ANALYSIS OF HIGH-SPEED INTERCONNECTS IN THE PRESENCE OF ELECTROMAGNETIC INTERFERENCE

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Abstract - The recently developed complex frequency hopping technique for interconnect analysis is expanded to include the effects of incident electromagnetic fields. The generalized technique is important for susceptibility analysis and is 2 to 3 orders of magnitude faster than conventional simulation techniques. In addition it can be easily extended to the analysis of interconnects with frequency dependent parameters and nonlinear terminations.

I - Introduction

Advances in fabrication methods have made interconnect analysis imperative for diverse technologies such as VLSI chips and packages, multi-chip modules, printed circuit boards and backplanes. Shrinking device sizes coupled with increasing operating speeds are highlighting the effects of ringing, signal delay, distortion, and reflections on single interconnect lines, as well as crosstalk between adjacent lines. These phenomena can, in turn, have undesirable side-effects such as false or delayed switching of digital circuits. At relatively higher speeds, interconnects can no longer be treated as lumped components. Instead, lossy coupled transmission line models with nonlinear terminations become necessary. Several methods have been proposed to simulate these models [1]. Recently moment matching techniques such as asymptotic waveform evaluation (AWE)[3],[4] and complex frequency hopping (CFH)[5],[6] proved to be efficient and reliable techniques, suited for VLSI and PCB designs where a large number of interconnects has to be considered. CFH is a simulation technique based on approximating the frequency response of a large linear subnetwork using multi-point padé expansions. CFH has been applied to networks containing lumped elements and lossy coupled transmission lines with frequency dependent parameters and nonlinear terminations[7].

As operating frequencies increase, electrically long interconnects function as efficient antennas and pick up emissions from other nearby electronic systems. This makes susceptibility to emissions a major concern to current system designers of high-frequency products[2]. This aspect of EMI is therefore becoming an important design requirement, and including it in the analysis at an early stage of the design can result in reduced costs, improved product reliability, and reduced time to market. In this paper a method is proposed to extend complex frequency hopping to the analysis of lossy coupled transmission lines in the presence of incident fields.

II - Network equations

Consider a linear network with lumped components and n lossy coupled transmission line sets. The linear equations representing such a network have been developed in [4]. In the presence of interference the modified nodal admittance matrix (MNA) [8] of the system becomes,

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$$Y(s)X(s) = \Psi(s) \quad (1)$$

or,

$$\begin{bmatrix} H+sW & D_1 & \dots & D_n \\ A_1 D_1^t & B_1 & 0 & 0 \\ \dots & 0 & \dots & 0 \\ A_n D_n^t & 0 & 0 & B_n \end{bmatrix} \begin{bmatrix} V(s) \\ I_1(s) \\ \dots \\ I_n(s) \end{bmatrix} = \begin{bmatrix} b(s) \\ b_1(s) \\ \dots \\ b_n(s) \end{bmatrix} \quad (2)$$

Where,

$H + sW$ represents the lumped components of the system, D_k is a current selector matrix, I_k is the current vector in transmission line set k, $b(s)$ represents the lumped sources in the system, $b_k(s)$ represents the effect of interference on transmission line set k, and A_k and B_k are related to the parameters of transmission line set k,

$$A_k V_k + B_k I_k = b_k \quad (3)$$

V_k and I_k are the terminal voltages and currents of transmission line set k.

III - Transmission line stamp in the presence of incident fields

This section describes the computation of A_k, B_k and b_k in (3), in terms of the transmission line parameters and the incident fields. The subscript k will be dropped for simplicity in the remainder of the paper. The transmission line equations in the presence of interference can be written in the frequency domain as,

$$\frac{d}{dz}\theta(z,s) = -(D+sE)\theta(z,s) + F(z,s) \quad (4)$$

where,

$$D = \begin{bmatrix} 0 & -R \\ -G & 0 \end{bmatrix} \qquad E = \begin{bmatrix} 0 & -L \\ -C & 0 \end{bmatrix} \quad (5)$$

$$\theta(z,s) = \begin{bmatrix} V(z,s) \\ I(z,s) \end{bmatrix} \quad (6)$$

$$F(z,s) = \begin{bmatrix} V_F \\ I_F \end{bmatrix} \quad (7)$$

R, L, C, and G are the resistance, inductance, capacitance and conductance matrices per unit length respectively. V and I are the total voltages and currents along the transmission line. V_F and I_F are the equivalent distributed voltage and current sources due to the presence of interference, and are given, in terms of the transverse incident electric field $\mathcal{E}_t^i$ and magnetic field $\mathcal{B}^i$, by[9],[10],

