Electromagnetic Modeling and Electromagnetic-Circuit Co-Simulation of Mixed-Signal Systems-on-Chip

Vikram Jandhyala*[1], Pavel Nikitin[1], Daniel White[2], John D. Rockway[2], Nathan Champagne[2], C.J. Richard Shi[1], John W. Rockway[3], David Allstot[1], and Robert Sharpe[2]

1 Dept of Electrical Engineering, University of Washington, Seattle WA 98125 {jandhyala,nikitin,cjshi,allstot}@ee.washington.edu; 2 Lawrence Livermore National Lab, 7000 East Ave, Livermore CA 94550 {dwhite, nchampagne, rockway2,rsharpe}@llnl.gov; 3 Space and Naval Warfare Systems Command, 4301 Pacific Hwy, San Diego CA 92110 rockway@spawar.navy.mil

1 Introduction

Electromagnetic (EM) modeling is a critical part of present and future analog and mixed-signal system-on-chip (SoC) simulation and design. This paper presents an overview of selected approaches for large-scale efficient simulation of EM-effects for such microelectronic systems. In particular, coupled formulations, fast solvers, fast frequency sweeps, material models, and time domain approaches are discussed. Further examples and references will be provided at the special session on computational challenges for mixed-signal integrated circuits and radio-frequency packaging.

2.1 Coupled Formulation in Time and Frequency Domains

The mixed-signal simulation environment embodies a complex interaction of digital, analog, and geometry-dependent EM effects and related modeling. Traditionally, different modalities have been modeled separately in an *ad hoc* manner, necessitating heavy user intervention, estimation and even guesswork, and using a myriad different simulation programs and methods to connect between them.

The first step is the development of a combined topology-geometry based description. The circuit description of the mixed-signal system is complemented by a layout-technology description. Selected sections are, either manually or automatically on the basis of previous templated results, chosen as EM-sensitive regions. These might involve interconnects, substrate coupling regions, or sensitive passive components, for example.

The figure below shows an example of the layout and sensitive regions. This separation enables a coupled formulation to be set up; both circuit simulation through modified modal analysis (MNA), and EM simulation, in this case through the method of moments (MoM) integral equation techniques, can be formulated as a coupled system. Such a system can then be hierarchical or *telescoped* to the degree required, depending on the choice of using circuit (or transmission line models) or EM simulation for a specific section of the mixed-signal system.

The coupled matrix represents the formal description of the overall solution; however in many cases, port model representations of the EM structures suffice. In the coupled formulation, this is exactly equivalent to a Schur decomposition of the two-by-two block system, and automatically enables EMI/EMC excitations in addition to circuit sources. The coupled formulation proves to be useful where the internals of the EM simulation results, as dependent on circuit components and sources, is critical. This is particularly useful in applications such as ground bounce prediction, where the location of circuit sources changes the potential distribution. In addition, in the time domain, a coupled SPICE-time domain integral equation formulation enables non-linear effects to be incorporated into EM models where the need arises, such as in large-signal models. Iteration-based design also benefits from the coupled formulation, where EM matrices can be pre-computed and represented by models. Alternatively, EM-based design can be performed by pre-computing and inverting circuit sub-matrices and using these as excitations into the EM sectionof the coupled formulation.

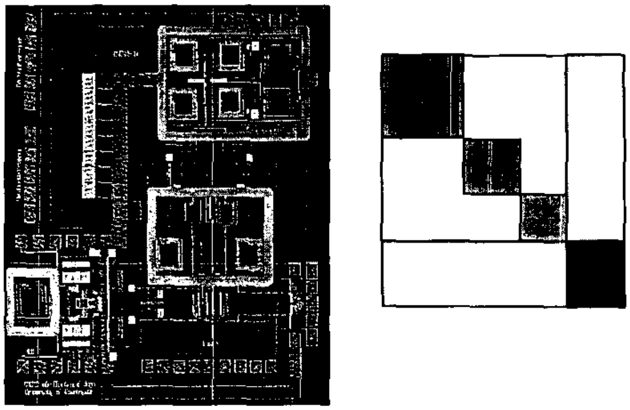

Figure 1: Left: Layout of a mixed-signal circuit, sensitive passives are outlined in red. Right: Associated coupled EM-circuit system. The block diagonal blocks depict EM modeling where interaction between sections has been ignored in this particular simulation instance. The lowest block in the right corner is the MNA; the two rectangular blocks are the sparse coupling matrices.

2.2 Fast Solvers

A necessary requirement in order to be able to model large-scale circuits is a physics-based fast solver for rapid solution of the EM and coupled problems. In particular, established fast methods such as the fast multipole method, and FFT-based techniques, may be exploited. Owing to (i) the multilayered environment and (ii) the presence of electrically small structures, our own solver is based on an alternative technology; the solver exploits a variant of the multilevel QR methodology developed at Lucent by Kapur and Long. An intriguing extension of the fast iterative solver based on this methodology is the promise it has shown as a direct solver, with the potential of solving poorly-conditioned systems and dramatically speeding up massive right hand side number problems.

