Modeling and simulation of circuit-electromagnetic effects in electronic design flow

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Abstract

The goal of this paper is to describe a methodology for modeling and simulation of circuit-electromagnetic (EM) effects that fits into a current electronic design flow. Our methodology is based on using time-domain macromodels implemented in a hardware description language (HDL). Simulation of the entire coupled circuit-EM system can be carried out either entirely in HDL simulator or in SPICE-type circuit simulator (using model compiler for macromodel import). We also describe in detail a circuit-EM contact interface and a neutral mesh format necessary to allow for flexibility in choice of EM simulators. At each step of our methodology, we provide an overview of current problems and solutions with reference to existing publications.

As a demonstration example, we consider a simple coupled system (MEMS resonator connected to a lumped circuit) and show that simulations using VHDL-AMS macromodel match full-wave EM results but easily fit in the design flow and take significantly less time. Our methodology is straightforward and permits the use of various EM simulators and macromodel identification algorithms[1].

1. Introduction

Electromagnetic effects have always been important in microwave circuits but now they have become an increasingly significant factor that affects the performance of modern integrated circuit (IC) systems, especially at multi-gigahertz frequencies [18]. Such systems include very large scale integrated (VLSI) chips as well systems-on-chips (SoC), and the examples of objects exhibiting EM behavior are interconnects, spiral inductors, traces, etc. This leads to a necessity of using accurate computer-automated design (CAD) tools for EM modeling and efficient use of those models in circuit simulation [6].

A variety of numerical electromagnetic field solving tools have been developed in the past, all of which have different limitations, capabilities, input and output formats, and computational costs. Choosing the best tool for a particular task and successfully employing and integrating it into an IC CAD design flow are challenging tasks.

Both circuit and EM simulations can be carried out either in time domain or frequency domain but mixed-signal circuit simulations are mostly performed in time domain (due to nonlinearity of analog circuits and sharp rise and fall times of digital signals) whereas EM simulations are mostly performed in frequency domain (due to well developed frequency domain EM methods).

There are three main approaches to incorporate EM simulation results in SPICE-type time-domain circuit simulators. First approach is to extract an equivalent RLC cir-

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cuit [1], which can be very large (i.e. for substrate coupling) and cumbersome to deal with (model order reduction is often needed). Second approach is to concurrently couple a circuit and EM simulator. While adding lumped passives to a full-wave EM simulation is straightforward, coupling a full-wave EM solver with a non-linear circuit solver is not a routine procedure (e.g. FDTD-SPICE coupling has been done but on case-by-case basis [15]). Third approach, which we describe in this paper, is to develop compact linear EM macromodels [10].

The last approach is very convenient because macromodels can be implemented in high-level hardware description languages used for design (such as VHDL-AMS [3] or Verilog-A [12]), easily interfaced to non-linear circuits, and re-used. Macromodeling permits significant speed-up of simulations and thus gains more and more attention in CAD community (e.g., for MEMS [17]). We should note that propositions to extend HDL's to directly support PDE's and hence EM modeling have also appeared in the literature [13] but this work is still in the research stage.

In this paper, we describe a methodology for modeling and simulation of circuit-EM effects on system performance by using compact linear EM macromodels implemented in a hardware description language. We provide an example – a simple circuit-driven MEMS system analyzed using VHDL-AMS macromodel extracted from time-domain EM simulation. We also describe specifics of circuit-EM contact interface and EM mesh format in a way that can be used by different circuit and EM simulators.

2. Methodology

Modern electronic design flow includes such steps as schematic capture and simulation, system layout, parasitic extraction, post-layout simulation, etc. At each stage, different tools and file formats, standard and proprietary, are used [9].

Analog and digital circuitry is typically described using SPICE- or VHDL-type netlists, which specify how lumped components or digital logic blocks are connected together. Layout is typically described using CIF or GDS II format files. These files contain 2D data about structures located at different chip layers and together with technology files (which contain information about thickness, material properties, and stacking of different layers) give a complete 3D description of a chip.

Having an ability to do an accurate post-layout simulation is critical for verification of functionality and performance of the complete system. Fully coupled circuit-electromagnetic simulations are very computationally intensive and are not commonly used. A typical approach used in the design process today is to perform parasitic extraction and include equivalent RLC circuits into a circuit simulator.

