fine resolution, but requires very large CPU times. On the other hand, the basic FDTD method on uniform grids is much faster and simpler, but is presumably less accurate. And yet, the accuracy of such a method may be quite sufficient for path loss modeling.

#### 2.1 FEM frequency-domain solver – Ansoft/ANSYS HFSS v. 12

A proprietary, high fidelity FEM human body geometry, shown in Fig. 4, has been supplied by Ansoft/ANSYS HFSS and is constructed with over 300 separate parts that represent specific organs, muscles, bones and other components with a resolution of 2mm. Discrete material types have been modeled with experimentally obtained frequency-dependent permittivity and conductivity values [26], [27].

![Fig. 4. High-fidelity human body mesh with 2mm resolution – Ansoft HFSS (ANSYS).](image)
Boundary conditions for the phantom in Fig. 4 have been implemented using a Perfectly Matched Layer (PML) [31] around the body/antenna volume. The size of the PML base box has been selected as 850×850×2100mm. Fine FEM meshes, with up to 1,400,000 tetrahedra have been considered. The FEM resolution within the body is 2mm, which corresponds to $\lambda_b / 50$ where $\lambda_b = 105.5$mm is in-body wavelength at 402 MHz assuming $\varepsilon_r = 50$.

### 2.2 Antennas
For all presented configurations, small center-fed blade dipole antennas with total lengths of 11.25 cm and widths of 1.25 cm are used at a frequency of 402 MHz. We do not include the dipole balun into consideration. At this frequency, these antennas are significantly less than the half wavelength of 37.3 cm in free space, producing large capacitive reactance and small radiation resistance. In other words, the antennas are not matched in free space.

The presence of the human body may or may not improve the impedance matching, due to anticipated dielectric loading. The exact match depends on the antenna distance from the body, and the antenna's relative position. Since the distance generally varies, we did not attempt to achieve a perfect match for a particular antenna configuration.

### 2.3 FDTD solver on uniform cubic grids
Simulations are carried out using a simple yet fully functional FDTD algorithm. All antenna parameters defined in section 2.2 are retained. The one-cell lumped port model for the transmitter is coupled with a resistive voltage source as shown in Fig. 1-left. For the receiver, the port is terminated into a load resistance – see Fig. 1 – right. In both cases, the port treatment follows Ref. [33]. The dipole blade is modeled as a PEC strip. The standard FDTD method is programmed in MATLAB using the Yee second-order differences on a 3D uniform staggered grid and is consistent with [1]. The FDTD resolution within the body is 12.5mm, which corresponds to $\lambda_b / 9$ where $\lambda_b = 105.5$mm is in-body wavelength at 402 MHz assuming $\varepsilon_r = 50$.

Fast first-order Mur’s Absorbing Boundary Conditions (ABCs) [34] supplemented by a superabsorption [35] update for the magnetic field, which corresponds to the second-order accuracy, are used. Liao’s ABCs [36] of 3rd and 4th order provide nearly identical results and may be a viable alternative. No PML ABCs have been employed in the present code. The FDTD solution is executed for a sinusoidal voltage generator feeding the TX antenna at 402 MHz. The source has the internal resistance, $R_s$, of 50Ω. The load resistance, $R_{load}$, of the RX circuit is also 50Ω. Once the solution has been stabilized, the transfer function at the frequency of interest is evaluated via a sliding-window Fourier transform. The entire FDTD algorithm is implemented as a relatively short vectorized MATLAB script taught in a computational electromagnetics ECE class at WPI.
The above method is straightforwardly modified by implementing a more accurate subcell wire dipole model for cylindrical dipoles, and an infinitesimal feeding gap as described below [37-38]. Also, edge field singularities have been addressed for blade dipole wings. A very promising hybrid method combining FDTD and MoM (for most recent development see [39-40]) may be a way to model small helical coil antennas along with the dipoles.

2.3.1 Subcell dipole model
Traditional FDTD simulations of dipole antennas were limited by errors inherent in what is called the ‘one-cell gap model’ [38]. Simulations employing this construct restrict the smallest width of the dipole feed to the size of a single FDTD cell. When the actual feed gap is smaller than the cell size, errors that are dependent on the cell size are observed that negatively impact input impedance results and may potentially prohibit the convergence of the calculation. For these reasons, the subcell dipole model, shown in Fig. 5, has been adopted for simulation of both TX and RX antennas, enabling an infinitesimally small feed gap. The governing equations around the feed are modified to reflect the fact that the majority of the magnetic fields in this area are due to current flow across the gap and that these fields are inversely proportional to the distance from the gap. This methodology has been proven to provide greater simulation accuracy with no impact on calculation speed.

Fig. 5. Dipole feeds are modeled with an infinitesimally small gap, often less than the size of an individual FDTD cell.

2.4 Body phantom used for comparison
The human body volume used in Ansoft simulations and shown in Fig. 4 has been exported to MATLAB® workspace and further to the FDTD cubic mesh using Ansoft’s Field Calculator. Any cube center node with a large permittivity/conductivity has been assigned average relative dielectric constant and body conductivity values of 50 and 0.5 S/m, respectively. Any FDTD node within body lungs has been modeled as air. The average values of medium parameters were used for every field node in the vicinity of the body-air interface. A detailed discussion of interface averaging is given in [41]. No subcell boundary models have been employed. The FDTD mesh consists of approximately 310,000 brick elements. The size of the entire FDTD domain has been selected as 800×800×2000mm.

2.5 Other body phantoms
To model the effect of various body shapes, we have also generated a number of our own proprietary human body surface (triangular) and volume (brick, homogeneous) meshes using Cyberware’s WB4 whole body color 3D scanner and MeshLab’s post-processing software. Those human body models are exported to MATLAB®. We further apply the FDTD algorithm to those models in order to study the effect of different body types on path loss between two antennas close to the human body. We intend to show that the path loss is weakly affected by a specific body shape.

