Structure Decomposition for Hybrid Analysis of Multilayer Interconnect Systems

Neven Orhanovic, Dileep Divekar, Norio Matsui
Applied Simulation Technology, Inc.
2025 Gateway Place, Suite 318; San Jose, CA 95110, USA
Phone: 408-436-9070, Fax: 408-436-9078
E-mail: {neven, dileep, matsui}@apsimtech.com

Abstract

A method for decomposing interconnect systems into signal propagation and power distribution parts is presented. The decomposed structure is amenable to hybrid analysis, where each part is analyzed using a separate analysis technique. The decomposition is performed around the discontinuities in the signal propagation paths.

Introduction

Due to the speed and complexity of today’s interconnect systems, it is becoming necessary to separate the analyzed interconnect system into parts and to analyze the individual parts using separate analysis techniques. When the connected parts are analyzed simultaneously, this type of analysis is often referred to as hybrid analysis. A typical example of such an approach is the time domain analysis of power distribution systems (PDS) in printed circuit boards (PCBs), multichip modules, integrated circuits (ICs), or IC packages. The conductors that form the power distribution network often have large electrical dimensions and they support field propagation in two or three directions at each point. The power distribution conductors are complemented by the conductors that form the signal propagation network. These signal conductors contain fine geometric detail and support field propagation primarily in one direction at each point. Finally, there are the active and passive devices, usually of small electrical dimensions, which connect the two networks. The three types of subsystems deserve different analysis approaches.

A number of approaches for decomposing electronic systems suitable for hybrid analysis have been proposed in the literature (e.g., [1]–[8]). This work introduces a general method for decomposing interconnect systems into power distribution and signal propagation parts around signal propagation discontinuities.

Problem Formulation

The objective is to separate the signal propagation network from the power distribution network at appropriately chosen interface surfaces. Figure 1 illustrates the problem for a planar structure. A portion of two power distribution conductors and two signal propagation conductors is shown. The interface surface is a plane chosen at the location of a discontinuity in the propagated signal current. The mutiterminal element shown as a black box represents an externally introduced component or a conventional lumped model of the signal conductor discontinuity.

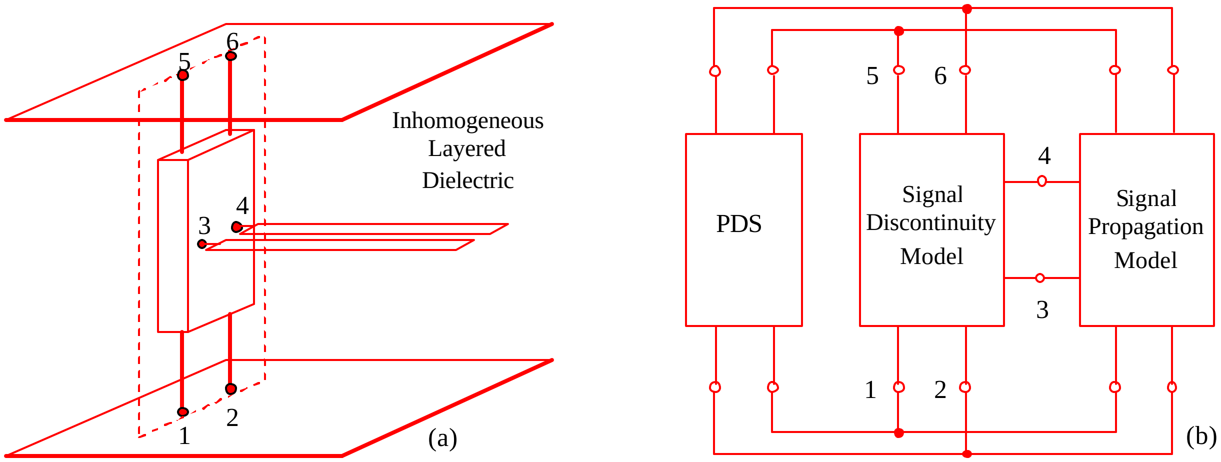


Figure 1: Separation of signal propagation from power distribution at a multiterminal signal discontinuity.

