An FDTD-Based Software Tool for Efficient Simulation of Microwave Devices and Antenna Systems

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***Abstract*— This paper presents a novel software tool for simulating microwave devices and antenna systems using the finite-difference time-domain numerical method. The tool is fully domestic software that operates independently of commercial software libraries. The paper first outlines the principal features of the implemented finite-difference time-domain solver. It then reviews the main functional capabilities of the tool. Specifically, the built-in mesh generator with integrated specialized pre-thining algorithms for 3D models is described. The excitation sources incorporated into the solver are also discussed, including a discrete port with arbitrary orientation capability and a plane wave with linear and elliptical polarization. Furthermore, RLC lumped load models based on specially developed schemes with semi-implicit current discretization are presented. Finally, field monitoring tools are described, consisting of a point field probe, near-field and far-field monitors. Additionally, simulation results for several benchmark problems are presented, that obtained using the developed finite-difference time-domain based tool and commercial electromagnetic simulation package. The results demonstrate good agreement, which confirms the operational capability and acceptable accuracy of the proposed software tool.**

Keywords*— *computational electromagnetics, finite-difference time-domain method, software tool, microwave devices, antennas.

I. Introduction

Electromagnetic simulation serves as a key design tool for modern microwave devices and antenna systems, enabling accurate prediction of their performance at early development stages – prior to prototype manufacturing and measurements. Engineering practice employs various numerical methods for electromagnetic analysis. The most widely adopted include the finite element method [1], [2], the method of moments (or boundary element method) [3], [4], and the finite-difference time-domain (FDTD) method [5], [6]. Compared to these alternative approaches, FDTD offers several advantages: reduced memory requirements, higher computational efficiency, and the capability to address ultra-wideband problems in a single simulation run [7]. These benefits have driven the widespread integration of FDTD-based solvers into established commercial electromagnetic analysis packages such as CST MWS, Altair FEKO, and Keysight EMPro. However, commercial software often remains inaccessible to many engineers and developers for various reasons, which sustains the relevance of developing simplified domestic alternatives.

This paper presents a novel FDTD-based software tool for efficient wideband simulation of microwave devices and antenna systems. We describe the principal features and capabilities of the developed tool and present simulation results for several benchmark problems to validate its performance.

II. Main Features of the Tool Implementation

The FDTD solver uses C++ to ensure high computational performance. The code also includes OpenMP directives to accelerate computations on multi-core workstations. The solver is built as a static library, which enables easy integration into various software systems. The application programming interface (API) provides a minimal set of functions for initialization, execution control, and obtaining simulation results. Input data, such as 3D geometry, excitation sources, loads, and mesh parameters, are specified in JSON files. The integrated open-source nlohmann-json library handles JSON parsing. The tool has no dependencies on other external software libraries, which simplifies compilation and deployment across different hardware platforms and operating systems.

To improve computational efficiency, the FDTD algorithm is divided into three stages. The pre-processing stage performs all preparatory operations required for the main iterative simulation loop. These operations execute only once and do not depend on the time step Δt. During the main stage, the solver computes primary parameters within the computational domain using finite-difference equations. These parameters include electric and magnetic field strengths, as well as electric and fictitious magnetic current densities. Finally, the post-processing stage calculates quantities required by the user based on these parameters, such as scattering matrices and radiation patterns.

The solver uses the standard three-dimensional Yee cell model [8] as its mathematical core. The current version supports frequency-independent dielectric and magnetic materials, perfect electric conductors, lossy metals, and anisotropic media defined by a diagonal tensor. To improve accuracy at material boundaries, the solver implements a

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procedure that averages material electro-physical properties across shared cell edges and faces (see Fig. 1). For boundary conditions, the solver uses the uniaxial perfectly matched layer model, which provides effective absorption of incident waves with minimal computational cost. For domain excitation, the solver supports standard and amplitude-modulated Gaussian pulses with parameters that adjust automatically based on the user-defined simulation frequency range.

