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Foreword by the Editor

The modeling of wearable antennas and their interaction with the human body are topics of considerable interest at present. This month's column describes work on a 402 MHz system. It shows that simplified body models can very adequately describe the coupling between antennas via the body. The

authors also discuss a number of tools that can assist in the generation of the complex meshes required for the numerical simulation of this problem. The editor thanks them for a very useful and practical contribution.

Modeling Accuracy and Features of Body-Area Networks with Out-of-Body Antennas at 402 MHz

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Voltage and power transfer functions for the path loss of a 402 MHz body-area network are reviewed. The corresponding expressions are valid in both the near- and far-fields of a transmitting antenna. It was shown that basic FDTD simulations for a homogeneous human-body model, implemented in *MATLAB*[®], agreed quite well with the advanced FEM solver for an inhomogeneous accurate human-body model. Both methods modeled 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 15 mm. The reason for the good agreement was that the propagation path was mostly determined by a diffraction of the electromagnetic signal around the body, and not by propagation through the (inhomogeneous) body. Such an observation made 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 three-dimensional body scanner is described. For a number of different white-male body meshes, the magnitudes of the received voltages matched exceptionally well when the antenna positions were measured from the top of the head.

Keywords: Body area networks; FDTD methods; path loss; electromagnetic propagation; antenna proximity factors

1. 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 wireless body-area networks 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's surface, operating at 900 MHz [1]; to create radiation patterns of $\lambda/4$ -wavelength monopole antennas in cell phones with the human head [2] at 1.8 GHz; to show the degree of interference between mobile communication systems and in-vivo sensors [3] at 900 MHz; and to 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]; have been 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 wireless body-area network 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. Good comparisons to results were obtained via the FDTD method and experimental measurements in the range of 2.4 to 6 GHz [12, 13]. Other major relevant commercial software packages include CST's *Microwave Studio* (Germany), packages by REMCOM (USA), and SEMCAD X (Switzerland).

Experimental characterization of wireless body-area network systems can provide a wealth of validation data, with studies having been conducted for implantable sensors at 403 MHz and 2.4 GHz [14], on the effect of body posture on received signal strength [15] at 2.4 GHz, and on the 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, presented still more applications of wireless body-area networks.

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 US Federal Communications Commission (FCC) established a new Medical Device Radiocommunication Service, and adopted technical and service rules for advanced wireless medical radio-communication devices used for diagnostic and therapeutic purposes in humans at 401-406 MHz. The FCC has also proposed to allocate up to 24 MHz of spectrum in the 413-457 MHz band for implantable micro-stimulation devices using wireless technologies.

The antenna-to-antenna link was established in the frequency and time domains. In the frequency domain, we used an accurate impedance-matrix approach to the antenna-to-antenna transfer function, due to Silver and Collin [22, 23]. This approach allowed us to avoid somewhat questionable equivalent-circuit models of the receiving antenna [22-25], and to proceed with the impedance and scattering parameters of the corresponding two-port network, which can be directly measured. We then compared basic FDTD simulations for the path loss around the human body, implemented entirely in *MATLAB*, with accurate Finite-Element Method (FEM) modeling of the inhomogeneous human body in Ansoft/ANSYS *HFSS v.12.1*. In the FEM, we routinely studied body meshes with more than 1,000,000 tetrahedra, and investigated the convergence accuracy at different mesh sizes.

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

We show that even the basic 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 ran many times faster than the FEM simulations, with greater ease of implementation.

Finally, we generated a number of our own proprietary human-body surface (triangular) and volume (brick, homogeneous) meshes using Cyberware's WB4 whole-body color three-dimensional scanner and post-processing software, *MeshLab*. Those human-body models were exported to *MATLAB*. We further applied the FDTD algorithm to those models in order to

study the effect of different body types on the path loss between two antennas close to the human body.

2. Voltage and Power Transfer Functions in the Near and Far Fields

2.1 Impedance-Matrix Approach

In this section, we describe an accurate impedance-matrix approach to the antenna-to-antenna transfer function, which originates from Silver and Collin [22, 23]. This approach is valid in both the near and far fields, 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 circuit form. Such a model works in both the frequency and time domains, as shown in Figure 1. The only real voltage source in the circuit is the generator voltage.

The model in Figure 1 becomes especially inviting in the frequency domain (see Figure 2). Of primary interest to us is the received-load phasor voltage, V_{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

$$T_V = \frac{V_{load}}{V_g}. \quad (1)$$

For a system with two lumped ports (transmitting and receiving 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 specified port impedances. The transmitting-receiving antenna network shown in Figure 2a is replaced by an equivalent two-port microwave network, described by an impedance matrix $\hat{Z}$, given by Equation (2) and shown in Figure 2b:

$$\hat{Z} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}. \quad (2)$$

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 Figure 2b with the impedance matrix given by Equation (2) is replaced by an equivalent T network (the Π equivalent is also possible, but it is not considered here). The resulting circuit is given in Figure 2c. The solution for the receiver voltage in Figure 2c then becomes an exercise in basic circuit analysis. One has

$$V_{load} = \frac{R_{load} Z_{21}}{(R_g + Z_{11})(R_{load} + Z_{22}) - Z_{21}^2} V_g = T_V V_g \quad (3)$$

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 transmitting and receiving antennas, 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, $Z_{21} \rightarrow 0$.

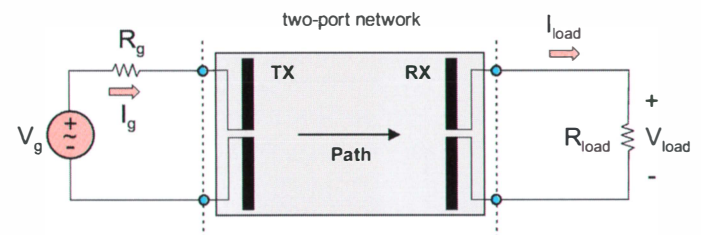


Figure 1. A path between the transmitting and receiving antennas in the form of a two-port network. The time-domain version is shown.

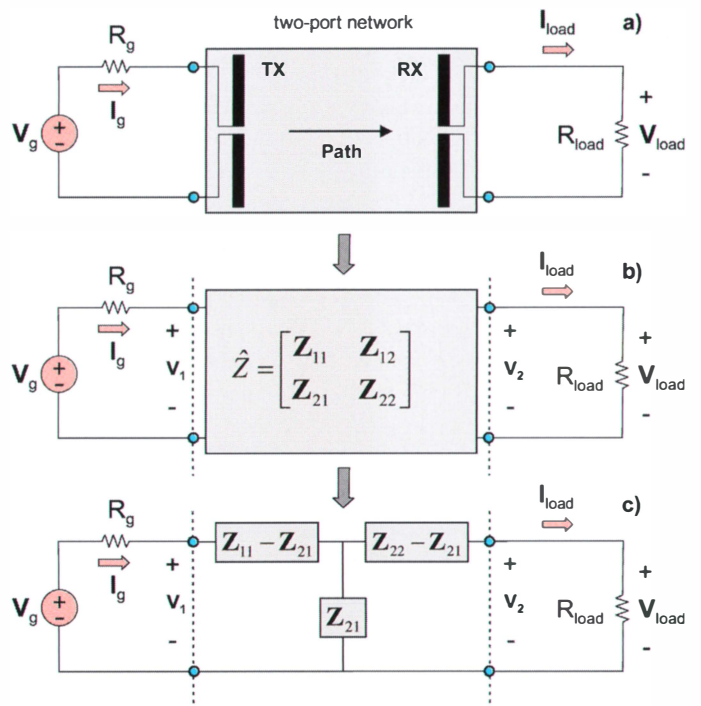


Figure 2. Transformations of the two-port antenna network in the frequency domain.

In that case, the transmitter in Figure 2c is shorted out, and the receiver gets no signal. Thus, at large separation distances, $|Z_{21}| \ll \min(|Z_{TX}|, |Z_{RX}|)$, and one has from Equation (3),

$$V_{load} = \frac{R_{load} Z_{21}}{(R_g + Z_{11})(R_{load} + Z_{22})} V_g = T_V V_g. \quad (4)$$

2.2 The Transfer Function in Terms of Voltage Across the Transmitting Antenna

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

$$T = \frac{V_{load}}{V_g}. \quad (5)$$

Solving the circuit in Figure 2c once again, one has

$$V_{load} = \frac{R_{load} Z_{21}}{Z_{11}(R_{load} + Z_{22}) - Z_{21}^2} V_1 = TV_1. \quad (6)$$

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

2.3 Scattering-Matrix Approach

Although the transfer functions given in Equations (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 Figure 1 or Figure 2a.

In Figure 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.,

$$Z_0 = R_g = R_{load}. \quad (7)$$

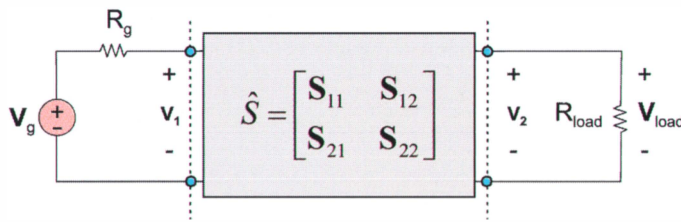


Figure 3. Network transformation of the antenna-to-antenna link: S-matrix approach.

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

$$S_{21} = \frac{2Z_{21}Z_0}{(Z_{11} + Z_0)(Z_{22} + Z_0) - Z_{21}^2}, \quad (8)$$

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

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

$$T_V = \frac{1}{2} S_{21}, \quad (10)$$

$$T = \frac{S_{21}}{1 + S_{11}}. \quad (11)$$

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

2.4 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

$$T_P \equiv |S_{21}|^2. \quad (12)$$

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 Figure 2 or 3,

$$P_{load} = \frac{1}{2} \frac{|V_{load}|^2}{R_{load}}, \quad (13a)$$

as a function of the power delivered to a transmitting antenna, P_a , if and only if the transmitting antenna was *perfectly matched* to the generator resistance [29], that is,

$$P_a = \frac{1}{8} \frac{|V_g|^2}{R_g}. \quad (13b)$$

3. FEM and FDTD Solvers

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

3.1 FEM Frequency-Domain Solver: Ansoft/ANSYS HFSS v. 12

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

The boundary conditions for the phantom in Figure 4 were implemented using a perfectly matched layer (PML) [31] around the volume of the body/antenna. The size of the perfectly match layer base box was selected as 850 mm $\times$ 850 mm $\times$ 2100 mm. Fine FEM meshes, with up to 1,400,000 tetrahedra, were considered. The FEM resolution within the body was 2 mm, which corresponded to $\lambda_b/50$, where $\lambda_b = 105.5$ mm was the in-body wavelength at 402 MHz, assuming $\epsilon_r = 50$.

3.2 Antennas

For all presented configurations, small center-fed blade dipole antennas, with total lengths of 11.25 cm and widths of 1.25 cm, were used, at a frequency of 402 MHz. We did not take the dipole balun into consideration. At this frequency, these antennas were 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 were *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's 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.

3.3 FDTD Solver on Uniform Cubic Grids

Simulations were carried out using a simple yet fully functional FDTD algorithm. All antenna parameters defined in

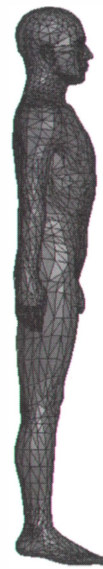


Figure 4. A high-fidelity human-body mesh with 2 mm resolution: Ansoft HFSS (ANSYS).

