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13. ABSTRACT (Maximum 200 words)

In recent years, a variety of computational schemes have been developed that accelerate the iterative solution of the dense matrix equations that arise upon discretizing boundary integral equations pertinent to the description of electromagnetic scattering problems. These schemes largely fall into two categories: (i) fast multipole methods and (ii) wavelet/multiresolution schemes. The overall goal of this project is to develop and catalogue all practical hybrids between fast multipole solvers and multiresolution schemes useful to the analysis of electromagnetic boundary value problems. To this end, we developed (i) hybrid plane wave time domain (PWTD) – multiresolution schemes pertinent to the construction of PWTD schemes for lossy media, (ii) PWTD schemes for 2D environments, (iii) PWTD solvers for microstrip structures, (iv) PWTD schemes for low-frequency solvers, (v) PWTD schemes for quasi-planar environments, (vi) PWTD schemes for periodic kernels, (vii) Time-Domain Adaptive Integral (TD-AIM) kernels for solving time-domain integral equations, (viii) TD-AIM accelerated hybrid time domain integral equation – SPICE based circuit solvers, and (ix) a novel multigrid accelerator for the full wave finite element analysis of electromagnetic phenomena. Each and every of these solvers uses a multiresolution framework, either in space, time, or space-time to accelerate a boundary integral or finite element solver pertinent to the analysis of electromagnetic radiation, scattering, or guidance problems beyond what is possible using vanilla fast-multipole methods.

14. SUBJECT TERMS

Computational electromagnetics, fast solvers, fast multipole methods, plane wave time domain methods, wavelets.

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1. Problem Statement

In recent years, a variety of computational schemes have been developed that accelerate the iterative solution of the dense matrix equations that arise upon discretizing boundary integral equations pertinent to the description of electromagnetic scattering problems. These schemes largely fall into two categories: (i) fast multipole methods (which rely on a sparse representation of the method of moment matrix through the use of a diagonal translation operator), and (ii) multiresolution, often wavelet and impedance matrix localization schemes (which achieve a sparsification of the method of moment matrix through the use of wavelet-based and beamforming basis functions, respectively). Herein, we propose to hybridize these two families of methods by incorporating multiresolution concepts into the fast multipole framework. We choose the time-domain version of the fast multipole method, also known as the plane wave time domain (PWTD) scheme, as our testbed. The overall goal of this project then is to research and catalogue all hybrids between fast solvers and multiresolution schemes for analyzing electromagnetic scattering, radiation, and guidance problems. By hybridizing the PWTD methods with multiresolution concepts we exploit the complementary nature of the sparsification mechanisms employed by both families of techniques to construct even faster and more memory efficient solvers. Indeed, we have shown that the resulting hybrids permit the analysis of electromagnetic scattering and radiation problems involving structures of larger electrical dimensions and geometrical complexity than was possible before, with reduced CPU and computer memory resources.

2. Key Results

Significant progress in identifying all workable hybrids between fast multipole and multiresolution-based solvers was made during the contract period. Specifically, nine schemes that call for a marriage between "fast multipole methods" or their time domain extensions, viz, PWTD schemes, and multiresolution or wavelet-like methods have been studied. They relate to (i) hybrid plane wave time domain (PWTD) – multiresolution schemes pertinent to the construction of PWTD schemes for lossy media, (ii) PWTD schemes for 2D environments, (iii) PWTD solvers for microstrip structures, (iv) PWTD schemes for low-frequency solvers, (v) PWTD schemes for quasi-planar environments, (vi) PWTD schemes for periodic kernels, (vii) Time-Domain Adaptive Integral (TD-AIM) kernels for solving time-domain integral equations, (viii) TD-AIM accelerated hybrid time domain integral equation – SPICE based circuit solvers, and (ix) a novel multigrid accelerator for the full wave finite element analysis of electromagnetic phenomena. These multiresolution inspired fast solvbers are discussed below. Numbered references are for papers published as a result of this activity listed in Section 4.

(i) PWTD schemes for lossy and dispersive media: Fast multiresolution-based evaluation of boundary kernels for finite difference time domain (FDTD) simulations [11,12,13,17,20,34,45,48].

The recently introduced plane wave time-domain (PWTD) algorithm (A. A. Ergin, B. Shanker, and E. Michielssen, *J. Comp. Phys.*, 146, 157-180, 1998) permits the efficient evaluation of so-called exact boundary kernels for truncating 3D FDTD grids. Assuming that an FDTD boundary is occupied by N_s equivalent sources that are active for N_t time steps, the classical evaluation of the fields they generate in a lossless medium at N_s observers requires O(N_t N_s^2) operations; this cost rises to O(N_t^2 N_s^2) if the medium is dissipative. PWTD algorithms accomplish the same in only O(N_t N_s log^2N_s) operations. PWTD schemes for dissipative media media (K. Yegin, A. A. Ergin, B. Shanker, and E. Michielssen, "Fast FDTD Boundary Kernels for Dissipative Media," 2001 URSI EMT Symposium, accepted) constitute a generalization of PWTD schemes for lossless media and likewise express three-dimensional wave fields as superpositions of plane waves. The evolution of these plane waves is governed by one-dimensional wave equations with dissipative term, and accomplished using a spectral scheme. The domain over which these plane waves evolve must however be truncated. To date, two fast schemes for accomplishing this truncation have been developed. Both schemes permit the fast convolution of 1D boundary kernels with bandlimited source densities to arbitrary (spectral) accuracy. The first scheme evaluates the boundary integral by breaking up these source densities into time-limited subsignals and by computing the fields they generate for future observation using a (hierarchical) FFT. The second scheme relinquishes the convolutional nature of the boundary integral and instead exploits rank deficiencies of the boundary operator to achieve a fast evaluation of the boundary fields by breaking up the time-space boundary relationships into a **multiresolution** basis. As a result of this project, the above scheme was improved upon and extended. The improved scheme, like the previous one, expresses wave fields in dissipative media as a superposition of plane waves, the evolution of each of which is tracked by solving a one-dimensional partial differential equation. The new scheme departs from the old one through the use of a translation function, which greatly diminishes the number of plane waves in the decomposition. The translation function, the existence of which eluded us previously, is constructed in the spectral domain and acts on spectral plane wave components. Its use greatly improves the efficiency of the scheme as it reduces the number of plane waves to be translated by a factor of 10-20! In addition, the old PWTD scheme for dissipative media was also extended to permit field computation in dispersive media. The dispersive medium PWTD scheme very much resembles that for dissipative media as in both enviro9nments the 1D and 3D Green functions are related by a simple space derivative.

(ii) Fast 2D PWTD solvers: Fast multiresolution-based evaluation of Hilbert transforms (in the context of PWTD solvers), Part I [9,10,11,13].