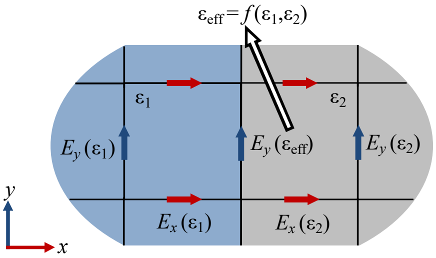

Fig. 1. Procedure for averaging the electrophysical properties of materials at the interface between two computational cells.

III. Mesh Generation

The FDTD-based tool includes a mesh generation module [9]. This module generates non-uniform structured meshes with a controlled size ratio between adjacent cells to reduce numerical dispersion. The mesh generation process uses a custom-developed fast iterative algorithm based on a user-defined maximum discretization step. The algorithm considers specified 3D objects, computational domain boundaries, and the coordinates of excitation sources, loads, field monitors, and other elements. Unlike other generators [10], [11], the tool does not use additional mesh optimization algorithms, which accelerates the generation process.

The module also integrates specialized pre-thining algorithms for 3D models. These algorithms prevent the generation of degenerate (or critically small) cells and excessively dense meshes when processing high-resolution polygonal models in formats such as STL, OBJ, or OFF, particularly those containing curved surfaces or surfaces non-orthogonal to the coordinate axes. Fig. 2 shows the mesh generation results for a circular resonator, comparing the output with and without the pre-thining algorithms applied.

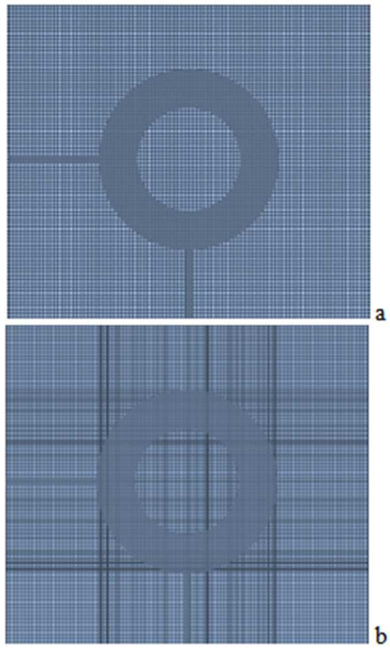

Fig. 2. Example of mesh generation for a polygonal 3D geometry using a pre-thining algorithm (a) and without it (b).

IV. Discrete Port Model

The tool implements a discrete port as one of its excitation sources. This source represents a lumped voltage source with user-defined internal impedance and a total input power of 1 W, connected to the gap in the center of a perfectly conducting thin wire. The tool supports an arbitrary number of ports, enabling computation of scattering matrices (*S*-parameters) as well as time-domain and frequency-domain responses for currents and voltages (Fig. 3). When calculating frequency-dependent characteristics, the tool normalizes the obtained responses to the spectrum of the Gaussian pulse excitation signal. This normalization ensures compatibility with results from third-party frequency-domain solvers.

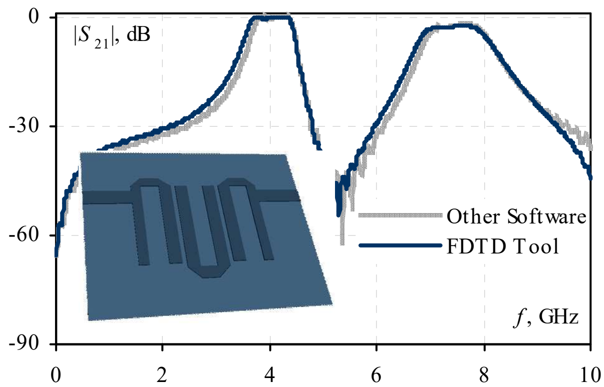

Fig. 3. Example of discrete port application: *S*-parameter simulation results for a microstrip filter obtained using the FDTD-based tool and commercial electromagnetic simulation software.

The port model allows defining its position using any two points specified within the computational domain. To discretize the resulting arbitrarily oriented thin wire, a custom-developed greedy algorithm automatically adjusting the decision criterion is used. Fig. 4 shows an example of this algorithm applied to a thin wire oriented non-orthogonally to the mesh lines.