Section 3.2 were retained. The one-cell lumped port model for the transmitter was coupled with a resistive voltage source, as shown in Figure 1 on the left. For the receiver, the port was terminated into a load resistance (see Figure 1 on the right). In both cases, the port treatment followed [33]. The dipole blade was modeled as a PEC strip. The standard FDTD method was programmed in *MATLAB* using the Yee second-order differences on a three-dimensional uniformly staggered grid, and was consistent with [1]. The FDTD resolution within the body was 12.5 mm, which corresponded to $\lambda_b/9$, where $\lambda_b = 105.5$ mm was the in-body wavelength at 402 MHz, assuming $\epsilon_r = 50$.

Fast first-order Mur's absorbing boundary conditions (ABCs) [34], supplemented by a super-absorption [35] update for the magnetic field (which corresponded to second-order accuracy), were used. Liao's absorbing boundary conditions [36] of third and fourth order provide nearly identical results, and may be a viable alternative. No perfectly matched layer absorbing boundary conditions were employed in the present code. The FDTD solution was executed for a sinusoidal voltage generator, feeding the transmitting antenna at 402 MHz. The source had an internal resistance, R_g , of 50 Ω . The load resistance, R_{load} , of the receiving circuit was also 50 Ω . Once the solution had been stabilized, the transfer function at the frequency of interest was evaluated via a sliding-window Fourier transform. The entire FDTD algorithm was implemented as a relatively short vectorized *MATLAB* script, taught in a computational electromagnetics ECE class at WPI.

The above method was straightforwardly modified by implementing a more-accurate subcell wire-dipole model for cylindrical dipoles, and an infinitesimal feeding gap [37, 38]. Also, edge-field singularities have been addressed for blade dipole wings. A very promising hybrid method, combining FDTD and MoM (for the most recent development, see [39, 40]) may be a way to model small helical-coil antennas along with the dipoles.

3.4 Body Phantom Used for Comparison

The human-body volume used in the Ansoft simulations and shown in Figure 4 was exported to the *MATLAB* workspace, and further to the FDTD cubic mesh, using Ansoft's *Field Calculator*. Any cube-center node with a large permittivity/conductivity was assigned an average relative dielectric constant of 50 and a body conductivity value of 0.5 S/m. Any FDTD node within the body's lungs was modeled as air. The average values of the medium parameters were used for every field node in the vicinity of the body-air interface. A detailed discussion of interface averaging was given in [41]. No subcell boundary models were employed. The FDTD mesh consisted of approximately 310,000 brick elements. The size of the entire FDTD domain was selected as 800 mm $\times$ 800 mm $\times$ 2000 mm.

3.5 Other Body Phantoms

To model the effects of various body shapes, we also generated a number of our own proprietary human-body surface (triangular) and volume (brick, homogeneous) meshes. This was done using Cyberware's WB4 whole-body color three-dimensional scanner, and MeshLab's post-processing software. Those human body models were exported to *MATLAB*. We further applied the FDTD algorithm to those models, in order to study the effects of different body types on the path loss between two antennas close to the human body. We intended to show that the path loss was weakly affected by a specific body shape.

4. FEM Accuracy Versus FDTD Accuracy for Voltage Transfer Function

4.1 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 Section 3.2) in free space, using the FDTD and FEM methods, respectively. In this simple case, the antenna center-to-center separation distance was 41.3 cm, suitable for studying the near-field link. The simulation domain and graphical display of the three-dimensional FDTD method in the antenna's E plane could be seen in the upper portion of Figure 5, 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 1 V, with an assumption that $R_g = R_{load}$. The voltage transfer function, T_v , given by Equation (3) or Equation (10) was used for that purpose, and implemented in both the FEM and FDTD.

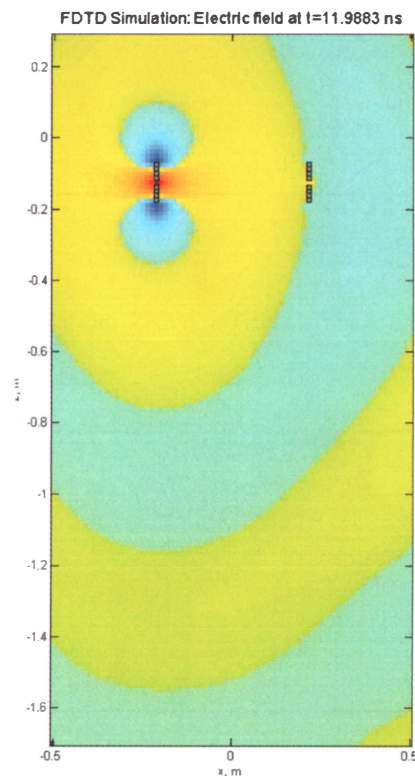


Figure 5a. The E-plane simulation results in free space for the FDTD simulation domain with two dipole antennas. The field scale follows Equation (14).

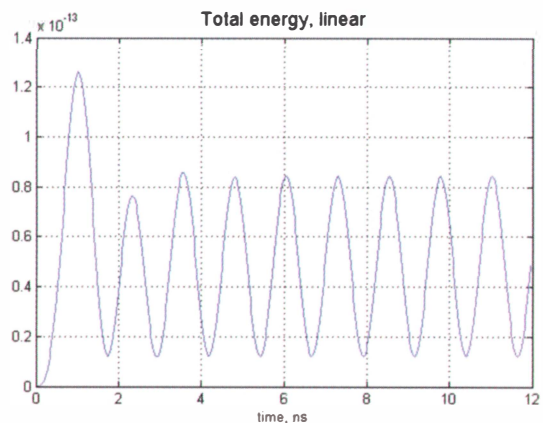
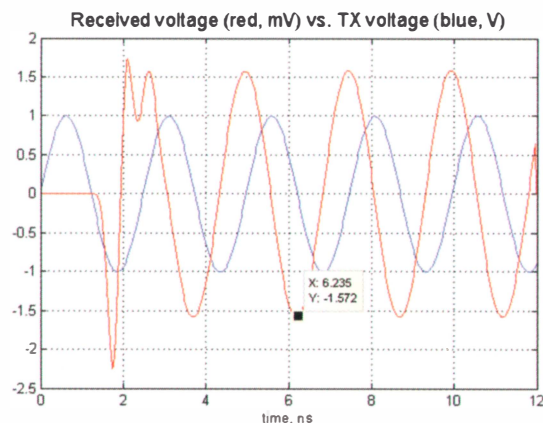


Figure 5b. The FDTD transmitting/receiving voltages for the two dipole antennas.

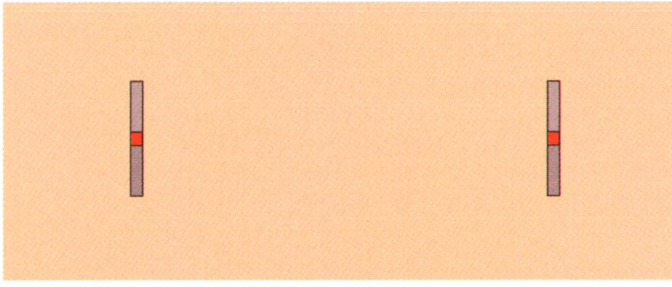


Figure 5c. The Ansoft/ANSYS HFSS model of the dipole geometry.

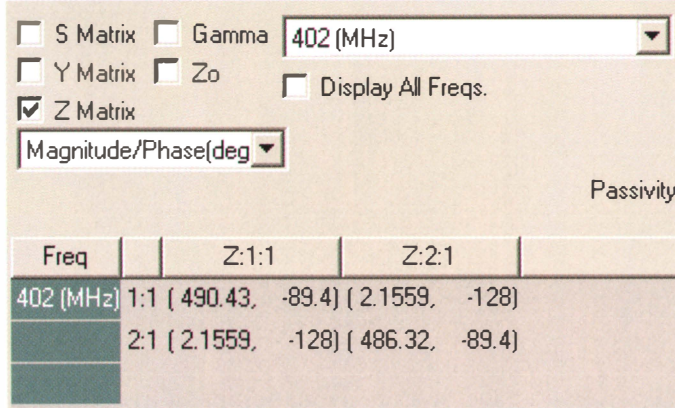


Figure 5d. The impedance matrix resulting from the simulations of Figure 5.

Results for two different values of $R_g = R_{load}$ are summarized in Table 1. In the worst case (a very large generator resistance), the difference between the two simulation methodologies did not exceed 9%. This was a reasonable accuracy for modeling path loss. The result for the 1000 Ω case was clearly less accurate, since the antennas at $R_g = R_{load} = 1000 \Omega$ acquired less *active* power, which increased the impedance mismatch and the related numerical noise.

4.2 Path Loss Near the Human Body

We 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 Figures 6 to 12). In all cases, the same antenna dimensions (a total length of 11.25 cm and a width of 1.25 cm) described above were retained, and $R_g = R_{load} = 50 \Omega$.

Table 1. The received voltage amplitudes for two different values of $R_g = R_{load}$ for the free-space setup in Figure 5. The source voltage had an amplitude of 1 V.

$R_g = R_{load}$	Ansoft HFSS Data for the Received Voltage Amplitude	FDTD Data for the Received Voltage Amplitude
50 Ω	0.44 mV	0.45 mV
1000 Ω	1.72 mV	1.57 mV

The results from these simulations are presented below. The 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 Equation (3) or Equation (10) was used, and implemented in both the FEM and FDTD. We accurately tracked the Ansoft convergence results for each case, and those results are also shown in Figures 6 to 12, as functions of the number of mesh-refinement steps and the current mesh size.

On its top, every figure shows 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 an average relative dielectric constant value of 50 and a body conductivity value of 0.5 S/m. 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 Figures 6 to 12, in the antenna's E plane, according to the dependence

$$|E_z|^{0.2} \text{sign}(|E_z|). \quad (14)$$

4.3 FEM Accuracy Versus FDTD Accuracy

Assuming the value produced by Ansoft/ANSYS HFSS at the final adapted mesh, consisting of approximately 1,200,000 to 1,400,000 tetrahedra, was an accurate value, the estimated relative error percentage could be calculated as

$$\delta = \frac{|V_{HFSS} - V_{FDTD}|}{V_{HFSS}} 100, \quad (15)$$

where v is the received voltage amplitude. Using Equation (15) for all cases produced 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 2. The antenna-configuration coordinates for the simulated cases: Ansoft/ANSYS HFSS for the high-fidelity body model and FDTD for a homogeneous body (except for the lungs). All coordinates were with respect to the Ansoft's human-body model.

Case Number	Antenna x coordinate (mm)	Antenna z coordinate (mm)
1	206.5	-130.5
2	206.5	-190.5
3	206.5	-390.5
4	306.5	-390.5
5	156.5	-390.5
6	146.5	-390.5
7	356.5	-390.5



Figure 6a. The FEM model simulations for case 1.

At first sight, it might appear counterintuitive 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 passed through the body experienced severe attenuation and appeared to be insignificant at the receiving antenna for virtually any link assembly in Figures 6 to 12. In other words, it was the diffraction around the human body that determined the transfer function for out-of-body antennas at 402 MHz.

4.4 FEM Running Time Versus FDTD Running Time

Another factor worth consideration is simulation running time. There was a very significant difference in running times between the FEM and FDTD models, with a relatively insignificant gain in relative error value: see Table 3. Typical running times for the higher-fidelity FEM models were on the order of a full day, while the lower-fidelity FDTD models ran in about 20 minutes.

