EMC/EMI in Wireless Communications

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UH: close to downtown of Houston
35,066 students

ECE Department: 35 faculty members, 250 graduate students

Electromagnetic Research at University of Houston:

NSF Center For Electromagnetic Compatibility Research

Areas:
Computational Electromagnetics
Antennas
High-Speed Signal Propagation
Bioelectromagnetics
Nano-devices
Wireless Propagation

Faculty Members:
6 faculty members
IEEE Board of Directors
past president of AP society
4 IEEE Fellows
Medical safety in MRI

Design of periodic structures

Nano-scale FSS modeling

Outline

- Introduction
- SAR Inter-lab comparison for wireless device
- MIMO SAR for future multi-antenna systems
- Telemetry interactions
- Wireless PCB Modeling
- Summary
Electric fields produced by cell phone near SAM head.

\[ \text{SAR} = \frac{\sigma |E|^2}{2\rho} \]

<table>
<thead>
<tr>
<th></th>
<th>USA</th>
<th>Europe</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANSI95</td>
<td>1</td>
<td>ENV5016</td>
<td>TTC/MPT</td>
</tr>
<tr>
<td>Whole Body</td>
<td>0.08 W/kg</td>
<td>0.08 W/kg</td>
<td>0.04 W/kg</td>
</tr>
<tr>
<td>Spatial Peak</td>
<td>1.6 W/kg</td>
<td>2 W/kg</td>
<td>2 W/kg</td>
</tr>
</tbody>
</table>

Commercial SAR measurement systems
IEEE 1528 - Body modeling

- Purpose
  - Must result in conservative over-estimate of SAR compared to real person

- Development of head model
  - Anthropomorphic vs. simplified
  - Large head gives higher SAR
  - Dimensions from US Army data
  - Compressed lossless ear model
  - CAD model available

- No hand model
  - Hand absorbs energy

IEEE 1528 - Tissue equivalent liquid

- Dielectric parameters
  - Representative of human tissue
  - Selected to result in conservative exposure
  - Consistent over time and temperature
  - Homogeneous to allow movement of E-field probe

- Other parameters
  - Low viscosity to allow easy probe movement
  - Safe to use
  - Not reactive with phantom or probe materials
ICES – TC34 – SC2 - Computational Standards

- IEEE 1528.1: Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: General Requirements for using the Finite Difference Time Domain (FDTD) Method for SAR Calculations
- IEEE 1528.2: Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: Specific Requirements for Finite Difference Time Domain (FDTD) Modeling of Vehicle Mounted Antennas
- IEEE 1528.3: Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: Specific Requirements for Finite Difference Time Domain (FDTD) Modeling of Mobile Phones/Personal Wireless Devices
- IEEE 1528.4: Recommended Practice for Determining the Peak Spatial Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz – 6 GHz: Requirements for Using the Finite-Element Method for SAR Calculations

IEEE 1528.1 - General Requirements for using the Finite Difference Time Domain (FDTD) Method for SAR Calculations

Purpose: ... is to describe the concepts, anatomical models for compliance assessments, techniques, validation procedures, uncertainties and limitations of the FDTD method when used for determining the spatial-peak SAR in standardized human anatomical models exposed to wireless communication devices. 1528.1 recommends and provides standardized anatomical models and provides general benchmark data for these models. 1528.1 will not recommend specific SAR values since these are found in other documents, e.g., IEEE C95.1-1999.

CONTENTS
- 1. Overview
- 2. Definitions
- 3. Basic FDTD requirements
- 4. Special techniques
  - 4.1 CAD import and meshing of the device under test
  - 4.2 Non-uniform mesh and sub-grids
  - 4.3 Conformal dielectric
  - 4.4 Conformal conductor
  - 4.5 Thin wires
  - 4.6 Thin sheets
  - 4.7 Convergence testing
  - 4.8 Frequency dependent materials/tissues
  - 4.9 Running DFT for multiple frequency calculations
  - 4.10 Far zone results
  - 4.11 ADI-FDTD and FDTD meshing of dielectric materials
Inter-Lab Numerical SAR calculation project

16 teams from the world involved to determine
1. Head model (SAM, Adult, 7 year old)
2. Software packages (XFDTD, SemCAD, homegrown...)

835 MHz, All Tissue, Cheek, 1g
80% 100% 120%
80% 100% 120%
80% 100% 120%
80% 100% 120%
80% 100% 120%
80% 100% 120%
80% 100% 120%
80% 100% 120%

1W 200mA 7-Yr Adult SAM
SAR Sensitivity:

SAR sensitivity on spacing and user effects provides information of what SAR change can be expected due to small variation of environment.

