Three Dimensional Conformal Alternating Direction Implici

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INTRODUCTION & OBJECTIVES

One drawback of the conventional FDTD method, e.g., in [1], is that the smallest spatial step limits the maximal stable time step. Therefore, spatially highly overdiscretized electromagnetic simulations are generally inefficient. In particular, EM simulations at low frequencies requiring detailed structures embedded within large environments would thus require tremendous runtime requirements. Typical applications include EMI and compliance of implanted devices for patients within MRI systems or general exposures to intermediate frequencies from 0.1 to 10 MHz.
To increase the time step, implicit time integration schemes, which are unconditionally stable, can be used. In 3-D the alternating direction implicit (ADI) FDTD method is an numerically efficient possibility [2,3,4]. ADI-FDTD is an approximate factorization of the Crank-Nicholson scheme (CN) applied to Yee discretization. On the other hand, conformal PEC FDTD models, reducing staircasing errors, may get a time step reduction to obtain the best accuracy.
The objectives of this study thus were the development and implementation of a conformal ADI-FDTD solver in 3-D.

METHODS

All implementations and comparisons were performed within the framework of the 3-D EM TCAD platform SEMCAD X [5]. In contrast to published C-FDTD schemes, the C-ADI-FDTD model presented here uses the conventional ADI-FDTD algorithm but with locally modified update coefficients (no splitting of curl coefficients). Therefore, the original ADI-FDTD update equations are used, while the coefficients calculation is conformally enhanced.
Instead of the well known C-FDTD schemes, a new conformal PEC model [7] using modified but conventional update coefficients was adapted to the ADI-FDTD method. The derived stability criterion was used to favor either speed or accuracy depending on the controlling parameter CFL, the time step reduction. The conformal dielectric model uses effective electromagnetic properties calculated in the area perpendicular to the dielectric edge. In detail, arithmetic averaging weighted with the conformal area fraction defines the effective electromagnetic properties.
Furthermore, no additional memory nor CPU time is needed for the C-ADI-FDTD algorithm compared to the conventional ADI-FDTD method. The proposed conformal PEC scheme is similar to the very recently (May 2006) published ADI-CFDTD method□[7].

Figure 3: CAD model and discretized model of the NOKIA 8310: The mesh is truncated by 8 layers of UPML media leading to an overall mesh size of 5.6 million voxels whose size varies between 0.01 mm and 12 mm. The default time step is 32CFL.

CONFORMAL ADI-FDTD THEORY

The proposed C-ADI-FDTD scheme uses the conventional ADI-FDTD updating equations but enhances the way of determining the updating coefficients with the geometrical details of the model. Therefore, the description of the method is organized by firstly explaining the connection between the conventional FDTD coefficients and the ADI-FDTD coefficients and secondly by the modifications to the FDTD coefficient functions due to the conformal enhancements.
The well known conventional Yee FDTD update scheme can be written as

$$E_x^{n+1} = \alpha_E(\Delta t) \cdot E_x^n + \beta_E(\Delta t) \cdot \left(\frac{\partial H_z^{n+1/2}}{\partial y} - \frac{\partial H_y^{n+1/2}}{\partial z} \right)$$

where E and H denote the electric and magnetic field, Δt is the time step, α_E and β_E are the conventional FDTD update coefficients, and n indicates the time $t = n \cdot \Delta t$.
The derivation of the ADI-FDTD algorithm starts with the same spatial discretization but with electric and magnetic fields coallocated in time. With a similar notation as in [3] the two subiterations of the ADI-FDTD scheme for the E_X field reads

