Electromagnetic interaction between cellular phones and a human head

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Abstract

New health concerns include the development of devices, such as the cellular phones, that radiate near the head. These concerns may be addressed with the proper study of the electromagnetic fields as they interact with skin, bone, blood, and brain tissue. Since desktop workstations have become quite powerful, the interactive study of these fields may be accomplished using the Finite Difference Time Domain (FDTD) method.

FDTD simulation of cellular phone antennas may be verified by comparison of computed field data to actual measurements. A selection from a list of commonly used antennas in cellular phones can be modeled with FDTD, and the data for an average human head should be obtained for construction into the FDTD domain. Using these specifications, the head and cellular phone antenna can be properly modeled in a FDTD domain.

The electromagnetic interaction is studied by using the powerful 3D graphics tools available on the Silicon Graphics workstation using the GL routines. By using GL, 3D graphics commands may be directly interfaced into the FDTD code. This will allow for animation of the fields in either user-specified plane cuts or 3D field vectors in the entire FDTD computational space. The geometrical model of the head is also visualized, and the user may rotate the view of the head or the induced electromagnetic fields to any angle.

In our analysis images based on actual magnetic resonance imaging (MRI) scans of the human head at 53 horizontal planes are used. These planes are used to define the head for the FDTD simulation program. The radiation from a cellular phone is simulated by a dipole antenna fed by a sinusoidal source operating at 835 MHz. The specific absorption rate (SAR) distribution due to the interaction of the radiated fields and the human head simulation is computed in the 53 planes. An example showing the actual MRI image, the corresponding FDTD simulation and the computed SAR at a plane cut in the middle of the head is shown in the figure.
Slice of the head 25 cm up from the chin.

Specific absorption rates in the slice.

Figure 1:
Interaction of Electromagnetic Fields and a Model of the Human Head

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Clayborne D. Taylor, Jr.

Summary. Antennas for personal communications devices transmit and receive electromagnetic (EM) waves (at microwave frequencies) near the operator’s head. We have used the finite-difference time-domain method to model this EM radiation as it interacts with a model of the human head, and have generated animated movies to visualize this interaction. We have studied two antennas in detail—a 900-MHz terrestrial wireless antenna and a 1.8-GHz handset-to-satellite link. In one of our studies, the model of the human head was derived from magnetic resonance images; in another study, the model came from pictures of anatomical cuts. Movies showing the evolution of the fields in these models are available at the Society of Exploration Geophysicists world wide web site.

1 Introduction

The growth of mobile communications has generated considerable interest in the interaction of the radiated electromagnetic (EM) fields with humans. Not only is the operator’s influence on the antenna’s gain, radiation pattern, and input impedance an issue for the performance of the hand-held devices, but there are also concerns about how the radiated EM energy affects human tissue.

Many authors have studied this interaction using different numerical techniques and different (approximate) models for the handset and the human head (Dimbylow, 1993; Toftgård et al., 1993; Dimbylow and Gandhi, 1993; Chen and Wang, 1994; Chuang, 1994; Martens, 1994; Colburn and Rahmat-Samii, 1995a,b; Gutschling and Weiand, 1995; Jensen and Rahmat-Samii, 1995). The finite-difference time-domain (FDTD) method (Yee, 1966; Tafove and Brodwin, 1975; Luebbers et al., 1992) is well suited for this problem because it can model EM fields in general geometries easily and efficiently. Also, because it computes the evolution of the fields at all points in space,

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the FDTD method allows a full visualization of the EM interaction. We have used the FDTD method and modern EM visualization techniques to study the interaction of two different handset antennas with the human head.

In our first example, a simple dipole antenna models a handset radiator at 900 MHz. The head model is created from actual magnetic resonance imaging (MRI) scans transformed onto an FDTD grid. The computational head model includes eight different tissue types, for which the electrical properties are prescribed at 900 MHz. In our second example, a circular polarized helix antenna represents the radiating element at 1.8 GHz. These models are good examples for cellular and satellite telecommunications. For each model, we compute near-field distributions, specific absorption rates (SAR), and far-field patterns. We have cast the time-domain simulations (of the dipole antenna interacting with the human head) into movie files that can be played on personal computers (PCs) under either Windows/DOS or MacOS (Elsherbeni and Taylor, 1995). Interested readers can obtain these movie files on the world wide web at http://www.seg.org/books/3d/selsher/elsher/elsher.html, or at http://www.olemiss.edu/~atelf/head/head.html.