Three fast methods for efficiently evaluating the transient linear wave fields due to two-dimensional (2D) surface scattering phenomena have been developed. These time-acceleration methods are named (i) Fast Fourier Transform (FFT) based acceleration method, (ii) truncated singular value decomposition (TSVD) based acceleration method, (iii) 2D plane wave time domain (PWTD) algorithm based acceleration method. The latter scheme expands fields due to a 2D line source in terms of Hilbert transformed plane waves. This expansion is evaluated efficiently using a **multiresolution** technique. With the application of these fast methods, computational complexities of $O(N_t \log^2 N_s^2)$ and $O(N_t \log N_t N_s^2$ contrary to $O(N_t^2 N_s^2)$ for the classical evaluation of fields are achieved if N_s spatial and N_t temporal unknowns are used in the numerical analysis. The third method is augmented to a marching on in time (MOT) integral equation solver to numerically validate the efficacy of the proposed approach. These fast methods render rapid analysis of integral equation based 2D transient scattering problems.

(iii) Fast PWTD solvers for microstrip environments: Fast Multiresolution-based evaluation of Hilbert transforms (in the context of PWTD solvers), Part II [19,43]

Microstrip elements are widely used to realize transmission lines, antennas, and filters. Not surprisingly, a multitude of computational schemes for analyzing microstrip structures have been studied; among them, the finite-difference time-domain algorithm dominates. In recent years, time domain integral equation (TDIE) methods however have been receiving increasing attention. A transient electric field integral equation (EFIE) pertinent to the analysis of microstrip structures is established and a marching-on-in-time (MOT) algorithm for solving this EFIE is being developed. Compared to earlier MOT schemes, the proposed algorithm requires no analytic approximation of the Green’s function kernel and therefore can be considered numerically exact. The computation of the matrix elements is facilitated by using the PWTD scheme. Fast temporal convolutions involving Hilbert Transforms are accomplished using a **multiresolution** (wavelet-like) decomposition of the signal. Our past work focused on accelerating this scheme by avoiding the direct use of images and its hybridization with a SPICE-like solver for the analysis of complex nonlinear circuits and PCB boards – see also (iv). This work was awarded the **"Best Student Paper Prize"** at the IEEE International Symposium on Antennas and Propagation, Boston, MA, July 2001. Improved versions of this scheme were developed in subsequent years. Specifically, we developed a new family of fast methods for analyzing transient excitations of a multilayered dielectric medium. In these new schemes, the layered medium is either embedded in between two homogeneous half-spaces or a homogeneous half space and a perfect electrically conducting sheet. The subject matter of the work presented herein is twofold. First, a novel representation of the field generated by a pulsed point source is arrived at by relying on the "causality trick" (CT). Second, an efficient approach to numerically calculate this field is developed by assuming that the layered medium is thin. The approach is applied to the calculation of Green's functions and an extension of the quasi-planar plane wave time domain algorithm. The CT permits the representation of transient wave fields by a sum of causal and anti-causal components. Specifically, CT allows for the restriction of all infinite integrations inherent in the Sommerfeld or Weyl type field representations, to finite ones. Here, it is shown that the integration contour for the invisible spectrum can be closed around pole singularities that correspond to (frequency domain) guided modes. Hence the CT field can be *exactly* represented in terms of two contributions: the *visible* spectrum and a *discrete* set of guided modes. The representation above is especially useful when dealing with a *thin* layered medium. To construct a Green function, it is noted that only a small number of guided modes exists. Hence the contribution of the invisible spectrum part can be calculated rapidly in terms of their inverse Fourier transform. For the visible spectrum a window is constructed, which, for a certain frequency band, tapers to zero where the integrand rapidly oscillates. Next, a quadrature rule containing *O(1)* nodes is build, leading to a scheme for computing the field for *any* observer location in terms of $N_t \log N_t$ operations (N_t being the number of the time sampling points). Note that the quadrature rules should take into account the possible closeness of the poles to the visible spectrum. For the transient field a set of windows can be constructed utilizing the multiresolution procedure suggested in. Finally, the above procedure is applied to extend the quasi-planar PWTD algorithm to layered medium configurations. Here, for the visible spectrum, a three stage algorithm results, where the reflection coefficient leads to a larger duration of the transient plane waves. The discrete spectrum part is represented in terms of a finite number of the azimuthal variable. Attention is to be paid to the *dispersive* nature of these poles and their residues.

(iv) Low-frequency PWTD schemes: Fast evaluation of fields produced by (potentially) clustered sources using multiresolution bullets [18,21,22,47].

Modern day electronic systems pose significant challenges to the electromagnetic modeler. Ever-increasing clock rates and circuit density call for the full wave modeling of printed circuit boards (PCBs) with fine geometric features, finite (and possibly inhomogeneous) dielectrics, and nonlinear loads and circuits. Under Year 2 funding, a new time domain integral equation solver that achieves such functionality was developed. Specifically, a marching-on-time (MOT) algorithm for solving a time domain electric field integral equation pertinent to the analysis of PCBs with conducting surfaces/wires/junctions and (potentially inhomogeneous) finite dielectrics was constructed. Given a bandlimited excitation, the MOT algorithm solves for induced surface currents on conducting elements and polarization currents in dielectric regions. For a geometry modeled using N_s surface/wire and N_v volumetric unknowns, the computational complexity of this solver scales as O(N_t (N_s+N_v)^2) where N_t denotes the number of simulation time steps. To reduce this complexity, the scheme is accelerated by the multilevel plane wave time domain algorithm (A. A. Ergin, B. Shanker, and E.

Michielssen, IEEE Antennas and Propagat. Mag., 41, 39-52, 1999). The computational complexity of the resulting solver scales as O(N_t (Ns+Nv) log^2(Ns+Nv)) when applied to the analysis of typical PCBs without small geometric details. Unfortunately, when applied to structures with fine detail, the speed of the scheme suffers due to a phenomenon known as "low frequency breakdown". To fix this problem, we introducd a new version of the PWTD scheme, the LF-PWTD. For all levels in the tree where boxes are too small to satisfy the subsignal constraints imposed by the classical MLPWTD scheme, temporal source signatures are *locally* sampled a higher rate to allow their representation by high frequency interpolants which can be used to construct a series of **multiresolution** subsignals satisfying the above constraints. Such subsignals, further termed "high frequency bullets" are then fired from source to observer regions, whenever the MOT solver requires observation of the field on the coarse time grid. Any lumped circuits are modeled by coupling modified nodal analysis equations to the MOT system of equations. A nonlinear Newton-based solver is used at each time step to solve a nonlinear system of equations the size of which is equal to the total number of nonlinear circuit elements in the system. Hence, the unknown currents and voltages in both the electromagnetic model and the circuit are solved for in a consistent way at each time step of the simulation. The proposed method has been applied to a number of structures including a shielded active microwave amplifier with a MESFET transistor. We expect this method to find extensive use in the EMC/EMI and signal integrity analysis of PCB devices with realistic complexity.

(v) Beamforming PWTD schemes: Fast computation of fields on quasi-planar structures using a multiresolution (angle-frequency) family of beams [16,24,39].