2.3 Broadband Simulation

Broadband simulation is another key element of mixed-signal simulation. This problem is approached here through two distinct methods. The first is the use of time domain integral equation techniques, wherein broadband simulation is automatically ensured. The second is the use of fast frequency sweep methods or model order reduction in the frequency domain. In the context of coupled simulation, this permits frequency sweeps of impedance, quality factor, and circuit/EM quantities of interest. The distinction between regular frequency sweep approaches and the ones used here is that a unified circuit-EM frequency sweep can be performed on the coupled system.

Complementary to these broadband approaches are formulations and quadrature specializations that are required for broadband integral-equation based simulation. In particular, loop-star and loop-tree methods, as well as new second-kind formulations, have enabled well-conditioned formulations. In addition, the skin effect behavior needs to be captured over a range of frequencies, where surface impedance approximations could be invalid. This is accomplished by a two-region formulation employing an interior medium lossy-Green's function based on polar coordinate quadrature schemes. As shown in Fig. 2, such formulations permits the automatic prediction, with a surface formulation, of all skin effect-related phenomena such as the leveling off of inductance at low and high frequencies (before self-resonance effects become dominant). The low frequency and high frequency values are within 1% of those computed with commercial finite element (for low frequency) and method of moments (for high frequency) solvers.

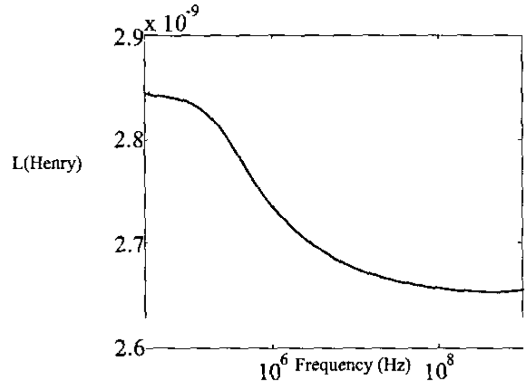

Fig. 2 Broadband frequency dependence of a single layer inductor with a two-region, low-frequency stabilized surface integral formulation

2.4 Hybrid Simulation

The presence of finite non-planar discontinuities, such as passivation, active region modeling, and substrates in general necessitates both surface and volume methods. In addition to surface integral equation methods, we also use a hybrid surface-volume integral equation method in the frequency domain. Also, time- and frequency- domain versions of the finite element method are coupled to integral equations for the hybrid problem, and act as exact boundary conditions for the partial differential equation representations of the inhomogeneous regions.

2.5 Link to VHDL-AMS

High-level behavioral modeling languages have become critical for not only digital modeling but also analog as well as multi-physics and multi-technology simulation. It is not surprising that there is also a trend in directly integrating EM simulation results and methods into these languages and formats. While VHDL-AMS is originally designed for time-domain simulation, there are emerging harmonic-balance based implementations for non-linear small-signal frequency domain modeling as well. In the presented approach, generation of time-domain macromodels is performed through state-space models generated directly from time domain EM simulation, as well as through reduced-order models in the frequency domain. Figure 3 depicts this simulation flow as used in conjunction with a behavioral modeling language. Note that EM sub-systems that include lumped circuits (such as decoupling capacitors in plane sub-sections, or tuning elements for distributed inductors) are modeled as coupled systems which are then converted into behavioral macromodels.

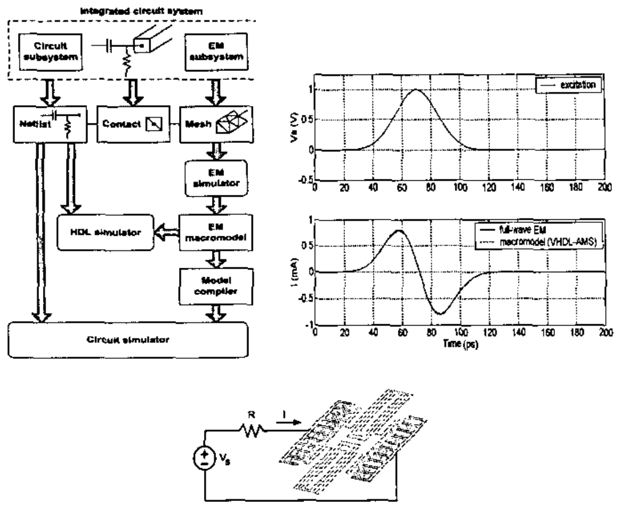

Fig. 3. Top left: Simulation flow into macromodelling language. Top right: EM response, as computed with a TDIE and VHDL-AMS state-space model, for the MEMS structure (bottom).

2.6 Sensitivity and Parametrics

Geometrical sensitivity of EM performance, and design enabling through parametrics is critical in mixed-signal systems. This has been implemented through incorporation of gradient-based methods into coupled formulations. Specifically, this is achieved by analytically computing spatial gradients within the integral equation matrices. These can then be used in gradient-based optimization as well as to estimate sensitivity of components to process (material and geometry) variation.

3 Conclusions

An overview of simulation requirements and methods for addressing the mixed-signal simulation problem are given. At the special session on Computational Electromagnetics Challenges for Mixed-Signal Circuits and RF Packaging, references, details, and further example will be provided that could not be incorporated here. This paper also aims to kickoff the special session where experts in the field will present complementary and competing specific simulation advances.

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