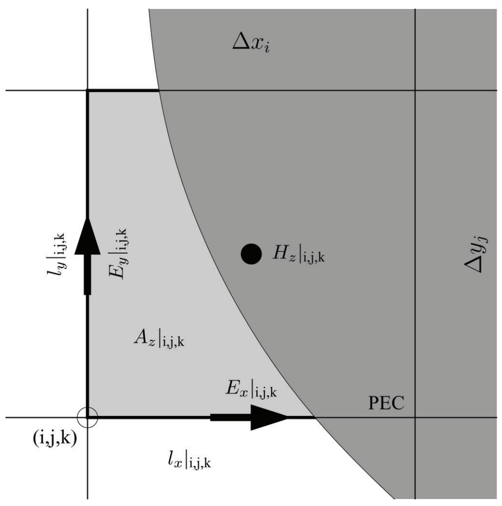
1. Subiteration $$\tilde{E}_x = \alpha_E(\Delta t/2) \cdot E_x^n + \beta_E(\Delta t/2) \cdot \left(\frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial H_y^n}{\partial z} \right)$$

2. Subiteration $$E_x^{n+1} = \alpha_E(\Delta t/2) \cdot \tilde{E}_x + \beta_E(\Delta t/2) \cdot \left(\frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial H_y^{n+1}}{\partial z} \right)$$

where $\tilde{E}$ and $\tilde{H}$ denote intermediate but non-physical field values. Important to note is that the ADI-FDTD equations use the same coefficient function α_E and β_E as the original Yee update.
The equation for the E_y and E_z component are obtained by cyclic permutation of the component's subscripts. For all H field component a similar equation with α_H and β_H as coefficient function can be written. Finally, the standard ADI-FDTD scheme with the six tridiagonal equation systems are obtained in the conventional way by substitution of the H update equations into the E update equations.

CONFORMAL PEC SCHEME

The well known conformal PEC FDTD methods are using the discrete form of Faraday's law (see Figure for geometrical details)



$$H_z|_{i,j,k}^{n+1/2} = H_z|_{i,j,k}^{n-1/2} + \frac{\Delta t}{\mu \cdot A_z|_{i,j,k}} \cdot \Big(E_x|_{i,j+1,k}^n \cdot l_x|_{i,j+1,k} - E_x|_{i,j,k}^n \cdot l_x|_{i,j,k} - E_y|_{i+1,j,k}^n \cdot l_y|_{i+1,j,k} + E_y|_{i,j,k}^n \cdot l_y|_{i,j,k} \Big)$$

Recently, a new conformal FDTD algorithm was introduced by the authors of this poster [7]. A major advantage is the formulation in terms of modified coefficient functions instead of altering the update equation itself. Therefore, the conformal FDTD method in [7] perfectly fits into the C-ADI-FDTD approach. The key changes to the update coefficient functions are

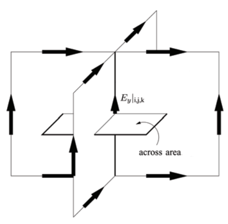
$$\tilde{\mu} := \mu \cdot A_{\text{ratio}} \qquad \tilde{\beta}_E(\Delta t) := \beta_E(\Delta t) \cdot \Delta_x^{\text{ratio}}$$

In summary, the conformal enhancement for the C-ADI-FDTD scheme could be formulated with the conventional ADI-FDTD updating scheme, but with locally modified coefficient functions.

CONFORMAL DIELECTRIC SCHEME

The dielectric model is based on the widely used effective material properties. For the electric permittivity, the formula reads.

$$\epsilon_{\text{eff}} = A_1^{\text{ratio}} \cdot \epsilon_1 + A_2^{\text{ratio}} \cdot \epsilon_2$$



Again, the conformal enhancement for the C-ADI-FDTD method is formulated with the conventional ADI-FDTD coefficients, but with modified material parameters.

RESULTS & BENCHMARKS

Starting with canonical validations, the versatile usage of the proposed C-ADI-FDTD method is demonstrated on real applications with increased complexity.