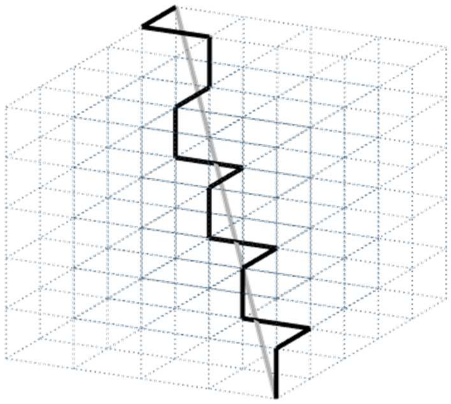

Fig. 4. Example of discretization (black line) of an arbitrarily oriented thin wire (gray line).

V. Plane Wave Source

In addition to the discrete port, the tool implements a plane wave source (Fig. 5). The source operates on the "Total Field/Scattered Field" formulation [12], which divides the computational domain into two regions: the scattered field region and the total field region that includes the excitation field. This formulation enables the tool to evaluate radar cross-section, compute transmission and reflection coefficients for metamaterials and frequency-selective surfaces, and address other specialized problems. The implemented source supports flexible configuration of the plane wave, including arbitrary propagation direction and user-defined amplitude and orientation of the electric field vector. Beyond the widely documented linearly polarized plane wave, the FDTD-based tool also supports an elliptically polarized wave model that allows arbitrary specification of polarization ellipse parameters.

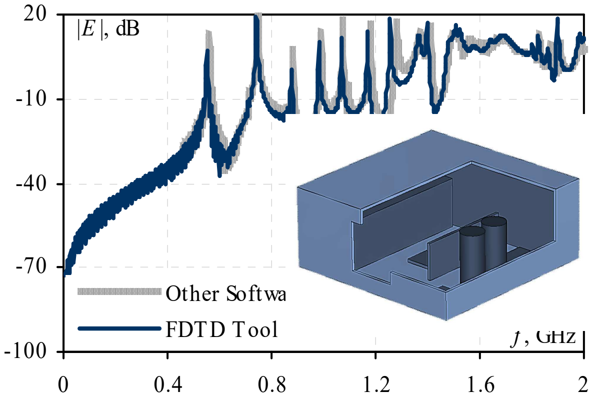

Fig. 5. Example of plane wave source application: electric field amplitude |*E*| simulation results inside a loaded shielding enclosure illuminated by a plane wave, obtained using the FDTD-based tool and commercial electromagnetic simulation software.

VI. Models of Lumped Elements

The tool includes two lumped load models: parallel and series RLC circuits. Both models use custom-developed schemes based on semi-implicit current discretization [13]. This scheme ensures numerical stability with minimal computational cost. To prevent numerical divergence with small RLC element values, the solver includes several specialized pre-processing algorithms. Consequently, the lumped load models remain stable even with zero or very small (comparable to parasitic values, below 0.1 nH and 0.1 pF) L and C values. As an example, Fig. 6 shows the calculated *S*-parameters of a microstrip line terminated with a series RLC circuit.

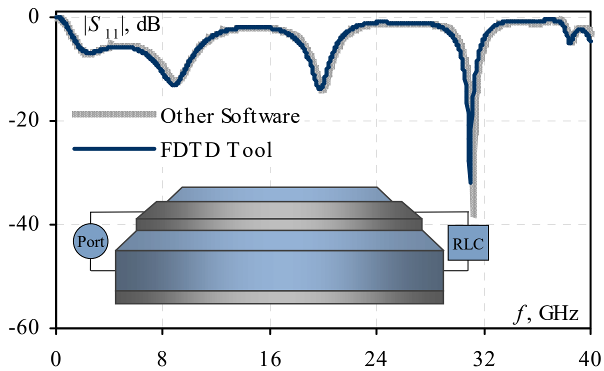

Fig. 6. Example of lumped elements application: *S*-parameter simulation results for a microstrip line with a series RLC circuit (R = 25 Ω, L = 0 H, C = 2 pF) obtained using the FDTD-based tool and commercial electromagnetic simulation software.

