Accelerated, Parallelized Time and Frequency Domain Simulators for Complex High-Speed Microsystems

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Abstract

The paper presents methodologies for efficient simulation and design of electromagnetic effects in microelectronic circuits for digital, analog, mixed-signal, RF and microwave applications in time and frequency domain. Also parallelization of the presented methodologies and incorporation into standard design flow has been discussed.

1. Introduction

With the growing speed, complexity and compactness of modern day microelectronic circuits, accurate and efficient simulation of electromagnetic effects, such as cross-talk, substrate coupling, radiation loss, proximity effects, etc. have become extremely important for reliability and speed of today's circuit designs. Boundary element methods [1] are extremely useful for such electromagnetic simulation but they suffer from the problem of generating a dense system matrix, whose storage and solution may become very expensive in a brute force direct approach for a complex simulation problem. This paper presents an efficient methodology using fast iterative solution [2] technique to compress the integral equation system matrix and expedite its solution with controllable solution accuracy. Also the presented methodology enables hierarchical simulation using coupled circuit-electromagnetic simulation in both time and frequency domain. The methodology is scalable and has been implemented for distributed memory Beowulf cluster. The simulator is compatible with the standard CAD design and is extendible to multi-physics applications.

2. Frequency Domain Simulation

In electric field integral equation (EFIE) total electric field is decomposed into an incident field $\mathbf{E}^{inc}$, and a scattered field $\mathbf{E}^{scat}$ caused by a set of equivalent surface currents $\mathbf{J}_s$ on the conductor [1], and equivalent volumetric polarization current $\mathbf{J}_V$ in the dielectric [3]. Alternatively, the dielectric can be modeled using a surface-based PMCHWT formulation for the cases of thick homogeneous regions. The scattered electric field is given by a combination of the magnetic vector potential $\mathbf{A}$ and the electric scalar potential ϕ . EFIE for the conductor is written as

$$\left(j\omega \mathbf{A}_{surf}(\mathbf{J}_l) + \frac{j\nabla \phi_{surf}(\nabla \cdot \mathbf{J}_l)}{\omega} + Z_S \mathbf{J}_l \right)_{\tan} = \mathbf{E}_{surf}^{inc}\Big|_{\tan} \tag{1}$$

where $\mathbf{J}_l$ represents $\mathbf{J}_s$ or $\mathbf{J}_V$ as appropriate and Z_S is the surface impedance. EFIE in the bulk of the dielectric is given by

$$j\omega \mathbf{A}_{vol}(\mathbf{J}_l) + \frac{j\nabla \phi_{vol}(\nabla \cdot \mathbf{J}_l)}{\omega} + \frac{\mathbf{J}_V}{j\omega(\varepsilon_r - \varepsilon_0)} = \mathbf{E}_{vol}^{inc} \tag{2}$$

where ω is the angular frequency of operation, ε_r and ε_0 are the permittivities of the dielectric material and the background. The subscript *surf* and *vol* indicates whether the potential and the field is computed on the surface of the conductor or in the volume of the dielectric objects. All the equivalent currents radiate in the homogeneous background region, and the material properties are incorporated through the localized third terms in the equations

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(1) and (2). The surface of the conductors and the volume of the dielectrics are discretized , and piece-wise linear basis functions are used to model the currents on/in the discretized geometry [1,3]. Finally equations (1) and (2) are tested [1] with appropriate testing functions and a dense system of linear equations is obtained[4] in the form of

$$\overline{\mathbf{Z}}\,\overline{\mathbf{I}} = \begin{pmatrix} \overline{\mathbf{Z}}_{SS} & \overline{\mathbf{Z}}_{SV} \\ \overline{\mathbf{Z}}_{VS} & \overline{\mathbf{Z}}_{VV} \end{pmatrix} \begin{pmatrix} \mathbf{I}_S \\ \mathbf{I}_V \end{pmatrix} = \begin{pmatrix} \mathbf{V}_S \\ \mathbf{V}_V \end{pmatrix} = \mathbf{V} \tag{3}$$