The recently developed plane wave time domain (PWTD) scheme (A. A. Ergin, B. Shanker, and E. Michielssen, *Journal of Computational Physics*, vol. 146, no. 1, pp. 157-180, 1998) permits the fast evaluation of transient electromagnetic fields radiated by surface-bound sources with N_t and N_s temporal and spatial degrees of freedom in O(N_t N_s log^2(N_s)) operations. The scheme is useful in accelerating the solution of time domain integral equations and in the construction of fast boundary kernels for finite difference time domain solvers. Just like its frequency domain counterpart, viz., the fast multipole algorithm, the PWTD scheme subdivides the source support into smaller entities. The scheme then proceeds by classically evaluating all interactions between sources that reside in each other's immediate vicinity. However, interactions between sources that are far removed from one another are accounted for through plane wave expansions that describe the source's far-field radiation patterns for all 4 Pi directions. Because PWTD algorithms apply to arbitrarily shaped scatterers, they are suboptimal when applied to quasi-planar structures source distributions, viz. sources residing on surfaces whose transverse dimensions far exceed their height (rough surfaces, microstrip antennas on a finite ground plane, etc.). Indeed, it was recently demonstrated that, for quasi-planar source distributions, the cost of PWTD schemes can be reduced significantly by windowing the plane wave translation function, that is, by only retaining plane waves in a narrow cone surrounding the transverse plane (E. Michielssen, A. Boag, and B. Shanker, Proceedings of the National Radio Science Meeting, pp. 89, Boulder, Jan. 2002). In that work, windows were constructed by brute force, that is, through entirely numerical means. A scheme for constructing these windows as superpositions of doubly orthogonal concentrated polynomials (E. A. Gilbert, D. Slepian, *SIAM J. Math. Anal.*, vol.8, no.2, pp.290-319, 1977) was developed. These functions are the polynomial equivalents of prolate spheroidal wave functions and can likewise be constructed through the solution of an eigenvalue problem. Optimal windows are constructed by linearly combining highly concentrated eigenfunctions subject to the condition that the windowed interaction signals are identical to those produced by the original PWTD scheme. It was demonstrated that, while it is impossible to construct a single window function for sources with baseband temporal signatures, high quality windows can be constructed for modulated sources. Therefore, the algorithm is applied to the construction of a set of **multiresolution** windows, each covering a given frequency band. Fields due to sources with baseband signatures are then reconstructed by representing the source signatures in a multiresolution basis. This scheme has many possible applications, ranging from the analysis of rough surface scattering to the characterization of fields on (non-enclosed) circuit boards to the analysis of finite antenna arrays.

During the final year of the contract period, the above schemes were extended and improved upon. Specifically, the family of windows used was extended along two directions. First, through the asymptotical technique, a family of analytic windows that provide excellent computational savings was constructed. Second, additional windows were constructed through completely numerical techniques/optimization. Because of these efforts, we are confident to have available now the optimal windows for use in quasi-planar PWTD kernels.

(vi) Periodic PWTD schemes: Fast evaluation of fields produced by sources on a periodic array using multiresolution techniques [14,29,44].

A fast time domain integral equation (TDIE) based solver pertinent to the analysis of transient scattering from doubly periodic, perfect electrically conducting (PEC) structures, was developed. The proposed solver relies on a fast scheme for evaluating transient electromagnetic fields generated by doubly periodic and temporally bandlimited source distributions that hinges on Floquet decomposition concepts as well as multiresolution-based accelerators.

In the past, transient scattering from doubly periodic structures has been analyzed using finite difference methods. Unfortunately, when the structure under study is obliquely excited, classically constructed finite-difference solvers require future fields values, i.e., noncausal data, to update current ones, and therefore cannot be applied. Most fixes to this problem are either hard to implement or limited in scope. A recently developed TDIE-based solver resolved the issue of noncausality through the introduction of time-shifted temporal basis functions and a prolate-like extrapolation scheme for bandlimited signals [N.-W. Chen, B. Shanker and E. Michielssen, *IEE Proceeding-Microwaves Antennas & Propagation.*, 2002, in press]. Unfortunately, this solver is computational expensive in the sense that its computational cost scales as $O(N_s^2 N_t^2)$, where N_s and N_t denote the number of spatial basis functions describing the currents on PEC elements in the mothercell—viz. where the integral equation is being enforced—and the number of time steps in the analysis, respectively. This scaling law precludes the application of this solver to the analysis of complicated structures. The computational cost of this solver can be attributed largely to its need to evaluate the scattered field, viz. the field radiated by the currents on the periodic structure, for every time step. The newly developed fast TDIE-based solver reduces this cost by expressing the scattered field in terms of time domain Floquet waves. Only a small number of Floquet waves suffices to represent the field provided that it is generated by quiescent bandlimited sources. The Floquet waves therefore cannot account for fields produced by sources in the immediate vicinity of the mothercell. As a result, fields in the mothercell are split into two components. First, there are the fields associated with sources in cells in its immediate vicinity: they are evaluated classically, using a low-frequency plane wave time domain algorithm [K. Aygün et al., *Proc. Int. Conf. in Electromagnetics in Advanced Applications*,769-782, 2002], or by a time domain AIM scheme [A. Yilmaz et al., *IEEE APS Symp. Dig.*, 166-169, 2002]. Second, there are the fields produced by sources that do not reside in the immediate vicinity of the mothercell: they are evaluated using the aforementioned Floquet expansion; this evaluation calls for a description of each term of the Floquet series in a **multiresolution** basis. By doing so, the computational complexity of the scheme scales as $O(N_{\text{mode}} N_s N_t \log^2 N_t)$ where N_{mode} denotes the number of modes used in the Floquet expansion. This scheme is currently being applied to the study of power-combining arrays – see also (viii).

(vii) Time-Domain Adaptive Integral Method based time domain integral equation solvers: Fast solution of time domain integral equations by multiresolution, blocked FFT schemes [7,25,28,31,32,33,36,41].

An efficient marching-on-in-time scheme for solving electric, magnetic, and combined field integral equations pertinent to the analysis of transient electromagnetic scattering from perfectly conducting surfaces residing in an unbounded homogenous medium was developed. The proposed scheme is the extension of the frequency-domain adaptive integral/pre-corrected FFT method to the time domain. Fields on the scatterer that are produced by space-time sources residing on its surface are computed (i) by locally projecting, for each time step, all sources onto a uniform auxiliary grid that encases the scatterer, (ii) by computing everywhere on this grid the transient fields produced by the resulting auxiliary sources via global, **multilevel/blocked, space-time FFTs**, and (iii) by locally interpolating these fields back onto the scatterer surface. As this procedure is inaccurate when source and observer points reside close to each other, (iv) near fields are computed classically, albeit (pre-)corrected, for errors introduced through the use of global FFTs. The proposed scheme has a computational complexity and memory requirement of $O\left(N_t N_s \log^2 N_s\right)$ and $O\left(N_s^{3/2}\right)$ when applied to quasi-planar structures, and of $O\left(N_t N_s^{3/2} \log^2 N_s\right)$ and $O\left(N_s^2\right)$ when used to analyze scattering from general surfaces. Here, and denote the number of spatial and temporal degrees of freedom of the surface current density. These computational cost and memory requirements are contrasted to those of classical marching-on-in-time solvers, which scale as $O\left(N_t N_s^2\right)$ and $O\left(N_s^2\right)$, respectively. A parallel implementation of the scheme on a distributed-memory computer cluster that uses the message-passing interface is described. Simulation results demonstrate the accuracy, efficiency, and the parallel performance of the implementation.

