Circuit Simulation of S-parameter based Interconnects via Passive Macromodels

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Abstract -- **This paper presents an efficient algorithm based on linear formulation for addressing passivity of macromodels from s-parameter subnetworks. It also describes fast and accurate algorithm for verification and compensation of s-parameter based macromodels. Examples are presented to demonstrate the validity and accuracy of the proposed algorithm.**

I. Introduction

It is becoming increasingly essential to model frequency-dependent signal integrity effects that can have considerable impact on the performance and functionality of a high-speed design. For example, design and analysis of modern high-speed VLSI and communication systems involves diverse technologies such as packages, multi-chip modules, printed circuit boards, connectors and backplanes. Signal propagation in such diverse environments suffers from high-frequency effects, such as ringing, signal delay, distortion, and reflections. However, with the increasing frequency and complexity, it is not always possible to find an analytical model for such high-frequency passive components [1]-[8]. For instance, interconnects in chip packages are usually nonuniform due to high circuit density, complex shapes and geometrical constraints at the edges of the chip. Similarly, the layout and fabrication of connector pins are also nonuniform. Also, other passive components such as vias, nonuniform transmission lines and on-chip passive components (such as inductors and transformers) present significant challenge to the available modeling tools. As a result, these passive components are generally characterized in a practical environment either through measurements or from the physical layout using rigorous full-wave electromagnetic simulations. In both cases, widely adapted method is to use s-parameter based characterization [1]-[2], [8].

However, transient simulation of s-parameter data in the presence of nonlinear devices to obtain a global electrical assessment is a CPU expensive process due to the mixed frequency/time problem. Prominent approaches to solve this difficulty are based on approximating the s-parameter data through rational-functions [1]-[8] and subsequently synthesizing a SPICE compatible macromodel/netlist from such an approximation. However, the primary challenge in such approaches is ensuring the passivity of the maromodel. Passivity is an important property, because stable but non-passive models may lead to unstable systems when connected to other passive components [2].

This paper describes an algorithm for passive macromodeling of high-frequency subnetworks characterized by s-parameters. A new set of linear passivity conforming constraints are presented to ensure passivity of macromodels from s-parameters. Since the constraints are linear, macromodel generation is highly CPU efficient as compared to using traditional nonlinear constraints. Also it describes an efficient methodology for passivity verification and compensation. Examples are presented to demonstrate the validity and efficiency of the proposed algorithm.

II. Development of the Proposed Algorithm

The scattering parameters ($\boldsymbol{S}$) are generally used to characterize multiport subnetworks at higher frequencies, by relating the incident travelling waves ($\boldsymbol{a}$) and the reflected travelling waves ($\boldsymbol{b}$). The rational approximation of S-parameters of a m-port subnetwork can be written as

$$\boldsymbol{b} = \boldsymbol{S}\boldsymbol{a}; \quad \boldsymbol{S}(s) = \left[S_{ij}(s)\right];$$

$$S_{ij}(s) = \frac{(a_0^{(i,j)} + \ldots + a_L^{(i,j)} s^L)}{(b_0^{(i,j)} + \ldots + b_N^{(i,j)} s^N)} \quad (i, j \in 1 \ldots m) \tag{1}$$

The challenge here is to ensure both the accuracy and passivity of the multiport macromodel. The loss of macromodel passivity can be a serious problem because transient simulations may encounter artificial oscillations. A network with scattering matrix $\boldsymbol{S}(s)$ is passive [2] iff,

(a) $\boldsymbol{S}(s^*) = \boldsymbol{S}^*(s)$, where '*' is the complex conjugate operator.

(b) $\boldsymbol{S}(s)$ is a bounded real matrix, i.e., $\|\boldsymbol{S}(j\omega)\| \leq 1$ for $\omega \in \Re$.

Condition (a) is automatically satisfied since the complex poles/residues of the transfer function are always considered along with their conjugates, leading to only real coefficients in rational functions of $S(s)$. However, ensuring condition (b) is not easy.