The process of RLC extraction from EM simulations is difficult, but works well in many cases, especially for capacitances of interconnects. Complex coupled problems result in large RLC networks and require a subsequent application of model order reduction methods, which are not well integrated into design flow. Thus there is a clear need for new approaches in coupled circuit-EM simulation.

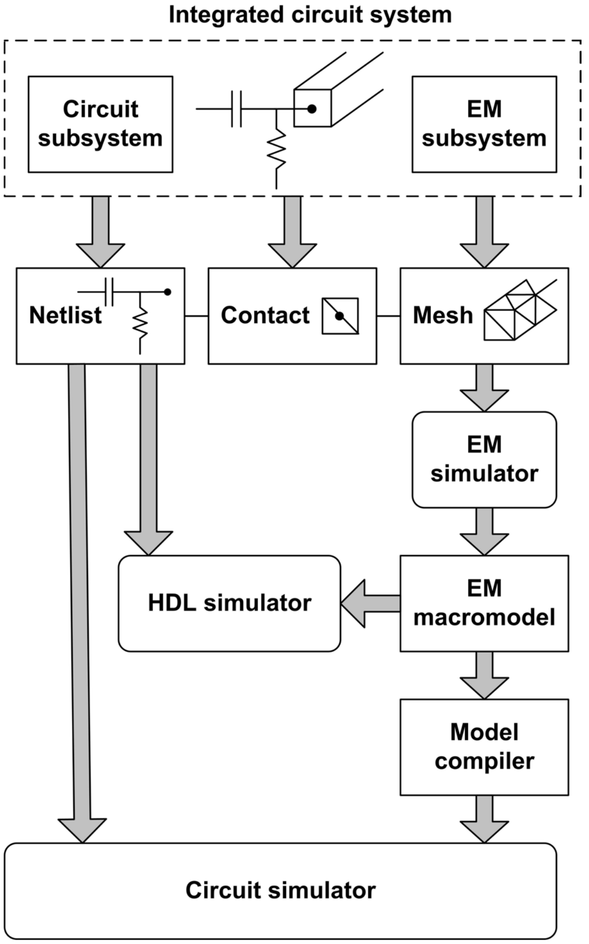

Figure 1. Methodology.

The methodology that we propose is illustrated in Figure 1. An IC system of interest contains lumped circuits connected at certain contact points to geometrical structures that exhibit EM behavior and need to be meshed and accurately modeled. Volumetric or surface mesh is stored in neutral mesh format reusable by various electromagnetic simulators. From frequency- or time-domain simulation data (depending on application and frequency range of inter-

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est), time-domain macromodel can be identified and extracted [20]. Such model can easily be implemented in a hardware description language (such as VHDL-AMS) and used either in HDL simulation of the whole system (circuit netlist needs to be converted from SPICE to HDL format) or, with recent advances in model compilers [7, 23], compiled for direct use in a SPICE-type circuit simulator.

2.1. EM simulation, contact interface, mesh format

In circuit simulation, the most popular method is node-based modified nodal analysis (MNA) [16]. In electromagnetic simulation, the variety of methods is richer and includes differential methods (FDTD – finite difference time domain, FEM – finite element method, etc.), integral equation methods (MoM – method of moments, BEM – boundary element method, etc.), hybrid methods [21], etc. Many of these methods can be utilized both in frequency or time domain but traditionally only FDTD has been used for time-domain modeling, and FEM and MoM have been used in frequency domain. Recently, new time-domain methods (TD-FEM [24], TD-MoM [26]) have been developed and successfully applied to a variety of problems. An excellent survey of existing EM methods can be found in [11].

Each method listed above has many variations and deserves a separate overview but most EM commercial tools are based on three major methods and their flavors – method of moments (e.g., *Sonnet* by Sonnet Technologies), finite element method (e.g., *HFSS* by Ansoft Corporation), and finite-difference time domain method (e.g., *XFDTD* by Remcom, Inc.). All electromagnetic solvers require creation of some sort of grid or mesh: either volumetric one that includes all problem space (FEM and FDTD) or surface mesh that covers only certain surfaces (MoM).