One can mention from Figures 6-12 that the accuracy of the FEM results for human-body modeling was insufficient when the mesh size was less than 500,000-700,000 tetrahedra (the running time was less than 5-7 hours).

5. The Use of Custom Homogeneous FDTD Body Meshes to Study the Effect of Different Body Types

In the previous section, we demonstrated that it was the diffractive path *around* the human body that determined the major propagation path when using out-of-body antennas at 402 MHz. In other words, the internal body composition had

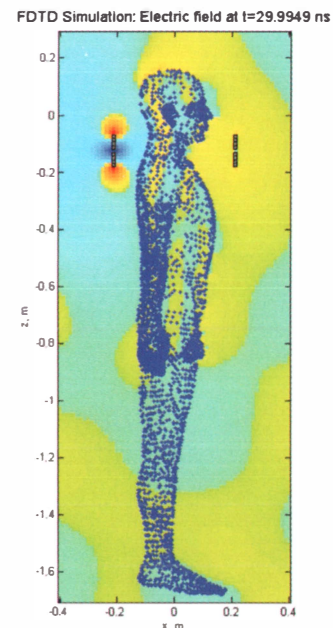


Figure 6b. The FDTD model simulations for case 1.

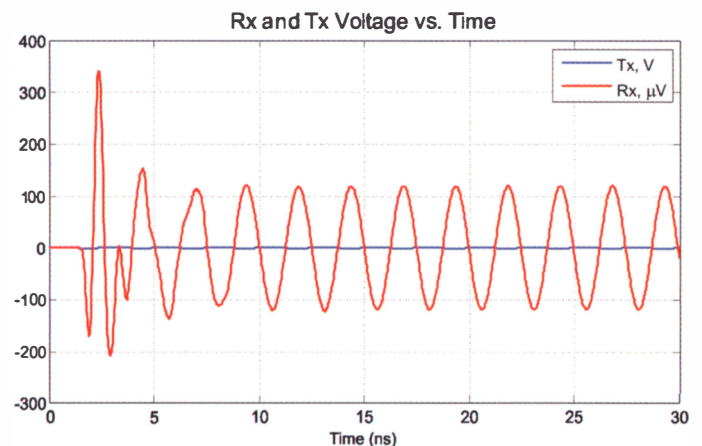


Figure 6c. The FDTD results for case 1.



Figure 7a. The FEM model simulations for case 2.



Figure 8a. The FEM model simulations for case 3.

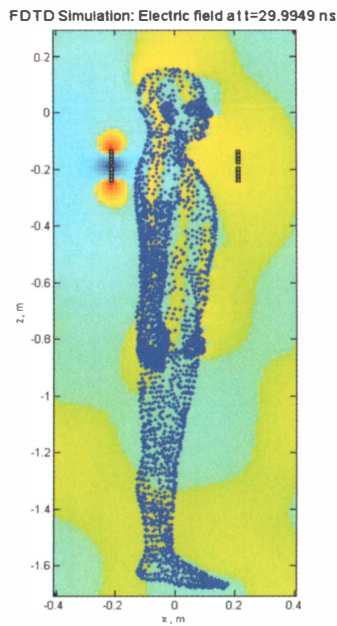


Figure 7b. The FDTD model simulations for case 2.

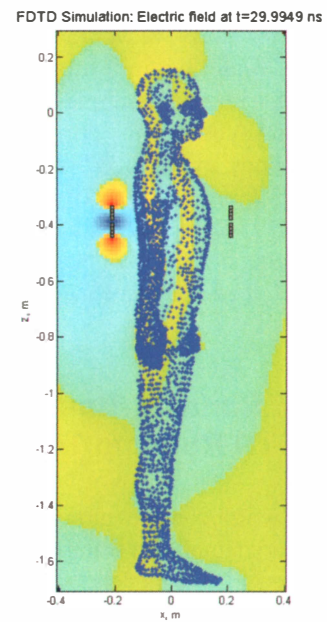


Figure 8b. The FDTD model simulations for case 3.

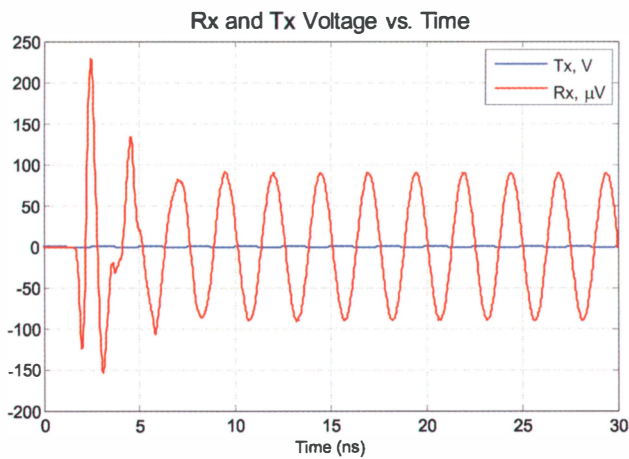


Figure 7c. The FDTD results for case 2.

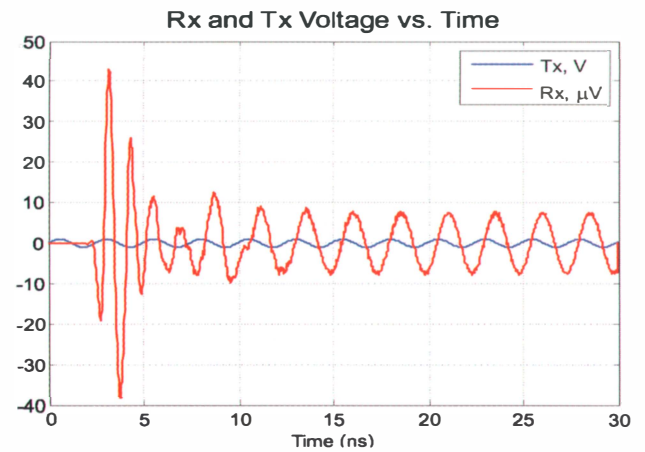


Figure 8c. The FDTD results for case 3.



Figure 9a. The FEM model simulations for case 4.



Figure 10a. The FEM model simulations for case 5.

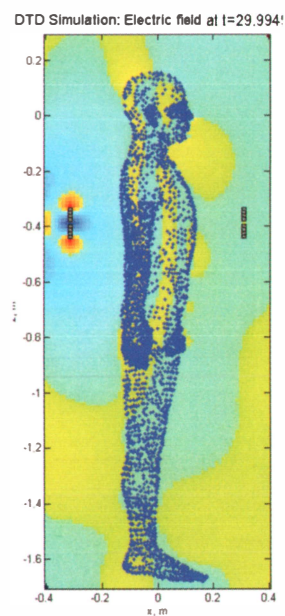


Figure 9b. The FDTD model simulations for case 4.

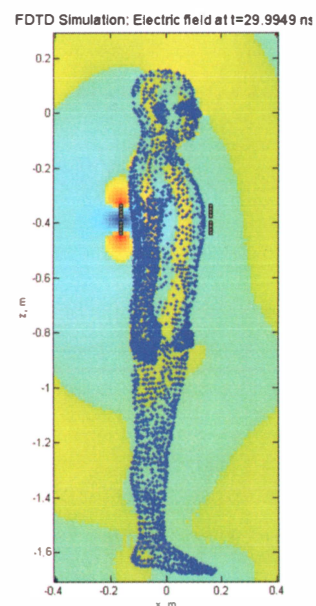


Figure 10b. The FDTD model simulations for case 5.

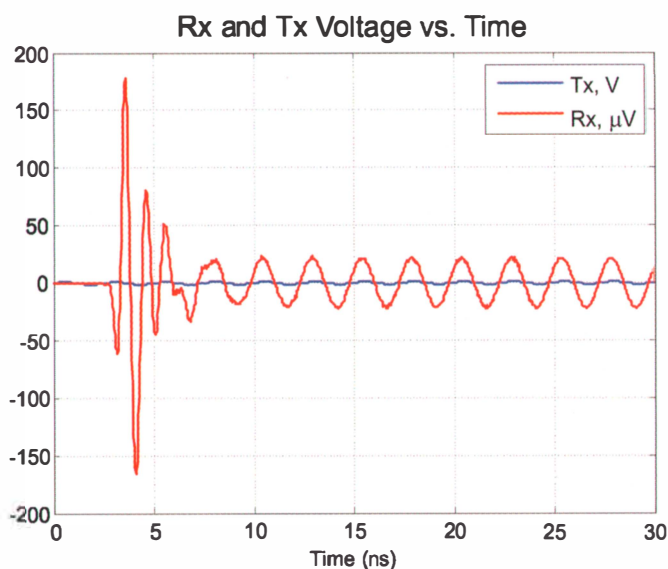


Figure 9c. The FDTD results for case 4..

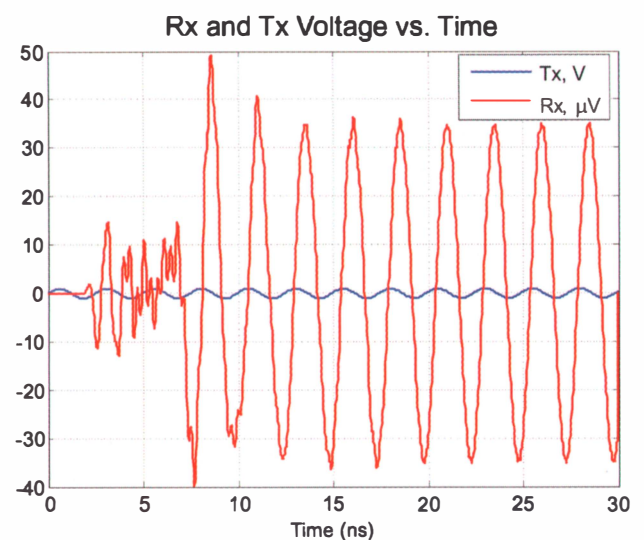


Figure 10c. The FDTD results for case 5.



Figure 11a. The FEM model simulations for case 6.



Figure 12a. The FEM model simulations for case 7.

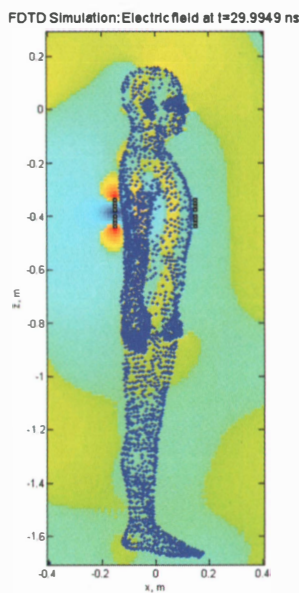


Figure 11b. The FDTD model simulations for case 6.

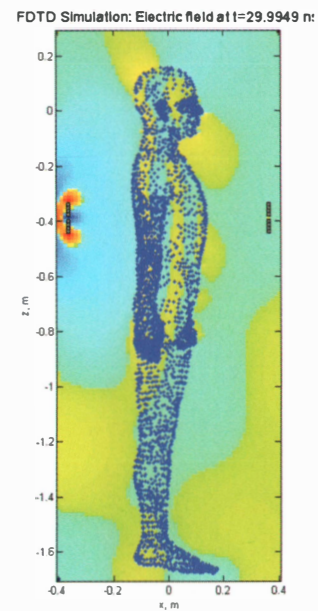


Figure 12b. The FDTD model simulations for case 7.