In order to ensure both accuracy and passivity of the macromodel a new algorithm is developed. The first step involves computation of a common multiport pole-set. This issue is well addressed in the literature [4]-[8]. In this work multiport vector fitting based algorithm is used for extracting a common multiport pole-set. The second step computes multiport residues, subject to certain linear constraints which help to ensure macromodel passivity. The third step checks for any possible passivity violation and corrects in case of violation. Details of second and third steps are given below.

Formulation of Residue Equations

Let w_{max} be the frequency corresponding to the highest given data point. Let the common pole set (P) in the ascending order be denoted as

$$\begin{gathered} P = [p_1, p_2 \ \dots \ p_{max0}, p_{max1} \dots, p_{max}]; \\ (\mathrm{imag}(p_1) < \dots < \dots < \mathrm{imag}(p_{max})) \\ (\mathrm{imag}(p_{max0}) < w_{max} < \mathrm{imag}(p_{max1})) \end{gathered} \tag{2}$$

Next, each $S_{i,j}$ can be expressed using the pole-residue relation and the frequency response as:

$$c^{i,j} + \frac{k_1^{i,j}}{s_h - p_1} + \frac{k_2^{i,j}}{s_h - p_2} + \dots + \frac{k_q^{i,j}}{s_h - p_q} = \psi^{i,j}(s_h);$$

$$q \rightarrow \text{total number of poles; } p_l, k_l \rightarrow l^{th} \text{pole-residue pair;}$$

$$\psi^{i,j}(s_h) \rightarrow \text{given tabulated data at } h^{th} \text{ freq point, } s_h \tag{3}$$

Equating both the real and imaginary parts of (3) separately at all the data points, we can write

$$\begin{bmatrix} G_r \\ G_e \end{bmatrix} \begin{bmatrix} K_r^{i,j} \\ K_e^{i,j} \end{bmatrix} = \begin{bmatrix} \psi_r^{i,j} \\ \psi_e^{i,j} \end{bmatrix}; \longrightarrow \quad GK^{i,j} = \psi^{i,j} \tag{4}$$

where the subscripts r and e correspond to the *real* and *imaginary* parts, respectively, for the corresponding parameters/formulations (vector $K_r^{i,j}$ also includes the direct coupling constant $c^{i,j}$). Direct solution of above residue equations do not guarantee the macromodel passivity. Also, straight-forward application of passivity constraints can lead to the problem of nonlinear optimization. To overcome this difficulty, in case of y-parameters, passivity conforming linear constraints can be found in the literature [4]. The next section describes passivity conforming linear constraints for the case of s-parameter based subnetworks.

Passivity Conforming Linear Constraints for S-parameter based subnetworks

Equation (4) describing s-parameter based subnetworks is solved subject to the following new set of passivity conforming linear constraints:

$$Solve \quad G^t G K^{i,j} = G^t \psi^{i,j} \quad such \ that$$

$$\left.\begin{aligned} &0 \le |c^{i,j}| < 1; && \text{(a)} \\ &|GK^{i,j}| \le |\psi^{i,j}|; && \text{(b)} \end{aligned}\right\} for \ (i = j)$$

$$\left.\begin{aligned} &c^{i,j} = 0; && \text{(c)} \\ &|GK^{i,j}| \le |\psi^{i,j}|; && \text{(d)} \\ &P = [p_1, \ p_2, \ \dots \ p_{max0}]; && \text{(e)} \end{aligned}\right\} for \ (i \ne j) \tag{5}$$

A brief discussion of the relevance of above constraints is given below. (it is assumed that the original data conforms to passivity conditions).

(a) Region $\omega = \infty$: Constraints 5(a) and 5(c) ensure that $\|S(j\omega)\| < 1$ at $\omega = \infty$.

(b) Region $(0 \le w \le w_{max})$: Constraints 5(b) and 5(d) help to ensure that $\|S(j\omega)\| < 1$ in this region. These constraints are based on the following Lemma.