3. FEM accuracy versus FDTD accuracy for voltage transfer function

3.1. Antenna-to-antenna link in free space
In order to establish a baseline for validation of the path loss expressions derived above, we simulated a pair of identical dipole antennas – see subsection 2.2 – in free space using the FDTD and FEM methods, respectively. In this simple case, the antenna center-to-center separation distance is 41.3 cm, suitable for the near-field link to be studied. The simulation domain and graphical display of the 3D FDTD method in the antenna E-plane can be seen in the upper portion of Fig. 6 while a drawing of the same configuration in Ansoft/ANSYS HFSS and the resulting impedance matrix are shown in the lower section.

The results were obtained with a transmission source amplitude of 1V with an assumption that \( R_g = R_{\text{load}} \). The voltage transfer function \( T_V \) given by Eq. (3) or Eq. (10) has been used for that purpose and implemented in both FEM and FDTD.

Results for two different values of \( R_g = R_{\text{load}} \) are summarized in Table 1. In the worst case (very large generator resistance), the difference between the two simulation methodologies does not exceed 9%. This is a reasonable accuracy for modeling path loss. The result for the 1000Ω case is clearly less accurate since the antennas at \( R_g = R_{\text{load}} = 1000\Omega \) acquire less active power, which increases impedance mismatch and the related numerical noise.
Fig. 6. Simulation results in free space: upper left – FDTD simulation domain with two dipole antennas – E-plane; upper right – FDTD TX/RX voltages; lower left – Ansoft/ANSYS HFSS model of dipole geometry; lower right – resulting impedance matrix. The field scale in Fig. 6 top-left follows Eq. (14).

Table 1. Received voltage amplitudes for two different values of $R_g = R_{load}$ for the free-space setup in Fig. 6. The source voltage has the amplitude of 1V.

<table>
<thead>
<tr>
<th>Freq (MHz)</th>
<th>1:1</th>
<th>2:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>402</td>
<td>(490.43, -83.4), (2.1559, -128)</td>
<td>(486.32, -83.4)</td>
</tr>
<tr>
<td>2.1</td>
<td>(2.1558, -128)</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Path loss near the human body
We have defined a series of different antenna configurations that were simulated in the presence of a human body. Antenna positions with reference to the human body position are summarized in Table 2 – see Figs. 7 to 13 that follow. In all cases, the same antenna dimensions (total length of 11.25 cm and width of 1.25 cm) described above are retained and $R_g = R_{load} = 50\Omega$. 

<table>
<thead>
<tr>
<th>$R_g = R_{load}$</th>
<th>Ansoft HFSS data for the received voltage amplitude</th>
<th>FDTD data for the received voltage amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>50\Omega</td>
<td>0.44mV</td>
<td>0.45mV</td>
</tr>
<tr>
<td>1000\Omega</td>
<td>1.72mV</td>
<td>1.57mV</td>
</tr>
</tbody>
</table>
Table 2. Antenna configuration coordinates for simulated cases – Ansoft/ANSYS HFSS for the high-fidelity body model vs. FDTD for a homogeneous body (except for lungs). All coordinates are with respect to the Ansoft’s human body model.

<table>
<thead>
<tr>
<th>Case Number</th>
<th>Antenna X coordinate (mm)</th>
<th>Antenna Z coordinate (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>206.5</td>
<td>-130.5</td>
</tr>
<tr>
<td>2</td>
<td>206.5</td>
<td>-190.5</td>
</tr>
<tr>
<td>3</td>
<td>206.5</td>
<td>-390.5</td>
</tr>
<tr>
<td>4</td>
<td>306.5</td>
<td>-390.5</td>
</tr>
<tr>
<td>5</td>
<td>156.5</td>
<td>-390.5</td>
</tr>
<tr>
<td>6</td>
<td>146.5</td>
<td>-390.5</td>
</tr>
<tr>
<td>7</td>
<td>356.5</td>
<td>-390.5</td>
</tr>
</tbody>
</table>

Results from these simulations are presented below. FDTD and Ansoft/ANSYS HFSS simulations were carried out for all cases using a Dell PowerEdge R815 Server populated with four AMD Opteron 6174 12-core Magny-Cours processors with each processor running at 2.2 GHz. A given simulation used a single processor with access to 192 GB of RAM.

The voltage transfer function $T_v$ given by Eq. (3) or Eq. (10) has been used and implemented in both FEM and FDTD. We accurately tracked the Ansoft convergence results for each case and those results are also shown in Figs. 7 to 13 as functions of the number of mesh refinement steps and current mesh size.

Every figure shows on its top the FEM results including the convergence and the received voltage as a function of the mesh resolution. The FDTD results are given on the bottom. The dots on the FDTD mesh indicate brick vertexes within the body. Those bricks were assigned average relative dielectric constant and body conductivity values of 50 and 0.5 S/m, respectively. The lung volume was filled with air.

To better observe and highlight weak signal propagation within the body, the vertical electric field was plotted in Figs. 7 to 13, in the antenna E-plane, according to the dependence