An electromagnetic solver applied to coupled circuit-EM problem must recognize the existence of ports or terminals that connect circuit and EM subsystems and through which the interaction happens [22]. Exact definition is different for different EM solving techniques [2]. Examples of specifying such interaction for FDTD can be found in [15] and for MoM in [26, 5]. Circuit world understands currents and voltages, and thus latter serve as common shared quantities at the points of circuit-EM interaction.

Assume that we have identified EM objects and lumped circuit elements connected to them (identification of IC package parts that must be modeled as EM objects is a separate challenging problems that we do not address here). Then circuit-EM contact interface can be defined as an area of the EM object surface to which a circuit element is attached. This concept is shown in Figure 2 (two contacts may form a microwave port).

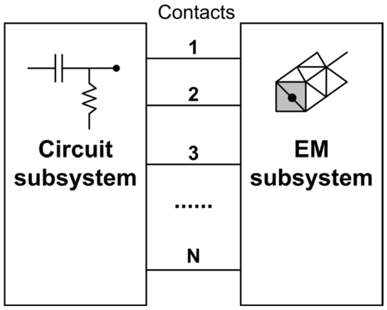

Figure 2. Circuit-EM contact interface.

The contact interface area can be specified in two ways: *mesh-dependent* and *mesh-independent*. *Mesh-dependent* method can be defined as specifying mesh elements that belong to the contact interface. *Mesh-independent* method can be defined as specifying 3D coordinates of contact points (using either x, y, z coordinates in the integrated chip reference frame or text labels in layout/technology files). After the mesh is created, mesh faces in the vicinity of that point (e.g, a spherical region of a certain radius) are recognized as part of contact interface.

Both ways described above have advantages and disadvantages. Mesh-dependent method is less portable as it requires the existence of prior mesh but is better for accurate coupled simulations. Mesh-independent method does not require prior mesh existence and has better portability but may suffer from potential problems related to mesh refinement in the process of EM solution.

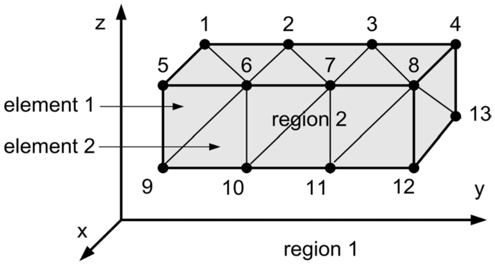

Figure 3. Mesh format.

Mesh itself can also be stored in a variety of ways. Currently, many different mesh formats for EM simulation exist. Unfortunately, there is no standard analogous to netlist standard for circuits. We propose to use the following neutral mesh format, simple and intuitive. To completely define a mesh, three files are needed: *node file*, *element file*, and *material file*. The format of those files can be illustrated with the example shown in Figure 3, where a surface of a perfectly conducting object positioned in free-space is meshed with triangles.

Node file lists coordinates of all nodes (in units selected by user) in the cartesian coordinate system. The node file for the example shown in Figure 3 is:

```
Node x  y  z
1    x1 y1 z1
2    x2 y2 z2
...
```

Element file lists all surface and volume elements (triangles, tetrahedra, etc.) formed by nodes which serve as element vertices. If an element belongs to a surface dividing two regions with different properties, those regions must be specified by their numbers. In the example shown in Figure 3 the elements are triangles on the surface dividing region 1 and region 2, and the node file is:

```
Element n1 n2 n3 region1 region2
1       5  6  9  1       2
2       6  9  10 1       2
...
```

Material file lists all regions (by number), their type (volume, surface, layer), and their properties (permittivity, permeability, and conductivity). Infinite conductivity for perfect electric conductors can be denoted as PEC. The example shown in Figure 3 contains free-space (region 1) and a PEC object (region 2). The material file for this example is:

```
Region eps mu sigma type
1      1   1  0     volume
2      1   1  PEC   volume
...
```

The mesh format, described above, can be used for different EM simulators and translated into mesh formats understood by any of the commercial tools. Once an EM simulation of the multi-port structure is completed, a macromodel needs to be extracted. This process is described in the next subsection.

2.2. Macromodeling

Macromodeling is extremely important for speeding up simulations of complex systems, such as coupled circuit-electromagnetic systems. In order to be easily implementable in a hardware description language, a macromodel must be casted into a time-domain differential equation form. Such model can be obtained from either frequency- or time-domain EM simulation.