The structure is decomposed around the discontinuity resulting in the diagram shown in Fig. 1(b). Each of the blocks in the decomposed model of Fig. 1(b) can be analyzed by its own analysis method as long as common variables are used at the interface terminals. Typically, the PDS part of the decomposed model is analyzed using an EM field solver and the remaining two parts are analyzed using a circuit simulator.

Proposed Decomposition Technique

The decomposition method is first described on the three conductor example of Fig. 2. There are two planar power distribution conductors and one signal conductor in the structure. The discontinuity in the signal conductor at the center of the structure is formed by the shown excitation circuit.

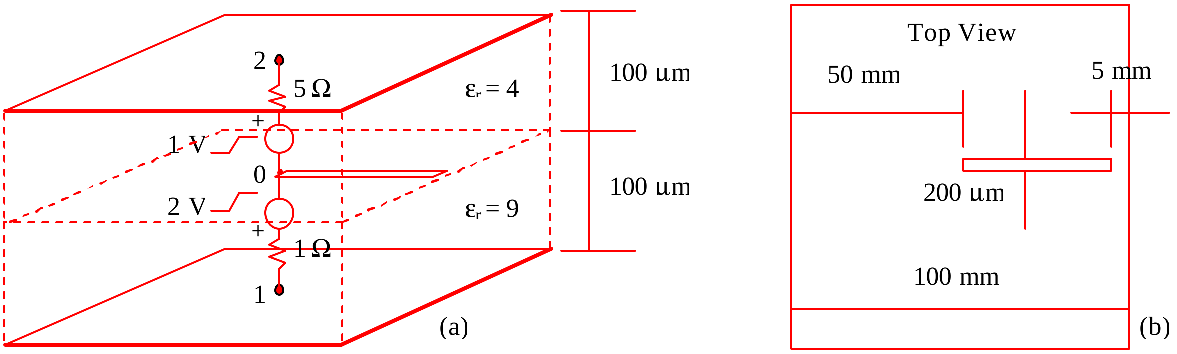


Figure 2: Planar structure with one signal and two power distribution conductors used to explain the method.

The signal propagated along the signal trace represents one dimensional propagation corresponding to one of the characteristic modes (eigenmodes) of the coupled interconnect system. This propagation can be modeled efficiently using a transmission line model. The speed of propagation of this mode, as well as the voltage and current eigenvectors of this mode, can be obtained from the cross section of the structure in the plane transverse to the propagation direction. The coupled line formed by the conductors in the right half of Fig. 2(b) is treated as a three conductor system with the signal conductor chosen as the reference. The remaining forms of propagation are determined by the two power distribution planes and the inhomogeneous dielectric in between. The main component of this power distribution propagation is the two dimensional propagation with zero current in the signal trace plane. Removing the signal trace from the system changes this propagation only slightly. This part is suitable for modeling by an EM field solver. The connection network between the two described models is determined as follows. The currents flowing out of the two discontinuity terminals are decomposed according to the equation

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} m_{I11} & +1 \\ m_{I21} & -1 \end{bmatrix} \begin{bmatrix} i_{\mathrm{M1}} \\ i_{\mathrm{PDS}} \end{bmatrix}. \qquad (1)$$

where m_{I11} and m_{I21} are the components of the current eigenvector (eigenvector of the 2×2 **CL** matrix) corresponding to the signal propagation, i_{PDS} is the current flowing from the power distribution conductors into the discontinuity circuit, and i_{M1} is the current of the signal propagation mode. Equation (1) is combined together with the voltage–current relations of the PDS, discontinuity model, and the signal mode propagation model. The resulting equivalent circuit is shown in Fig. 3.