$$|E_z|^2 \text{sign}(E_z)$$

(14)
Table 3. Simulated results of case 1.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage(mV)</th>
<th>Ansoft (1st)</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 388,240</td>
<td>$Z_{11} = 86\angle 88.1^\circ$  $Z_{22} = 170.8\angle 87.7^\circ$  $Z_{21} = 0.499\angle 167^\circ$</td>
<td>$S_{11} = 0.9711\angle -60.3^\circ$  $S_{22} = 0.9782\angle -32.6^\circ$  $S_{21} = 2.75e - 3\angle -36.9^\circ$</td>
<td>1.4</td>
<td>0.119</td>
<td>01:18:19</td>
</tr>
<tr>
<td>2 465,892</td>
<td>$Z_{11} = 236.47\angle -89.1^\circ$  $Z_{22} = 327.1\angle -88.7^\circ$  $Z_{21} = 0.4686\angle -171^\circ$</td>
<td>$S_{11} = 0.9935\angle -23.9^\circ$  $S_{22} = 0.9931\angle -17.4^\circ$  $S_{21} = 5.821e - 4\angle -13.5^\circ$</td>
<td>0.291</td>
<td>0.119</td>
<td>02:56:47</td>
</tr>
<tr>
<td>3 559,074</td>
<td>$Z_{11} = 397.68\angle -89.4^\circ$  $Z_{22} = 425.97\angle -89.1^\circ$  $Z_{21} = 0.48\angle -171^\circ$</td>
<td>$S_{11} = 0.9972\angle -14.5^\circ$  $S_{22} = 0.9962\angle -13.4^\circ$  $S_{21} = 2.825e - 4\angle -6.11^\circ$</td>
<td>0.139</td>
<td>0.119</td>
<td>05:41:02</td>
</tr>
<tr>
<td>4 670,892</td>
<td>$Z_{11} = 448.5\angle -89.5^\circ$  $Z_{22} = 462.2\angle -89.2^\circ$  $Z_{21} = 0.464\angle -170^\circ$</td>
<td>$S_{11} = 0.9979\angle -12.7^\circ$  $S_{22} = 0.997\angle -12.3^\circ$  $S_{21} = 2.21e - 4\angle -3.47^\circ$</td>
<td>0.11</td>
<td>0.119</td>
<td>10:30:06</td>
</tr>
<tr>
<td>5 805,074</td>
<td>$Z_{11} = 474.4\angle -89.5^\circ$  $Z_{22} = 477.4\angle -89.2^\circ$  $Z_{21} = 0.4498\angle -170^\circ$</td>
<td>$S_{11} = 0.9982\angle -12^\circ$  $S_{22} = 0.9972\angle -12^\circ$  $S_{21} = 1.96e - 4\angle -3.65^\circ$</td>
<td>0.098</td>
<td>0.119</td>
<td>15:19:00</td>
</tr>
<tr>
<td>6 966,089</td>
<td>$Z_{11} = 483.3\angle -89.5^\circ$  $Z_{22} = 484.8\angle -89.3^\circ$  $Z_{21} = 0.4447\angle -170^\circ$</td>
<td>$S_{11} = 0.9983\angle -11.8^\circ$  $S_{22} = 0.9974\angle -11.8^\circ$  $S_{21} = 1.874e - 4\angle -3.38^\circ$</td>
<td>0.0937</td>
<td>0.119</td>
<td>20:14:30</td>
</tr>
<tr>
<td>7 1,074,751</td>
<td>$Z_{11} = 489.59\angle -89.5^\circ$  $Z_{22} = 488.2\angle -89.3^\circ$  $Z_{21} = 0.4425\angle -170^\circ$</td>
<td>$S_{11} = 0.9983\angle -11.7^\circ$  $S_{22} = 0.9974\angle -11.7^\circ$  $S_{21} = 1.835e - 4\angle -3.24^\circ$</td>
<td>0.0914</td>
<td>0.119</td>
<td>27:09:30</td>
</tr>
<tr>
<td>8 1,141,585</td>
<td>$Z_{11} = 489.6\angle -89.5^\circ$  $Z_{22} = 490.1\angle -89.3^\circ$  $Z_{21} = 0.441\angle -170^\circ$</td>
<td>$S_{11} = 0.9983\angle -11.7^\circ$  $S_{22} = 0.9975\angle -11.6^\circ$  $S_{21} = 1.816e - 4\angle -3.18^\circ$</td>
<td>0.0908</td>
<td>0.119</td>
<td>23:29:10</td>
</tr>
</tbody>
</table>

Fig. 7. Simulations for case 1: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 4. Simulated results of case 2.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage (mV)</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
</table>
| 1 388,089                         | $Z_{11} = 106.7 \angle -88.1^\circ$  
$Z_{22} = 54.8 \angle -88.4^\circ$  
$Z_{21} = 0.208 \angle 166^\circ$ | $S_{11} = 0.9753 \angle -50.2^\circ$  
$S_{22} = 0.9729 \angle -84.7^\circ$  
$S_{21} = 2.316e - 3 \angle -83.7^\circ$ | 1.2 | 01:09:17 |
| 2 465,709                         | $Z_{11} = 287.8 \angle -89.4^\circ$  
$Z_{22} = 180.5 \angle -88.8^\circ$  
$Z_{21} = 0.256 \angle 168^\circ$ | $S_{11} = 0.9963 \angle -19.7^\circ$  
$S_{22} = 0.9896 \angle -31^\circ$  
$S_{21} = 4.638e - 4 \angle -39.2^\circ$ | 0.232 | 02:31:47 |
| 3 558,855                         | $Z_{11} = 394.7 \angle -89.5^\circ$  
$Z_{22} = 354.7 \angle -89.1^\circ$  
$Z_{21} = 0.335 \angle 169^\circ$ | $S_{11} = 0.9977 \angle -14.4^\circ$  
$S_{22} = 0.9957 \angle -16^\circ$  
$S_{21} = 2.341e - 4 \angle -27.6^\circ$ | 0.117 | 05:15:30 |
| 4 670,631                         | $Z_{11} = 449.5 \angle -89.5^\circ$  
$Z_{22} = 440 \angle -89.2^\circ$  
$Z_{21} = 0.352 \angle 169^\circ$ | $S_{11} = 0.9982 \angle -12.7^\circ$  
$S_{22} = 0.997 \angle -13^\circ$  
$S_{21} = 1.752e - 4 \angle -25^\circ$ | 0.0876 | 10:37:06 |
| 5 804,762                         | $Z_{11} = 471.5 \angle -89.6^\circ$  
$Z_{22} = 470.4 \angle -89.3^\circ$  
$Z_{21} = 0.347 \angle 169^\circ$ | $S_{11} = 0.9984 \angle -12.1^\circ$  
$S_{22} = 0.9974 \angle -12.1^\circ$  
$S_{21} = 1.543e - 4 \angle -24.1^\circ$ | 0.0772 | 17:58:02 |
| 6 964,718                         | $Z_{11} = 481.3 \angle -89.6^\circ$  
$Z_{22} = 482 \angle -89.3^\circ$  
$Z_{21} = 0.343 \angle 169^\circ$ | $S_{11} = 0.9985 \angle -12.1^\circ$  
$S_{22} = 0.9975 \angle -12.1^\circ$  
$S_{21} = 1.46e - 4 \angle -24.1^\circ$ | 0.073 | 22:26:22 |
| 7 1,054,674                       | $Z_{11} = 486.7 \angle -89.6^\circ$  
$Z_{22} = 487.1 \angle -89.3^\circ$  
$Z_{21} = 0.341 \angle 169$ | $S_{11} = 0.9985 \angle -11.7^\circ$  
$S_{22} = 0.9976 \angle -11.7^\circ$  
$S_{21} = 1.419e - 4 \angle -23.6^\circ$ | 0.071 | 24:53:08 |
| 8                                 | **Matrix Solver Exception: failed** |                       |                       | 0.119 |                       |