Lemma 1: If S is a complex matrix of size $m \times n$, then its 2-norm $\|S\| \le \sqrt{\|S\|_1 \|S\|_\infty}$ [11], where

$$\begin{aligned} \|S\|_1 &= \max_{1 \le j \le n} \sum_{i=1}^{m} |S_{ij}|; \\ \|S\|_\infty &= \max_{1 \le i \le m} \sum_{j=1}^{n} |S_{ij}| = \|(S^*)^t\|_1 \end{aligned} \tag{6}$$

Constraints 5(b) and 5(d) ensure that the absolute value of each entry of the fitted scattering matrix is equal to or less than the corresponding elements of the scattering matrix of given the data. From (6), this ensures that the

1-norm and infinity-norm of the fitted scattering matrix is equal to or less than that of the scattering matrix of the given data, which implies that the 2-norm of the fitted scattering matrix is less than or equal to that of the scattering matrix of the given data. This ensures that the fitted model is bounded real in the frequency region $(0 \le w \le w_{max})$.

(c) Region $\omega_{max} \le \omega \le \infty$ **:** Constraint 5(c) and 5(e) help in ensuring that $\|S(j\omega)\| < 1$ in this region.

Enforcing the above conditions and performing linear constrained optimization, will lead to passive macromodels for most cases of practical measured/ simulated data. It is important to note that, for macromodels thus generated, the post-processing or compensation requirement is very minimum. Also, since the constraints are linear, macromodel generation is highly CPU efficient.

It is to be noted that, since the above constraints are not strict passivity enforcing conditions, there may be minor chances of passivity violation, which may require post passivity compensation. For efficient passivity verification, theorems based on formulation of Hamiltonian matrices can be used [5], [12]-[13]. Using these theorems *exact locations where the norm of the scattering matrix* $S(j\omega)$ *of the macromodel exceeds one, can be found independent of where it happens in the frequency spectrum.* In addition, this is achieved without resorting to any frequency sweep. This information can be used to carry out the passivity compensation by the approaches such as [7]. Having ensured the passivity of the matrix-transfer function, a time-domain macromodel can be synthesized as a set of first-order differential equations [3], which can be easily linked to nonlinear simulators since they are described in time-domain. Alternatively, they can be directly stamped to the simulator, based on simulator interface capabilities such as Laplace element of HSPICE [14].

III. Computational Results

The proposed algorithm was performed on measured S-parameters (data is given up to 6GHz) of a 3-port distributed subnetwork [3]. Fig. 1 shows the norm of matrix $S(j\omega)$ of the model plotted against frequency by using the frequency sweep (conventional method) up to 50GHz and it can be seen that the norm is less than one, which implies that the model is passive (if the constraints 5(b) and 5(d) are not used during the fitting process, the model violated the bounded real condition). Fig. 2 shows the accuracy comparison of the real part of macromodel responses with the original data, and they match accurately. Similarly Fig. 3 shows the comparison of imaginary part of the macromodel with the original data. Fig. 4 shows the comparison of macromodel transient responses (in the presence of nonlinear terminations) with the SPICE simulation of the original circuit, which match accurately.

IV. Conclusions

In this paper an efficient technique has been presented for transient simulation of s-parameter based subnetworks in the presence of other linear and nonlinear devices. CPU efficient linear constraints for s-parameter based subnetworks have been proposed, which help in preserving the passivity of resulting macromodels.