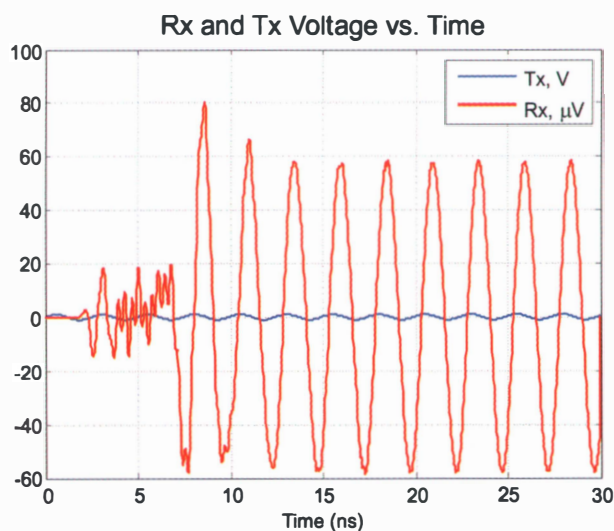


Figure 11c. The FDTD results for case 6.

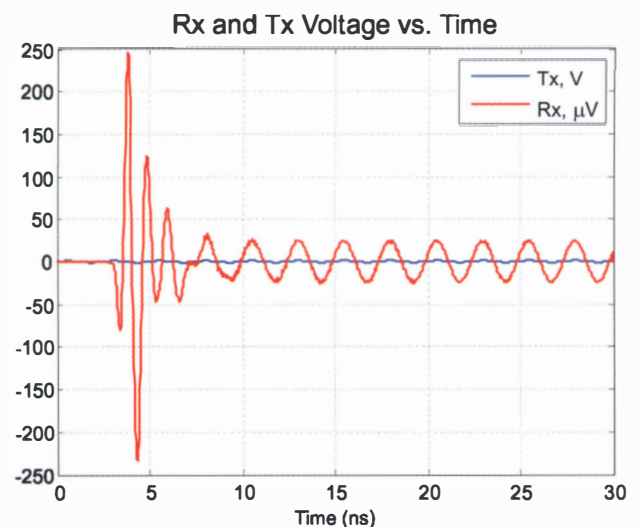


Figure 12c. The FDTD results for case 7.

Table 3. The simulated results for case 1.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
1 388,240	$Z_{11} = 86\angle -88.1^\circ$ $Z_{22} = 170.8\angle -87.7^\circ$ $Z_{21} = 0.499\angle -167^\circ$	$S_{11} = 0.9711\angle -60.3^\circ$ $S_{22} = 0.9782\angle -32.6^\circ$ $S_{21} = 2.75e-3\angle -36.9^\circ$	1.4	01:18:19
			0.119	
2 465,892	$Z_{11} = 236.47\angle -89.1^\circ$ $Z_{22} = 327.1\angle -88.7^\circ$ $Z_{21} = 0.4686\angle -171^\circ$	$S_{11} = 0.9935\angle -23.9^\circ$ $S_{22} = 0.9931\angle -17.4^\circ$ $S_{21} = 5.821e-4\angle -13.5^\circ$	0.291	02:56:47
			0.119	
3 559,074	$Z_{11} = 397.68\angle -89.4^\circ$ $Z_{22} = 425.97\angle -89.1^\circ$ $Z_{21} = 0.48\angle -171^\circ$	$S_{11} = 0.9972\angle -14.5^\circ$ $S_{22} = 0.9962\angle -13.4^\circ$ $S_{21} = 2.825e-4\angle -6.11^\circ$	0.139	05:41:02
			0.119	
4 670,892	$Z_{11} = 448.5\angle -89.5^\circ$ $Z_{22} = 462.2\angle -89.2^\circ$ $Z_{21} = 0.464\angle -170^\circ$	$S_{11} = 0.9979\angle -12.7^\circ$ $S_{22} = 0.997\angle -12.3^\circ$ $S_{21} = 2.21e-4\angle -4.37^\circ$	0.11	10:30:06
			0.119	
5 805,074	$Z_{11} = 474.4\angle -89.5^\circ$ $Z_{22} = 477.4\angle -89.2^\circ$ $Z_{21} = 0.4498\angle -170^\circ$	$S_{11} = 0.9982\angle -12^\circ$ $S_{22} = 0.9972\angle -12^\circ$ $S_{21} = 1.96e-4\angle -3.65^\circ$	0.098	15:19:00
			0.119	
6 966,089	$Z_{11} = 483.3\angle -89.5^\circ$ $Z_{22} = 484.8\angle -89.3^\circ$ $Z_{21} = 0.4447\angle -170^\circ$	$S_{11} = 0.9983\angle -11.8^\circ$ $S_{22} = 0.9974\angle -11.8^\circ$ $S_{21} = 1.874e-4\angle -3.38^\circ$	0.0937	20:14:30
			0.119	
7 1,074,751	$Z_{11} = 489.59\angle -89.5^\circ$ $Z_{22} = 488.2\angle -89.3^\circ$ $Z_{21} = 0.4425\angle -170^\circ$	$S_{11} = 0.9983\angle -11.7^\circ$ $S_{22} = 0.9974\angle -11.7^\circ$ $S_{21} = 1.835e-4\angle -3.24^\circ$	0.0914	27:09:30
			0.119	
8 1,141,585	$Z_{11} = 489.6\angle -89.5^\circ$ $Z_{22} = 490.1\angle -89.3^\circ$ $Z_{21} = 0.441\angle -170^\circ$	$S_{11} = 0.9983\angle -11.7^\circ$ $S_{22} = 0.9975\angle -11.6^\circ$ $S_{21} = 1.816e-4\angle -3.18^\circ$	0.0908	23:29:10
			0.119	

Table 4. The simulated results for case 2.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
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
			0.09	
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
			0.09	
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
			0.09	
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
			0.09	
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
			0.09	
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
			0.09	
7 1,054,674	$Z_{11} = 486.7\angle -89.6^\circ$ $Z_{22} = 487.1\angle -89.3^\circ$ $Z_{21} = 0.341\angle 169^\circ$	$S_{11} = 0.9985\angle -11.7^\circ$ $S_{22} = 0.9976\angle -11.7^\circ$ $S_{21} = 1.419e-4\angle -23.6^\circ$	0.071	24:53:08
			0.09	
8	Matrix Solver Exception: Failed			
			0.119	

Table 5. The simulated results for case 3.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
1 400,358	$Z_{11} = 156.6\angle -88.3^\circ$ $Z_{22} = 95.86\angle -87.9^\circ$ $Z_{21} = 0.072\angle -32.6^\circ$	$S_{11} = 0.9826\angle -35.4^\circ$ $S_{22} = 0.9698\angle -55.1^\circ$ $S_{21} = 3.95e-4\angle 98.9^\circ$	0.1975	01:41:35
			0.008	
2 480,430	$Z_{11} = 308.1\angle -89.2^\circ$ $Z_{22} = 264.2\angle -89.3^\circ$ $Z_{21} = 0.061\angle -35.1^\circ$	$S_{11} = 0.9954\angle -18.4^\circ$ $S_{22} = 0.9956\angle -21.4^\circ$ $S_{21} = 7.291e-5\angle 123^\circ$	0.0362	03:09:06
			0.008	
3 576,520	$Z_{11} = 417.9\angle -89.4^\circ$ $Z_{22} = 405.4\angle -89.5^\circ$ $Z_{21} = 0.059\angle -35^\circ$	$S_{11} = 0.9977\angle -13.6^\circ$ $S_{22} = 0.9979\angle -14.1^\circ$ $S_{21} = 3.441e-5\angle 130^\circ$	0.0171	06:38:42
			0.008	
4 691,827	$Z_{11} = 455.0\angle -89.5^\circ$ $Z_{22} = 454.5\angle -89.6^\circ$ $Z_{21} = 0.0563\angle -35.1^\circ$	$S_{11} = 0.9982\angle -12.5^\circ$ $S_{22} = 0.9984\angle -12.6^\circ$ $S_{21} = 2.684e-5\angle 132^\circ$	0.0134	10:49:25
			0.008	
5 830,194	$Z_{11} = 473.6\angle -89.6^\circ$ $Z_{22} = 473.8\angle -89.6^\circ$ $Z_{21} = 0.0546\angle -34.7^\circ$	$S_{11} = 0.9984\angle -12.1^\circ$ $S_{22} = 0.9986\angle -12^\circ$ $S_{21} = 2.4e-5\angle 132^\circ$	0.012	13:43:17
			0.008	
6 996,235	$Z_{11} = 482.5\angle -89.6^\circ$ $Z_{22} = 482.6\angle -89.6^\circ$ $Z_{21} = 0.0538\angle -34.7^\circ$	$S_{11} = 0.9985\angle -11.8^\circ$ $S_{22} = 0.9987\angle -11.8^\circ$ $S_{21} = 2.281e-5\angle 133^\circ$	0.011	22:12:00
			0.008	
7 1,130,503	$Z_{11} = 486.9\angle -89.6^\circ$ $Z_{22} = 487\angle -89.6^\circ$ $Z_{21} = 0.0533\angle -34.7^\circ$	$S_{11} = 0.9985\angle -11.7^\circ$ $S_{22} = 0.9987\angle -11.7^\circ$ $S_{21} = 2.221e-5\angle 133^\circ$	0.011	22:08:02
			0.008	
8 1,250,345	$Z_{11} = 489.4\angle -89.6^\circ$ $Z_{22} = 489.35\angle -89.6^\circ$ $Z_{21} = 0.0531\angle -34.7^\circ$	$S_{11} = 0.9986\angle -11.7^\circ$ $S_{22} = 0.9987\angle -11.7^\circ$ $S_{21} = 2.19e-5\angle 133^\circ$	0.011	27:55:01
			0.008	