(viii) Time-Domain Adaptive Integral Method based hybrid time domain integral equation – SPICE circuit solvers: Fast solution of time domain integral equations by multiresolution, blocked FFT schemes [8,15,37,42,46,49].

A novel fast electromagnetic field-circuit simulator that permits the full-wave modeling of transients in nonlinear microwave circuits is proposed. This time-domain simulator is composed of two components: (i) A full-wave solver that models interactions of electromagnetic fields with conducting surfaces and finite dielectric volumes by solving time-domain surface and volume electric field integral equations, respectively; (ii) A circuit solver that models field interactions with lumped circuits, which are potentially active and nonlinear, by solving Kirchoff equations through modified nodal analysis. These field and circuit analysis components are consistently interfaced and the resulting coupled set of nonlinear equations is evolved in time by a multidimensional Newton-Raphson scheme. The solution procedure is accelerated by allocating field- and circuit-related computations across the processors of a distributed-memory cluster, which communicate using the message-passing interface standard. Furthermore, the electromagnetic field solver, whose demand for computational resources far outpaces that of the circuit solver, is accelerated by an FFT based algorithm, viz. the time-domain adaptive integral method. The resulting parallel FFT accelerated transient field-circuit simulator is applied to the analysis of various active and nonlinear microwave circuits, including power-combining arrays.

(ix) Hierarchical multilevel and multigrid preconditioners for robust fem-based electromagnetic modeling [1,2,3,4,5,6].

We have developed and implemented hierarchical multilevel and multigrid preconditioners that enable the robust solution of finite element approximations of electromagnetic boundary value problems.

These preconditioners address many of the convergence and numerical instability shortcomings of popular vector finite element solvers. To elaborate, the convergence of iterative solvers tends to be unpredictable for electromagnetic wave problems, even when common preconditioners, such as incomplete LU factorization, are used to improve convergence. The reasons for the slow convergence of the iterative solver are by now well understood. They are associated with the dc modes contained in the null space of the curl operator, and the ill-conditioning of the FEM matrix resulting from the oversampling of the low-frequency physical modes. Spurious dc modes can be canceled through the introduction of a spurious electric charge and the enforcement of the divergence free nature of the electric flux density explicitly in the weak statement of the electromagnetic problem. Use of the vector-scalar potential formulation for the development of the FEM approximation is most suitable for this purpose. On the other hand, the difficulties associated with low-frequency physical modes can be tackled effectively by solving problems tentatively on coarser grids or in lower-order basis function spaces. More specifically, those modes that are oversampled on the original FEM grid can be solved without loss of accuracy using an FEM system with much fewer degrees of freedom. Subsequently, through an interpolation process, the generated numerical solutions are projected back onto the original grid on which the higher-frequency modes are to be calculated accurately. The demonstrated success of these remedies led us to propose their combination into a multigrid vector-scalar potential finite element preconditioner that has been shown to exhibit outstanding convergence in conjunction with the analysis of three-dimensional electromagnetic problems. There are two types of multigrid techniques, geometric and hierarchical. The geometric multigrid technique uses a set of nested multigrids obtained by dividing each tetrahedron in the coarsest grid into eight equal-volume sub-tetrahedra; hence, the geometric multigrid technique functions as an h-adaptive finite element method. However, for those cases where the domain under study contains sub-domains where the electromagnetic field variation is sufficiently smooth, p-adaptive schemes can tackle numerical dispersion error more effectively than h-adaptive ones. Therefore, for such cases a hierarchical multilevel vector-scalar potential finite element preconditioner is more suitable. Such a preconditioner uses only one grid and a set of hierarchical basis function spaces, i.e. H0(curl) and H1(curl), for the FEM approximation and numerical solution of the electromagnetic boundary value problem. We have implemented both classes of preconditioners and examined their attributes in the context of the various classes of boundary value problems that arise in antenna and microwave circuit analysis and design as well as the modeling of electromagnetic scattering and radiation problems. These studies have demonstrated that with the proper choice of the preconditioning technique a very robust and fast converging FEM analysis can be performed for all the aforementioned classes of electromagnetic problems.

3. Scientific personnel supported by this project and honors/awards/degrees received

- Mingyu Lu (Ph.D. granted in August 21, 2002; after that Post-doctoral Fellow on this project; he will join UT Arlington as an Assistant Professor of Electrical and Computer Engineering)
- Yu Zhu (Ph.D. granted, December, 2002; currently with Cadence)
- Korkut Yegin (Post-doctoral Fellow January 2001-August 2002, currently with GM)
- Eric Michielssen, Professor
- Andreas Cangellaris, Professor
- Vitaliy Lomakin (August 2002-present: Post-doctoral Fellow; he will join UCSD as an Assistant Professor of Electrical and Computer Engineering).
- Jiang Peilin (Ph.D student, expected graduation date August 2005)
- Ali Yilmaz (Ph.D. student, August 2001-August 2003; currently Visiting Assistant Professor at UIUC).

The paper "A Marching-on-in-Time Based Transient Electric Field Integral Equation Solver for Microstrip Structures", *Proceedings of the 2001 IEEE International Antenna and Propagation Symposium*, Boston, MA, July 2001 by M. Lu and E. Michielssen received a “Best Student Paper Prize”.

Eric Michielssen was chosen as one of six 2002-2005 University Scholar for his work on Time Domain Integral Equation Solvers. In addition, he was elected IEEE Fellow and named Sackler Scholar at Tel Aviv University.

Eric Michielssen delivered several invited lectures based on the work performed under this grant, including presentations at the Institute for Pure and Applied Electromagnetics (IPAM) at UCLA (June 2004), the Oberwolfach meeting on computational electromagnetics (February 2004)

4. List of papers

Journal papers

1. Y. Zhu and A. Cangellaris, “Nested multigrid vector and scalar potential finite element method for fast computation of two-dimensional electromagnetic scattering,” IEEE Transactions on Antennas and Propagation. Vol. 50, no. 12, pp. 1850-1858. Dec. 2002
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9. M. Lu, K. Yegin, B. Shanker, and E. Michielssen, “Fast time domain integral equation solvers for analyzing two-dimensional scattering phenomena; Part I: temporal acceleration,” *Electromagnetics*, vol. 24, no. 6, pp. 425-449, 2004.
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11. M. Lu, M. Lv, A. A. Ergin, B. Shanker, and E. Michielssen, “Multilevel plane wave time domain-based global boundary kernels for two-dimensional finite difference time domain simulations,” *Radio Science*, vol. 39, no. 4, Art. No. RS4007, Aug. 2004.