BENCHMARK 1: VALIDATION WITH MIE SCATTERING

As canonical benchmark example, the scattering of a metal sphere was investigated on the near and scattered field. The total field, scattered field technique [13] adapted to ADI-FDTD was used to irradiate the sphere by an incident plane wave at a frequency of 100MHz.
Mie series served as analytical reference solution. The boundary was terminated with 10 layers of UPML. The simulation was performed at 100MHz with a uniform grid resolution of 8mm, which gives overdiscretized 375 grid points per wavelength. The discrete norm $$$L^h_2$$$ (square root of the mean value of squared differences) was used to compare the simulated E field to the analytical solution.
Figure 1 depicts the relative norms of the near field errors of ADI-FDTD and C-ADI-FDTD methods. With the conventional FDTD time step (CFL = 1), the accuracy of the two ADI algorithms recover the accuracy of the FDTD and C-FDTD method (not shown). As expected, the accuracy of the (C-)ADI-

t FDTD Solver (C-ADI-FDTD)

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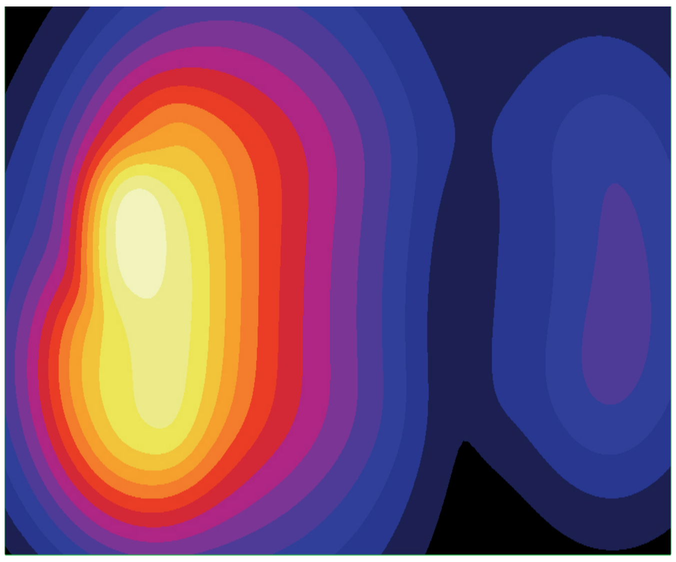
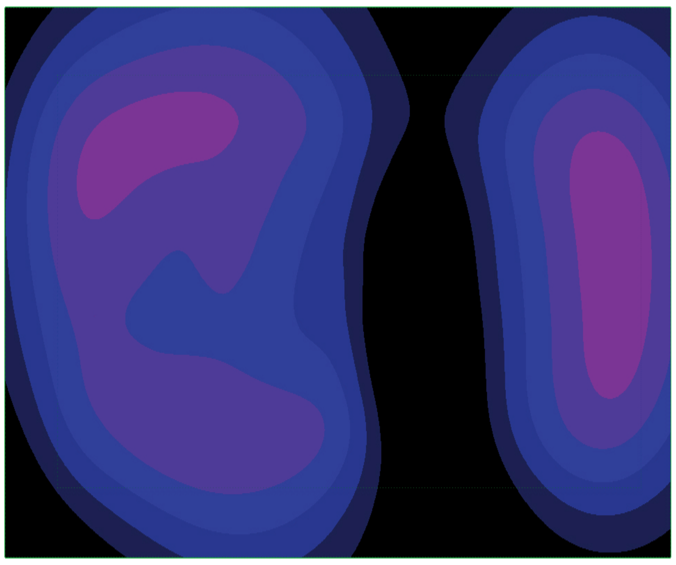
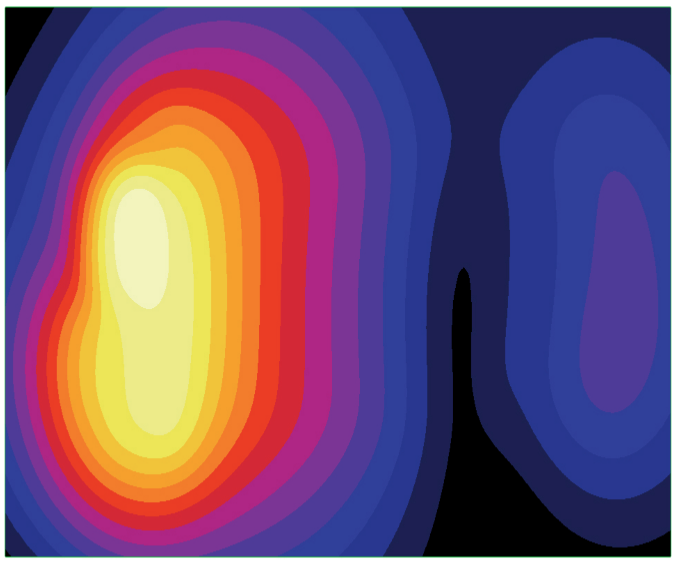