**Definition of Sensitivity:**

\[ S(x) = \frac{\partial \text{SAR}}{\partial x} \cdot \frac{x}{\text{SAR}} \]

**Example:**

- Sensitivity: \( S(\epsilon) = 0.4 \)
- Dielectric constant change: \( \epsilon \pm 5\% \)
- \( \text{SAR} = \text{SAR}(\epsilon) \pm 2\% \)

**Evaluation**

\[
\frac{\partial \text{SAR}}{\partial x} = \frac{\text{SAR}(x + \Delta x) - \text{SAR}(x - \Delta x)}{2\Delta x} - \frac{2}{3!} \text{dx}^3 \text{SAR}''' \bigg|_x + \ldots
\]

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**SAR Sensitivity Analysis**

**Spacing Effect**

<table>
<thead>
<tr>
<th>Distance from Head</th>
<th>Peak SAR</th>
<th>1g SAR average(normalized)</th>
<th>Absorption power</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d = 0 \text{ mm} )</td>
<td>1</td>
<td>0.66</td>
<td>68%</td>
</tr>
<tr>
<td>( d = 3 \text{ mm} )</td>
<td>0.58</td>
<td>0.39</td>
<td>52%</td>
</tr>
</tbody>
</table>

**User effect - Head Size**

<table>
<thead>
<tr>
<th>Head Size</th>
<th>Peak SAR (normalized)</th>
<th>1g average SAR (normalized)</th>
<th>Absorption power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>0.96</td>
<td>0.64</td>
<td>67%</td>
</tr>
<tr>
<td>Regular</td>
<td>1</td>
<td>0.66</td>
<td>68%</td>
</tr>
<tr>
<td>Large</td>
<td>0.96</td>
<td>0.64</td>
<td>71%</td>
</tr>
</tbody>
</table>
### User effect : materials effect

<table>
<thead>
<tr>
<th>Dielectric</th>
<th>Peak SAR (normalized)</th>
<th>1g average SAR (normalized)</th>
<th>Absorption power</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>1</td>
<td>0.65</td>
<td>69%</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>0.65</td>
<td>68%</td>
</tr>
<tr>
<td>44</td>
<td>0.99</td>
<td>0.65</td>
<td>68%</td>
</tr>
</tbody>
</table>

### User effect : materials effect

<table>
<thead>
<tr>
<th>Conductivity</th>
<th>Peak SAR (normalized)</th>
<th>1g average SAR (normalized)</th>
<th>Absorption power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.26</td>
<td>0.92</td>
<td>0.63</td>
<td>67%</td>
</tr>
<tr>
<td>1.4</td>
<td>1</td>
<td>0.66</td>
<td>68%</td>
</tr>
<tr>
<td>1.56</td>
<td>1.08</td>
<td>0.68</td>
<td>71%</td>
</tr>
</tbody>
</table>

### Hand Effect:

- Hand effect: rigid body transformation
- Add sphere
- Absorption power
Sub-grid (helical Antenna)

Radiation Pattern

$yz$ plane ($\phi = 90^\circ$, $\theta$ changes from $0^\circ$ to $360^\circ$)

$xz$ plane ($\phi = 0^\circ$, $\theta$ changes from $0^\circ$ to $360^\circ$)
Radiation Pattern

No-hand

Hand

YZ Plane  XZ Plane

Multi-Antenna SAR Evaluation

MIMO (Multiple input and multiple output)

4G required
Challenges in SAR estimations

1) For fast switching multi-transmitter systems, how to simulate these SAR distributions when SAR patterns are changing

2) How to effectively measure all possible SAR patterns generated by these new technologies

Decomposition and Superposition Approach

Technique

1. Electric field/SAR simulation from each antenna with unit excitation
2. Superposition results from individual simulation

Advantage:

1. Minimum measurement required
2. Worst SAR estimation
Modeling

Plate: 5*20mm
Antenna length: 5mm
Sampling volume:
  relative dielectric constant: 40
  conductivity: 0.1s/m
Feeding: sinusoid, frequency: 1.5GHz, magnitude: 1V

Simulation Results

Electric field excited by each individual antenna
Electric Field Optimization

\[ \overline{E}_{\text{total}}(x, y, z) = \sum_{i=1}^{N} w_i \overline{E}_i(x, y, z) \]

Constraint:

\[ \sum_{i=1}^{N} |w_i|^2 = P_i \]

\[ w_i = R_i \angle \theta_i \]

Electric Field-Compare The Results

The minimized summation of field is less than 25.78% of the original one.

Complex coefficient

\[ w_1 = 0.8918 \angle -29^\circ \]
\[ w_2 = 1.1887 \angle 43.5^\circ \]
\[ w_3 = 0.88974 \angle -30^\circ \]
SAR minimization

1) Electric field available only
2) SAR available only

\[ \overline{E}_{total}(x, y, z) = \sum_{i=1}^{N} w_i \overline{E}_i(x, y, z) \]

\[ SAR_z = \frac{1}{4} \left( \frac{\sigma_{11} |E_{1x}|^2}{2 \rho_{1x}} + \frac{\sigma_{22} |E_{2x}|^2}{2 \rho_{2x}} + \frac{\sigma_{33} |E_{3x}|^2}{2 \rho_{3x}} + \frac{\sigma_{44} |E_{4x}|^2}{2 \rho_{4x}} \right) \]

\[ SAR = SAR_x + SAR_y + SAR_z \]
Upper Bound & Lower Bound of the SAR

\[ \text{SAR}_{\text{lower bound}} = 0.1288 \text{W/Kg} \]
\[ w_1 = 0.57071 \angle -62.3^\circ \]
\[ w_2 = 0.28769 \angle 44.3^\circ \]
\[ w_3 = 0.76911 \angle 17.5^\circ \]

\[ \text{SAR}_{\text{upper bound}} = 0.4012 \text{W/Kg} \]
\[ w_1 = 0.75967 \angle 12.9^\circ \]
\[ w_2 = 0.61093 \angle -68^\circ \]
\[ w_3 = 0.22287 \angle 55.7^\circ \]

