Coupled Circuit-Electromagnetic Simulation with Time Domain Integral Equations

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1.Introduction

Time domain electromagnetic solvers are useful for simulating coupled circuit-electromagnetic (EM) problems involving integrated circuit packages and systems-on-chip, wherein effects of nonlinearities of circuit elements can be modeled accurately [1]. The surface-based time domain integral equation (TDIE) approach has been gaining in popularity owing to its flexibility in modeling arbitrarily-shaped structures and its enhanced computational performance due to advances in fast solution methods.

Existing methods to couple TDIE formulations to circuits have been based on port models, convolution methods, and the partial element equivalent circuit (PEEC) approach [2,3]. However, a seamless approach to integrate circuit and EM interactions without converting to circuits has not been developed within the scope of TDIEs.

In this work, a generalized rigorous coupling scheme, to simultaneously simulate circuits with SPICE-like time-domain simulation, and EM interactions with a TDIE method, is presented. This approach enables direct solution of circuit-EM equations without the need for generating port models. The method permits both circuit and EM excitations and thereby has potential as a signal integrity and as an EMI/EMC modeling tool.

2. Formulation

Consider a conducting object to be modeled with distributed EM simulation, with surface *S*, connected to arbitrary circuits, through terminals to be defined later, excited through voltage and current sources within the circuit, and optionally illuminated by one or more EM wave excitations. Assuming a surface impedance approximation for modeling finite connectivity, the boundary condition for the electric field on the surface of the object is

$$\left[\mathbf{E}^{s}(\mathbf{J})+\mathbf{E}^{inc}\right]_{\tan}=\left[Z_{s}*\frac{\partial \mathbf{J}}{\partial t}\right]_{\tan} \tag{1}$$

where $\mathbf{E}^{s}$ is the scattered electric field produced by the induced equivalent surface current $\mathbf{J}$, $\mathbf{E}^{inc}$ is the incident electric field, tan denotes the tangential components on the *S*, * denotes temporal convolution, and $Z_s(t)=\sqrt{\mu/\pi\sigma t}$ is the time domain representation of surface impedance. The surface *S* comprises of two disjoint surfaces, S_{EM} and S_{CK} such that on S_{EM} the standard continuity equation relating the surface current and charge holds

$$\nabla_{s}\cdot\mathbf{J}(\mathbf{r},t)+\frac{\partial \rho(\mathbf{r},t)}{\partial t}=0 \quad \forall\mathbf{r}\in S_{EM} \tag{2}$$

where ∇_s represents surface divergence. On S_{CK}, the *terminal* surfaces, the circuit current flowing onto S_{CK} from a corresponding circuit node introduces an additional source term that alters the surface current and charge on S. This permits connection of two disparate domains, the topology-based (connectivity only) circuit domain, and the geometry-based EM domain.

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Let S_{CK} itself be comprised of M disjoint surfaces $S_{CK}^{m} \quad m = 1,...,M$. Each such unique sub-surface S_{CK}^{m} is termed one of *M terminals*. On S_{CK}^{m} the modified continuity equation has the following form

$$\nabla_s \cdot \mathbf{J}(\mathbf{r},t) + \frac{\partial \rho(\mathbf{r},t)}{\partial t} = J_c^m(\mathbf{r},t) \quad \forall\, \mathbf{r} \in S_{CK}^{m} \quad m = 1,..,M \tag{3}$$

where J_c^m represents the scalar volumetric current density produced on S_{CK}^{m} via a circuit interconnection. The current density introduced by the circuit interconnection produces an additional source or sink of charge that alters the time-dependent scalar potential and the resulting electric field.