$$V_F(z,s) = s\begin{bmatrix} \dots \\ \int\left(\vec{\mathcal{B}}^i \cdot \vec{a}_n\right)dl \\ \dots \end{bmatrix} \quad (8)$$

$$I_F(z,s) = -G\begin{bmatrix} \dots \\ \int \vec{\mathcal{E}}_t^i \cdot dl \\ \dots \end{bmatrix} - sC\begin{bmatrix} \dots \\ \int \vec{\mathcal{E}}_t^i \cdot dl \\ \dots \end{bmatrix} \quad (9)$$

The solution of (4) can be written as,

$$\theta(l) = e^{-\varphi l}\theta(0) + e^{-\varphi l}\int_0^l e^{\varphi z}F(z)\,dz \quad (10)$$

where l is the length of the line and,

$$\varphi = D + sE \quad (11)$$

Using (10) the elements of $\Psi(s)$ in (2) can be expressed as,

$$b(s) = e^{-\varphi l}\int_0^l e^{\varphi z}F(z)\,dz \quad (12)$$

In the following section the CFH algorithm is extended to handle the new transmission line stamp.

IV - Complex Frequency Hopping and Moment evaluation

Moment matching is a technique whereby the Taylor series expansion of the network equations is used to generate, via matching, a low-order transfer function approximation. Complex frequency hopping (CFH) extends the process to multiple expansion points in the complex plane and near or on the imaginary axis using a binary search algorithm. With a minimized number of frequency point expansions, enough information is obtained to enable the generation of an approximate transfer function that matches the original function up to a pre-defined highest frequency. Details of the CFH algorithm can be found in [6]. A taylor expansion of $X(s)$ in (1) about the complex frequency s_o is given by,

$$X(s) = \sum_{n} M_n (s - s_o)^n \qquad (13)$$

where M_n are the moments of the system and s_o is the expansion point of the CFH algorithm. Padé approximation is then used on (13) to obtain a low order rational transfer function for the system which can be used to evaluate the frequency response of the network, calculate its poles and residues and obtain the transient response[6]. A recursive equation for the evaluation of the moments M_n can be obtained in the form,

$$Y(s_o) M_0 = \Psi_0 \qquad (14)$$

$$Y(s_o) M_n = - \sum_{r=1}^{n} \frac{\left.\frac{\partial^r}{\partial s^r} Y(s)\right|_{s=s_o} M_{n-r}}{r!} + \Psi_n \qquad (15)$$

where Ψ_n are the taylor coefficients of $\Psi(s)$ in (1). Those coefficients are found from the derivatives of $b(s)$ in (12).

The derivatives $Y^{(r)}(s)$ are also needed for the calculations of the moment in (15). A simple expression of the derivatives of $Y(s)$ in terms of the derivatives of A and B can be obtained. In[3],[4] a method based on determining the eigenvalues and eigenvectors of the system in (3) have been proposed to determine the derivatives of A and B. This method suffers from rounding errors which increase with each new moment generated[6]. To eliminate this problem, a matrix exponential technique was proposed in[5].

The coefficients of the transfer function are obtained from the system moments using Padé approximation. A search algorithm that minimizes the number of frequency hops, and an efficient method for the extraction of the poles of the system can be found in[5].

V - Computational results

An incident electromagnetic field was applied to a transmission line with termination resistors as shown in Figure 3. The EM field was pulsed with a 0.5ns rise time. The CFH algorithm converged with only two hops with the highest frequency set to 5GHz. The frequency and time domain responses are shown in Figure 1, and Figure 2. The results were consistent with results published in[10].