2 Numerical approach

2.1 FDTD method

The FDTD method has an extensive literature, so we will give only a brief description here. The FDTD method steps Maxwell’s equations in time on a discrete grid; its simplicity lends itself for use in computing EM fields in complex geometries. On a rectangular grid, centered difference approximations for the spatial and temporal derivatives in Maxwell’s equations result in explicit equations for values of all field components at the next time step in terms of their values at present and past steps. The centered spatial differences operate naturally on a discretization of space into unit cells, termed Yee cells, which are rectangular parallelepipeds of dimensions $\Delta x$, $\Delta y$, and $\Delta z$. The electric-field components lie along edges of the Yee cells, and the magnetic-field components are perpendicular to cell faces in a staggered fashion. Centered differences in time are constructed such that the electric and magnetic fields are computed half a time step apart, which allows leap-frogging between the electric and the magnetic fields.

The material characteristics of each unit cell can be assigned independently to allow for modeling of inhomogeneous media. To simulate infinite space in a finite computational domain, the FDTD grid is terminated by a special (absorbing) boundary conditions to simulate outgoing waves in free space. The computation starts by introducing a prescribed electric field into the grid and continues until the fields in the domain go to zero or a steady state is achieved, depending on the type of excitation used. Frequency-domain quantities can be determined by Fourier transformation of the temporal values. Subunit cell features, like thin wires, can be handled by modifying the difference equations locally.

2.2 Power absorption and SAR

Various quantities can serve to assess the absorption of energy in tissue. The real power delivered to the antenna ($P_{\text{in}}$) is the sum of the power radiated to the far-field ($P_{\text{rad}}$)
and the power absorbed within the lossy tissue ($P_{abs}$). The quantities ($P_{abs}$) and ($P_{rad}$) can be determined by

$$P_{abs} = \frac{1}{2} \int_V \sigma |E|^2 dV, \quad (1)$$

$$P_{rad} = \frac{1}{2} \text{Re} \left\{ \int_S E \times H^* \cdot \hat{n} dS \right\}, \quad (2)$$

where $E$ and $H$ are the frequency-domain electric and magnetic fields (phasors) and $\sigma$ is the medium's conductivity. The symbols $V$, $S$, and $\hat{n}$ represent the volume containing the tissue, a surface completely surrounding the antenna, and the unit outward normal to the surface, respectively.

SAR is a measure of the power absorbed per unit mass of tissue. This quantity is defined as

$$\text{SAR} = \frac{\sigma}{2\rho} |E|^2 \quad (3)$$

where $\rho$ is the material density. The values of $\sigma$ and $\rho$ for the different tissue types used in the computational head models are listed in Table 1 at 900 MHz and 1.8 GHz. The SAR averaged over any 1 g of tissue for 30 minutes or more should remain under 1.6 mW/g (American National Standards Institute, 1991; Fischetti, 1993).

3 Dipole antenna

We present first a study of a dipole antenna next to an adult head. An important part of the study is the generation of a realistic computational model for the human-head model. We describe a procedure that generates such a model automatically from MRI. The procedure allows one to adjust the level of discretization to the physical resolution desired or to the computer resources available.

3.1 Construction of a 3-D human-head model

The input for the head model was obtained from the World Wide Web in the form of MRI scans (Johnson and Becker, 1995). Figure 1 shows a sample scan. The circle at the top of this figure is at the intended location of the antenna, which is transmitting in the simulations.

The MRI scans were downloaded as graphical interchange files (GIF) in binary format. The set consists of 54 axial slices through a human head. For each axial slice, three separate MRI scans were acquired, each concentrating on a different tissue types. The three types of MRI scans are designated as PD-, T1-, and T2-weighted (see Johnson and Becker, 1995) for explanation of the scan types.