Table 6. The simulated results for case 4.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
1 400,142	$Z_{11} = 68.6\angle -85.7^\circ$ $Z_{22} = 56.3\angle -80.9^\circ$ $Z_{21} = 0.164\angle -10.9^\circ$	$S_{11} = 0.9304\angle -72.1^\circ$ $S_{22} = 0.853\angle -83.1^\circ$ $S_{21} = 2.296e-3\angle -83.6^\circ$	1.2	01:02:58
			0.0223	
2 480,173	$Z_{11} = 164.7\angle -88.0^\circ$ $Z_{22} = 229.0\angle -88.1^\circ$ $Z_{21} = 0.135\angle 6.3^\circ$	$S_{11} = 0.9805\angle -33.8^\circ$ $S_{22} = 0.986\angle -24.6^\circ$ $S_{21} = 3.298e-4\angle 153^\circ$	0.165	02:56:59
			0.0223	
3 576,213	$Z_{11} = 345.9\angle -88.9^\circ$ $Z_{22} = 397.4\angle -89.1^\circ$ $Z_{21} = 0.127\angle 8.25^\circ$	$S_{11} = 0.9944\angle -16.4^\circ$ $S_{22} = 0.9962\angle -14.3^\circ$ $S_{21} = 9.02e-5\angle 171^\circ$	0.045	07:05:07
			0.0223	
4 691,457	$Z_{11} = 433.7\angle -88.2^\circ$ $Z_{22} = 451.4\angle -89.3^\circ$ $Z_{21} = 0.112\angle 7.65^\circ$	$S_{11} = 0.9968\angle -13.2^\circ$ $S_{22} = 0.9973\angle -12.6^\circ$ $S_{21} = 5.61e-5\angle 173^\circ$	0.028	12:33:51
			0.0223	
5 829,750	$Z_{11} = 466.8\angle -89.3^\circ$ $Z_{22} = 474.1\angle -89.4^\circ$ $Z_{21} = 0.107\angle 7.7^\circ$	$S_{11} = 0.9973\angle -12.2^\circ$ $S_{22} = 0.9977\angle -12^\circ$ $S_{21} = 4.741e-5\angle 174^\circ$	0.024	16:46:48
			0.0223	
6 995,703	$Z_{11} = 480.7\angle -89.3^\circ$ $Z_{22} = 483.9\angle -89.4^\circ$ $Z_{21} = 0.105\angle 7.75^\circ$	$S_{11} = 0.9975\angle -11.9^\circ$ $S_{22} = 0.9978\angle -11.8^\circ$ $S_{21} = 4.426e-5\angle 175^\circ$	0.022	21:00:35
			0.0223	
7 1,088,680	$Z_{11} = 486.7\angle -89.3^\circ$ $Z_{22} = 488.5\angle -89.4^\circ$ $Z_{21} = 0.103\angle 7.76^\circ$	$S_{11} = 0.9975\angle -11.9^\circ$ $S_{22} = 0.9978\angle -11.8^\circ$ $S_{21} = 4.426e-5\angle 175^\circ$	0.021	24:23:31
			0.0223	
8 1,226,879	$Z_{11} = 489.8\angle -89.3^\circ$ $Z_{22} = 490.9\angle -89.4^\circ$ $Z_{21} = 0.103\angle 7.77^\circ$	$S_{11} = 0.9977\angle -11.7^\circ$ $S_{22} = 0.9979\angle -11.6^\circ$ $S_{21} = 4.227e-5\angle 175^\circ$	0.021	29:32:16
			0.0223	

Table 7. The simulated results for case 5.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
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
			0.0349	
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
			0.0349	
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
			0.0349	
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
			0.0349	
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
			0.0349	
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
			0.0349	
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
			0.0349	
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
			0.0349	

Table 8. The simulated results for case 6.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
1 400,328	$Z_{11} = 192.7\angle -88.5^\circ$ $Z_{22} = 219.8\angle -87.3^\circ$ $Z_{21} = 0.174\angle -14.9^\circ$	$S_{11} = 0.987\angle -29.1^\circ$ $S_{22} = 0.9796\angle -25.6^\circ$ $S_{21} = 3.8133e-4\angle 154^\circ$	0.191	01:09:04
			0.0581	
2 480,422	$Z_{11} = 350.8\angle -88.7^\circ$ $Z_{22} = 328.8\angle -88^\circ$ $Z_{21} = 0.207\angle -11.4^\circ$	$S_{11} = 0.9939\angle -16.2^\circ$ $S_{22} = 0.9899\angle -17.3^\circ$ $S_{21} = 1.741e-4\angle 149^\circ$	0.087	02:58:32
			0.0581	
3 576,510	$Z_{11} = 414.5\angle -89^\circ$ $Z_{22} = 371.4\angle -88.2^\circ$ $Z_{21} = 0.202\angle -10.2^\circ$	$S_{11} = 0.9957\angle -13.8^\circ$ $S_{22} = 0.9919\angle -15.3^\circ$ $S_{21} = 1.28e-4\angle 153^\circ$	0.063	04:52:22
			0.0581	
4 691,815	$Z_{11} = 441.1\angle -89.1^\circ$ $Z_{22} = 388.3\angle -88.3^\circ$ $Z_{21} = 0.196\angle -9.8^\circ$	$S_{11} = 0.9963\angle -12.9^\circ$ $S_{22} = 0.9926\angle -14.7^\circ$ $S_{21} = 1.125e-4\angle 154^\circ$	0.056	08:11:20
			0.0581	
5 830,184	$Z_{11} = 451.4\angle -89.1^\circ$ $Z_{22} = 395.6\angle -88.4^\circ$ $Z_{21} = 0.194\angle -9.8^\circ$	$S_{11} = 0.9965\angle -12.6^\circ$ $S_{22} = 0.9929\angle -14.4^\circ$ $S_{21} = 1.068e-4\angle 154^\circ$	0.053	11:19:46
			0.0581	
6 996,227	$Z_{11} = 456.8\angle -89.1^\circ$ $Z_{22} = 399.5\angle -88.4^\circ$ $Z_{21} = 0.193\angle -9.7^\circ$	$S_{11} = 0.9967\angle -12.5^\circ$ $S_{22} = 0.9931\angle -14.3^\circ$ $S_{21} = 1.04e-4\angle 154^\circ$	0.052	15:19:59
			0.0581	
7 1,179,976	$Z_{11} = 459.4\angle -89.1^\circ$ $Z_{22} = 401.4\angle -88.4^\circ$ $Z_{21} = 0.193\angle -9.63^\circ$	$S_{11} = 0.9967\angle -12.4^\circ$ $S_{22} = 0.9932\angle -14.2^\circ$ $S_{21} = 1.027e-4\angle 155^\circ$	0.051	20:58:45
			0.0581	
8 1,280,114	$Z_{11} = 460.7\angle -89.1^\circ$ $Z_{22} = 402.4\angle -88.4^\circ$ $Z_{21} = 0.193\angle -9.62^\circ$	$S_{11} = 0.9967\angle -12.4^\circ$ $S_{22} = 0.9932\angle -14.2^\circ$ $S_{21} = 1.02e-4\angle 155^\circ$	0.051	25:08:17
			0.0581	

Table 9. The simulated results for case 7.

Adaptive Step Mesh Size (elements)	Z-Matrix (Ω)	S-Matrix	Received Voltage: Ansoft (top) FDTD (bottom) (mV)	Ansoft Running Time (HH:MM:SS)
1 399,884	$Z_{11} = 51.76\angle -83.3^\circ$ $Z_{22} = 75\angle -84.5^\circ$ $Z_{21} = 0.186\angle -25.7^\circ$	$S_{11} = 0.889\angle -88^\circ$ $S_{22} = 0.915\angle -67.3^\circ$ $S_{21} = 2.596e-3\angle 69.3^\circ$	1.3	01:11:38
			0.0246	
2 479,861	$Z_{11} = 134.2\angle -87.5^\circ$ $Z_{22} = 209\angle -87.9^\circ$ $Z_{21} = 0.153\angle -21.6^\circ$	$S_{11} = 0.9721\angle -40.9^\circ$ $S_{22} = 0.9838\angle -26.9^\circ$ $S_{21} = 4.854e-4\angle 120^\circ$	0.243	03:12:03
			0.0246	
3 575,834	$Z_{11} = 328.2\angle -88.7^\circ$ $Z_{22} = 377.5\angle -88.9^\circ$ $Z_{21} = 0.166\angle -18.3^\circ$	$S_{11} = 0.9932\angle -17.3^\circ$ $S_{22} = 0.9952\angle -15.1^\circ$ $S_{21} = 1.304e-4\angle 143^\circ$	0.063	07:24:23
			0.0246	
4 691,003	$Z_{11} = 423\angle -89^\circ$ $Z_{22} = 444.9\angle -89.2^\circ$ $Z_{21} = 0.152\angle -17.7^\circ$	$S_{11} = 0.996\angle -13.5^\circ$ $S_{22} = 0.9969\angle -12.8^\circ$ $S_{21} = 7.961e-5\angle 147^\circ$	0.04	12:41:40
			0.0246	
5 829,204	$Z_{11} = 463.7\angle -89.2^\circ$ $Z_{22} = 473\angle -89.3^\circ$ $Z_{21} = 0.142\angle -17.7^\circ$	$S_{11} = 0.997\angle -12.3^\circ$ $S_{22} = 0.9974\angle -12.1^\circ$ $S_{21} = 6.39e-5\angle 149^\circ$	0.032	16:49:03
			0.0246	
6 995,047	$Z_{11} = 479.8\angle -89.2^\circ$ $Z_{22} = 483.7\angle -89.3^\circ$ $Z_{21} = 0.138\angle -17.8^\circ$	$S_{11} = 0.9973\angle -11.9^\circ$ $S_{22} = 0.9977\angle -11.8^\circ$ $S_{21} = 5.879e-5\angle 149^\circ$	0.029	21:27:27
			0.0246	
7 1,102,183	$Z_{11} = 486.9\angle -89.3^\circ$ $Z_{22} = 488.9\angle -89.3^\circ$ $Z_{21} = 0.136\angle -17.8^\circ$	$S_{11} = 0.9974\angle -11.7^\circ$ $S_{22} = 0.9977\angle -11.7^\circ$ $S_{21} = 5.655e-5\angle 149^\circ$	0.028	24:56:38
			0.0246	
8 1,164,687	$Z_{11} = 490.4\angle -89.3^\circ$ $Z_{22} = 491.2\angle -89.3^\circ$ $Z_{21} = 0.136\angle -17.8^\circ$	$S_{11} = 0.9975\angle -11.6^\circ$ $S_{22} = 0.9977\angle -11.6^\circ$ $S_{21} = 5.556e-5\angle 149^\circ$	0.028	25:47:53
			0.0246	

**Table 10. A summary of the relative error and simulation running time values.
The results varied depending on the server occupancy.**

Case Number from Table 2	Estimated Relative Error (%) Compared to the Finest FEM Mesh	Ansoft/ANSYS HFSS Running Time (HH:MM:SS)	FDTD Running Time (MM:SS)
1	23.7	23:29:10	10:57
2	21.1	24:53:08	15:22
3	27.0	27:55:01	28:01
4	6.2	29:32:16	28:12
5	5.8	27:57:15	27:51
6	13.9	25:08:17	15:12
7	12.1	25:47:53	27:45



Figure 13. Cyberware's model WB4 whole-body color three-dimensional scanner.

