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Direct Computation of Reduced-Order Models for Circuit Simulation of 3-D Interconnect Structures*

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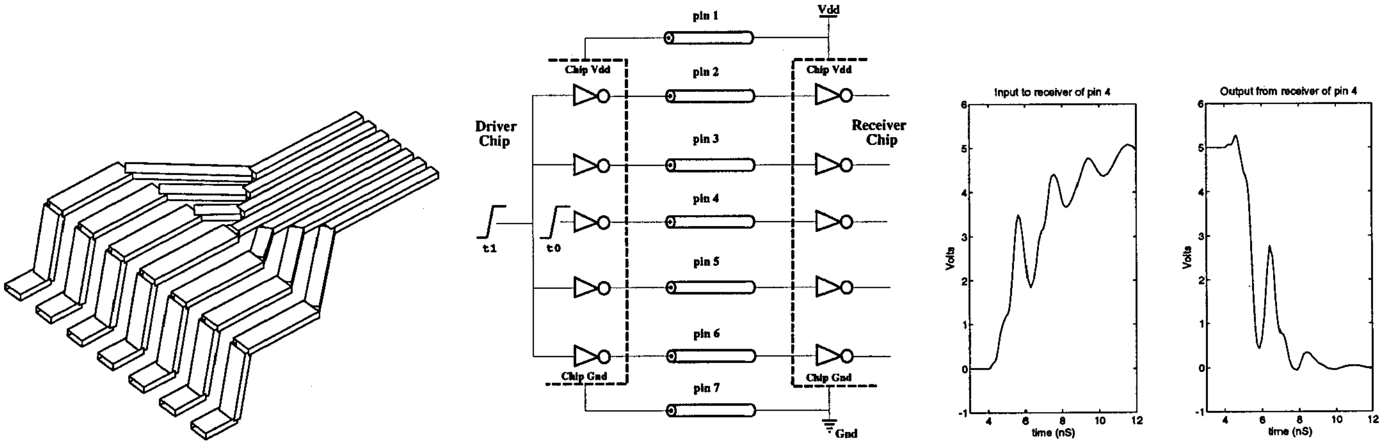
The dense three-dimensional packaging now commonly used in compact electronic systems may produce magnetic interactions which interfere with system performance. Such effects are difficult to simulate because they occur only as a result of an interaction between the field distribution in a complicated geometry of conductors, and the circuitry connected to those conductors. One approach to performing the coupled simulation is to use a 3-D field solver to compute the frequency-dependent impedance matrix associated with the geometry of conductors, and then use frequency-domain fitting and model-order reduction to construct a model suitable for circuit simulation.

In order to use frequency-domain fitting as described above, it is necessary to use the field solver to compute impedance matrices at dozens of frequency points, and this is computationally expensive. It is possible to derive a more efficient approach by exploiting the fact that 3-D field solvers typically use Krylov-subspace based iterative methods. These iterative methods can provide more than just a solution at a particular frequency, they can be used to directly construct reduced-order models.

A method of achieving this goal is to use the Arnoldi process directly on the state-space representation of the system of equations that describe the interconnect problem, represented by a triplet of matrices, $[\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}]$. The Arnoldi process generates a mutually orthogonal set of vectors which spans the space $\boldsymbol{A}^k \boldsymbol{B}, k = 0, \ldots, q-1$ [1]. The cost of each Arnoldi iteration is equivalent to that of a matrix vector product, which can be computed using a hierarchical multipole-algorithm as in FASTHENRY [2].

As the iterations proceed, the Arnoldi process constructs an orthogonal matrix $\boldsymbol{V}_q \in \mathbb{R}^{\geqslant \times ''}$ and an upper Hessenberg matrix $\boldsymbol{H}_q \in \mathbb{R}^{'' \times ''}$. A q^{th} order model is then obtained as $\boldsymbol{G}_q^A(s) = ||\boldsymbol{B}|| \boldsymbol{C}^T \boldsymbol{V}_q (\boldsymbol{I} - s\boldsymbol{H}_q)^{-1} e_1$. We note that this approximation is *not* the traditional Padé approximation and that the computational cost of computing the Arnoldi model is smaller than that for an equivalent Padé approximation.

Once the model is constructed, it can be used to simulate complex interconnect geometries. In Figure 1-b) the set of package pins shown in 1-a) is being used to connect a driver and a receiver chip. Using the Arnoldi process a 5^{th} order model is obtained which can be included in a standard circuit simulator such as SPICE. The result of a transient simulation, shown in 1-c) indicate that significant crosstalk can occur in the connector.



(a) (b) (c)

Figure 1: (a) Seven pins of a cerquad pin package. (b) General configuration for the connection between receiver and driver chips. (c) Results of a transient simulation using 5^{th} order model.

[1] Peter Feldmann and Roland W. Freund. Efficient linear circuit analysis by Padé approximation via the Lanczos process. In *Proceeding of the Euro-DAC*, September 1994.

[2] M. Kamon, M. J. Tsuk, and J. White. Fasthenry, a multipole-accelerated 3-d inductance extraction program. In *Proceedings of the ACM/IEEE Design Automation Conference*, Dallas, June 1993.

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