SAR Analysis on Human Head Exposed to Radiating Dipole Antenna for 500 MHz - 5 GHz Frequency Band Using FDTD Method

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Abstract – Investigations have been carried out on specific absorption rate (SAR) for a human head exposed to electromagnetic waves irradiated from a half-wave dipole antenna at the frequency range from 500 MHz to 5 GHz using finite difference time domain (FDTD) method. For simplicity, the human head is modeled as a rectangular cube consists of 40×40×50 Yee cells and the dielectric constant and conductivity of human head are assumed to be homogeneous. Distance between the head and dipole antenna is varied in the range of 1.0 cm to 3.0 cm to calculate maximum local SARs. It is found that the maximum local SAR induced in the head is below the FCC and IEEE’s upper safety limit when distance of the head from the dipole antenna is more than 1.0 cm.

I. INTRODUCTION

The biological effects due to the electromagnetic absorption in the human head are quickly becoming the area of interest of many researchers. During the last several years, there have been increasing interests in the application of numerical techniques to calculate the intensity of electric fields in the human head models [1-9]. In this regard the SAR value is an important quantity because the human exposure guidelines are set in terms of it. Numerical simulations are also important, because it is not possible to actually measure the distribution of electromagnetic fields or SAR values inside a human head. In the present work the well-established FDTD method is used to carry out all numerical calculations [10,11].

II. FINITE DIFFERENCE IN TIME DOMAIN

There are different techniques for the computational evaluation of RF energy absorption in physiological structures. Among them the FDTD method, introduced by Yee in 1966 is one of the most powerful and popular numerical technique in computations involving the electromagnetic waves in three dimensional structures [10].

FDTD method starts with the Maxwell’s time-dependent curl equations which may be written as:

\[ \nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \]  \hspace{1cm} (1)

\[ \nabla \times \vec{H} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} \]  \hspace{1cm} (2)

Where the parameters \( \sigma \), \( \mu \) and \( \varepsilon \) are conductivity, permeability and permittivity respectively.

As \( \vec{E} \) and \( \vec{H} \) are the vectors in three dimensions so the solutions of equations (1) and (2) produce a set of six scalar equations in the rectangular co-ordinate system (x, y, z):

\[ \frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x \right) \]  \hspace{1cm} (3)

\[ \frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right) \]  \hspace{1cm} (4)

\[ \frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon} \left( \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \right) \]  \hspace{1cm} (5)

\[ \frac{\partial H_x}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right) \]  \hspace{1cm} (6)

\[ \frac{\partial H_y}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right) \]  \hspace{1cm} (7)
\[
\frac{\partial H_z}{\partial t} = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial y} - \frac{\partial E_x}{\partial x} \right)
\]

(8)

These six equations have been solved by discretizing the space into a number of Yee cells and assigning each cell to the corresponding permittivity and conductivity to obtain the components of the electric and magnetic fields. The method follows the propagation, reflection and absorption of an electromagnetic wave in a domain comprising the target and surrounding space. Following the Yee’s notation at each grid points all the components of the electric and magnetic fields are calculated.

Unpredictable reflections of the electromagnetic waves from the edges of the problem space were encountered during the simulation by the FDTD method. To eliminate the reflection Berenger perfectly matched layer (PML) has been used as the absorbing boundary condition [11].

To obtain the reflection coefficient \( S_{11} \), the incident and the reflected waveforms must be known at the feeding point of the antenna. \( S_{11} \) is determined from the ratio of the discrete Fourier transform (DFT) of these transient waveforms by:

\[
S_{11} = \frac{DFT(E_{ref})}{DFT(E_{inc})}
\]

(9)

Where \( E_{inc} \) = incident electric field and \( E_{ref} \) = reflected electric field.

The value of \( |S_{11}| \) is computed in dB by:

\[
|S_{11}|_{dB} = 20 \log_{10} |S_{11}|
\]

(10)

The local SAR in W/Kg for the \((i, j, k)\)-th cell in the head model is obtained from [5]:

\[
SAR(i, j, k) = \frac{\sigma(i, j, k)E(i, j, k)^2}{2\rho(i, j, k)}
\]

(11)

Where \( E \) = r.m.s value of the electric field (V/m), \( \sigma \) = conductivity of the head (S/m) and \( \rho \) = mass density of the head (Kg/m³).

III. SYSTEM MODEL

To simplify the numerical calculations, the other parts of the human body except the head are excluded in the simulation. The human head is modeled as a rectangular cube consists of \(40\times40\times50\) Yee cells. The geometry of the dipole antenna and human head used for the simulation is shown in Figure 1, where the Yee cell length \([\delta]\) = 0.5 cm. The outer boundary area as shown in the figure consists of Berenger perfectly matched layers. The half-wave dipole antenna having length 15.5 cm and diameter of 0.5 cm is chosen as the radiating element. A metallic material with \( \varepsilon_r = 9.5 \) and \( \sigma = 3.86 \times 10^7 \) S/m was employed to simulate the dipole antenna.

Human head is inhomogeneous in nature but in this study it is considered to be homogeneous for simplicity. The mass density \( \rho \) of the human head is taken as 1050 Kg/m³. In this study, variation of dielectric constant \( \varepsilon_r \) and conductivity \( \sigma \) of human head at the different frequencies have been taken into consideration to calculate SAR. Average relative dielectric constant \( \varepsilon_r \) and conductivity \( \sigma \) of the human head at the desired frequency range were interpolated from the Table I [6-8].