Fig. 8. Simulations for case 2: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 5. Simulated results of case 3.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage (mV)</th>
<th>Ansoft 1st</th>
<th>FDTD 2nd</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 400,358</td>
<td>$Z_{11} = 156.6 \angle -88.3^\circ$</td>
<td>$S_{11} = 0.9826 \angle -35.4^\circ$</td>
<td>0.1975</td>
<td>0.008</td>
<td>0.008</td>
<td>01:41:35</td>
</tr>
<tr>
<td>2 480,430</td>
<td>$Z_{11} = 308.1 \angle -89.2^\circ$</td>
<td>$S_{11} = 0.9954 \angle -18.4^\circ$</td>
<td>0.0362</td>
<td>0.008</td>
<td>0.008</td>
<td>03:09:06</td>
</tr>
<tr>
<td>3 576,520</td>
<td>$Z_{11} = 417.9 \angle -89.4^\circ$</td>
<td>$S_{11} = 0.9977 \angle -13.6^\circ$</td>
<td>0.0171</td>
<td>0.008</td>
<td>0.008</td>
<td>06:38:42</td>
</tr>
<tr>
<td>4 691,827</td>
<td>$Z_{11} = 455.0 \angle -89.5^\circ$</td>
<td>$S_{11} = 0.9982 \angle -12.5^\circ$</td>
<td>0.0134</td>
<td>0.008</td>
<td>0.008</td>
<td>10:49:25</td>
</tr>
<tr>
<td>5 830,194</td>
<td>$Z_{11} = 473.6 \angle -89.6^\circ$</td>
<td>$S_{11} = 0.9984 \angle -12.6^\circ$</td>
<td>0.012</td>
<td>0.008</td>
<td>0.008</td>
<td>13:43:17</td>
</tr>
<tr>
<td>6 996,235</td>
<td>$Z_{11} = 482.5 \angle -89.6^\circ$</td>
<td>$S_{11} = 0.9985 \angle -11.8^\circ$</td>
<td>0.011</td>
<td>0.008</td>
<td>0.008</td>
<td>22:12:00</td>
</tr>
<tr>
<td>7 1,130,503</td>
<td>$Z_{11} = 486.9 \angle -89.6^\circ$</td>
<td>$S_{11} = 0.9985 \angle -11.7^\circ$</td>
<td>0.011</td>
<td>0.008</td>
<td>0.008</td>
<td>22:08:02</td>
</tr>
<tr>
<td>8 1,250,345</td>
<td>$Z_{11} = 489.4 \angle -89.6^\circ$</td>
<td>$S_{11} = 0.9986 \angle -11.7^\circ$</td>
<td>0.011</td>
<td>0.008</td>
<td>0.008</td>
<td>27:55:01</td>
</tr>
</tbody>
</table>