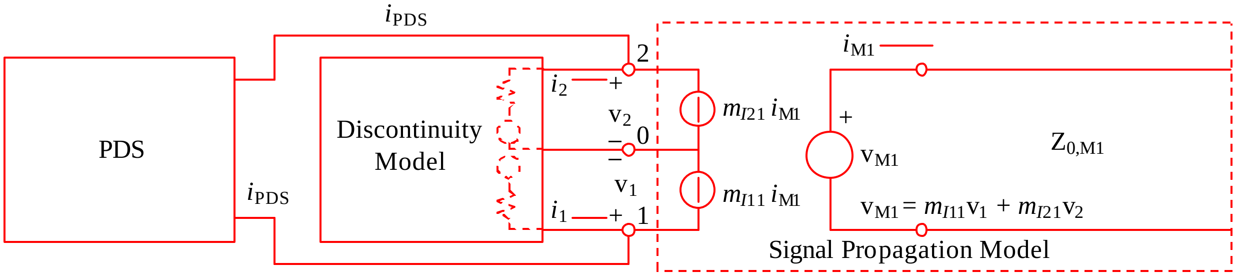


Figure 3: Equivalent circuit model of the decomposed power distribution and signal propagation networks.

The decomposition given by (1) is allowed as long as the two columns in the transformation matrix are linearly independent. This is always true since the second column corresponds to the case of zero current in the signal conductor and the first corresponds to a propagating mode with nonzero current in the signal conductor. The two therefore must be linearly independent.

The voltage of the signal propagation mode in Fig. 3 is expressed in terms of the voltages across the discontinuity circuit. The expression is obtained from the standard modal decomposition of inhomogeneous coupled transmission lines: $\mathbf{v}_M = (\mathbf{M}_V)^{-1}\mathbf{v} = (\mathbf{M}_I)^T\mathbf{v}$, where $\mathbf{M}_V$ is the matrix whose columns are the voltage eigenvectors of the coupled transmission line, $\mathbf{M}_I$ is the matrix of current eigenvectors, and $\mathbf{v}$ and $\mathbf{v}_M$ are column vectors of the line voltages and modal voltages, respectively. In a general purpose circuit simulator, the circuit of Fig. 3 can be implemented using voltage dependent voltage sources, current dependent current sources, and an uncoupled transmission line model.

Generalization to Multiple Signal and Power Distribution Conductors

The essence of the decomposition method is in identifying one signal propagation mode per signal conductor and extracting these signal modes from the interconnect system. The generalization of the above decomposition to more conductors is straightforward. Figure 4 shows the general decomposition circuit for N power distribution conductors and P signal conductors.

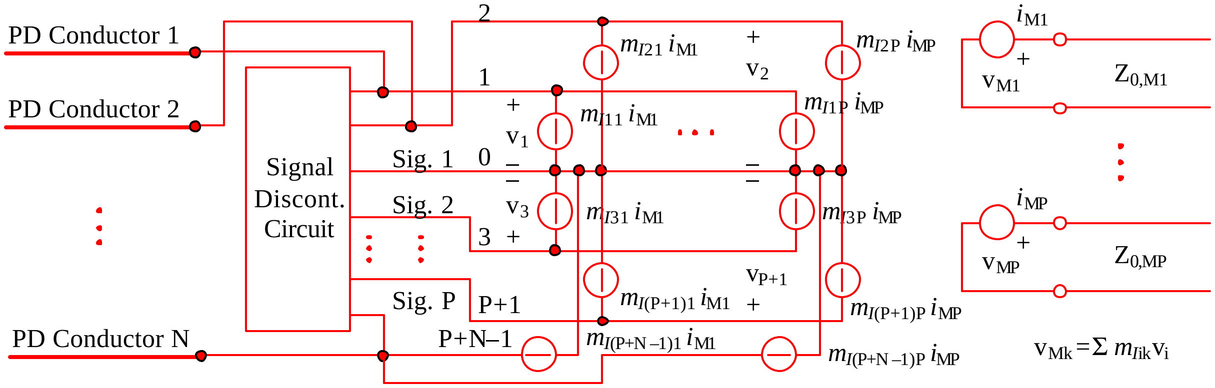
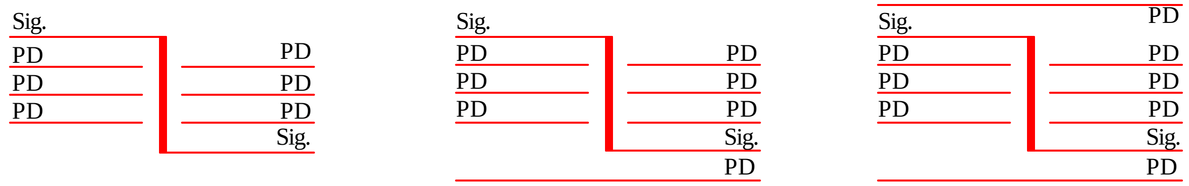