![Figure 1. Geometry of the dipole antenna and the human head used for simulation by the FDTD method](image)

TABLE I

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>( \varepsilon_r )</th>
<th>( \sigma ) (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>82.0</td>
<td>0.53</td>
</tr>
<tr>
<td>350</td>
<td>60.0</td>
<td>0.65</td>
</tr>
<tr>
<td>900</td>
<td>56.8</td>
<td>1.1</td>
</tr>
<tr>
<td>1800</td>
<td>51.8</td>
<td>1.5</td>
</tr>
<tr>
<td>2450</td>
<td>48.9</td>
<td>1.81</td>
</tr>
<tr>
<td>6000</td>
<td>30.0</td>
<td>5.3</td>
</tr>
</tbody>
</table>
IV. SOURCE CONSIDERATIONS

For SAR calculation 0.6 watt power is assumed to be radiated from the dipole antenna which is considered as average radiated power level for some modern cellular phones [4]. It has also been assumed that the dipole antenna is radiating the carrier frequency continuously without any modulation.

For calculation of $|S_{11}|$ or SAR vs. frequency, a Gaussian pulse is chosen as excitation voltage. A nearly flat frequency spectrum from dc to desired cut-off frequency can be obtained by adjusting the width of the Gaussian pulse. A Gaussian pulse is applied at the dipole antenna feed point with the maximum voltage amplitude $V = \sqrt{2R_aP}$, where $P$ = radiated power from the dipole antenna (0.6 watts), $R_a = 50$ Ohms.

SAR distributions at different layers of head are investigated and a sinusoidal voltage source is chosen as excitation for these purposes.

V. RESULTS

The presence of the human head in the vicinity of the radiating antenna acts like a dielectric resonator which alters the input impedance and resonating frequency of the dipole antenna. In this study the length of the antenna has been optimized keeping the head model 2 cm away from it such that the value of $|S_{11}|$ remains below -10 dB in the WLL band (824MHz – 894MHz). Variation of $|S_{11}|$ with frequency for the half-wave dipole antenna placed at 2 cm distance from the head model is shown in Figure 2.

For the fundamental mode the antenna along with head resonates at 835 MHz and for this frequency the value of $|S_{11}|$ is -11.8 dB. Next two higher order modes are found at 2.7GHz and 4.4GHz, respectively but the value of $|S_{11}|$ remains greater than -10 dB at these frequencies.

Induced SAR distributions in a human head model by the electromagnetic fields irradiated from the antenna have been calculated at 835 MHz for 2 cm of distance between the head and the dipole antenna. For these purpose the dipole antenna was fed with a sinusoidal voltage source. SAR distributions at various layers within the head for 1000th time step are shown in the Figures 3-5. From the figures it is found that the nature of SAR distribution in human head changes from layer to layer. The polarization of propagating wave remains horizontal for all the layers and standing waves of multiple wavelengths are clearly visible.

![Figure 2](image2.png)

Figure 2. Variation of $|S_{11}|$ vs. frequency for the dipole antenna of length 15.5 cm placed in front the head model.

![Figure 3](image3.png)

Figure 3. SAR distributions in the 1st layer counted from the antenna side of the head.

![Figure 4](image4.png)

Figure 4. SAR distributions in the 20th (middle) layer counted from the antenna side of the head.
The variation of maximum local SAR with frequency has been studied for different distances between head and antenna. Instead of simple SAR, maximum local SAR induced in the human head model has been calculated which gives more information regarding the biological effects of the electromagnetic fields at any point inside the head. Figure 6 shows the maximum local SAR induced in the human head for the frequency range 500 MHz to 5 GHz for a set of distances (‘d’) in the range of 1.0 cm to 3.0 cm, respectively. When the distance is less than or equal to 1.0 cm then the maximum local SAR is above FCC and IEEE’s upper safety limit (1.6 W/kg) [12,13]. The value of the maximum local SAR goes below the upper safety limit if the distance increases over 1.0 cm.

VI. CONCLUSION

This study further confirms the complex interaction of RF energy with human head consisting of tissue with varying dielectric properties. Absorption of electromagnetic energy in human head from radiating dipole antenna has been investigated for the frequency range from 500MHz to 5GHz using FDTD method. Maximum local SAR decreases with the increase of distance between head and antenna. When the distance is less than or equal to 1.0 cm then the maximum local SAR is above FCC and IEEE’s upper safety limit (1.6 W/kg). As the distance increases over 1.0 cm then the value of the maximum local SAR goes below the upper safety limit. The variation of $|S_{11}|$ and maximum local SAR with frequency has been studied for difference distances between head and antenna. The conductivity of human head is a nonlinear function of frequency and the maximum local SAR is linearly proportional to the conductivity of head but it contributes small change in the resonating frequency of the dipole antenna. As a result the frequency for maxima of local maximum SAR doesn’t match with the frequency for minima of $|S_{11}|$.

Due to the huge complexity of the human head, limitations of FDTD method and computational resources, many assumptions have been made in the present work. For further study to obtain better results, these assumptions should be modified. Even though the SAR has been calculated considering human head as the homogeneous box but actually it is spherical shaped inhomogeneous dielectric medium consisting of several tissue types with varying dielectric properties. The homogeneous box type human head model should be replaced with the actual inhomogeneous spherical type human head model. It is assumed that the dipole antenna is radiating the carrier frequency only but in case of actual handsets the time-averaged power under real operating condition is a fraction of the carrier power. Absorption of electromagnetic energy not only varies with the operating frequency but also with the polarization. Though the vertically polarized electromagnetic waves are used in this study but horizontally polarized electromagnetic waves may also be used which will give different values than those obtained by vertically polarized electromagnetic waves. The dipole antenna...
should be replaced with the multiband compact microstrip antenna for further realistic analysis.

REFERENCES