Fig. 9. Simulations for case 3: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 6. Simulated results of case 4.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage (mV)</th>
<th>Ansoft (1st)</th>
<th>FDTD (2nd)</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 400,142</td>
<td>$Z_{11} = 68.6 \angle -85.7^\circ$&lt;br&gt;$Z_{22} = 56.3 \angle -80.9^\circ$&lt;br&gt;$Z_{21} = 0.164 \angle -10.9^\circ$</td>
<td>$S_{11} = 0.9304 \angle -72.1^\circ$&lt;br&gt;$S_{22} = 0.853 \angle -83.1^\circ$&lt;br&gt;$S_{21} = 2.296e-3 \angle -83.6^\circ$</td>
<td>1.2</td>
<td>0.0223</td>
<td>01:02:58</td>
<td></td>
</tr>
<tr>
<td>2 480,173</td>
<td>$Z_{11} = 164.7 \angle -88.0^\circ$&lt;br&gt;$Z_{22} = 229.0 \angle -88.1^\circ$&lt;br&gt;$Z_{21} = 0.135 \angle 6.3^\circ$</td>
<td>$S_{11} = 0.9805 \angle -33.8^\circ$&lt;br&gt;$S_{22} = 0.986 \angle -24.6^\circ$&lt;br&gt;$S_{21} = 3.298e-4 \angle 153^\circ$</td>
<td>0.165</td>
<td>0.0223</td>
<td>02:56:59</td>
<td></td>
</tr>
<tr>
<td>3 576,213</td>
<td>$Z_{11} = 345.9 \angle -88.9^\circ$&lt;br&gt;$Z_{22} = 397.4 \angle -89.1^\circ$&lt;br&gt;$Z_{21} = 0.127 \angle 8.25^\circ$</td>
<td>$S_{11} = 0.9944 \angle -16.4^\circ$&lt;br&gt;$S_{22} = 0.9962 \angle -14.3^\circ$&lt;br&gt;$S_{21} = 9.02e-5 \angle 171^\circ$</td>
<td>0.045</td>
<td>0.0223</td>
<td>07:05:07</td>
<td></td>
</tr>
<tr>
<td>4 691,457</td>
<td>$Z_{11} = 433.7 \angle -88.2^\circ$&lt;br&gt;$Z_{22} = 451.4 \angle -89.3^\circ$&lt;br&gt;$Z_{21} = 0.112 \angle 7.65^\circ$</td>
<td>$S_{11} = 0.9968 \angle -13.2^\circ$&lt;br&gt;$S_{22} = 0.9973 \angle -12.6^\circ$&lt;br&gt;$S_{21} = 5.6e-5 \angle 173^\circ$</td>
<td>0.028</td>
<td>0.0223</td>
<td>12:33:51</td>
<td></td>
</tr>
<tr>
<td>5 829,750</td>
<td>$Z_{11} = 466.8 \angle -89.3^\circ$&lt;br&gt;$Z_{22} = 474.1 \angle -89.4^\circ$&lt;br&gt;$Z_{21} = 0.107 \angle 7.7^\circ$</td>
<td>$S_{11} = 0.9973 \angle -12.2^\circ$&lt;br&gt;$S_{22} = 0.9977 \angle -12^\circ$&lt;br&gt;$S_{21} = 4.741e-5 \angle 174^\circ$</td>
<td>0.024</td>
<td>0.0223</td>
<td>16:46:48</td>
<td></td>
</tr>
<tr>
<td>6 995,703</td>
<td>$Z_{11} = 480.7 \angle -89.3^\circ$&lt;br&gt;$Z_{22} = 483.9 \angle -89.4^\circ$&lt;br&gt;$Z_{21} = 0.105 \angle 7.75^\circ$</td>
<td>$S_{11} = 0.9975 \angle -11.9^\circ$&lt;br&gt;$S_{22} = 0.9978 \angle -11.8^\circ$&lt;br&gt;$S_{21} = 4.426e-5 \angle 175^\circ$</td>
<td>0.022</td>
<td>0.0223</td>
<td>21:00:35</td>
<td></td>
</tr>
<tr>
<td>7 1,088,680</td>
<td>$Z_{11} = 486.7 \angle -89.3^\circ$&lt;br&gt;$Z_{22} = 488.5 \angle -89.4^\circ$&lt;br&gt;$Z_{21} = 0.103 \angle 7.76^\circ$</td>
<td>$S_{11} = 0.9975 \angle -11.9^\circ$&lt;br&gt;$S_{22} = 0.9978 \angle -11.8^\circ$&lt;br&gt;$S_{21} = 4.426e-5 \angle 175^\circ$</td>
<td>0.021</td>
<td>0.0223</td>
<td>24:23:31</td>
<td></td>
</tr>
<tr>
<td>8 1,226,879</td>
<td>$Z_{11} = 489.8 \angle -89.3^\circ$&lt;br&gt;$Z_{22} = 490.9 \angle -89.4^\circ$&lt;br&gt;$Z_{21} = 0.103 \angle 7.77^\circ$</td>
<td>$S_{11} = 0.9977 \angle -11.7^\circ$&lt;br&gt;$S_{22} = 0.9979 \angle -11.6^\circ$&lt;br&gt;$S_{21} = 4.227e-5 \angle 175^\circ$</td>
<td>0.021</td>
<td>0.0223</td>
<td>29:32:16</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 10. Simulations for case 4: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 7. Simulated results of case 5.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage (mV)</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
</table>
| 1 400,193                         | $Z_{11} = 165.8 \angle -88^\circ$
$Z_{22} = 226.3 \angle -88.2^\circ$
$Z_{21} = 0.171 \angle -29.3^\circ$ | $S_{11} = 0.981 \angle -33.5^\circ$
$S_{22} = 0.9872 \angle -24.9^\circ$
$S_{21} = 4.187e-4 \angle 118^\circ$ | 0.21 | 01:10:16 |
| 2 480,239                         | $Z_{11} = 319.4 \angle -89^\circ$
$Z_{22} = 356.7 \angle -88.8^\circ$
$Z_{21} = 0.161 \angle -25^\circ$ | $S_{11} = 0.9947 \angle -17.8^\circ$
$S_{22} = 0.9945 \angle -16^\circ$
$S_{21} = 1.378e-4 \angle 136^\circ$ | 0.069 | 02:46:16 |
| 3 576,290                         | $Z_{11} = 418.4 \angle -89.2^\circ$
$Z_{22} = 415.2 \angle -89^\circ$
$Z_{21} = 0.156 \angle -23.5^\circ$ | $S_{11} = 0.9969 \angle -13.6^\circ$
$S_{22} = 0.996 \angle -13.7^\circ$
$S_{21} = 8.845e-5 \angle 141^\circ$ | 0.044 | 05:05:49 |
| 4 691,549                         | $Z_{11} = 451.98 \angle -89.3^\circ$
$Z_{22} = 436.8 \angle -89.1^\circ$
$Z_{21} = 0.151 \angle -23.1^\circ$ | $S_{11} = 0.9974 \angle -12.6^\circ$
$S_{22} = 0.9964 \angle -13.1^\circ$
$S_{21} = 7.519e-5 \angle 143^\circ$ | 0.038 | 08:19:50 |
| 5 829,863                         | $Z_{11} = 465.7 \angle -89.4^\circ$
$Z_{22} = 446.2 \angle -89.1^\circ$
$Z_{21} = 0.148 \angle -23^\circ$ | $S_{11} = 0.9976 \angle -12.3^\circ$
$S_{22} = 0.9966 \angle -12.8^\circ$
$S_{21} = 7.032e-5 \angle 143^\circ$ | 0.035 | 12:26:51 |
| 6 995,836                         | $Z_{11} = 472.2 \angle -89.4^\circ$
$Z_{22} = 451.5 \angle -89.1^\circ$
$Z_{21} = 0.147 \angle -22.9^\circ$ | $S_{11} = 0.9977 \angle -12.1^\circ$
$S_{22} = 0.9967 \angle -12.6^\circ$
$S_{21} = 6.793e-5 \angle 143^\circ$ | 0.034 | 17:21:15 |
| 7 1,134,472                       | $Z_{11} = 475.5 \angle -89.4^\circ$
$Z_{22} = 454.2 \angle -89.1^\circ$
$Z_{21} = 0.146 \angle -22.9^\circ$ | $S_{11} = 0.9978 \angle -12^\circ$
$S_{22} = 0.9968 \angle -12.6^\circ$
$S_{21} = 6.675e-5 \angle 143^\circ$ | 0.033 | 25:49:41 |
| 8 1,361,367                       | $Z_{11} = 477.3 \angle -89.4^\circ$
$Z_{22} = 455.7 \angle -89.1^\circ$
$Z_{21} = 0.146 \angle -22.9^\circ$ | $S_{11} = 0.9978 \angle -12^\circ$
$S_{22} = 0.9968 \angle -12.5^\circ$
$S_{21} = 6.612e-5 \angle 143^\circ$ | 0.033 | 27:57:15 |

