Advances in FDTD Modeling Capabilities for Enhanced Analysis of Antennas Embedded in Complex Environments

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Abstract—A novel 3-D FDTD subgrid scheme is presented. It was developed under the objective of maximum stability and robustness with respect to implementation into a semi-automated TCAD modeling environment designed for simulating EM transmitters operating within highly complex EM environments. The novel scheme has proven not only to be greatly robust but also highly efficient since it may be staggered without losing stability. Implementation into a state-of-the-art simulation platform has proven its capabilities for automated mesh generation, even for complex geometric structures. The performance of the implemented algorithm was benchmarked on the base of a previously defined generic phone equipped with a helical antenna arranged within different setup configurations. In addition to these validations the advanced modeling capabilities were applied to simulate a complex real-world engineering situation.

I. INTRODUCTION

During the last two decades, the Finite-Difference Time-Domain (FDTD) method has become the preferred technique for simulating antennas in complex environments. Neverthelss, restrictions in geometrical resolution due to computational limitations prevent simulations of highly detailed or grid non-conformal objects within a larger space. Furthermore, applications to real-world engineering needs are often restrained by poorly combined graphical user interfaces and enhanced FDTD modeling capabilities. A highly efficient way to overcome restrained grid resolution is the introduction of a subgrid consisting of smaller mesh cells, placed within a subvolume of the computation domain as has been reported, e.g., in [1]. These often highly efficient schemes are only of limited use for engineering applications if they do not provide of most robustness within a semi-automated grid generation environment. The objective of this study was the development of a subgridding scheme providing very high stability and robustness as well as efficiency when implemented in such TCAD modeling environments designed for simulating transmitters operating within highly complex EM environments.

II. METHODS

A. Subgrid - Spatial Interpolation Algorithm

The focus on the developed algorithm was on a smooth and stable transition between the coarse and the fine grids. Another important criterion was applicability within inhomogeneous material transitions. A small refinement factor of two was not considered as a disadvantage, since subgrids can easily be stepped sequentially when smooth and stable, leading to refinement factors of $2^n$ with $n \in \mathbb{N}^+$ which has been successfully tested for refinements up to 1:16.

The best solution for temporal updating was achieved by a spatial positioning of the subgrid shifted by a quarter of the coarse grid’s cell dimensions in each direction, which leads to the smoothest transition, since all magnetic fields of the coarse as well as the fine mesh are collocated in a way simplifying spatial interpolation. Figure 1 depicts a detailed view of this setup with a single subgrid cell placed into a $3 \times 2 \times 2$ coarse grid structure while $E_{\text{coarse}}$ and $E_{\text{fine}}$ are the electric field components in the coarse and the fine grids, respectively. $H_{\text{coarse}}$ and $H_{\text{fine}}$ indicate the corresponding magnetic field components in the two coupled grids. For the exchange of information between the two grids a scheme is proposed which uses the electric and magnetic field components in the most external surface of the subgrid for information transfer from the coarse to the fine grid as well as the magnetic field components inside the inner subgrid region for a transfer in the opposite direction.

Fig. 1. Arrangement of coarse grid, subgrid and spatial interpolation.
For the determination of the $E_{\text{fine}}$-field components in the transition region, various 3-D cubic spline schemes were examined. For certain cases, particularly in the initial propagation stage, the basic interpolating cubic spline leads to over- and underestimated values. A spline can be slightly smoothed to decrease the amount of misestimation and therefore further reduce instabilities:

$$S(p) = p \sum_{i} \{y_i - f(x_i)\}^2 + (1 - p) \int f''(x)^2$$

where $f(x)$ defines a cubic spline through a series of $(x_i, y_i)$ data points.

In figure 1 for each direction three corresponding $E_{\text{coarse}}$ components are used which leads to a system of 27 field values for the interpolation in this case. The magnetic $H_{\text{fine}}$ components which are located in the inner transition region are determined by application of 1-D or 2-D cubic splines on the correlated $H_{\text{coarse}}$ field components, depending on their position.

B. Subgrid - Temporal Updating Scheme

Since the updating frequency in the subgrid is twice the one in the coarse grid, there will be some missing temporal information in the common FDTD updating scheme. Most of the proposed subgridding schemes use a temporal extrapolation to determine this information, since due to high refinement factors the missing components cannot be assessed from the coarse grid. In this paper a novel approach is presented which uses field data from the coarse grid at the current, past and the following time step to perform an interpolation in time. Figure 2 shows the detailed sequence of a full updating cycle. The determination of the temporal missing $H_{\text{fine}}$ components at $t = n - \frac{1}{2}$ is shown in figure 3. For all cases where no PEC material traverses the transition region, a reduction factor of 0.95 $dt_{\text{max}}$ allowed by the Courant criterion leads to stable solutions, otherwise a value of 0.93 was applied.