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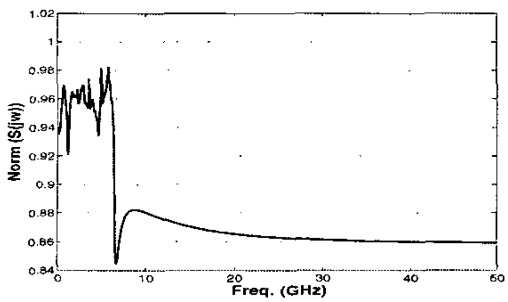

Fig. 1. Norm v/s freq. of *S(jw)* up to 50GHz

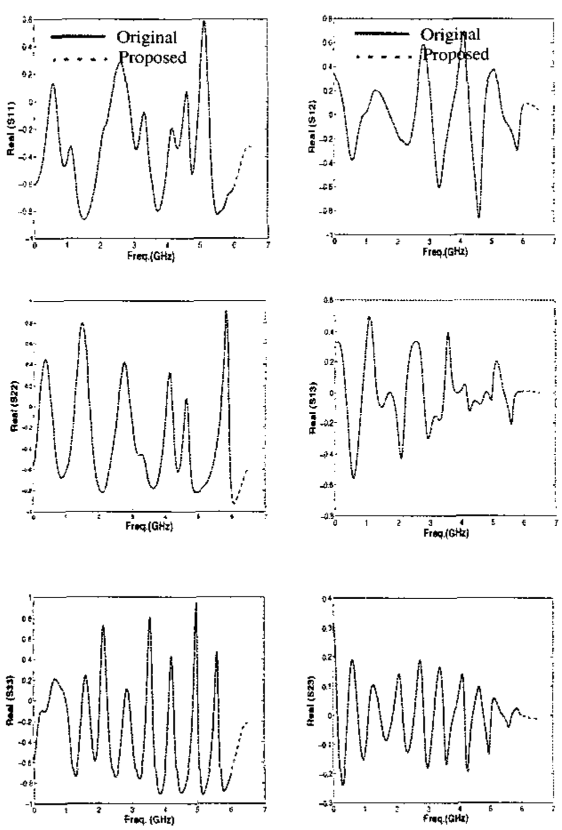

Fig. 2. Three-port scattering parameters (real parts)

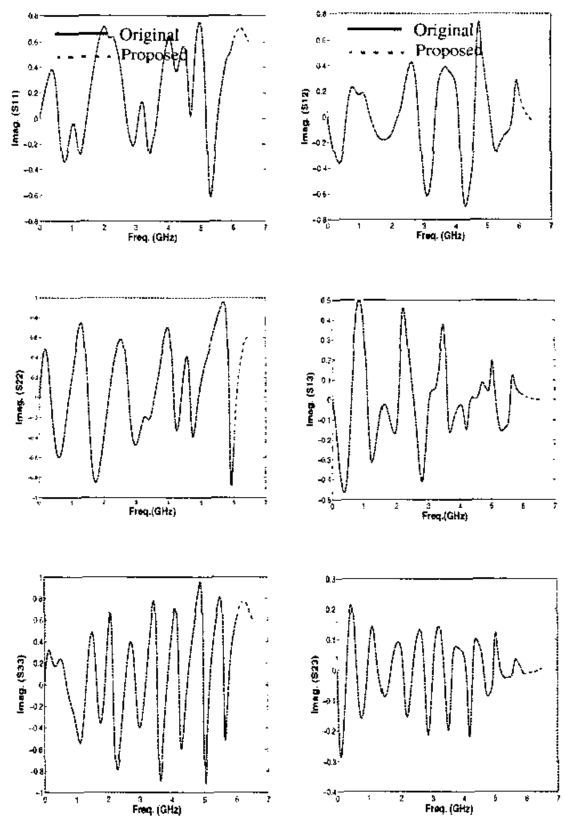

Fig. 3. Three-port scattering parameters (imag. parts)

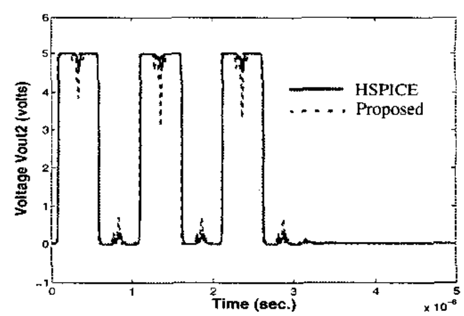

Fig. 4. Transient results