12. Q. Chen, M. Lu and E. Michielssen, “Integral-equation-based analysis of transient scattering from surfaces with an impedance boundary condition,” *Microwave and Optical Technology Letters*, vol. 42, no. 3, pp. 213-220, Aug. 2004
13. M. Lu, B. Shanker, and E. Michielssen, “Elimination of spurious solutions associated with exact transparent boundary conditions in FDTD solvers,” *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 4, pp. 59-62, 2004.
14. N.-W. Chen, M. Lu, F. Capolino, B. Shanker, and E. Michielssen, “Floquet-wave-based analysis of transient scattering from doubly periodic perfectly conducting bodies,” to appear in *Radio Science*.
15. Ali E. Yilmaz, Jian-Ming Jin, and Eric Michielssen, “A TDIE-Based Asynchronous Electromagnetic-Circuit Simulator “, Microwave and Wireless Circuit Letters, Submitted
16. S. Li, A. Boag, B. Shanker, and E. Michielssen, “Quasi-planar plane wave time domain kernels,” To be submitted to Journal of Computational Physics, draft available upon request.
17. P. Jiang, B. Shanker, and E. Michielssen, “Lossy medium Plane wave time domain kernels,” To be submitted to Journal of Computational Physics, draft available upon request.
18. M. Lu, K. Aygun, Mingyu Lu, and E. Michielssen, “Low frequency PWTD kernels”, To be submitted to Journal of Computational Physics, draft available upon request.

Conference papers

19. M. Lu and E. Michielssen "A Marching-on-in-Time Based Transient Electric Field Integral Equation Solver for Microstrip Structures", *Proceedings of the 2001 IEEE International Antenna and Propagation Symposium*, Boston, MA, July 2001**, “Best Student Paper Prize”.**
20. K. Yegin, B. Shanker, A. Ergin, and E. Michielssen, " Fast FDTD boundary kernels for dissipative media", *Proceedings of the 2001 IEEE International Antenna and Propagation Symposium*, Boston, MA, July 2001.
21. K. Aygün, B. Shanker, and E. Michielssen, "Low frequency plane wave time domain kernels," invited paper, presented at the *International Conference on Electromagnetics in Advanced Applications*, Torino, Italy, Sep. 10-14, 2001.
22. K. Aygün, B. Shanker, and E. Michielssen “Fast Time Domain Characterization of Finite Size Printed Circuit Board Structures,” invited paper, presented at the *Fourth International Workshop on Computational Methods in the Time Domain: TLM/FDTD and Related Techniques (CEM-TD*), Nottingham, UK, Sep. 17-19, 2001.
23. E. Michielssen, B. Shanker, and A. Boag, “Quasi-planar plane wave time domain kernels,” *Proceedings of the URSI-Boulder Meeting*, Boulder, January 2002.
24. S. Li, A. Boag, B. Shanker, and E. Michielssen, “New quasi-planar plane wave time domain kernels,” *URSISNC-Boulder Meeting*, San Antonio, June 2002.
25. A. Yilmaz, S. Li, J. Jin and E. Michielssen, “A Parallel Framework for FFT-Accelerated Time-Marching Algorithms,” *Proc. of the 2002 USNC/URSI*, p. 319, June 16-21, 2002, San Antonio, TX.
26. M. Lu and E. Michielssen, “Closed Form Evaluation of Time Domain Fields Due to Rao-Wilton-Glisson Sources for Use in Marching-on-in-Time Based EFIE Solvers,” *Proc. of the IEEE 2002 Antennas and Propagation Symposium*, vol. 1, pp. 74-77, June 16-21, 2002, San Antonio, TX.
27. D. Weile, N. Chen, B. Shanker and E. Michielssen, “An Accurate Time-Marching Solution Method for the Electric Field Integral Equation Using a Bandlimited Extrapolator,” *Proc. of the IEEE 2002 Antennas and Propagation Symposium,* vol. 2, pp. 162-165, June 16-21, 2002, San Antonio, TX.
28. A. Yilmaz, K. Aygun, J. Jin and E. Michielssen, “Matching Criteria and the Accuracy of Time Domain Adaptive Integral Method,” *Proc. of the IEEE 2002 Antennas and Propagation Symposium*, vol. 2, pp. 166-169, June 16-21, 2002, San Antonio, TX.

29. N. Chen, M.Lu, B. Shanker, and E. Michiellsen, "Fast Integral-Equation-Based Analysis of Transient Scattering from Doubly Periodic Perfectly Conducting Structures", Proceedings of the URSI, pp.710, June 22-27, 2003, Columbus, OH.
30. J. Meng, K. Aygun, and E. Michielssen, "An Improved Fast Algorithm for Transient Simulation of Microwave Circuits with Nonlinear Electronics", Proceedings of the URSI, pp.198, June 22-27, 2003, Columbus, OH.
31. A. E. Yilmaz, B. Shanker, J. M. Jin, and E. Michielssen, "Efficient Solution of Time Domain Volume Integral Equations using the Adaptive Integral Method", Proceedings of the URSI, pp.711, June 22-27, 2003, Columbus, OH.
32. A. E. Yilmaz, J. Jin, and E. Michielssen, "Discrete Wavelet Transform Compression for Time Domain Integral Equations", Proceedings of the URSI, pp.712, June 22-27, 2003, Columbus, OH.
33. A. E. Yilmaz, J. M. Jin, and E. Michielssen, "Time Domain Adaptive Integral Method for the Combined Field Integral Equation", Proceedings of the AP-S, pp.543-546, vol. 3, June 22-27, 2003, Columbus, OH.
34. P. Jiang, K. Yegin, S. Li, B. Shanker, and E. Michielssen, "An Improved Plane Wave Time Domain Algorithm for Dissipative Media", Proceedings of the AP-S, pp.563-566, vol. 3, June 22-27, 2003, Columbus, OH.
35. H. Bagci, A. E. Yilmaz, V. Lomakin, E. Michielssen, "Fast and Accurate Solution of Time Domain Electric Field Integral Equation for Dielectric Half-Space", Proceedings of the AP-S, pp.583-586, vol. 3, June 22-27, 2003, Columbus, OH.
36. E. Yilmaz, A. C. Cangellaris, J.-M. Jin and E. Michielssen, "Time domain adaptive integral method for EMI/EMC applications," *URSI National Radio Science Meeting*, Monterey, CA, June 21-24, 2004.
37. A. E. Yilmaz, J.-M. Jin and E. Michielssen, "A parallel time-domain adaptive integral method based hybrid field-circuit simulator," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol. III, pp. 3309-3312, June 21-24, 2004.
38. Q. Chen, M. Lu and E. Michielssen, "Integral equation based analysis of transient scattering from surfaces with impedance boundary condition," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol. IV, pp. 3891-3894, June 21-24, 2004.
39. S. Li, V. Lomakin and E. Michielssen, "Enhanced transmission through truncated compound periodic arrays of subwavelength holes," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol. IV, pp. 4172-4175, June 21-24, 2004.
40. P. Jiang and E. Michielssen, "Fast evaluation of near-field contributions in a PWTD-enhanced MOT scheme for lossy media," *URSI National Radio Science Meeting*, Monterey, CA, June 21-24, 2004.
41. A. E. Yilmaz, J.-M. Jin and E. Michielssen, "Broadband analysis of electromagnetic scattering from dielectric coated conductors with parallel TD-AIM," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol. IV, pp. 4220-4223, June 21-24, 2004.
42. H. Bagci, A. E. Yilmaz, A. C. Cangellaris and E. Michielssen, "Analysis of transient electromagnetic coupling into platform-mounted cables using the time-domain adaptive integral method," *URSI National Radio Science Meeting*, Monterey, CA, June 21-24, 2004.
43. V. Lomakin and E. Michielssen, "Efficient calculation of transient fields in multilayered media," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol, IV, pp. 4232-4235, June 21-24, 2004.
44. N.-W. Chen, M. Lu, P. Jiang, F. Capolino, B. Shanker and E. Michielssen, "A time-marching scheme for analyzing transient scattering from nonplanar doubly periodic structures," *IEEE International Antennas & Propagation Symposium*, Monterey, CA, Vol. IV, pp. 4535-4538, June 21-24, 2004.