where $\overline{\mathbf{Z}}_{SS}$, $\overline{\mathbf{Z}}_{SV}$, $\overline{\mathbf{Z}}_{VS}$, $\overline{\mathbf{Z}}_{VV}$ represent the surface to surface, volume to surface, surface to volume and volume to volume interactions with appropriate basis and testing functions. $\mathbf{I}_S$ and $\mathbf{I}_V$ are the unknown strengths of the surface and volumetric basis functions representing the current densities, and $\mathbf{V}_S$, $\mathbf{V}_V$ represent the incident electric fields tested with the surface and volumetric basis functions. This system of equation can be solved and the required simulation output can be computed by post-processing the surface and volumetric current densities.

Equation (3) can be solved using direct LU decomposition techniques, but the solution time and the memory requirements to store the entire matrix scales as $O(N^3)$ and $O(N^2)$. The solution time can be reduced to $O(pN^2)$ using a Krylov subspace iterative solver such as GMRES , and p is the number of iterations needed for converging to a solution with a desired residual. Portions of the matrix, e.g. a given submatrix $\overline{\overline{\mathbf{Z}}}_{m\times n}$ representing the interactions between n basis functions and m testing functions can be compressed as $\overline{\overline{\mathbf{Z}}}_{m\times n} \approx \overline{\mathbf{Q}}_{m\times r}\overline{\mathbf{R}}_{r\times n}$ using the modified Gram-Smidt algorithm, where the basis and testing functions are well-separated. r represents the rank of the submatrix, that can be predetermined based on a multi-level oct-tree structure, and is independent of m and n. It has been demonstrated [2] that the overall cost of matrix storage, set up and matrix vector product can be reduced to $O(N \log N)$. For very high frequency applications, such as in antenna, the low-rank behavior of the far-away interactions does not hold true due to the oscillatory nature of the interactions and a hybrid of oct-tree based multilevel fast multipole algorithm and the low-rank decomposition algorithm can be used [5]. The over-all solution time depends on the number of iterations taken for the iterative solver to converge within a given residue. In general the number of iterations needed for convergence for a realistic problem is large. To alleviate this problem, a three-stage preconditioner [6] including loop-tree decomposition [7], basis function rearrangement [7] and sparse incomplete LU factorization [8] is used.

In EM simulation of a complex microelectronic circuit certain portions of the geometries, e.g. the vias can be replaced by lumped circuit elements and the hybrid system is solved by EM-circuit co-simulation to reduce the simulation time and memory. The EM-circuit co-simulation [9] is performed by defining a set of connection triangles on the surface of the conductor geometry where the lumped circuit elements are connected. Continuity equation on those triangles are modified with an additional term representing the extra time-varying charge introduced by the lumped circuit elements. Also the electrostatic potentials on the connection triangles are equated with the voltage of the respective circuit nodes they attach to. The resultant system of equations is expressed as a square matrix, that can be compressed and preconditioned and solved using a Krylov subspace iterative solver as described above.

3. Time Domain Simulation

Time domain integral equations (TDIE) are particularly useful for simulation of microelectronic circuit with nonlinearities and broadband simulations. Here the scattered electromagnetic field at the m^{th} time instance t_m has contributions from the equivalent currents $\mathbf{J}_l$ at time t_m and the currents at all past time instances[10]. The system of linear equations is given by

$$\overline{\mathbf{Z}}_0\mathbf{I}(t_m)=\sum_{i=1}^{m}\overline{\mathbf{Z}}_i\mathbf{I}(t_{m-i})+\mathbf{V}(t_m) \quad (4)$$

where $\overline{\mathbf{Z}}_i$ is the sparse time domain EFIE matrix with time delay t_i. It is important to note that material modeling and coupled EM-circuit simulation can be incorporated into the time domain integral equation described by (4) in a manner analogous to the frequency domain approach presented in section 2.