Figure 11. Simulations for case 5: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 8. Simulated results of case 6.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage(mV)</th>
<th>Ansoft (1st)</th>
<th>FDTD (2nd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 400,328</td>
<td>Z₁₁ = 192.7° ± 88.5°</td>
<td>S₁₁ = 0.987° ± 29.1°</td>
<td>0.191</td>
<td>0.0581</td>
<td>01:09:04</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 219.8° ± 87.3°</td>
<td>S₁₂ = 0.9796° ± 25.6°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.174° ± 14.9°</td>
<td>S₂₁ = 3.8133e⁻¹ ± 154°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 480,422</td>
<td>Z₁₁ = 350.8° ± 88.7°</td>
<td>S₁₁ = 0.9939° ± 16.2°</td>
<td>0.087</td>
<td>0.0581</td>
<td>02:58:32</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 328.8° ± 88°</td>
<td>S₁₂ = 0.9899° ± 17.3°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.207° ± 11.4°</td>
<td>S₂₁ = 1.741e⁻¹ ± 149°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 576,510</td>
<td>Z₁₁ = 414.5° ± 89°</td>
<td>S₁₁ = 0.9957° ± 13.8°</td>
<td>0.063</td>
<td>0.0581</td>
<td>04:52:22</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 371.4° ± 88.2°</td>
<td>S₁₂ = 0.9919° ± 15.3°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.202° ± 10.2°</td>
<td>S₂₁ = 1.28e⁻¹ ± 153°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 691,815</td>
<td>Z₁₁ = 441.1° ± 89.1°</td>
<td>S₁₁ = 0.9963° ± 12.9°</td>
<td>0.056</td>
<td>0.0581</td>
<td>08:11:20</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 388.3° ± 88.3°</td>
<td>S₁₂ = 0.9926° ± 14.7°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.196° ± 9.8°</td>
<td>S₂₁ = 1.125e⁻¹ ± 154°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 830,184</td>
<td>Z₁₁ = 451.4° ± 89.1°</td>
<td>S₁₁ = 0.9965° ± 12.6°</td>
<td>0.053</td>
<td>0.0581</td>
<td>11:19:46</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 395.6° ± 88.4°</td>
<td>S₁₂ = 0.9929° ± 14.4°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.194° ± 9.8°</td>
<td>S₂₁ = 1.068e⁻¹ ± 154°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 996,227</td>
<td>Z₁₁ = 456.8° ± 89.1°</td>
<td>S₁₁ = 0.9967° ± 12.5°</td>
<td>0.052</td>
<td>0.0581</td>
<td>15:19:59</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 399.5° ± 88.4°</td>
<td>S₁₂ = 0.9931° ± 14.3°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.193° ± 9.7°</td>
<td>S₂₁ = 1.04e⁻¹ ± 154°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 1,179,976</td>
<td>Z₁₁ = 459.4° ± 89.1°</td>
<td>S₁₁ = 0.9967° ± 12.4°</td>
<td>0.051</td>
<td>0.0581</td>
<td>20:58:45</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 401.4° ± 88.4°</td>
<td>S₁₂ = 0.9932° ± 14.2°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.193° ± 9.63°</td>
<td>S₂₁ = 1.027e⁻¹ ± 155°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 1,280,114</td>
<td>Z₁₁ = 460.7° ± 89.1°</td>
<td>S₁₁ = 0.9967° ± 12.4°</td>
<td>0.051</td>
<td>0.0581</td>
<td>25:08:17</td>
</tr>
<tr>
<td></td>
<td>Z₁₂ = 402.4° ± 88.4°</td>
<td>S₁₂ = 0.9932° ± 14.2°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Z₁₃ = 0.193° ± 9.62°</td>
<td>S₂₁ = 1.02e⁻¹ ± 155°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 12. Simulations for case 6: (a) FEM model; (b) FDTD model; (c) FDTD results.
Table 9. Simulated results of case 7.

<table>
<thead>
<tr>
<th>Adaptive Step Mesh Size (elements)</th>
<th>Z-matrix, Ω</th>
<th>S-Matrix</th>
<th>Received voltage (mV)</th>
<th>Ansoft (1&lt;sup&gt;st&lt;/sup&gt;)</th>
<th>FDTD (2&lt;sup&gt;nd&lt;/sup&gt;)</th>
<th>Ansoft Runtime (HH:MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 399,884</td>
<td>$Z_{11} = 51.76 \angle -83.3^\circ$</td>
<td>$S_{11} = 0.889 \angle -88^\circ$</td>
<td>$S_{22} = 0.915 \angle -67.3^\circ$</td>
<td>1.3</td>
<td>0.0246</td>
<td>01:11:38</td>
</tr>
<tr>
<td>2 479,861</td>
<td>$Z_{11} = 134.2 \angle -87.5^\circ$</td>
<td>$S_{11} = 0.9721 \angle -40.9^\circ$</td>
<td>$S_{22} = 0.9838 \angle -26.9^\circ$</td>
<td>0.243</td>
<td>0.0246</td>
<td>03:12:03</td>
</tr>
<tr>
<td>3 575,834</td>
<td>$Z_{11} = 328.2 \angle -88.7^\circ$</td>
<td>$S_{11} = 0.9932 \angle -17.3^\circ$</td>
<td>$S_{22} = 0.9952 \angle -15.1^\circ$</td>
<td>0.063</td>
<td>0.0246</td>
<td>07:24:23</td>
</tr>
<tr>
<td>4 691,003</td>
<td>$Z_{11} = 423 \angle -89^\circ$</td>
<td>$S_{11} = 0.996 \angle -13.5^\circ$</td>
<td>$S_{22} = 0.9969 \angle -12.8^\circ$</td>
<td>0.04</td>
<td>0.0246</td>
<td>12:41:40</td>
</tr>
<tr>
<td>5 829,204</td>
<td>$Z_{11} = 463.7 \angle -89.2^\circ$</td>
<td>$S_{11} = 0.997 \angle -12.3^\circ$</td>
<td>$S_{22} = 0.9974 \angle -12.1^\circ$</td>
<td>0.032</td>
<td>0.0246</td>
<td>16:49:03</td>
</tr>
<tr>
<td>6 995,047</td>
<td>$Z_{11} = 479.8 \angle -89.2^\circ$</td>
<td>$S_{11} = 0.9973 \angle -11.9^\circ$</td>
<td>$S_{22} = 0.9977 \angle -11.8^\circ$</td>
<td>0.029</td>
<td>0.0246</td>
<td>21:27:27</td>
</tr>
<tr>
<td>7 1,102,183</td>
<td>$Z_{11} = 486.9 \angle -89.3^\circ$</td>
<td>$S_{11} = 0.9974 \angle -11.7^\circ$</td>
<td>$S_{22} = 0.9977 \angle -11.7^\circ$</td>
<td>0.028</td>
<td>0.0246</td>
<td>24:56:38</td>
</tr>
<tr>
<td>8 1,164,687</td>
<td>$Z_{11} = 490.4 \angle -89.3^\circ$</td>
<td>$S_{11} = 0.9975 \angle -11.6^\circ$</td>
<td>$S_{22} = 0.9977 \angle -11.6^\circ$</td>
<td>0.028</td>
<td>0.0246</td>
<td>25:47:53</td>
</tr>
</tbody>
</table>