45. P. L. Jiang and E. Michielssen, “Multilevel plane wave time domain-enhanced MOT solver for analyzing electromagnetic scattering from objects residing in lossy media,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.
46. H. Bagci, A. E. Yilmaz, and E. Michielssen, “EMC/EMI analysis of electrically large and multiscale structures loaded with coaxial cables by a hybrid TDIE-FDTD-MNA approach,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.
47. J. Meng, M. Lu, and E. Michielssen, “A fast space-adaptive algorithm to evaluate transient wave fields due to low-frequency source constellations,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.
48. Q. Chen, M. Lu, and E. Michielssen, “Time domain integral equation based analysis for thin scatterers using impedance boundary conditions,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.
49. A. E. Yilmaz, J.-M Jin, and E. Michielssen, “Hybrid time-domain integral equation/circuit solvers for nonlinearly loaded antennas on complex platforms,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.
50. A. E. Yilmaz, J-.M. Jin, and E. Michielssen, “A dual/variable time stepping framework for TDIE-based hybrid field-circuit simulators,” *IEEE International Antennas & Propagation Symposium*, Washington, DC, June 21-24, 2005.

Abstracts of selected papers

1. Y. Zhu and A. Cangellaris, "Nested multigrid vector and scalar potential finite element method for fast computation of two-dimensional electromagnetic scattering," IEEE Transactions on Antennas and Propagation. Vol. 50, no. 12, pp. 1850-1858. Dec. 2002

   Abstract: Nested multigrid techniques are combined with the ungauged vector and scalar potential formulation of the finite-element method to accelerate the convergence of the numerical solution of two-dimensional electromagnetic scattering problems. The finite-element modeling is performed on nested meshes of the same computational domain. The conjugate gradient method is used to solve the resultant finite-element matrix for the finest mesh, while the nested multigrid vector and scalar potential algorithm acts as the preconditioner of the iterative solver. Numerical experiments are used to demonstrate the superior numerical convergence and efficient memory usage of the proposed algorithm.

2. Y. Zhu and A. Cangellaris, "Robust multigrid preconditioner for fast finite element modeling of microwave devices, IEEE Microwave and Wireless Components Letters. Vol. 11, no. 10, pp. 416-418. Oct. 2001

   Abstract: A robust preconditioning technique is presented for the fast finite element modeling of microwave devices. The proposed preconditioner is based on a multigrid scheme for the vector-scalar potential finite element formulation of electromagnetic problems. Numerical experiments from the application of the new preconditioner to the finite element analysis of microwave devices are used to demonstrate its superior numerical convergence and efficient memory usage.

3. Y. Zhu and A. Cangellaris, "Hybrid multilevel/multigrid potential preconditioner for fast finite element modeling," IEEE Microwave and Wireless Components Letters. Vol. 12, no. 8, pp. 290-292. Aug. 2002.

   Abstract: A robust hybrid multilevel/multigrid potential preconditioner is introduced for the fast and robust finite-element modeling of electromagnetic structures. The proposed preconditioning process combines the advantages of the hierarchical multilevel preconditioner and the nested multigrid potential preconditioner into a novel preconditioner with superior computational versatility. Numerical experiments from the application of the new preconditioner to the finite-element analysis of microwave devices demonstrate its superior numerical convergence and efficient memory usage.

4. Y. Zhu and A. Cangellaris, "Application of nested multigrid finite elements to two-dimensional electromagnetic scattering," Micr. Opt. Tech. Lett. Vol. 30, no. 2, pp. 97-101. 20 July 2001.

   Abstract: Nested multigrid techniques are combined with the finite-element method for the fast numerical solution of two-dimensional electromagnetic scattering problems. The finite-element modeling is performed on nested meshes of the same computational domain. The conjugate-gradient method is used to solve the resultant finite-element matrix for the finest mesh, while the multigrid method acts as the preconditioner of the iterative solver. Numerical experiments are used to demonstrate the efficiency as well as the limits of the proposed methodology.

5. Y. Zhu and A. Cangellaris, “Hierarchical multilevel potential preconditioner for fast finite-element analysis of microwave devices,” IEEE Transactions on Microwave Theory and Techniques. Vol. 50, no. 8, pp. 1984-1989. Aug. 2002.

   <u>Abstract</u>: A robust hierarchical multilevel preconditioning technique is presented for the fast finite-element analysis of microwave devices. The proposed preconditioner is based on a hierarchical multilevel scheme for the vector-scalar potential finite-element formulation of electromagnetic problems. Numerical experiments from the application of the new preconditioner to the finite-element analysis of microwave devices are used to demonstrate its superior numerical convergence and efficient memory usage.

6. Y. Zhu and A. Cangellaris, “Nested multigrid vector and scalar potential finite element method for three-dimensional time-harmonic electromagnetic analysis”, Radio Science. Vol. 37, no. 3, pp. 81-810. 2002.

   <u>Abstract</u>: A new finite element methodology is presented for fast and robust numerical simulation of three-dimensional electromagnetic wave phenomena. The new methodology combines nested multigrid techniques with the ungauged vector and scalar potential formulation of the finite element method. The finite element modeling is performed on nested meshes over the computational domain of interest. The iterative solution of the finite element matrix on the finest mesh is performed using the conjugate gradient method, while the nested multigrid vector and scalar potential algorithm acts as the preconditioner for the iterative solver. Numerical experiments from the application of the new methodology to three-dimensional electromagnetic scattering are used to demonstrate its superior numerical convergence and efficient memory usage.

7. A. E. Yilmaz, J. M. Jin, and E. Michielssen, "Time domain adaptive integral method for surface integral equations," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 10, pp. 2692-2708, Oct. 2004.