VII. Field Data Monitoring

The tool also implements several devices (virtual sensors) for monitoring electromagnetic fields within the computational domain. Specifically, it includes a probe model that computes electric or magnetic field values at a user-specified observation point (Fig. 5). This model calculates individual *x*-, *y*-, *z*-field components as well as their absolute values in the time domain or peak amplitudes in the frequency domain. Similar to the discrete port model, the field probe normalizes frequency-dependent data to the excitation signal spectrum. The probe position remains independent of the computational mesh, and the required field components at the specified point are determined from surrounding known values through trilinear interpolation.

In addition to the field probe, the tool includes a far-field monitor model. This monitor takes the form of a cuboid with adjustable dimensions. During solver operation, the monitor boundaries compute electric and fictitious magnetic currents. To reduce memory usage, the tool stores these currents in the frequency domain (at a user-defined far-field calculation frequency). This approach performs the discrete Fourier transform on-the-fly during the main iterative solution. The far-field calculation occurs during post-processing using the «Near-Field-to-Far-Field» transformation [14], which integrates the computed currents over the monitor surface. The result includes amplitude and phase radiation patterns, gain and directivity angular diagrams, and other characteristics required for antenna system analysis. Fig. 7 shows an example of the far-field monitor in use.

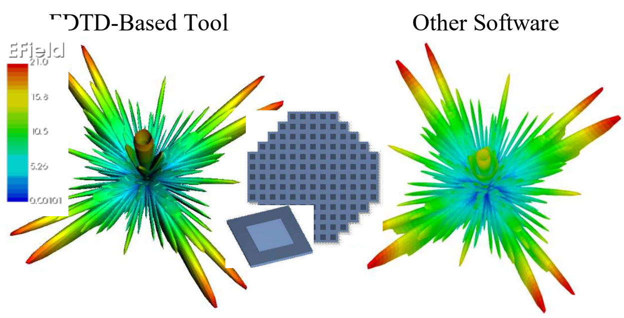

Fig. 7. Example of far-field monitor application: radiation pattern simulation results for a patch antenna array (129 elements) obtained using the FDTD-based tool and commercial electromagnetic simulation software.

Based on the far-field monitor, the tool also implements a near-field monitor. This monitor calculates and stores electric or magnetic field components within a user-defined cuboid for subsequent three-dimensional visualization and analysis. Fig. 8 compares test results for near-zone electric field distributions of a printed antenna array, obtained with the developed FDTD-based tool and with third-party software.

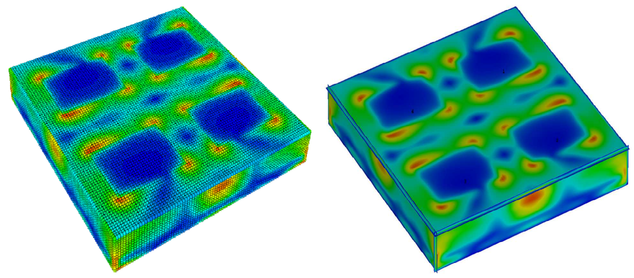

Fig. 8. Example of near-field monitor application: electric field distribution results for a patch antenna array (4 elements) obtained using the FDTD-based tool and commercial electromagnetic simulation software.

VIII. RESULTS

This paper presents a developed FDTD-based tool for simulating antenna systems and microwave devices. We describe the main implementation features and functional capabilities of the tool. The paper provides a brief overview of the implemented models for mesh generation, excitation sources, lumped loads, and monitoring devices for simulated characteristics. We also present calculation examples that compare results from the developed tool with those from a commercial electromagnetic simulation package.

IX. CONCLUSION

Overall, the implemented functions make the tool a complete software solution for analyzing antennas and microwave devices, and the presented results confirm its accuracy. Future updates will extend its functionality by adding waveguide ports, near-field sources, and periodic boundary conditions. To improve modeling accuracy for complex and curved 3D objects, the tool will integrate a conformal cell model. Finally, extensive work is planned to optimize the software code and implement hardware acceleration, including SIMD instructions and GPU computing.

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