Fig. 2. Detailed sequence of steps for a full updating procedure in the FDTD coarse and fine grid.

C. Special Treatment of Traversing PEC Materials

For traversing PEC materials a special treatment of the interpolation algorithm has to be performed if at least one of the components is located inside the conductor. Therefore all affected components are determined using a slightly modified spline interpolation scheme which performs a 2-D or a 1-D spline interpolation depending on the localization of the cell for a virtually introduced $E_{\text{fine}}$ component while including only those $E_{\text{coarse}}$ components which are not located inside the conducting material.

D. Integration Into a TCAD / Automeshing Environment

Any local refinement scheme is of limited application when it cannot be effectively integrated within and supported by an ergonomic user interface. Only the combination of the three entities TCAD, Subgrid and Automeshing form the powerful instrument needed to make full usage of advanced FDTD modeling capabilities. Therefore the scheme was integrated within an ACIS 3-D based solid modeling environment featured by automated generation of graded meshes as well as material assignment. All features were implemented into the commercial package SEMCAD (Schmid & Partner Engineering AG, Switzerland).

III. RESULTS AND VALIDATION

A. Benchmark 1: Plane Wave Traversing Subgrid

As a first benchmark, the reflection at the subgrid boundary should be assessed for a plane-wave traversing the subgrid area. Therefore a subspace consisting of $27 \times 27 \times 11$ fine cells was placed inside a coarse grid computation domain extended about 3A in each direction at $f_{\text{max}} = 15$ GHz with a minimum mesh step of $\lambda_{\text{min}}/100$ as shown in figure 4. In order to observe the reflections from the subgrid boundary, a field sensor was placed at a two cell distance from the transition region. In figure 5 the reflection is depicted for the selected frequency range of 15 GHz. The type of splines applied in the scheme leads to very low reflections of about -70 dB even at higher frequencies.
B. Benchmark 2: Helical Antenna on Generic Phone

Within a second validation, the subgrid was applied to model a previously defined generic phone [2] equipped with a helical antenna. The dimensions of the box were 40 mm × 16 mm × 140 mm. The axial-mode helix had 7 turns with a diameter of 6.4 mm and a pitch angle of 7.2°, whereby the feeding wire was 5 mm long and the helix wire cross-section was 1.3 mm in diameter. The feedpoint was placed at 8 mm from the edges. Figure 6 depicts a detailed view of the helix model located inside a 1:2 subgrid with the discretized structure shown in a specific slice. Using a homogeneous subgrid resolution of 0.325 mm in the region of the helix enabled a detailed representation of the helical cross wire section by 4 × 4 cells. For the free space computation domain extended by 1.2λ in each direction, a non-homogeneous mesh with a maximum step of 8 mm (ratio = 1.2) was applied. As reference calculation a computation using the same grid parameters but without integration of the subgrid was applied.

![Helix located in 1:2 subgrid region](image)

![Thin modeled loop and square helices](image)

In addition to the validation of the subgridding scheme, the influence of modeling and meshing detail intensity on the obtained results was assessed. Therefore two helices, round and square shaped, were modeled which consist only of single edges in wire diameter instead of multiple cells as shown in figure 7. All additional grid parameters as well as the electrical length of the helices were kept constant compared to the subgrid model. In all calculations the computation space was bounded by 8 layer PML.

Furthermore, all simulations have been validated by experimental data using the DASY3 near-field scanning system [3] performing measurements on a physical model of the generic phone.

In figure 8 the feedpoint impedance for all simulations as well as for the measurement is compared. Both solutions obtained from subgrid and reference calculations agree very well with the experimental data, whereas the thin modeled helices deviate substantially from the reference solution in both real and imaginary parts. The comparison of the far-field pattern to the reference simulation shows good agreement only for the subgrid solution (deviation < 0.5%). The φ component of both round and square modeled thin helices show variations up to 15%.

The analysis of a 2-D error distribution of the subgrid compared to the reference solution in a plane which intersects the antenna’s feedpoint region shows a very low deviation of less than 0.1 dB in most of the regions observed.

![Comparison of feedpoint impedance for reference, subgrid and thin helix calculations to measurements](image)

C. Benchmark 3: Helical Antenna - Generic Phantom

In this example the 2nd benchmark has been extended with respect to complexity by placement of a generic head phantom model beside the generic phone. The generic phantom consisted of a plastic shell filled with a tissue simulating liquid [4]. Within the simulation a 1:2 sub-grid was applied to achieve an identical grid resolution and geometrical detail of the helix as in benchmark 2. Including the generic phantom the whole base-grid computation domain consisted of about 4 × 10⁶ cells, whereby a graded mesh (Δs_min = 0.65 mm³, Δs_max = 10 mm³, ratio = 1.2) was used.