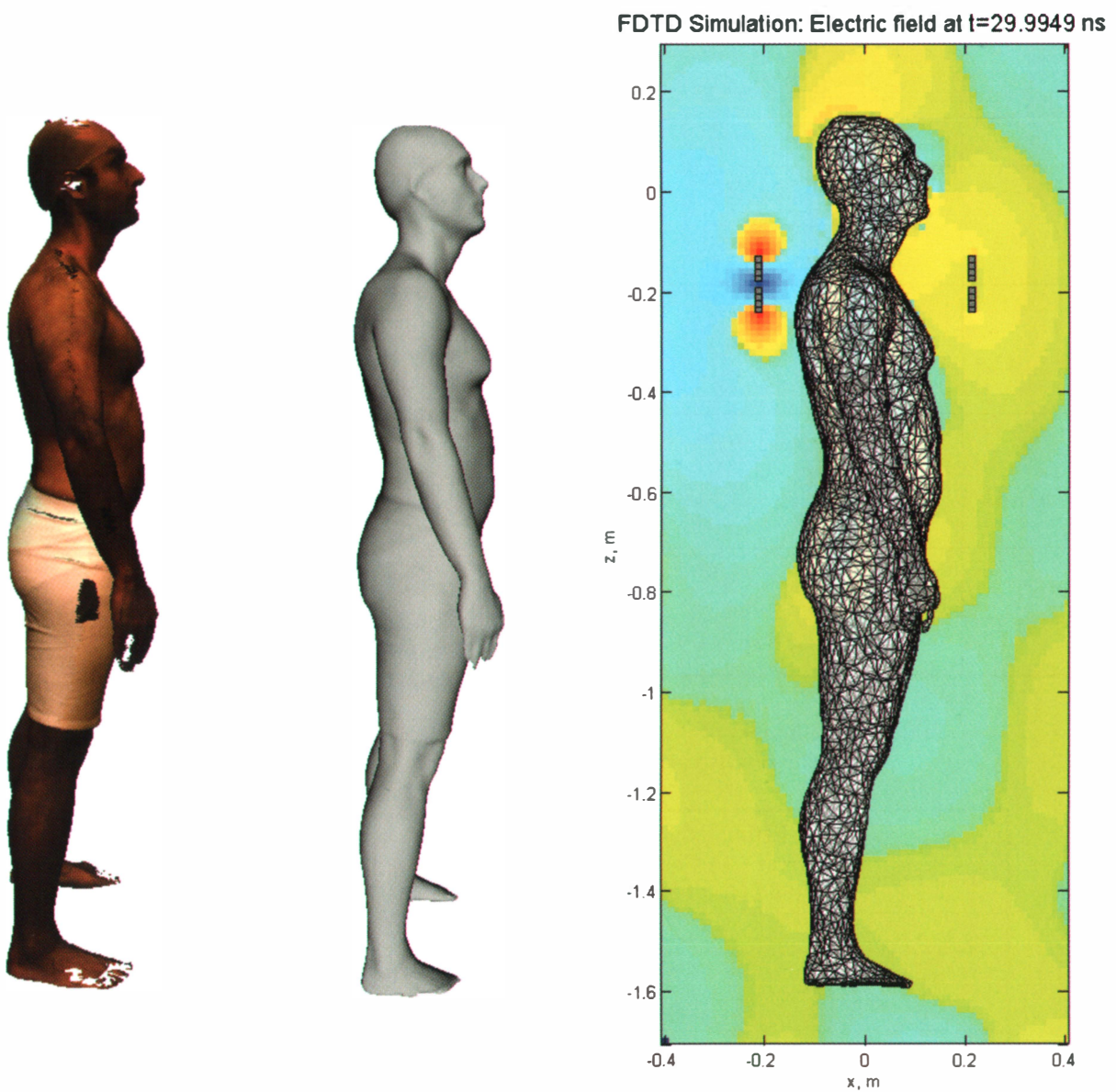


Figure 14. The process of transforming a three-dimensional color scan into a surface triangular mesh: (l) the original color scan; (c) the surface mesh resulting from Poisson surface reconstruction in *MeshLab*; (r) the FDTD mesh in the simulation domain.

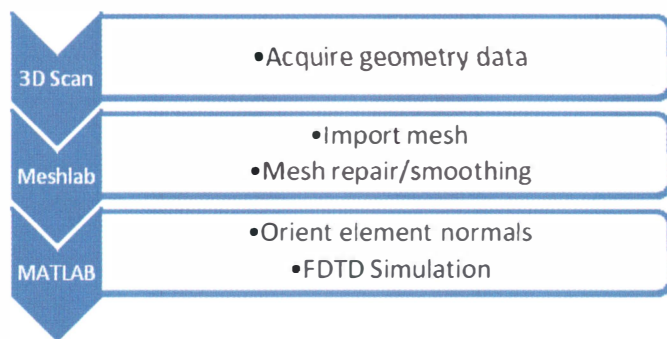


Figure 15. An overall flow diagram, presenting the geometry-data acquisition, manipulation, and FDTD simulation procedure.

little influence on the path loss, as long as body's relative dielectric constant and conductivity were large. This observation made it possible to use various homogeneous body meshes in order to study the effect of different body shapes.

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

5.1 Body Surface Scan

The process began by scanning the human body using a Model WB4 whole-body color scanner, manufactured by Cyberware [42], as shown in Figure 13. This platform was able to acquire a full three-dimensional human geometry quickly, using a combination of four sensors and software to assimilate data and output the data to a variety of file formats. The system setup enabled 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 data sets for analysis.

Geometric data acquired in this manner most likely will require post-processing 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, was 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 the creation of a full

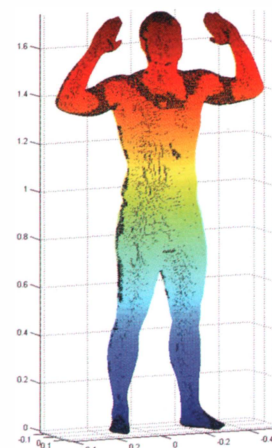


Figure 16a. Examples of different body types and positions: arms raised.

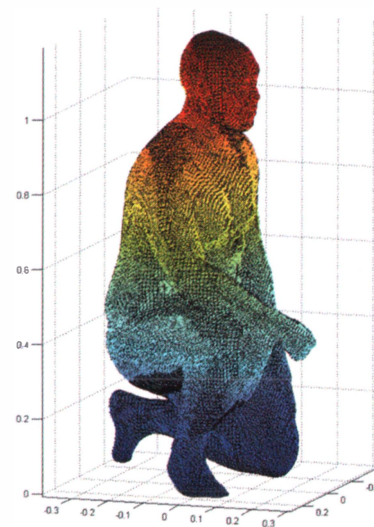


Figure 16b: Examples of different body types and positions: (b) kneeling.

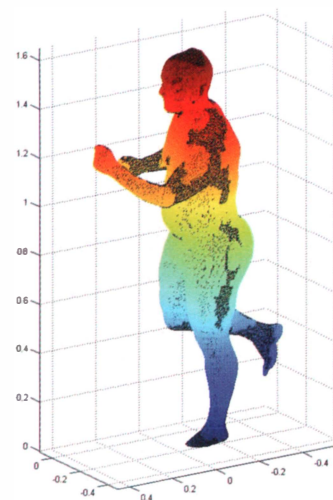


Figure 16c: Examples of different body types and positions: running.

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 Figure 14.

After this step, the mesh was ready to be operated on in *MATLAB*. We used a pair of scripts by Mr. Luigi Giaccari (Italy), called *MyRobustCrust.m* and *InPolyedron.m*. The first was responsible for final surface-mesh construction and element normal alignment, while the second identified the nodes strictly within this surface mesh. Both scripts are available via the *MATLAB* File Exchange database. At this point, the mesh was ready for FDTD simulation in *MATLAB*, as previously described.

The entire mesh-generation process is summarized in Figure 15. Several different body types and positions obtained in this way are shown in Figure 16.

4.2. Effects of Different Body Shapes on Voltage Transfer Function

This subsection is directed toward answering the following question: how severe was the change in the transfer function if different homogeneous body shapes were used in the previous section, while keeping the antenna location the same? In other words, how severe was 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 was always *measured from the top of a human head*. The generator voltage amplitude was again 1 V, and $R_g = R_{load} = 50 \Omega$.

Selected results from the FDTD simulations, related to two different body models (subject A: male, age 60; and subject B: male, age 30), with identical antenna positions (with respect to the top of the head), are presented in Figures 17 to 21. One could see that the magnitudes of the received voltage values matched 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 confirmed this observation, although the deviations were slightly larger.

These observations suggest that a generic semi-empirical theoretical model might exist that 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 would leave freedom for taking into account particular antenna features, matching properties, and detuning close to the human body.

5.3 Parallel *MATLAB*-Based FDTD

The FDTD method was successfully implemented in the past using the *Message Passing Interface (MPI)* on distributed

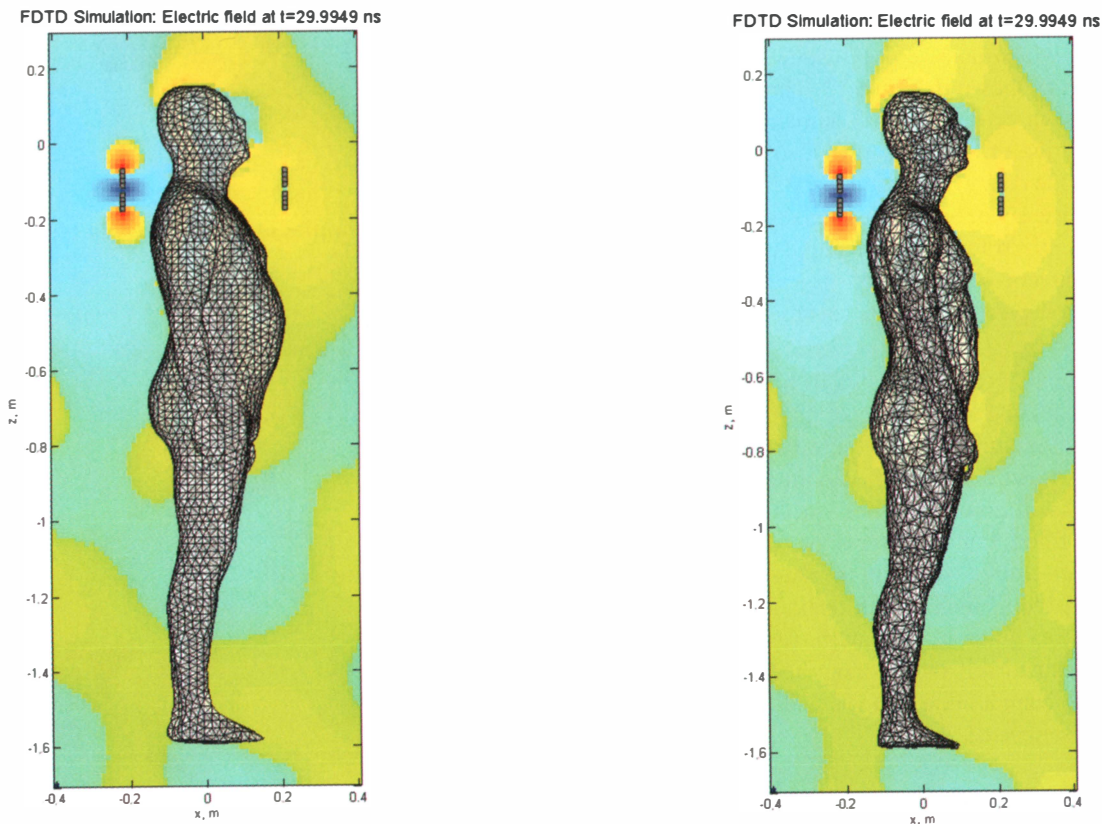


Figure 17. Subjects A (left) and B (right) configured for the case 1 antenna arrangement in Table 2. The receiving-antenna voltage for each model was identical to that of the FEM case (0.119 mV).