ADI-FDTD 32CFL simulation
E-field distribution in back plane



ADI-FDTD 32CFL simulation
E-field distribution in front plane



FDTD simulation
E-field distribution in back plane

FDTD simulation
E-field distribution in front plane

Figure 4: ADI-FDTD and FDTD simulations of E-field distributions in front and back plane of the phone.

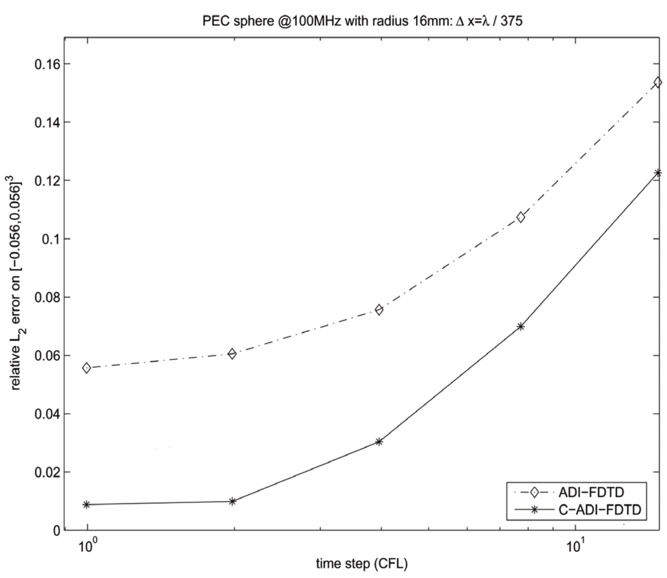


Figure 1: Canonical benchmark: Mie scattering at a PEC sphere. Mie series serves as analytical reference solution.

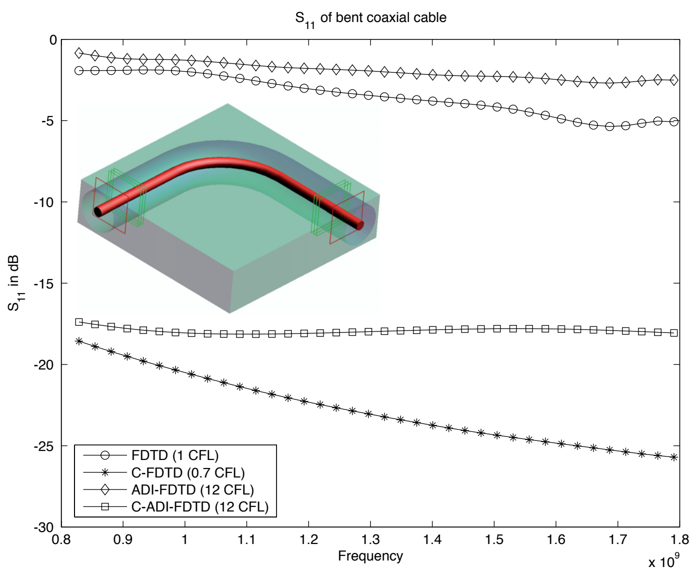


Figure 2: Return loss for different solvers and as inset the model. A low reflection is expected.

FDTD methods are slightly suffering while increasing the time step above the FDTD time step limit CFL > 1. However, the C-ADI-FDTD method is always more accurate than the conventional ADI-FDTD scheme, because the conformal method benefits the most from geometrical details.
Comparing the two conformal schemes reveals, that the presented C-ADI-FDTD methods needs more than 17 times less time steps to complete the simulation. The immediate benefit of the C-ADI-FDTD scheme proposed in this publication is obvious.