For the following validation, all absorption and antenna parameters were evaluated for the “touch” and “100°” positions according to IEEE Std. 1528-200X. All simulation results have been validated using data obtained from measurements on physical models of precisely the same setup configurations (DASY3).

![Helical antenna on generic phone placed within subgrid region close to phantom model](image)

TABLE I

<table>
<thead>
<tr>
<th>Type</th>
<th>SAR_M [W/kg]</th>
<th>SAR_S [W/kg]</th>
<th>Diff [%]</th>
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<tbody>
<tr>
<td>1g Touch</td>
<td>6.9</td>
<td>6.5</td>
<td>-7</td>
</tr>
<tr>
<td>10g Touch</td>
<td>4.69</td>
<td>4.64</td>
<td>-3</td>
</tr>
<tr>
<td>1g Tilted</td>
<td>13.3</td>
<td>15.0</td>
<td>+11</td>
</tr>
<tr>
<td>10g Touch</td>
<td>6.32</td>
<td>7.73</td>
<td>+16</td>
</tr>
</tbody>
</table>

In table I, the results for the measured and simulated spatial peak SAR values (norm. to 1 W input power) averaged over 1 g and 10 g are summarized. Very good agreement is obtained for both positions, whereby the maximum
deviations are within the uncertainty of the simulation and the tolerances of the measurement system. Figures 10 and 11 show the measured and simulated feedpoint impedance for both positions in a 200 MHz frequency range. For both real and imaginary parts good agreement is obtained.

![Fig. 10. Feedpoint impedance in touch position.](image1)

![Fig. 11. Feedpoint impedance in 100° position.](image2)

**D. Enhanced Modeling: Nested Subgrids - Graded Mesh**

In benchmark 3 the subgrid approach already enabled a reduction of the computational memory and runtime requirements by a factor of 2-3. The current example clearly demonstrates the advantages of improved modeling capabilities when applied to real-world usage. Figure 12 depicts a setup where a miniature antenna on the generic phone is placed beside a high resolution non-homogeneous human head model. The bifilar antenna [5] which operates at 2.4 GHz has very small dimensions for specific parts, e.g., a 100 µm thickness for the helical loops. In contrast, these detailed structures are embedded within a computation domain extended by a sub-meter range with lower resolution.

![Fig. 12. Miniature antenna on generic phone close to non-homogeneous head model.](image3)

To achieve such advanced FDTD modeling needs, a nested 1:4 subgrid was combined with a graded mesh approach as shown in figure 13. The most inner subgrid had a high resolution of 0.1 mm³ which enabled a modeling of the thin metallic parts, consisting of a total number of 700 × 10⁶ cells. The outer subgrid is composed of 190 × 10⁶ mesh cells, which results in a total of 5 × 10⁸ cells for the surrounding base-grid using a grading from 0.4 mm up to 8 mm. This enhanced approach was compared with respect to computational requirements to a common graded mesh. Very low reflections are obtained in the mesh interface region, even for materials traversing the boundary. High stability is achieved, even in case of staggered utilization. We were able to integrate the scheme into a highly advanced CAD modeling environment providing semi-automated meshing features. Applications to structures like electrically small advanced antennas operating in the vicinity of non-homogeneous human head models demonstrated the suitability of the presented technique and its implementation for analysis and optimization of complex real-world engineering needs.

**Fig. 13. Enhanced modeling by combination of nested subgrids and graded mesh.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Base-Cells</th>
<th>Memory</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub 1:4</td>
<td>5 × 10⁶</td>
<td>650 MB</td>
<td>19 h</td>
</tr>
<tr>
<td>Graded</td>
<td>20 × 10⁶</td>
<td>2.5 GB</td>
<td>≈ 8 days</td>
</tr>
<tr>
<td>Homogeneous</td>
<td>11 × 10⁶</td>
<td>1.5 TB</td>
<td>≈ 2 years</td>
</tr>
</tbody>
</table>

**IV. Conclusions**

A novel three dimensional subgridding scheme for FDTD has been presented. It applies a smoothing cubic spline for spatial updating as well as an improved interpolation in time. Very low reflections are obtained in the mesh interface region, even for materials traversing the boundary. High stability is achieved, even in case of staggered utilization. We were able to integrate the scheme into a highly advanced CAD modeling environment providing semi-automated meshing features. Applications to structures like electrically small advanced antennas operating in the vicinity of non-homogeneous human head models demonstrated the suitability of the presented technique and its implementation for analysis and optimization of complex real-world engineering needs.

**V. Acknowledgments**

This study was supported by the Commission for Technology and Innovation (KTI); Schmid & Partner Engineering AG (SPEAG), Switzerland; Nortel, Great Britain; and the Mobile Manufacturers Forum (MMF), Belgium.

**References**