Figure 4: Decomposition for the case of M power distribution conductors and N signal conductors.

Example Applications

Figure 5 shows example PCB signal discontinuity structures to which the decomposition method shown in Fig. 4 can be applied, together with the corresponding circuit models for the discontinuity. The method must be applied at each interface shown by dashed lines. The signal conductors are labeled “Sig” and the power distribution conductors are labeled “PD”. A simple LC discontinuity model is shown for illustration. If the power distribution conductors can be considered uncoupled, the resulting decomposed circuits are very simple.



Microstrip to Microstrip Through N Planes   Microstrip to Stripline (N Planes)   Stripline to Stripline (N Planes)

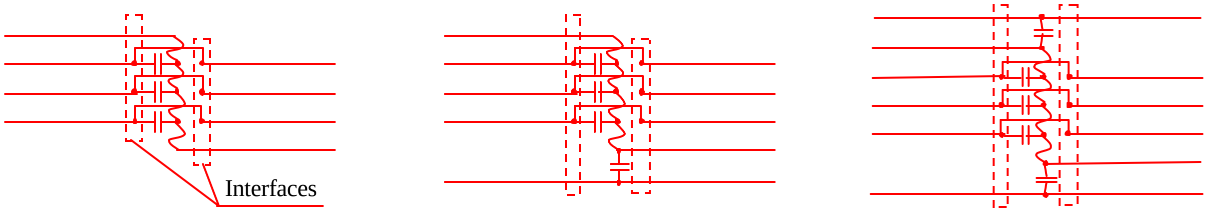


Figure 5: Example signal discontinuities suitable for decomposition together with their discontinuity circuit models.

Numerical Example

The structure of Fig. 2 is analyzed using two approaches. In the first approach the interconnect structure, without the discontinuity circuit, is analyzed using FDTD while the discontinuity circuit is analyzed using SPICE. The two methods are tied together using 3D FDTD–SPICE techniques. A fine nonuniform grid was used in the FDTD analysis. In the second approach the structure is decomposed according to Fig. 3 and the resulting circuit is analyzed using SPICE. Only the power distribution planes are analyzed using FDTD with one cell per dielectric layer in the vertical (z) direction and a uniform grid in the remaining two directions. The voltages launched from the discontinuity are shown in Fig. 6. In Fig. 6(a) the response obtained by the first approach is labeled "FDTD" and the response obtained using the proposed decomposition approach shown in Fig. 3 is labeled "Circuit". Fig. 6(b) shows the voltage distribution between the planes obtained from the FDTD analysis of the full structure. The presence of two modes in the plane to plane voltage due to the inhomogeneous nature of the structure is evident.