4. Distributed Computing

The proposed fast iterative solution technique is implemented on a distributed memory Beowulf cluster. The block matrices representing the near-field full-rank interactions in the dense form and the far-field low-rank interactions in the compressed factorized form can be distributed evenly amongst the processors using an appropriate load-balancing technique [11] and minimizing the inter-processor communication. Subsequently inside the iterative solver, portions of the matrix vector product can be computed by the individual processors and the results can be accumulated in a single processor.

5. Sensitivity Analysis for Gradient-Based Optimization

To obtain the sensitivity [12] of a desired output with respect to a geometrical or material input parameter x it is imperative to compute $\left(\frac{\partial \mathbf{I}}{\partial x}\right)$ as

$$\left(\frac{\partial \mathbf{I}}{\partial x}\right)=\left(\frac{\partial \mathbf{V}}{\partial x}\right)-\overline{\mathbf{Z}}^{-1}\left(\frac{\partial \overline{\mathbf{Z}}}{\partial x}\right)\mathbf{I} \quad (5)$$

The sensitivity measure is useful for fast gradient based optimization of the microelectronic design under simulation. Derivative of the system matrix with respect to the parameter p can be obtained using analytic means or finite difference depending on the nature of the parameter.

6. Integration in Standard Design Flow

The presented methodology for fast electromagnetic solution can be integrated into the standard design flow of the commercially available CAD tools in the following way (Fig. 1)

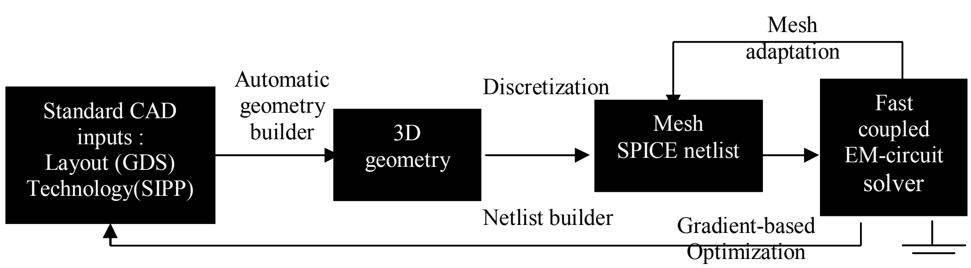
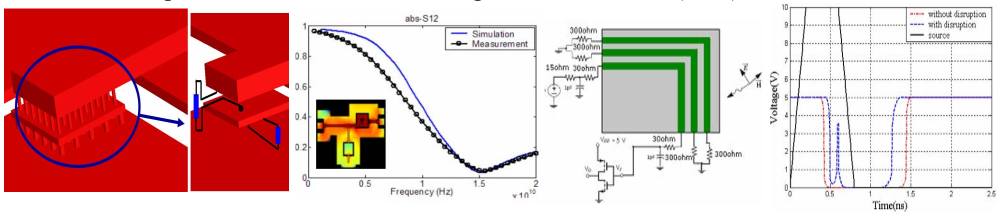


Fig. 1: Flow diagram of a typical design optimization using the presented solver

7. Numerical Results

Examples of the typical outputs of the presented solver are given in Fig. (2a-2d). Figure 2a shows the replacement of a large number of vias with lumped circuit elements to enhance simulation efficiency for portion of the LC filter shown in Fig. (2b). The correlation between the simulation and measurement results in the magnitude of the insertion loss is shown in Fig. 2b as a function of frequency. Figure 2c shows a non-linear inverter circuit with interconnects, simulated using TDIE, and figure 2d shows the additional spike produced in the inverter output due to external electromagnetic interference (EMI) field.



(a) (b) (c) (d)

Fig. 2 : Simulation structures (a,c) and results(bd) of the frequency and time domain solvers.

8. Summary

A methodology for efficient coupled EM-circuit co-simulation is presented in time and frequency domain along with discussions on the parallelization aspects. These methodologies can be further extended for complex multi-physics simulation including thermal, biological and quantum applications.

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