We used the Xview (see Bradley) program to convert and save each image in a postscript format. Figure 2 shows a section of one of the MRI postscript files, which are in hexadecimal format. Each pixel is represented by two hexadecimal characters which are converted to decimal and fall within the range of (0,255). Each MRI images occupies a 256 × 256 pixel grid; each pixel has a value in the range (0,255). The physical material type at each pixel location then is determined by the value of the pixel in the MRI image. Table 2 is a pixel-range-to-tissue-type conversion based on the T2-weighted image.
Table 1. Material parameters at 900 and 1800 MHz

<table>
<thead>
<tr>
<th>Tissue type</th>
<th>$\rho$, g/cm$^3$</th>
<th>$\sigma$, S/m</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$, S/m</th>
<th>$\varepsilon_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>1.85</td>
<td>0.105</td>
<td>8.0</td>
<td>0.15</td>
<td>8.0</td>
</tr>
<tr>
<td>Skin/Fat</td>
<td>1.10</td>
<td>0.60</td>
<td>34.5</td>
<td>0.57</td>
<td>32.0</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.04</td>
<td>1.21</td>
<td>58.5</td>
<td>1.76</td>
<td>56.0</td>
</tr>
<tr>
<td>Brain</td>
<td>1.03</td>
<td>1.23</td>
<td>55.0</td>
<td>1.58</td>
<td>53.0</td>
</tr>
<tr>
<td>Humour</td>
<td>1.01</td>
<td>1.97</td>
<td>73.0</td>
<td>2.27</td>
<td>74.0</td>
</tr>
<tr>
<td>Lens</td>
<td>1.05</td>
<td>0.8</td>
<td>44.5</td>
<td>1.19</td>
<td>42.0</td>
</tr>
<tr>
<td>Cornea</td>
<td>1.02</td>
<td>1.85</td>
<td>52.0</td>
<td>2.29</td>
<td>51.0</td>
</tr>
</tbody>
</table>

Figure 1. MRI slice of the head at 11.5 cm up from the chin.

Figure 2. Section of the postscript code that describes the MRI scan.
Initially only the T2 image scans were considered. For every pixel in the head, a material type was assigned on the basis of the pixel value in the T2 image file. This was the first approximation of the human head, which consisted only of pixels assigned a physical location and material type. Next, an interactive program refined the first head model with data from the PD and T1 images. The program would first display the three different weighted MRI scans as shown in Fig. 3 along with the current head model. Next, the user was allowed to choose a material type and “paint” any desired corrections to that material-type placement with the mouse cursor to any of the 54 layer scans. This painting to correct the material-type designation could be done either directly on the head model or on any one of the MRI scans. These refinements were automatically entered in the head model. We found that the interactive program was a very efficient method for refining initial models.
Table 2. Material gray scale and respective color

<table>
<thead>
<tr>
<th>Tissue type</th>
<th>Gray level</th>
<th>Color value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0–60</td>
<td>Black</td>
</tr>
<tr>
<td>Skin</td>
<td>60–90</td>
<td>Yellow</td>
</tr>
<tr>
<td>Bone</td>
<td>90–110</td>
<td>White</td>
</tr>
<tr>
<td>Muscle</td>
<td>110–130</td>
<td>Dark red</td>
</tr>
<tr>
<td>Fat</td>
<td>130–160</td>
<td>Light gray</td>
</tr>
<tr>
<td>Brain</td>
<td>160–200</td>
<td>Dark gray</td>
</tr>
<tr>
<td>Eye</td>
<td>200–220</td>
<td>Blue</td>
</tr>
<tr>
<td>Blood</td>
<td>220–255</td>
<td>Red</td>
</tr>
</tbody>
</table>

Figure 4. Group of material types in one cell.

Figure 5. Resulting bone cell type.