When triangle-pair-based RWG spatial basis functions are used [4,5], the scattered field is written as

$$\begin{aligned} \mathbf{E}^s(\mathbf{r},t) = &-\frac{\partial}{\partial t}\frac{\mu}{4\pi}\sum_{i=1}^{N_e}\int_{T_{i+}\cup T_{i-}}\frac{\mathbf{J}(\mathbf{r}',t-|\mathbf{r}-\mathbf{r}'|/c)}{|\mathbf{r}-\mathbf{r}'|}ds' + \nabla\frac{1}{4\pi\varepsilon}\sum_{i=1}^{N_e}\int_{T_{i+}\cup T_{i-}}\int_0^{t-|\mathbf{r}-\mathbf{r}'|/c}\frac{\nabla_s\cdot\mathbf{J}(\mathbf{r}',\tau)}{|\mathbf{r}-\mathbf{r}'|}d\tau\, ds' \\ &-\nabla\frac{1}{4\pi\varepsilon}\sum_{m=1}^{M}\sum_{k=1}^{N_{p,CK}^m}\int_{T_{k,CK}^m}\int_0^{t-|\mathbf{r}-\mathbf{r}'|/c}\frac{J_{c,k}^m(\mathbf{r}',\tau)}{|\mathbf{r}-\mathbf{r}'|}d\tau\, ds' \end{aligned} \tag{4}$$

where N_e is the total number of triangular patches, $N_{p,CK}$ is the total number of triangular patches on all terminals, $T_{k,CK}^m$ denotes the *k*th triangular patch on terminal *m*, and T_{i+} and T_{i-} are the two patches associated with the *i*th edge. The standard procedure of testing [4,5] the above equation in space and time leads to a matrix equation of the form

$$\sum_{i=1}^{N_e} Z_{mi}^a(t_l) + \Delta t\sum_{i=1}^{N_e} Z_{mi}^b(t_l) + \Delta t\sum_{n=1}^{M}\sum_{k=1}^{N_{p,CK}^n} Q_{mnk}^a(t_l) = \Delta t\, F_m(t_l) + \sum_{i=1}^{N_e} Z_{mi}^a(t_{l-1}) + Z_m^c(t_l) \tag{5}$$

where the first matrix on the left relates to field from vector potential, the second matrix relates to field from scalar potential, and the third relates to field from scalar potential due to coupling currents. The first term on the right is the incident field, the second term is the history of vector potential and the third term is surface impedance contributions in a recursive convolution form. In addition to the scattered field, two more conditions are required for the circuit interconnection; electrically small terminals are assumed to be equipotential, leading to

$$\sum_{i=1}^{N_e} Z_{nk,i}^d(t_l) + \sum_{n'=1}^{M}\sum_{k'=1}^{N_{p,CK}^{n'}} Q_{nk,n'k'}^b(t_l) = V_m(t_l) \tag{6}$$

for $n = 1,...,M; k = 1,..,N_{p,CK}^n$ where V_m is the circuit potential at the circuit node connected to terminal *m*, the first matrix represents scalar potential from surface current, and the second term is due to scalar potential from coupling currents. The final set of self-consistency equations relates to the application of Kirchoff's Current Law at the *M* nodes connected to the terminals :

$$\sum_{j=1}^{adj(n)} i_j^n(t_l) = \int_{S_{CK}^n} J_c^n(t_l)\,ds \tag{7}$$

for $n = 1,...,M$ where $adj(n)$ denotes the number of nodes adjacent (neighboring) to the circuit node associated with terminal *n*, i_j^n is the circuit current entering node *n* from its *j*-th immediate neighbor, and J_c^n is the volume conduction current density at terminal *n*.

The systems of Equations (5-7) can be combined to yield the time-domain circuit-EM coupled system. The linear and non-linear circuits connected to the terminals are modeled by