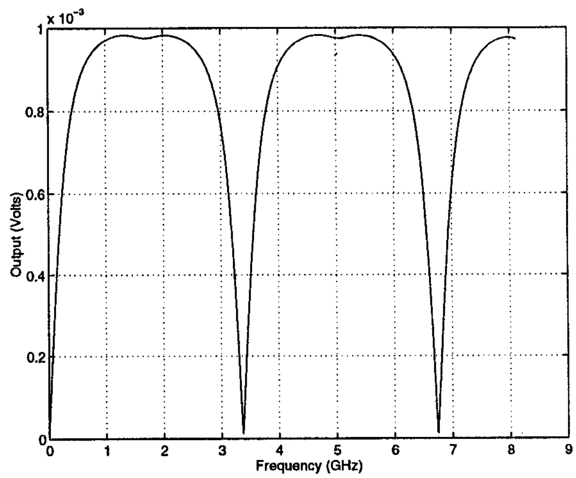

Figure 1: Frequency response

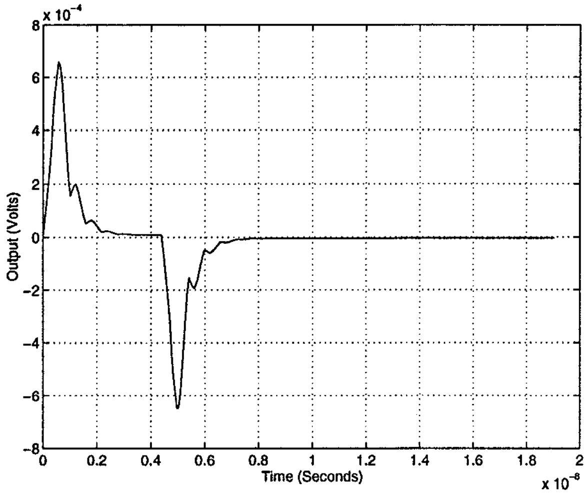

Figure 2: Time domain response

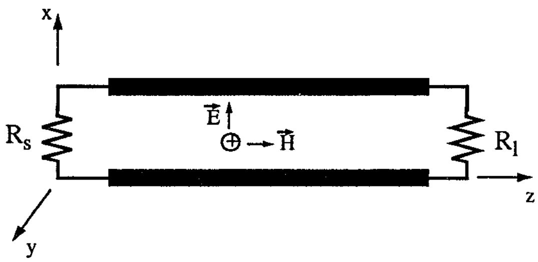

Figure 3: Two lines excited with an incident field.

VI - Conclusion

A method has been developed for the simulation of interconnect networks in the presence of incident electromagnetic fields. A new interconnect stamp based on the MNA formulation has been presented, and the complex frequency hopping algorithm was generalized to handle the new stamp. The new technique allows the simulation of the electromagnetic immunity of high-speed systems while benefiting from the CPU speed-up generated by the complex frequency hopping technique.

REFERENCES

[1] W. W. M. Dai (Guest Editor) "Special issue on simulation, modeling, and electrical design of high-speed and high-density interconnects," *IEEE Trans. Circuits Syst.* vol. 39 no. 11, pp. 857-982, Nov. 1992.

[2] C. R. Paul, *Introduction to Electromagnetic Compatibility*, New York: John Wiley, 1992.

[3] J. E. Bracken, V. Raghavan and R. A. Rohrer, "Interconnect simulation with Asymptotic Waveform Evaluation (AWE)", *IEEE Trans. on CAS I,* vol. 39, pp. 869-878, Nov, 1992.

[4] T. K. Tang and Michel Nakhla, "Analysis of high-speed VLSI interconnects using the asymptotic waveform evaluation technique", *IEEE Trans. Computer-Aided Design,* vol. 11, pp. 341-352, March, 1992.

[5] E. Chiprout, and M. Nakhla, "Analysis of interconnect networks using complex frequency hopping (CFH)," *IEEE trans. Computer-Aided Design*, vol. 14, No. 2, pp. 186-200, Feb 1995.

[6] E. Chiprout and M. Nakhla, *Asymptotic Waveform Evaluation and Moment Matching for Interconnect Analysis*, Boston: Kluwer Academic Publishers, 1993.

[7] D. Xie and M. Nakhla, "Delay and crosstalk simulation of high-speed VLSI interconnects with nonlinear terminations," *IEEE Trans. Computer Aided Design*, pp. 1789-1811, Nov. 1993.

[8] C. W. Ho, A. E. Ruehli and P. A. Brennan, "The modified nodal approach to network analysis," *IEEE Trans. Circuits and Systems*, vol. CAS-22, pp. 504-509, June 1975.

[9] C. R. Paul, "Literal solutions for the time-domain response of a two-conductor transmission line excited by an incident electromagnetic field," *IEEE Trans. on EMC*, vol. 37, No. 2, May 1995.

[10] C. R. Paul, *Analysis of Multiconductor Transmission Lines,* New York: John Wiley, 1994.