   <u>Abstract</u>: An efficient marching-on-in-time scheme is presented for solving electric, magnetic, and combined field integral equations pertinent to the analysis of transient electromagnetic scattering from perfectly conducting surfaces residing in an unbounded homogenous medium. The proposed scheme is the extension of the frequency-domain adaptive integral/pre-corrected FFT method to the time domain. Fields on the scatterer that are produced by space-time sources residing on its surface are computed (i) by locally projecting, for each time step, all sources onto a uniform auxiliary grid that encases the scatterer, (ii) by computing everywhere on this grid the transient fields produced by the resulting auxiliary sources via global, multilevel/blocked, space-time FFTs, and (iii) by locally interpolating these fields back onto the scatterer surface. As this procedure is inaccurate when source and observer points reside close to each other, (iv) near fields are computed classically, albeit (pre-)corrected, for errors introduced through the use of global FFTs. The proposed scheme has a computational complexity and memory requirement of $O\left(N_t N_s \log^2 N_s\right)$ and $O\left(N_s^{3/2}\right)$ when applied to quasi-planar structures, and of $O\left(N_t N_s^{3/2} \log^2 N_s\right)$ and $O\left(N_s^2\right)$ when used to analyze scattering from general surfaces. Here, and denote the number of spatial and temporal degrees of freedom of the surface current density. These computational cost and memory requirements are contrasted to those of classical marching-on-in-time solvers, which scale as $O\left(N_t N_s^2\right)$ and $O\left(N_s^2\right)$, respectively. A parallel implementation of the scheme on a distributed-memory computer cluster that uses the message-passing interface is described. Simulation results demonstrate the accuracy, efficiency, and the parallel performance of the implementation.

8. A. E. Yilmaz, J. M. Jin, and E. Michielssen, "A parallel FFT accelerated transient field-circuit simulator," *IEEE Trans. Microwave Theory Tech.*, to appear in September 2005.

   Abstract: A novel fast electromagnetic field-circuit simulator that permits the full-wave modeling of transients in nonlinear microwave circuits is proposed. This time-domain simulator is composed of two components: (i) A full-wave solver that models interactions of electromagnetic fields with conducting surfaces and finite dielectric volumes by solving time-domain surface and volume electric field integral equations, respectively; (ii) A circuit solver that models field interactions with lumped circuits, which are potentially active and nonlinear, by solving Kirchoff equations through modified nodal analysis. These field and circuit analysis components are consistently interfaced and the resulting coupled set of nonlinear equations is evolved in time by a multidimensional Newton-Raphson scheme. The solution procedure is accelerated by allocating field- and circuit-related computations across the processors of a distributed-memory cluster, which communicate using the message-passing interface standard. Furthermore, the electromagnetic field solver, whose demand for computational resources far outpaces that of the circuit solver, is accelerated by an FFT based algorithm, viz. the time-domain adaptive integral method. The resulting parallel FFT accelerated transient field-circuit simulator is applied to the analysis of various active and nonlinear microwave circuits, including power-combining arrays.

9. M. Lu, K. Yegin, B. Shanker, and E. Michielssen, “Fast time domain integral equation solvers for analyzing two-dimensional scattering phenomena; Part I: temporal acceleration,” *Electromagnetics*, vol. 24, no. 6, pp. 425-449, 2004.

   Abstract: The primary impediment to analyzing two-dimensional transient scattering phenomena using classical marching-on-in-time-based integral equation solvers is these schemes’ high computational complexity that scales as $O(N_s^2 N_t^2)$, where N_s and N_t denote the number of spatial and temporal degrees of freedom of the current on the scatterer. Here, three schemes that reduce this cost by permitting the rapid evaluation of the temporal convolution of a bandlimited transient source signature with the two-dimensional wave equation Green function are studied; these three methods rely on (i) blocked fast Fourier transforms, (ii) truncated singular value decompositions, and (iii) multiresolution concepts. The computational cost of all three proposed algorithms scales as $O(N_s^2 N_t \log^{\alpha} N_t)$ with $\alpha \le 2$. The three schemes are compared on their respective multiplicative constants inherent in this cost estimate, their memory requirements, and their ease of implementation.

10. M. Lu, B. Shanker, and E. Michielssen, “Fast time domain integral equation solvers for analyzing two-dimensional scattering phenomena; Part II: full PWTD acceleration,” *Electromagnetics*, vol. 24, no. 6, pp. 451-470, 2004.

    Abstract: The primary impediment to using marching-on-in-time (MOT) schemes for solving time domain integral equations pertinent to the analysis of large-scale two-dimensional (2D) transient electromagnetic scattering phenomena is their high computational complexity. If N_s and N_t are the number of spatial and temporal degrees of freedom in the analysis, then this computational complexity scales as $O(N_s^2 N_t^2)$. Recently, it has been theoretically demonstrated that if classical MOT schemes are augmented with 2D plane wave time domain (PWTD) algorithms, their computational complexity can be reduced to $O(N_s N_t \log N_s \log N_t)$. This article elucidates key steps in implementing such a scheme within the context of 2D transient TM_z and TE_z electromagnetic scattering analysis. Several numerical examples that demonstrate the efficacy of the proposed schemes and also confirm the aforementioned computational complexity are presented.

11. M. Lu, M. Lv, A. A. Ergin, B. Shanker, and E. Michielssen, "Multilevel plane wave time domain-based global boundary kernels for two-dimensional finite difference time domain simulations," *Radio Science*, vol. 39, no. 4, Art. No. RS4007, Aug. 2004.

    Abstract: Time domain boundary integrals are used to impose global transparent boundary conditions in two-dimensional finite difference time domain solvers. Augmenting classical methods for imposing these conditions with the multilevel plane wave time domain scheme reduces the computational cost of enforcing a global transparent boundary condition from $O(\tilde{N}_s^2 \tilde{N}_t^2)$ to $O(\tilde{N}_t \tilde{N}_s \log \tilde{N}_t \log \tilde{N}_s)$; here $\tilde{N}_s$ and $\tilde{N}_t$ denote the number of equivalent source boundary nodes and their time samples used to integrate external fields, respectively. Numerical results demonstrate that for thin and concave material objects, plane wave time domain-accelerated global transparent boundary kernels outperform perfectly matching layer-based absorbing boundary schemes without loss of accuracy.

12. Q. Chen, M. Lu and E. Michielssen, "Integral-equation-based analysis of transient scattering from surfaces with an impedance boundary condition," *Microwave and Optical Technology Letters*, vol. 42, no. 3, pp. 213-220, Aug. 2004

    Abstract: A marching-on-in-time (MOT)-based scheme for the analysis of transient scattering from closed surfaces characterized by an impedance boundary condition (IBC) is described. The time-domain integral equations being solved involve no analytical approximation and are free of spurious solutions. The proposed scheme is validated by a host of numerical examples.

13. M. Lu, B. Shanker, and E. Michielssen, "Elimination of spurious solutions associated with exact transparent boundary conditions in FDTD solvers," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 4, pp. 59-62, 2004.