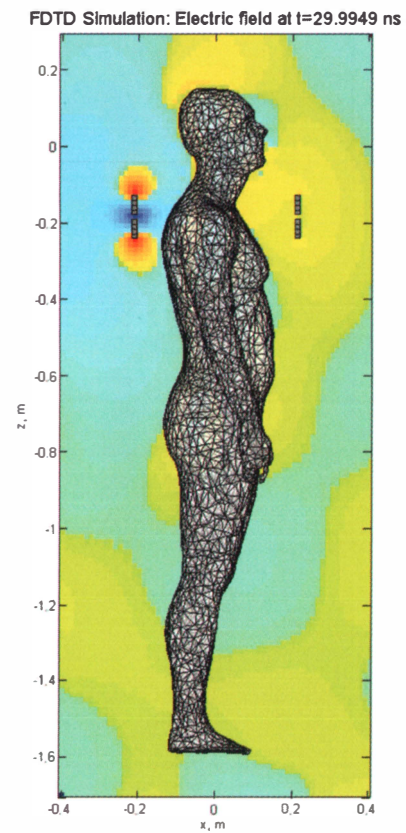
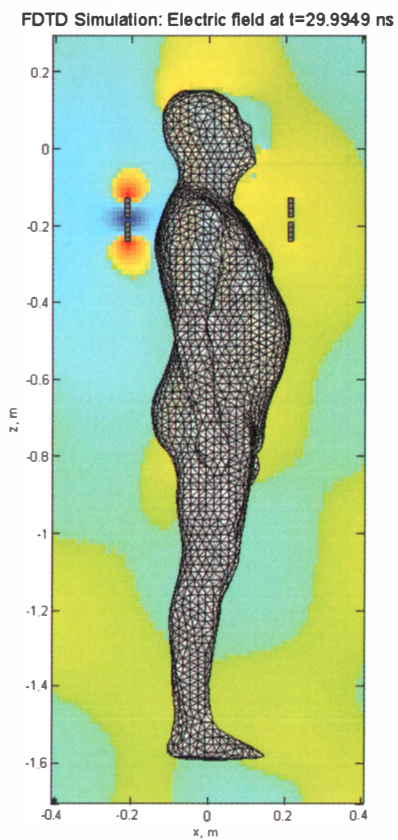


Figure 18. Subjects A (left) and B (right) configured for the case 2 antenna arrangement in Table 2. The receiving-antenna voltage for each model was identical to that of the FEM case (0.09 mV).

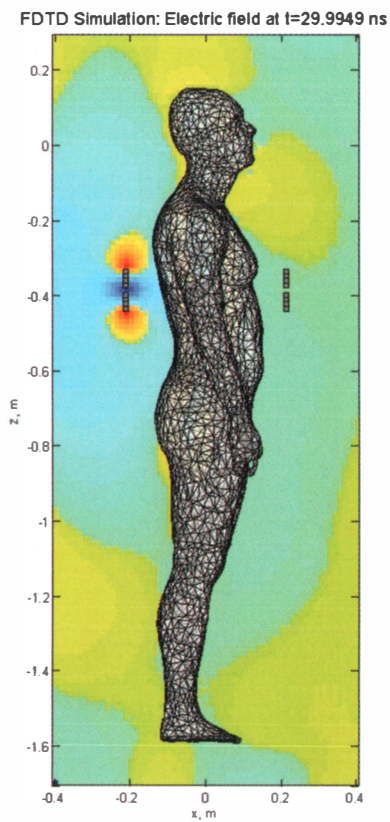
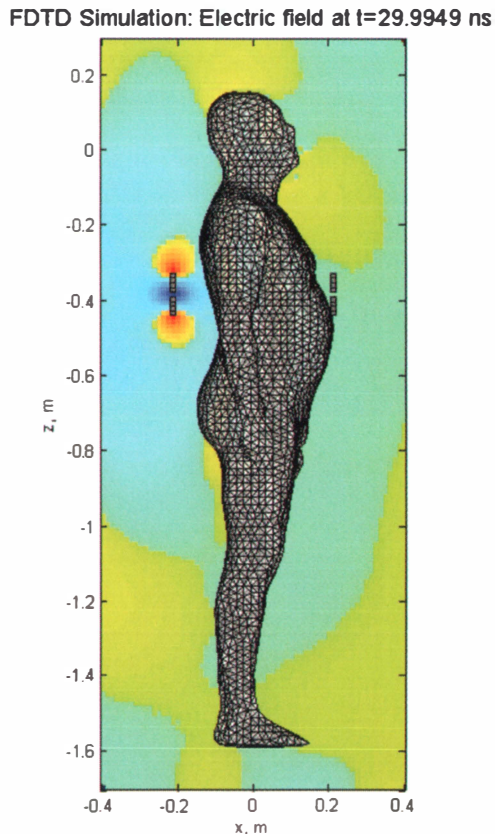


Figure 19. Subjects A (left) and B (right) configured for the case 3 antenna arrangement in Table 2. The receiving-antenna voltage for each model was very close to that of the FEM case (7.7 μ V and 7.8 μ V, respectively).

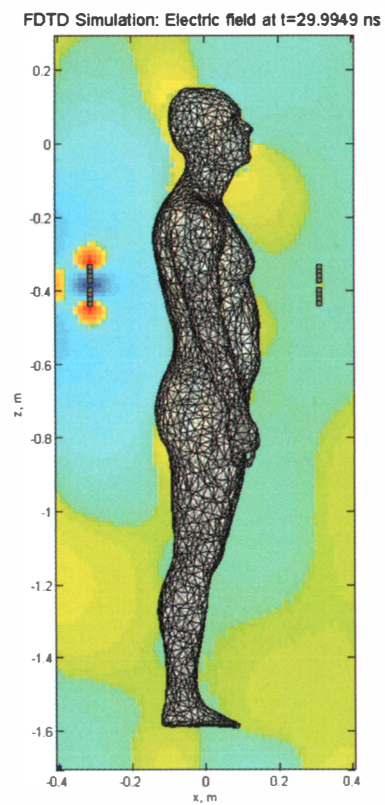
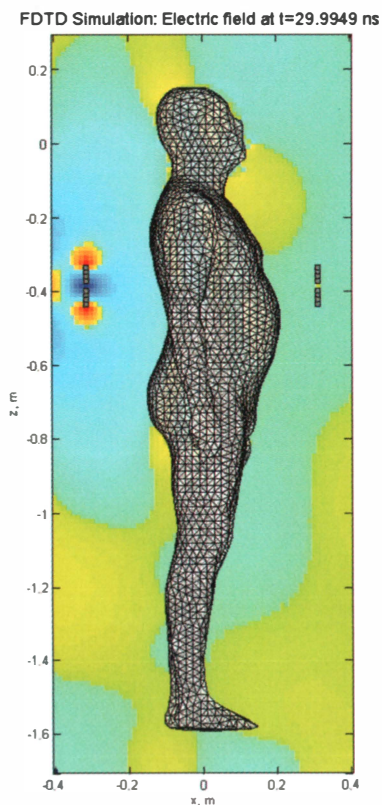


Figure 20. Subjects A (left) and B (right) configured for the case 4 antenna arrangement in Table 2. The receiving antenna voltage for each model was very close to that of the FEM case ($22 \mu\text{V}$ and $22.3 \mu\text{V}$, respectively).

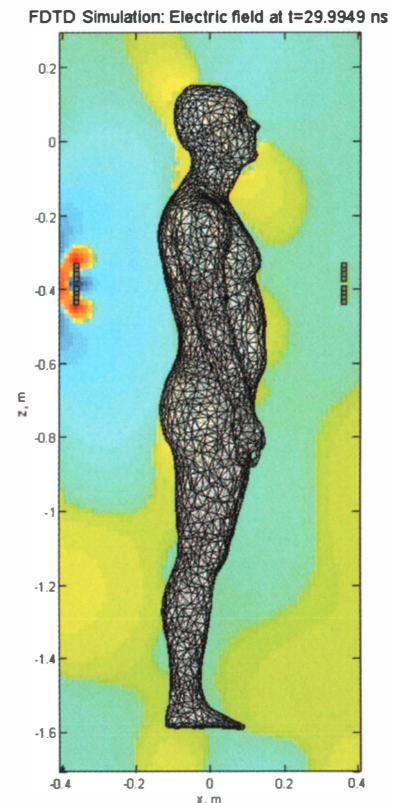
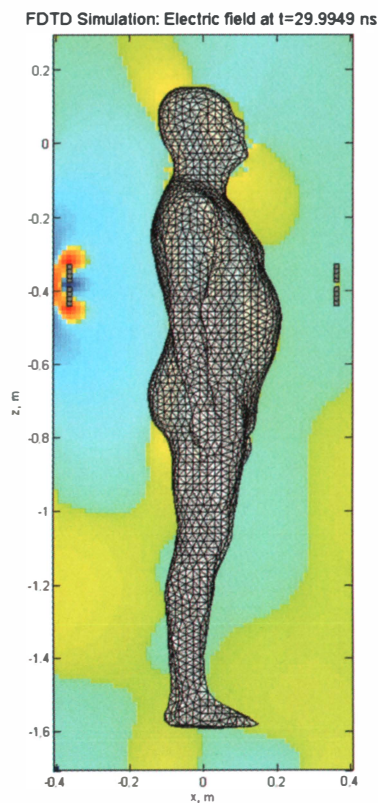


Figure 21. Subjects A (left) and B (right) configured for the case 7 antenna arrangement in Table 2. The receiving antenna voltage for each WPI model was very close to that of the FEM case ($24.8 \mu\text{V}$ and $24.6 \mu\text{V}$, respectively).

systems, with a significant reduction in simulation time [45, 46]. It was used to examine the radiation characteristics of a dipole antenna operating at 900 MHz and 1.8 GHz in close proximity to a human head [47]. It was 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 was 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. They have been shown to be very applicable to the FDTD method [50].

Given that our FDTD algorithm was written entirely in *MATLAB*, the most immediate realization of parallel capabilities on our hardware would 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 the Compute Unified Device Architecture (CUDA). To date, our efforts have met with mixed results.

6. 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 the near and far fields of a transmitting antenna.

It was next shown that basic FDTD simulations for a homogeneous human-body model, implemented in *MATLAB*, agreed quite well with the advanced FEM solver for an inhomogeneous accurate human-body model. Both methods modeled 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 15 mm. The reason for the good agreement was that the propagation path was mostly determined by diffraction of the electromagnetic signal around the body, and not by 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,

- The out-of-body wireless link weakly depended on the internal body composition;
- The out-of-body wireless link weakly depended on body shape;
- The critical diffraction parameters included path length and body area projected onto the plane perpendicular to the 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 three-dimensional body scanner was described. For a number of white male body meshes, the magnitudes of the received voltages matched exceptionally well when the antenna positions were measured from the top of the head.

Relevant (extended) FDTD *MATLAB* scripts may be accessed as *P*-codes via the Internet [54].

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8. References

1. H. Terchoune, D. Lautru, A. Gati, A. C. Carrasco, M. F. Wong, J. Wiat, and V. F. Hanna, "On-Body Radio Channel Modeling for Different Human Body Models Using FDTD Techniques," *Microwave and Optical Technology Letters*, **51**, 10, October 2009, pp. 2498-2501.
2. M. Slegban, S. Mazur, and C. Törnevik, "Comparisons of Measurements and FDTD Calculations of Mobile Phone Electromagnetic Far-Fields and Near-Fields," *Antennas and Propagation Society International Symposium*, Montreal, **2**, July 1997, pp. 978-981.
3. F. Gustrau, A. Bahr, U. Gollor, and D. Köther, "Interference of Active Medical Implants with GSM and UMTS Mobile Phones and Base Stations," *Biomedizinische Technik/Biomedical Engineering*, **48**, 2003.
4. W. G. Scanlon and N. E. Evans, "Numerical Analysis of Bodyworn UHF Antenna Systems," *Electronics & Communication Engineering Journal*, April 2001, pp. 55-64.
5. A. Fort, C. Desset, J. Ryckaert, P. De Doncker, L. Van Biesen, and S. Donnay, "Ultra Wide-Band Body Area Channel Model," *IEEE International Conference on Communications*, **4**, August 2005, pp. 2840-2844.
6. A. Fort, F. Keshmiri, G. R. Crusats, C. Craeye, and C. Oestges, "A Body Area Propagation Model Derived From Fundamental Principles: Analytical Analysis and Comparison with Measurements," *IEEE Transactions on Antennas and Propagation*, **AP-58**, 2, February 2010, pp. 503-514.