An FDTD grid then was created for the head model. Because of limited computer resources, each FDTD grid cell incorporated multiple pixels from the head model. The material characteristics assigned to each FDTD cell were taken as the material type that had the highest occurrence in the volume of that unit cell. Figures 4 and 5 illustrate the quantization process in two dimensions. With this procedure, the same head model can generate FDTD grids of different resolution on the basis of available computer resources. This process of dynamically setting the simulation resolution is a key feature in the modeling technique.

The materials used to make up the FDTD head model have electrical properties that are frequency dependent. Table 1 lists the electrical properties of the material of the adult human head at 900 MHz and 1800 MHz (Dimbylow, 1993).

3.2 Visualization of computed data

To visualize the results of the simulations, we developed an animated surface plotting program using the GL graphical programming language. The program can create movie files showing the propagation of the electric or magnetic fields through and around the head. These movie files were generated on a Silicon Graphics workstation and were converted to a format suitable for viewing on PCs. Samples of these movie files can be found on the network at http://www.seg.org/books/3dem/elsher/elsher.html, or at http://www.olemiss.edu/~atef/head/head.html.
Figure 6. Positioning of antenna and artificial box surrounding the head model in the FDTD mesh domain. Dimensions are in terms of cell numbers.

Figure 7. Computed electric field for dipole antenna at eye locations with and without the computational head model present: (a) right eye, (b) left eye.

3.3 Dipole antenna geometry and results

For these dipole simulations, a $55 \times 38 \times 54$ unit-cell head model was used. Considering the head size to be $17.5 \text{ cm} \times 11.5 \text{ cm} \times 20 \text{ cm}$, the physical dimensions of the unit cell were $3.125 \text{ mm} \times 3.125 \text{ mm} \times 3.636 \text{ mm}$. The boundary condition used in these dipole simulations was Liao’s third order. A 20-cell boundary buffer on all sides of the computational domain was used, except the side closest to the antenna where a 25-cell buffer was used, as shown in Fig. 6.

The dipole antenna was 12 cm long with a 0.6-mm radius and was located approximately 6 mm away from the head model. The dipole antenna was excited by a 900-MHz sinusoidal voltage source, with the amplitude appropriately chosen to deliver 0.6 W.

For this configuration, the total electric fields induced in the right and the left eyes are shown in Figs. 7a and 7b. In these figures, the corresponding field values at the same positions also are shown for the dipole antenna radiating in free space (dashed
Electromagnetic fields from a dipole 0.5 cm away from a human head next to the ear.

\[ |E_{tot}| \]

-30.00 dB \quad 70.00 dB

Figure 8. Electric field across a slice of the head model at 12 cm up from the chin with a dipole antenna close to the left ear; eyes are facing the y-axis.

line), illustrating the effects of the head model on the radiation from the antenna. One can also see from these figures that the steady-state response was achieved after a very short period of time. The electric- and magnetic-field distributions across an x-y plane cut 12 cm up from the chin are shown in Figs. 8 and 9, respectively. These two figures are single frames from the movie files, illustrating the time interaction between the radiation from the dipole antenna and the head model. The movie files show a complex standing-wave pattern in the brain area, and a very obvious surface wave that surrounds the head. The computed SAR distribution in the x-y plane cut containing the voltage source is shown in Fig. 10.

4 Helix antenna

We also studied a square, thin-wire helix antenna, as a model for a personal satellite transceiver handset. The purpose was to look for possible effects of the operator on the radiation characteristics of this circularly polarized antenna, and to see how the radiated fields from this antenna acted on the head model. This study used a slightly different head model.

4.1 Biological tissue modeling

In Jensen and Rahmat-Samii (1995), a computational head model was included in the FDTD simulations in order to ascertain the impact that the user's presence has on the radiation characteristics of the transceiver at 915 MHz. To construct that head model, a grid with a 6.56-mm spatial resolution was placed on cross-sectional images of the head
Electromagnetic fields from a dipole 0.5 cm away from a human head next to the ear.

\[ \text{time: 2.7688 ns} \]

\[ |H_{\text{total}}| \]

\[ -65.00 \text{ dB} \quad 15.00 \text{ dB} \]

Figure 9. Magnetic field across a slice of the head model at 12 cm up from the chin with a dipole antenna close to the left ear; eyes are facing the \( y \)-axis.

\[ 10 \log(\text{SAR/Pdel}) \]

Figure 10. Computed SAR for an \( x-y \) plane cut of the head model that contains the voltage source that excites the antennas shown in Fig. 6 at 900 MHz.
obtained from an anatomy atlas (Eycleshymer and Schoemaker, 1911). Each cell in the grid then was assigned permittivity and conductivity classifications corresponding to the type of tissue that filled the majority of the cell. Figure 11 illustrates a midsagittal cross-section of the head model.