Figure 13. Simulations for case 7: (a) FEM model; (b) FDTD model; (c) FDTD results.
3.3 FEM accuracy vs. FDTD accuracy
Assuming the value produced by Ansoft/ANSYS HFSS at the final adapted mesh consisting of approximately 1,200,000-1,400,000 tetrahedra is an accurate value, the estimated relative error percentage can be calculated as:

\[
\delta = \left| \frac{V_{HFSS} - V_{FDTD}}{V_{HFSS}} \right| \times 100
\]  

(15)

where \( V \) is the received voltage amplitude. Using Eq. (15) for all cases produces a maximum estimated relative error of 27\%, a surprisingly low result considering the major simplifications made in moving from the inhomogeneous to homogeneous body methodology. A summary of the estimated relative errors is provided in Table 10.

Table 10. Summary of relative error and simulation runtime values. The results vary depending on the server occupancy.

<table>
<thead>
<tr>
<th>Case number from Table 2</th>
<th>Estimated relative error (%) vs. the finest FEM mesh</th>
<th>Ansoft/ANSYS HFSS runtime (HH:MM:SS)</th>
<th>FDTD runtime (MM:SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.7</td>
<td>23:29:10</td>
<td>10:57</td>
</tr>
<tr>
<td>2</td>
<td>21.1</td>
<td>24:53:08</td>
<td>15:22</td>
</tr>
<tr>
<td>3</td>
<td>27.0</td>
<td>27:55:01</td>
<td>28:01</td>
</tr>
<tr>
<td>4</td>
<td>6.2</td>
<td>29:32:16</td>
<td>28:12</td>
</tr>
<tr>
<td>5</td>
<td>5.8</td>
<td>27:57:15</td>
<td>27:51</td>
</tr>
<tr>
<td>6</td>
<td>13.9</td>
<td>25:08:17</td>
<td>15:12</td>
</tr>
<tr>
<td>7</td>
<td>12.1</td>
<td>25:47:53</td>
<td>27:45</td>
</tr>
</tbody>
</table>

At first sight, it might appear counter-intuitive that a heterogeneous, high fidelity FEM model with advanced boundary conditions would perform in a similar manner to a homogeneous model with rather simple boundary conditions. We may therefore conclude that the portion of the signal that passes through the body experiences severe attenuation and appears to be insignificant at the receiving antenna, for virtually any link assembly in Figs. 7 to 13. In other words, it is the diffraction around the human body that determines the transfer function for out-of-body antennas at 402 MHz.

3.4 FEM runtime vs. FDTD runtime
Another factor worth consideration is simulation runtime. There is a very significant difference in runtimes between the FEM and FDTD models with a relatively insignificant gain in relative error value – see Table 3 above. Typical runtimes for the higher fidelity FEM models are on the order of a full day while the lower fidelity FDTD models run in about 20 minutes.

One can mention from Figs. 7-13 that the accuracy of the FEM results for human body modeling is insufficient when the mesh size is less than 500,000-700,000 tetrahedra (runtime is less than 5-7 hours).
4. Use of custom homogeneous FDTD body meshes to study the effect of different body types

In the previous section, we have demonstrated that it is the diffractive path *around* the human body that determines the major propagation path when using out-of-body antennas at 402 MHz. In other words, the internal body composition has little influence on the path loss as long as body’s relative dielectric constant and conductivity are large. This observation makes it possible to use various homogeneous body meshes in order to study the effect of different body shapes.

While the high fidelity volume mesh is excellent for providing baseline values for comparison, the body position is fixed and cannot be modified. In our pursuit to obtain geometries for different body types and positions, we have created a methodology for generating our own surface and homogeneous volume meshes which we can customize as needed.

4.1. Body surface scan
The process begins by scanning the human body using a Model WB4 whole body color scanner manufactured by Cyberware [42], shown in Fig. 14. This platform is able to acquire a full 3D human geometry quickly using a combination of 4 sensors and software to assimilate data and output to a variety of file formats. The system setup enables a variety of body types and positions of interest to be accurately digitized for further manipulation. For this study, four male volunteers were scanned in a number of different positions, producing almost 30 datasets for analysis.

Fig. 14. Cyberware’s model WB4 whole body color 3D scanner.
Geometric data acquired in this manner most likely will require postprocessing of some type due to a variety of reasons. The actual volume of data is quite large and may call for data coarsening. Also, masking of certain areas (for example, under the arms) will produce ‘holes’ in the resulting data set that need to be filled.

For these types of operations, MeshLab v1.3.0b, an open source software package has been used [43]. MeshLab is capable of many mesh operations, including creating an initial triangular surface mesh, removal of unwanted or hanging nodes and self intersecting faces, automatic filling of holes and mesh smoothing. Many standard input and output file formats are supported.