SAR Available Only

\[ \text{SAR}_{\text{median}} (x, y, z) = \frac{\sigma}{2\rho} \text{E}_{\text{median}} \int \left( \sum_{i=1}^{N} |w_i E_i| \right)^2 = \left( \sum_{i=1}^{N} \frac{\sigma}{2\rho} |w_i E_i| \right)^2 = \left( \sum_{i=1}^{N} |w_i| \right)^2 \text{SAR} (x, y, z) \]

IEEE P1528.1™/D1.0
Worst SAR

\[ \text{SAR}_{\text{max}}^{\text{worst}} (x, y, z) = \left( \sum_{i=1}^{n} \left| W_i \right|^{2/3} \right)^{3/2} \]

\[ \left| W_i \right|^{2} = R_i^{2} = W_i (0 \leq W_i \leq 1) \]

\[ \sum_{i=1}^{n} W_i = P_{\text{in}} \]

\[ \text{SAR}_{\text{worst case bound}} = 0.4511 \text{W/Kg} \]

\[ W_1 = 0.5170 \]
\[ W_2 = 0.3533 \]
\[ W_3 = 0.1297 \]

Multi-PIFA antenna model
Antenna #1: S11 S21 S31

PIFA antenna and head model

Adult Visible Human Head in above figure (IEEE SCC 34 SC-2 WG-2) is used especially for cell phone SAR simulation, tissue assigned to corresponding frequency.
The figures above give two slices of the human head model (IEEE SCC 34 SC-2 WG-2). The resolution of this head model is 1 mm. The different colors in the figures indicate the different tissues in human body.

Optimize the SAR close to the MIMO PIFA antenna

Optimize the SAR near the antenna, on the left side of the green plane.

Results:

\[
\begin{align*}
\text{w1} &= 0.5283 + 0.2833i \\
\text{w2} &= 0.1607 + 0.0235i \\
\text{w3} &= 0.6298 - 0.4665i
\end{align*}
\]

SAR before optimize is 0.3850 W/Kg
SAR after optimize is 0.2095 W/Kg, which is 45\% smaller.
The SAR in the whole head volume

The maximum SAR after optimization is 45% of the SAR without optimization.

Optimize SAR close to the antenna, around ear

Increase the region to 24-40, the results show that the maximum and minimum of spatial maximum SAR would not change.
A typical police car (Ford Crown Victoria)  
CAD model of the car  
Car with medal parts only  
According to IEEE P1528.2

Ground is 30cm thick slab, with relative permittivity 8 and conductance 0.01 S/m, extend 10cm in x and y Direction beyond the car/bystander.

According to IEEE 1528.3 On the Ground Modeling Implementation

Three facing direction:
- Bystander model 1 -- facing the car
- Bystander model 2 -- facing front
- Bystander model 3 -- face off the car

Four seat modeling:
- Passenger no additional parts
- Passenger model 1 --> with medal seat
- Passenger model 2 --> with spring coils
- Passenger model 3 --> with both seat & coils
Design of Implantable Antenna
Trunk mounted antenna

Passenger back center 1/4 antenna at 450MHz

Electric Field Distribution at 900 MHz
<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>SAR with Device (W/kg)</th>
<th>SAR W/O Device (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.0028</td>
<td>0.0020</td>
</tr>
<tr>
<td>450</td>
<td>0.0041</td>
<td>0.0034</td>
</tr>
<tr>
<td>900</td>
<td>0.0077</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

Interconnect Modeling

HW 07-02-2005
Interconnects Modeling Approaches

Circuit level

- Lumped elements (L,C)
- T-line model

Electromagnetic level

- Lumped element
- Quasi-static
- Full wave

\[ V = RI \]

\[ \int \int \vec{H} \cdot \vec{dl} = \int \vec{E} \cdot \vec{dA} \]

Circuit simulation

On Chip Interconnects

- Capacitance extraction
- Inductance extraction
- Developing Rigorous/Efficient EM modeling
  
  (skin effects, nonlinearity, substrate coupling)
 silicon to package interconnects

- Flip Chip interconnect
- Underfill

Effects of solder bumps with full-wave simulation

on package interconnects

- T-line
- Via inductance
System board interconnects

Low frequency $\rightarrow$ lumped
Higher freq. $\rightarrow$ T-line
Extreme freq. $\rightarrow$ full wave

Examples
T-line parameter extraction (RLGC)

Examples

Reflection

Transmission

HW 07-02-2005
Summary

1. Various challenges EMC/EMI Issues in the design of wireless products
2. Accurate EM modeling techniques may help understanding these issues
3. Many challenges