We used a similar computational phantom head in our simulation of a satellite communication transceiver near a user. Although the same structure and approximate head size were used, the electrical parameters of the head model were changed to those of head tissue at 1.8 GHz (Dimbylow, 1993) as shown in Table 1. The FDTD grid size used in the computations was 3.33 mm.

4.2 Antenna geometry and results for satellite-handset link

Figure 12 shows a modified-helix structure in which the thin-wire element is constructed only of straight wire segments. This square-helix geometry has been seen to exhibit pattern and circuit characteristics similar to those of a standard circular-helix structure (Colburn and Rahmat-Samii, 1995b). In the square-helix structure, all vertically oriented
Figure 13. FDTD-computed far-field pattern for square-helix antenna illustrated in Fig. 12.

Figure 14. (a) Illustration of square-helix antenna on handset positioned near the head model; (b) y-z plane cut and (c) x-z plane cut of head model and handset.
wire segments are 0.06λ in length and all horizontally oriented wire segments are 0.24λ in length. This square-helix structure has a geometry that is easier to integrate with the handset, and can be simulated on a rectangular FDTD grid. Figure 13 is a plot of the computed far-field pattern in two φ cuts in terms of right-hand circularly polarized (RHCP) and left-hand circularly polarized (LHCP) components for the square-helix structure shown in Fig. 12 using a Cartesian-grid-based FDTD code.

Figure 14a illustrates the computational head model positioned near the transceiver handset shown in Fig. 12. The frequency of interest was 1.8 GHz, which fixes the FDTD grid size of 0.02λ to 3.33 mm and the size of the transceiver box to 8 x 8 x 13.33 cm. In the computations performed, the handset and head model were spaced two cells apart. Figures 14b and 14c are schematics in the y-z and x-z cuts of the exact geometry analyzed.

Figure 15 is a plot of the FDTD-computed far-field pattern for the square-helix structure positioned next to the phantom head seen in Fig. 14. The pattern plots in Fig. 15 can be compared directly to the pattern plots for the handset itself shown in Fig. 12. The computations indicate that approximately 13% of the total delivered power is lost in the head model, which is less than the losses reported by Jensen and Rahmat-Samii (1995) and is mainly attributed to the greater distance between the head model and the antenna element. Besides the radiated-power loss due to absorption in the head model, it can be seen in Fig. 15 that there are significant distortions to the computed far-field pattern because of the presence of the head model. This results in a very poor axial ratio performance. The computed electric-field distribution in the vicinity of the handset is shown with (Fig. 16b) and without (Fig. 16a) the head model present in the computational domain. From Figs. 16a and 16b, one can see the perturbations of the fields caused by the head’s presence. Figure 17 is a plot of the computed SAR averaged over 1 g of tissue in the computational head model for this case.

5 Summary and conclusions

The FDTD method can simulate very efficiently the interaction of EM fields from portable communications devices with the human operator. We used models of a human head, generated semiautomatically from MRI scans, in FDTD simulations of radiation from dipole and helix antennas. The evolution of the EM fields in the models has been captured in movies that can be played on PCs. The simulations demonstrate that the
Figure 16. FDTD-computed fields in the vicinity of the handset: (a) without the head model in the computational domain; (b) with the head model in the computational domain.

Figure 17. Computed SAR in the case of the square helix on the handset next to the head model.

tissue has a noticeable effect on the antenna radiation patterns, polarization state, and directivity. Most of the energy absorbed by the head is concentrated on the illuminated side of the skin and bone layers of the head model.

Acknowledgments

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