Modified Nodal Analysis (MNA). The details for the linear and non-linear stamps in the MNA matrices and related solution methods are not discussed here. The combined system has the form

$$\begin{bmatrix} \overline{\mathbf{Z}_0^{ab}} & \overline{\mathbf{Q}_0^{a}} & \overline{\mathbf{0}} \\ \overline{\mathbf{Z}_0^{c}} & \overline{\mathbf{Q}_0^{b}} & \overline{\mathbf{C}} \\ \overline{\mathbf{0}} & \overline{\mathbf{C}^{\mathbf{T}}} & \overline{\mathbf{MNA}_0} \end{bmatrix} \begin{bmatrix} \mathbf{I}(t_j) \\ \mathbf{J}_c(t_j) \\ \mathbf{ckt}(t_j) \end{bmatrix} = \sum_{i=1}^{j} \begin{bmatrix} \overline{\mathbf{Z}_i^{ab}} & \overline{\mathbf{Q}_i^{a}} & \overline{\mathbf{0}} \\ \overline{\mathbf{Z}_i^{c}} & \overline{\mathbf{Q}_i^{b}} & \overline{\mathbf{0}} \\ \overline{\mathbf{0}} & \overline{\mathbf{0}} & \overline{\mathbf{MNA}_i} \end{bmatrix} \begin{bmatrix} \mathbf{I}(t_{j-i}) \\ \mathbf{J}_{\mathbf{c}}(t_{j-i}) \\ \mathbf{ckt}(t_{j-i}) \end{bmatrix} + \begin{bmatrix} \mathbf{src}_{EM}(t_j) \\ \mathbf{0} \\ \mathbf{src}_{CK}(t_j) \end{bmatrix} \quad (8)$$

where the unknown vector at time t_j relates to the strengths of surface currents, coupling currents, and circuit quantities. The sub-matrix subscripts refer to the type of matrices generated earlier. The vector $\mathbf{src}_{EM}(t_j)$ represents the tested incident field, and the vector $\mathbf{src}_{CK}(t_j)$ denotes the values of circuit sources. The matrix $\overline{\mathbf{C}}$ is a sparse bipolar adjacency matrix that is used for enforcing Kirchoff's Voltage and Current Laws at the circuit nodes connected to the terminals. This approach enables both linear and non-linear (through local Newton-Raphson on the MNA sub-matrix) circuit simulation in conjunction with EM simulation.

3. Numerical Results

In the first example, the coupled noise between an active signal pin and a passive signal pin located in the center of the structure is computed, and the impact of ground pins on the crosstalk between the two signal pins is analyzed (Fig. 1). Either end of the active pin is connected to its corresponding ground through a 52 Ω resistor, with a ramp voltage source in series with the resistor at top end. The passive pin is connected to the grounds through two similar resistors only. The voltage drop across the top and bottom end resistors of the passive pin are plotted. As more ground pins are added, the crosstalk dramatically decreases due to shorter return paths.

In the second example, incident field coupling to a nonlinear circuit through distributed bends is simulated (Fig. 2). A trapezoidal voltage source is applied to the nonlinear circuit, and a Gaussian pulse excitation is used to model the incident field. The simulation result shown is the output voltage at the inverter without and with the disruption of the incident field. The field causes switching times to change and also introduces an extra noise pulse, which can cause spurious switching.

4. Conclusions

A coupling scheme to simultaneously time-step MNA and TDIE equations was developed in this paper in order to model complex circuits with different levels of hierarchy. The method enables nonlinear simulation as well as EMI/EMC modeling.

5. Acknowledgements

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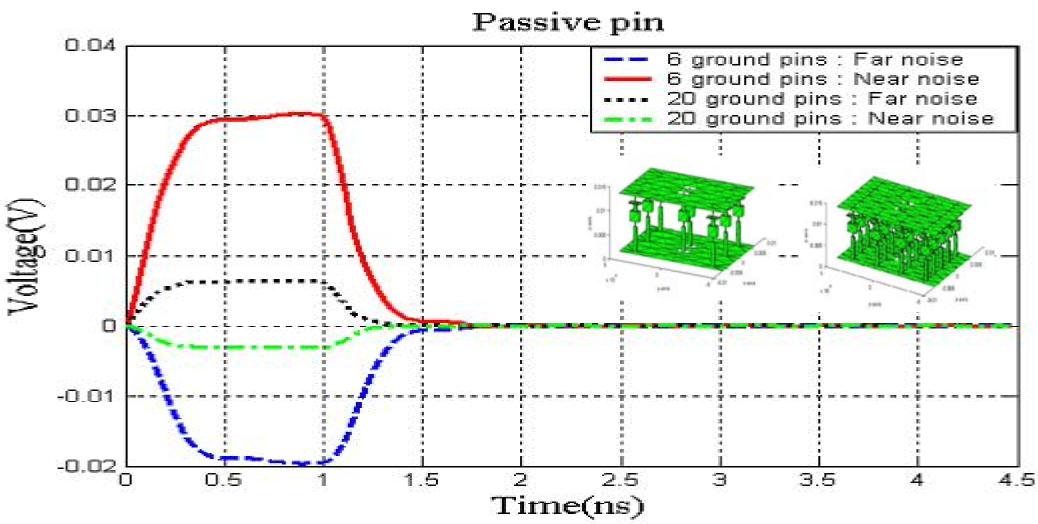