    Abstract: An analysis of spurious solutions that often plague finite-difference time-domain solvers supplemented with certain transparent boundary conditions (TBC) is presented. It is shown that the electric- and magnetic-field TBC kernels may support undesired spurious modes. A combined-field TBC kernel is proposed that does not allow for the buildup of resonant modes. Its functionality is demonstrated by two numerical examples.

14. N.-W. Chen, M. Lu, F. Capolino, B. Shanker, and E. Michielssen, "Floquet-wave-based analysis of transient scattering from doubly periodic perfectly conducting bodies," to appear in *Radio Science*.

    Abstract: A Floquet-wave-based algorithm for solving a time-domain electric field integral equation pertinent to the analysis of transient plane wave scattering from doubly periodic, discretely planar, perfect electrically conducting structures is presented. The proposed scheme accelerates the evaluation of fields generated by periodic constellations of bandlimited transient currents via their expansion in time-domain Floquet waves and use of blocked fast Fourier transforms. The validity and effectiveness of the resulting algorithm are demonstrated through a number of examples.

15. Ali E. Yilmaz, Jian-Ming Jin, and Eric Michielssen, "A TDIE-Based Asynchronous Electromagnetic-Circuit Simulator ", Microwave and Wireless Circuit Letters, Submitted

Abstract: A time-domain integral-equation based hybrid electromagnetic (EM)-circuit (CKT) simulator that allows the signals (fields/voltages/currents) in each EM or CKT subsystem to be sampled and tracked using a local, subsystem-specific, time-step size is proposed. The proposed asynchronous time-stepping/coupling approach generalizes the standard synchronous time-stepping/coupling approach, where all the signals in the entire system are tracked using one system-global time-step size. The nonlinear analysis of a BJT driven chip-to-package interconnect demonstrates that the asynchronous simulator exhibits improved accuracy, efficiency, and convergence.

16. S. Li, A. Boag, B. Shanker, and E. Michielssen, "Quasi-planar plane wave time domain kernels," To be submitted to Journal of Computational Physics, draft available upon request.

Abstract: A windowed plane wave time domain (PWTD) algorithm is proposed for fast analysis of radiation and scattering by quasi-planar structures. Quasi-planar geometries , whereas one of the dimensions (say the vertical one) is much smaller than the others (i.e., the horizontal extent) are characteristic of numerous problems such as phased arrays, rough and frequency selective surfaces, as well as integrated circuit interconnects. For quasi-planar geometries the conventional (PWTD) algorithm appears to be suboptimal since it requires calculating transient plane waves over the entire unit sphere. In contrast, the proposed algorithm employs a judiciously constructed window function for the elevation angle and consequently uses only a small number of plane wave elevation directions around the horizon of quasi-planar structures. Asymptotic analysis demonstrates that a particular choice of analytic window function provides exponentially accurate representation for signals with relatively narrow bandwidth. A recursive multiresolution scheme is developed for wideband sources through constructing a set of windows each window covering a given frequency subband. A new anterpolation method is developed for the multilevel implementation of the windowed PWTD kernel. The proposed scheme allows the number of plane waves elevation directions to be always retained of $O(1)$ at all levels. The complexity of the windowed PWTD marching-on-in-time (MOT) algorithms is reduced to $O(N_t N_s \log N_s)$ compared with that of $O(N_t N_s \log^2 N_s)$ for regular PWTD enhanced MOT schemes and $O(N_t N_s^2)$ in classical MOT schemes, where the surfaces fields and sources are represented by N_s spatial and N_t temporal samples. This makes the windowed PWTD algorithms attractive for the analysis of transient electromagnetic phenomena in large scale quasi-planar geometries.

17. P. L. Jiang [a], S. Q. Li [a], K. Yegin [a], B. Shanker [b], E. Michielssen [a] "A plane wave time domain algorithm for fast evaluation of transient waves in lossy media," To be submitted to Journal of Computational Physics, draft available upon request.

Abstract: A novel plane wave time domain (PWTD) algorithm is presented for accelerating the numerical analysis of transient waves scattered from objects residing in lossy media. It relies on the angular spectrum representation of the three-dimensional (3D) transient fields in terms of propagating plane waves. To facilitate this representation, the 3D lossy medium Green function is derived from the spatial derivative of its one-dimensional (1D) counterpart and the 3D field is obtained from the lossless propagation in space of a 1D field evolving in time. The 1D field is updated via a spectral updating scheme that is convenient for using an exact time-stepping scheme and the construction of diagonal translation operators. Truncatable translation operators, which dramatically reduce the number of spherical samples in numerical integration, are constructed in the spectral domain. A boundary updating scheme for truncating the 1D incoming rays at the lowest level and a large time-step updating scheme for time-stepping incoming rays at higher levels are provided to guarantee minimum computational complexity. The accuracy and convergence of the

algorithm are demonstrated by numerical experiments. This PWTD algorithm can be readily integrated into classical 3D time domain integral equation solvers for surface scattering problems. For a problem with N_s spatial and N_t temporal unknowns, the computational complexity scales as $O\left(N_s N_t \log N_s \log^2 N_t\right)$ in a multilevel implementation as opposed to $O\left(N_s^2 N_t^2\right)$ for classical solvers. This makes it feasible to analyze 3D transient scattering phenomena involving large surfaces using integral equations.

18. M. Lu, K. Aygun, Mingyu Lu, and E. Michielssen, "Low frequency PWTD kernels", To be submitted to Journal of Computational Physics, draft available upon request.

Abstract: In this paper, a new set of fast algorithms is introduced for accelerating computation of radiated transient fields that satisfy the time domain wave equation. Previously, a multilevel plane wave time domain (ML-PWTD) algorithm was developed for fast calculation of fields due to uniformly spaced source distributions where the average source separation distance was dictated by the minimum wavelength included in the excitation/source pulses [1, 2]. In this paper, first, a novel low-frequency PWTD (LF-PWTD) algorithm and an adaptive low-frequency PWTD (ALF-PWTD) algorithm are developed that enable fast evaluation of fields due to (i) uniformly distributed sources where the average source separation distance is much smaller and the maximum dimension of the problem domain is smaller than the wavelength, and (ii) nonuniformly distributed sources where the source separation distance varies in space, yet, the maximum dimension of the problem domain is still smaller than the wavelength, respectively. It is shown that the computational complexity of both LF- and ALF-PWTD algorithms scale as $O(N_t N_s \log N_s)$ compared to $O(N_t N_s^2)$ complexity of direct methods, where N_t and N_s denote the number of degrees of freedom in time and space, respectively. Next, the ALF-PWTD scheme is hybridized with the original ML-PWTD scheme. The resulting adaptive multilevel PWTD (AML-PWTD) algorithm facilitates fast analysis of radiation from quite arbitrary source distributions where high and low density clusters can coexist and the largest dimension of the problem domain can be significantly larger than the wavelength (i.e., a hybrid low-to-high frequency problem). It is shown that the computational complexity of the AML-PWTD algorithm is bounded by that of the multilevel PWTD algorithm that scales as $O(N_t N_s \log^2 N_s)$.