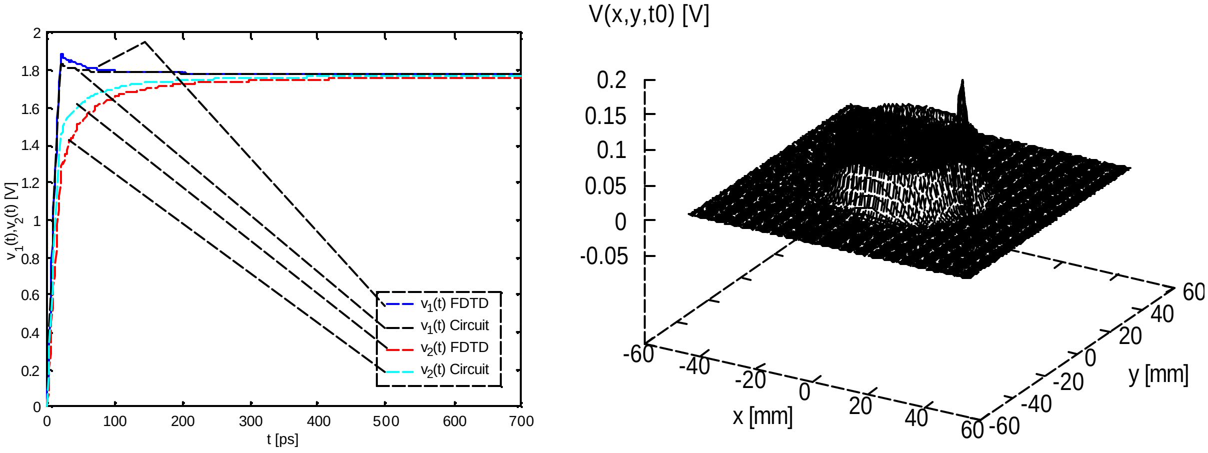


Figure 6: Voltage waves launched from the discontinuity of Fig. 2: (a) Comparison of voltage responses for full structure and decomposed structure; (b) spatial distribution of voltages between the planes at t=200 ps.

Concluding Remarks

A method for decomposing interconnect structures in inhomogeneous dielectric media around multiterminal discontinuity circuits has been proposed. The decomposed circuit is suitable for hybrid analysis. The method shows promising results for planar structures resulting in relatively simple decomposed circuits. Further improvements in the decomposition technique are possible by adding elements to account for the effects of the two-directional to one-directional conversion of the propagated signal fields around the discontinuity (current spreading effect).

References

[1] K. Guillouard, et al., "A new global time-domain electromagnetic simulator of microwave circuits including limped elements based on finite-element method," *IEEE Trans. MTT*, vol. 49, no. 10, pp. 2045–2048, Oct. 1999.

[2] W. Sui, D. A. Christensen, C. H. Durney, "Extending the two-dimensional FDTD method to hybrid electromagnetic systems with active and passive lumped elements," IEEE Trans. Microwave Theory Tech., vol. 40, no. 4, pp. 724–730, Apr. 1992.

[3] B. Toland, B. Houshmand, T. Itoh, "Modeling of nonlinear active regions with the FDTD method," *IEEE Microwave and Guided Wave Lett.*, vol. 3, no. 9, pp. 333–335, Sept. 1993.

[4] J. Fang, Y. Chen, Z. Wu, D. Xue, "Modeling of interaction between vias and metal planes in electronic packaging," *IEEE 3rd EPEP.*, pp. 211–214, Nov. 1994.

[5] H. J. Liaw and Henri Merkelo, "Mode conversion at vias in multilayer interconnections," *Proc. 45th ECTC Conference*, pp. 361–367, May, 1995.

[6] Z. Zhou, H. Ji, W. Hong, "An efficient algorithm for parameter extraction of 3D-interconnect structures in VLSI circuits: domain-decomposition method," *IEEE Trans. MTT*, vol. 45, no. 8, pp. 1179–1184, Aug. 1997.

[7] J. Choi, M. Swaminathan, "Computation of the frequency response of multiple planes in gigaherz packages and boards," *IEEE 8th EPEP*, pp. 157–160, Oct. 1999.

[8] R. Abhari, G. V. Eleftheriades, E. van Deventer-Perkins, "Physics-Based CAD Models for analysis of vias in parallel-plate environments," *IEEE Trans. MTT*, vol. 49, no. 10, pp. 1697–1707, October 2001.