Figure 1: Near and Far end Noise voltage across a victim via due to an active via in the presence of grounding pins. Inset: Structures with 6 and 20 grounding pins

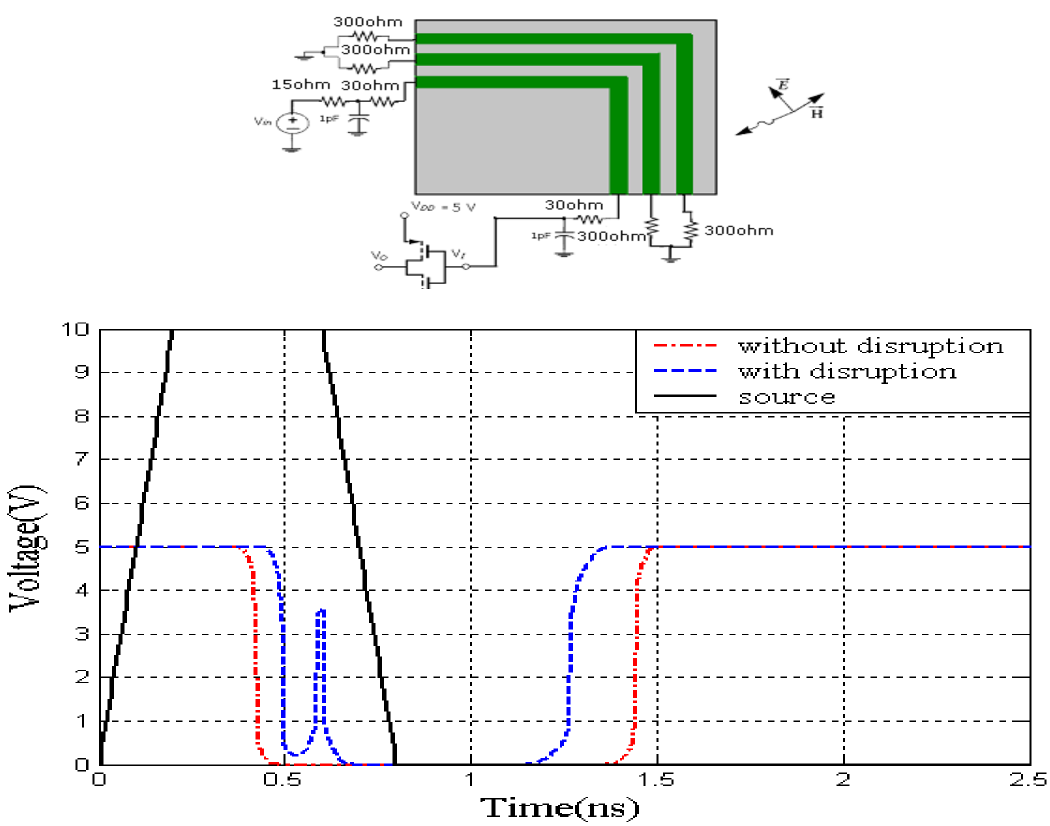

Figure 2: Output voltage (bottom) at inverter with and without a Gaussian pulse disruption of 10 KV/m. The input is a trapezoidal pulse to a three-conductor bend structure with ground on two conductors (top).