7. A. Sani, Y. Zhao, A. Alomainy, Y. Hao, and C. Parini, "Modeling of Propagation and Interaction Between Body-Mounted Antennas, and the Modeling of Body-Centric, Context Aware Application Scenarios," 2nd IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications, London, April 2009, pp. 1-6.
8. J. N. Bringuier, R. Mittra, and J. Wiart, "Efficient Modeling of Body Area Networks Using the Parallelized FDTD, Its Serial Parallel Extension and the Time Domain Green's Function Method," The 2nd European Conference on Antennas and Propagation, 2007, pp. 1-5.
9. L. Roelens, S. Van den Bulcke, W. Joseph, G. Vermeeren, and L. Martens, "Path Loss Model for Wireless Narrowband Communication Above Flat Phantom," *Electronics Letters*, **42**, 1, January 2006, pp. 10-11.
10. D. Kurup, W. Joseph, G. Vermeeren, and L. Martens, "Path Loss Model for In-Body Communication in Homogeneous Human Muscle Tissue," *Electronics Letters*, **45**, 9, April 2009, pp. 453-454.
11. H.-R. Chuang, W.-T. Chen, "Numerical Computation of EM Interaction Between Human Body and Loop Antennas with Arbitrary Orientation," Antennas and Propagation Society International Symposium, Montreal, July 1997, pp. 1186-1189.
12. W.-B. Yang, K. Sayrafian-Pour, J. Hagedorn, J. Terrill, and K. Y. Yazdandoost, "Simulation Study of Body Surface RF Propagation for UWB Wearable Medical Sensors," 2nd International Symposium on Applied Sciences in Biomedical and Communication Technologies, November 2009, pp. 1-6.
13. Y. Hao, A. Alomainy, P. S. Hall, Y. I. Nechayev, C. G. Parini, and C. C. Constantinou, "Antennas and Propagation for Body Centric Wireless Communications," 2005 IEEE/ACES International Conference on Applied Computational Electromagnetics, Honolulu, April 2005, pp. 586-589.
14. B. Zhen, K. Takizawa, T. Aoyagi, and R. Kohno, "A Body Surface Coordinator for Implanted Biosensor Networks," IEEE International Conference on Communications, Dresden, August 2009, pp. 1-5.
15. A. Guraliuc, A. A. Sera, P. Nepa, G. Manara, F. Potorti, and P. Barsocchi, "Body Posture/Activity Detection: Path Loss Characterization for 2.4 GHz On-Body Wireless Sensors," IEEE International Symposium on Antennas and Propagation, Charleston, July 2009, pp. 1-4.
16. E. Reusens, W. Joseph, B. Latré, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, "Characterization of On-Body Communication Channel and Energy Efficient Topology Design for Wireless Body Area Networks," *IEEE Transactions on Information Technology in Biomedicine*, **13**, 6, November 2009, pp. 933-945.
17. R. D'Errico and L. Ouvry, "A Statistical Model for On-Body Dynamic Channels," *International Journal of Wireless Information Networks*, Netherlands, Springer, 2010.
18. A. Alomainy and Y. Hao, "Radio Channel Models for UWB Body-Centric Networks with Compact Planar Antenna," IEEE International Symposium on Antennas and Propagation, Albuquerque, July 2006, pp. 2173-2176.
19. B. Zhen, M. Kim, J. Takada, and R. Kohno, "Characterization and Modeling of Dynamic On-Body Propagation at 4.5 GHz," *IEEE Antennas and Wireless Propagation Letters*, **8**, 2009, pp. 1263-1267.
20. W. Thompson, K. Walker, R. Cepeda, M. Beach, and J. McGeehan, "Ultra Wideband Body Area Network Channel Measurement and Analysis using Textile Antennas," 2nd IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications, London, April 2009, pp. 1-5.
21. Y. P. Zhang and Q. Li, "Performance of UWB Impulse Radio with Planar Monopoles over On-Human-Body Propagation Channel for Wireless Body Area Networks," *IEEE Transactions on Antennas and Propagation*, **AP-55**, 10, October 2007, pp. 2907-2914.
22. R. E. Collin, "Limitations of the Thévenin and Norton Equivalent Circuits for a Receiving Antenna," *IEEE Antennas and Propagation Magazine*, **45**, 2, April 2003, pp. 119-124.
23. S. Silver, *Microwave Antenna Theory and Design*, New York, McGraw Hill, 1949, pp. 40-48.
24. J. Van Bladel, "On the Equivalent Circuit of a Receiving Antenna," *IEEE Antennas and Propagation Magazine*, **44**, 1, February 2002, pp. 164-165.
25. A.W. Love, "Comment: On the Equivalent Circuit of a Receiving Antenna," *IEEE Antennas and Propagation Magazine*, **44**, 5, October 2002, pp. 124-125.
26. S. Gabriel, R. W. Lau and C. Gabriel, "The Dielectric Properties of Biological Tissues: II. Measurements in the Frequency Range 10 Hz to 20 GHz," *Physics in Medicine and Biology*, **41**, 11, November 1996, pp. 2251-2269.
27. P. Hall, Y. Hao, H. Kawai, and K. Ito, "Electromagnetic Properties and Modeling of the Human Body," in Peter S. Hall and Yang Hao (eds.), *Antennas and Propagation for Body-Centric Wireless Communications*, Norwood, MA, Artech House, 2006, pp. 11-38.
28. C. A. Balanis, *Antenna Theory, Third Edition*, New York, Wiley, 2005, pp. 83.
29. R. F. Harrington, *Time-Harmonic Electromagnetic Fields*, New York, McGraw Hill, 1961 (reprinted by IEEE/Wiley, 2001), pp. 349.
30. W. L. Weeks, *Electromagnetic Theory for Engineering Applications*, New York, Wiley, 1964.
31. J.-P. Béranger, "A Perfectly Matched Layer for the Absorption of Electromagnetic Waves," *J. Comput. Phys.*, **114**, October 1994, pp. 185-200.

32. D. M. Pozar, *Microwave Engineering, Third Edition*, New York, Wiley, 2005, pp. 187.
33. M. Picket-May, A. Taflove, and J. Baron, "FD-TD Modeling of Digital Signal Propagation in 3-D Circuits with Passive and Active Loads," *IEEE Transactions on Microwave Theory and Techniques*, **MTT-42**, 8, August 1994, pp. 1514-1523.
34. G. Mur, "Absorbing Boundary Conditions for the Finite-Difference Approximation of the Time-Domain Electromagnetic Field Equations," *IEEE Transactions on Electromagnetic Compatibility*, **EMC-23**, 4, November 1981, pp. 377-382.
35. K. K. Mei and J. Fang, "Superabsorption – A Method to Improve Absorbing Boundary Conditions," *IEEE Transactions on Antennas and Propagation*, **AP-40**, 9, September 1992, pp. 1001-1010.
36. Z. P. Liao, H. L. Wong, B. P. Yang, and Y. F. Yuan, "A Transmitting Boundary for Transient Wave Analyses," *Scientia Sinica*, **27**, 10, October 1984, pp. 1062-1076.
37. K. R. Umashankar, A. Taflove, and B. Beker, "Calculation and Experimental Validation of Induced Currents on Coupled Wires in an Arbitrary Shaped Cavity," *IEEE Transactions on Antennas and Propagation*, **AP-35**, 11, November 1987, pp. 1248-1257.
38. S. Watanabe and M. Taki, "An Improved FDTD Model for the Feeding Gap of a Thin-Wire Antenna," *IEEE Microwave and Guided Wave Letters*, **8**, 4, April 1998, pp. 152-154.
39. R. Mittra and J. N. Bringuier, "Challenging Problems Arising in the Simulation of Body Area Networks (BANs)," *EuCAP 2009*, March 2009, pp. 453-454.
40. R. Mittra and J. N. Bringuier, "A Hybrid Multiscale FDTD Methodology for Modeling Fine Features in Body-Centric Communication Systems," *EuCAP 2010*, April 2010, pp. 1-3.
41. C. Furse, C. Waterman, and L. Griffiths, "To-Average or Not-to-Average in FDTD Modeling of Dielectric Interfaces," *Applied Computational Electromagnetics Society Journal*, **21**, 2, 2006.
42. <http://www.cyberware.com/products/scanners/wb4.html>
43. <http://meshlab.sourceforge.net>
44. M. Kazhdan, M. Bolitho, and H. Hoppe, "Poisson Surface Reconstruction," *Symposium on Geometry Processing*, 2006, pp. 61-70.
45. O. Ramadan, O. Akaydin, M. Salamah, and A. Oztoprak, "Parallel Implementation of the Wave-Equation Finite-Difference Time-Domain Method Using the Message Passing Interface," *Lecture Notes in Computational Science*, **3280**, 2004, pp. 810-818.
46. D. Yang, J. Xiong, C. Liao, and L. Jen, "A Parallel FDTD Algorithm Based on Domain Decomposition Method Using the MPI Library," *PDCAT 2003 Proceedings of the Fourth International Conference on Parallel and Distributed Computing, Applications and Technologies*, 2003, pp. 730-733.
47. P. D. Sewell, D. P. Rodohan, and S. R. Saunders, "Comparison of Analytical and Parallel FDTD Models of Antenna-Head Interactions," *Ninth International Conference on Antennas and Propagation*, 1995, pp. 67-71.
48. J. Wang, O. Fujiwara, S. Watanabe, and Y. Yamanaka, "Computation with a Parallel FDTD System of Human-Body Effect on Electromagnetic Absorption for Portable Telephones," *IEEE Transactions on Microwave Theory and Techniques*, **MTT-52**, 1, January 2004, pp. 53-58.
49. W. Yu, X. Yang, Y. Liu, L. Ma, T. Su, N. Huang, R. Mittra, R. Maaskant, Y. Lu, Q. Che, R. Lu, and Z. Su, "A New Direction in Computational Electromagnetics; Solving Large Problems Using the Parallel FDTD on the BlueGene/L Supercomputer Providing Teraflop-Level Performance," *IEEE Antennas and Propagation Magazine*, **50**, 2, April 2008, pp. 26-44.
50. D. De Donno, A. Esposito, L. Tarricone, and L. Catarinucci, "Introduction to GPU Computing and CUDA Programming: A Case Study on FDTD," *IEEE Antennas and Propagation Magazine*, **52**, 3, June 2010, pp. 116-122.
51. B. R. Levy and J. B. Keller, "Diffraction by a Smooth Object," *Commun. Pure Appl. Math.*, **12**, 1959, pp. 159-209.
52. G. L. James, *Geometrical Theory of Diffraction for Electromagnetic Waves*, Stevenage, Herts, England, Peter Peregrinus, 1976.
53. P. Pathak, W. Burnside, and R. J. Marhefka, "A Uniform GTD Analysis of the Diffraction of Electromagnetic Waves by Smooth Convex Surface," *IEEE Transactions on Antennas and Propagation*, **AP-28**, 5, September 1980, pp. 631-642.
54. <http://nevaelectromagnetics.com/> 