BENCHMARK 2: BENT COAXIAL CABLE

This benchmark shows a bent coaxial cable. The outer and inner radius of the cable are 0.1435mm and 0.6mm, respectively. The relative permittivity of the dielectric is 2.7. The coaxial cable is bent 90 degrees with a radius of 2mm of the coaxial center line. The non-uniform grid resolves the inner and outer radius with 4 and 13 cells, respectively.

The two open boundaries are terminated with a 10 layered UPML absorbing boundary. Figure 2 shows the model in the graphical user interface of the simulation platform.

Figure 2 shows the return loss S11 for the different solvers. The conformal technique outperforms the conventional staircase technique by orders in terms of accuracy.

Comparing the two conformal schemes reveals, that the presented C-ADI-FDTD methods needs more than 17 times less time steps to complete the simulation. The immediate benefit of the C-ADI-FDTD scheme proposed in this publication is obvious.

BENCHMARK 3: NOKIA 8310

Our objective was to replicate with the ADI-FDTD solver a previous joint study carried out with the Nokia Research Center (NRC, Finland) aiming at evaluating to which degree FDTD is capable of accurately simulating an entire CAD derived model (CATIA) of the NOKIA 8310 (Figure 3).
An important aspect of this study concerns the near-field analysis in which E-fields (dB normalized to maximum) are compared for the DCS1800 band in two horizontal planes located at 3 mm from either side of the phone. The ADI-FDTD simulations have been run for different time steps and are compared with their corresponding FDTD simulation (used as the reference simulation). For all simulations, PML absorbing boundaries [6] are used. The time steps of the C-ADI-FDTD simulations are specified as multiples of the CFL criteria.
Comparisons between C-ADI-FDTD simulations and the FDTD reference simulation bear on E field modules or H field modules and are characterized by their deviation calculated by

$$D = \frac{\left\| E_{rms}^{ADI-FDTD} - E_{rms}^{FDTD} \right\|_2}{\left\| E_{rms}^{FDTD} \right\|_2}$$

Both ADI-FDTD and FDTD simulations show that the energy is mostly radiated out of the back of the phone through the high E-fields located above the antenna (Figure 4). This is desirable because the energy is thus directed away from the user, as intended with the use of an integrated antenna.
The deviations between the FDTD reference simulation and the ADI-FDTD simulations are very small up to a time step of 32CFL as indicated in Table 1. This benchmark shows not only that ADI-FDTD is as robust as FDTD for complex simulations but also that it is significantly more efficient.

solver time step	FDTD CFL	ADI 4CFL	ADI 8CFL	ADI 16CFL	ADI 32CFL	ADI 48CFL
deviation of E front	0%	**0.4%**	**0.5%**	**2.1%**	**2.6%**	**5.7%**
deviation of E back	0%	**0.07%**	**0.3%**	**0.6%**	**2.7%**	**6.1%**
Antenna Efficiency	**63%**	**63%**	**63%**	**62%**	**63%**	**62%**

Table 1: phone simulations: comparison of E field deviations from reference FDTD simulation for different time step factors (CFL).

CONCLUSIONS

Aside from canonical benchmarks, complex CAD based electromagnetic engineering problems have demonstrated the suitability and benefits of the presented C-ADI-FDTD method compared to the conventional FDTD method. Since the ADI-FDTD scheme decreases accuracy with increasing overtuning of the conventional timestep, a tradeoff between speed and accuracy has to be taken into account. However, the developed C-ADI-FDTD method allows the effective computation of complex CAD derived configurations, in particular for overdiscretized models, which would require unacceptable runtime requirements using conventional FDTD. Furthermore, the proposed conformal ADI-FDTD scheme has neither an impact on the memory consumption nor on the speed compared to the conventional ADI-FDTD method, since both use the conventional ADI-FDTD coefficients. Therefore, the C-ADI-FDTD method improves the accuracy of simulation results without deficiencies and should be favored even over the ADI-FDTD method.

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