For the meshes obtained in our study, we imported the scanned results as binary Polygon File Format files into MeshLab and automatically filled all small holes. The resulting geometry ‘shells’ were the basis for creation of a full surface mesh via Poisson Surface Reconstruction [44], producing a watertight unstructured triangular mesh. This step can be seen in the left and central portions of Fig. 15.

Fig. 15. The process of transforming a 3D color scan into a surface triangular mesh: Left – the original color scan; center – the surface mesh resulting from Poisson surface reconstruction in MeshLab; right – the FDTD mesh in the simulation domain.

After this step, the mesh is ready to be operated on in MATLAB®. We have used a pair of scripts by Mr. Luigi Giaccari (Italy) called MyRobustCrust.m and InPolyedron.m. The first is responsible for final surface mesh construction and element normal alignment while the second identifies the nodes strictly within this surface mesh. Both scripts are available via the MATLAB File Exchange database. At this point, the mesh is ready for FDTD simulation in MATLAB® as previously described.
The entire mesh generation process is summarized in Fig. 16. Several different body types and positions obtained in this way are shown in Fig. 17. Human body phantoms are shown in Fig. 18, depicting arrays of either other antennas or field sensing nodes.

Fig. 16. Overall flow diagram presenting the geometry data acquisition, manipulation, and FDTD simulation procedure.

Fig. 17. Examples of different body types and positions: (a) arms raised; (b) kneeling; (c) running.
Fig. 18. Human body phantoms of various configurations: (a) torso surrounded by an array of antennas; (b) head with internal field sensing nodes; (c) typical results.

4.2. Effect of different body shapes on voltage transfer function

This subsection is aimed to answer the following question: how severe is the change in the transfer function if different homogeneous body shapes would be used in the previous section while keeping the antenna location the same? In other words, how severe is the effect of the slightly different path lengths around the body?
The antenna location needs to be specified uniquely. In this study, for different body shapes, the antenna location is always measured from the top of a human head. The generator voltage amplitude is again 1V, and $R_g = R_{load} = 50\Omega$.

Selected results from FDTD simulations, which are related to two different body models (subject A: male, age 60 and subject B: male, age 30) with the identical antenna positions (versus the top of the head), are presented in Figs. 19 to 23.

One can see that the magnitudes of the received voltage values match exceptionally well not only with each other, but also with those of the Ansoft/ANSYS human body mesh given in the previous section. Other homogeneous human body models used for the present study confirm this observation although the deviation could be slightly larger.

Fig. 19. Subjects A (left) and B (right) configured for case 1 antenna arrangement in Table 2. Receiving antenna voltage for each model was identical to that of the FEM case (0.119 mV).
Fig. 20. Subjects A (left) and B (right) configured for case 2 antenna arrangement in Table 2. Receiving antenna voltage for each model was identical to that of the FEM case (0.09 mV).

Fig. 21. Subjects A (left) and B (right) configured for case 3 antenna arrangement in Table 2. Receiving antenna voltage for each model was very close to that of the FEM case (7.7 μV vs. 7.8 μV, respectively).
Fig. 22. Subjects A (left) and B (right) configured for case 4 antenna arrangement in Table 2. Receiving antenna voltage for each model was very close to that of the FEM case (22 μV vs. 22.3 μV, respectively).
These observations suggest that a generic semi-empirical theoretical model might exist, which estimates the path loss around the human body reasonably well for out-of-body antennas at 402 MHz while keeping in mind a variety of specific body shapes. Indeed, this model shall leave freedom for taking into account particular antenna features, matching properties, and detuning close to the human body.

### 4.3. Parallel MATLAB-based FDTD

The FDTD method has been implemented successfully in the past using the Message Passing Interface (MPI) on distributed systems with a significant reduction in simulation time [45] and [46]; used to examine radiation characteristics of a dipole antenna operating at 900 MHz and 1.8 GHz in close proximity to a human head [47]; and applied to the study of portable phone signal reception at 900 MHz in the presence of human hands [48]. Proper execution of the parallel FDTD method has been validated against experimental measurements and accomplished at relatively large scales (up to 4,000 processors) with high efficiency (90%) [49]. Graphical Processing Units (GPUs) offer another parallel processing avenue with potentially lower infrastructure costs and decreased implementation complexity and have been shown to be very applicable to the FDTD method [50].

Given that our FDTD algorithm has been written entirely in MATLAB®, the most immediate realization of parallel capabilities on our hardware will be to adapt our program based on guidelines established within the MATLAB® parallel computing toolbox. This set of high-level constructs enables parallel computing on eight cores without dealing with the programming complexities associated with MPI or Compute Unified Device Architecture (CUDA). To date, our efforts have been met with mixed results.

### 5. Conclusions

In this study, voltage and power transfer functions for the path loss of a 402 MHz body area network have been reviewed. The corresponding expressions are valid in both near- and far-field of a TX antenna.

Next, it has been shown that basic FDTD simulations for a homogeneous human body model implemented in MATLAB® agree quite well with the advanced FEM solver for an inhomogeneous accurate human body model. Both methods model a voltage transfer function (path loss) for out-of-body dipole antennas at 402 MHz at different antenna locations, as close to the body as 15mm.

The reason for the good agreement is that the propagation path is mostly determined by a diffraction of the electromagnetic signal around the body, not by the propagation through
the (inhomogeneous) body. This diffraction is similar to a *creeping wave* in the GTD (Geometrical Theory of Diffraction) for smooth surfaces [51-53]. In summary,

- Out-of-body wireless link weakly depends on internal body composition;
- Out-of-body wireless link weakly depends on body shape;
- Critical diffraction parameters include path length and body area projected onto the plane perpendicular to path.

Such observations make it possible to use various homogeneous body meshes in order to study the effect of different body types and positions for out-of-body antennas. A method of creating such meshes using a 3D body scanner is described. For a number of white male body meshes, the magnitudes of the received voltages match exceptionally well when the antenna positions are measured from the top of the head.

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References