A number of different algorithms for extracting macromodels and reduced order models from data are available [14, 8]. An advantage of using time-domain data is that in most cases passivity and stability of obtained macromodel are easier to guarantee than when working with frequency-domain data. Thus, for illustration of our methodology, we choose an approach where a linear compact macromodel is identified from a time-domain electromagnetic response as described in [25].

All possible information about system dynamics is theoretically contained in an impulse response – a system response to a delta-function excitation. System response to any input can be found as a convolution of the impulse response with the input signal. This process is very computationally expensive, especially for highly-resonant devices with long impulse responses. In addition, delta-function causes numerical problems in time-domain EM solvers, and more commonly used excitation is Gaussian pulse:

$$u(t) = u_o\, e^{-\frac{(t-\tau)^2}{2T^2}} \tag{1}$$

with -3dB bandwidth of 0.13/T.

System response to a Gaussian pulse can allow one to identify a continuous time-domain macromodel in its classical state-space form:

$$\begin{aligned} \dot{\vec{x}} &= \hat{A}\,\vec{x} + \hat{B}\,\vec{u} + \hat{K}\,\vec{e}, \\ \vec{y} &= \hat{C}\,\vec{x} + \hat{D}\,\vec{u} + \vec{e}, \end{aligned} \tag{2}$$

where $\vec{x}(t)$ is the vector of state variables, $\vec{u}(t)$ is the excitation, $\vec{y}(t)$ is the output, and $\vec{e}(t)$ is the noise signal. The process of identification can be described as finding $\hat{A}$, $\hat{B}$, $\hat{C}$, $\hat{D}$, and $\hat{K}$ from given $\vec{u}(t)$ and $\vec{y}(t)$.

There exists a large number of different methods and tools for system identification (see, e.g., *MATLAB*[2] system identification toolbox). The order of the model (dimension of the $\hat{A}$ matrix) can be determined from the data. The accuracy and other issues associated with macromodel identification, such as passivity and stability, are not discussed here since they are well covered in the literature (see, e.g., [4, 19]) and lie outside the scope of this paper.

The time-domain state-space model (2) is essentially a set of ordinary differential equations that can easily be implemented in a hardware description language for later use in circuit simulation, as it is shown in the next section.

3. Example

For demonstration of modeling flow methodology described above, consider a simple example: MEMS resonator (micromachined comb structure, approximately 1.5 mm × 0.5 mm in size, and positioned in free-space) driven by an external voltage source as shown in Figure 4. This MEMS structure represents an electromagnetic subsystem and can be thought of as part of a larger integrated package. The voltage source and the resistor represent a lumped circuit subsystem (which can be any transistor circuit).

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[2] Trademark of *Mathworks, Inc.*

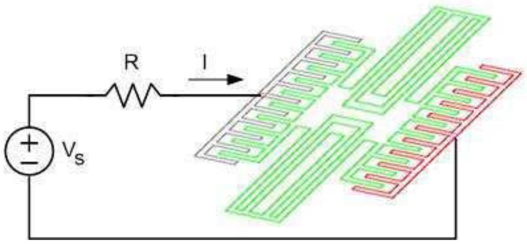

Figure 4. Circuit-driven MEMS resonator.

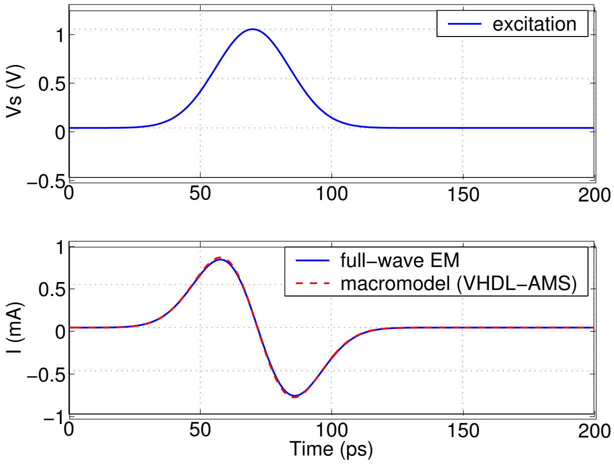

Figure 5. Results of the simulations for the system shown in Figure 4.

The voltage source generates a Gaussian pulse of the form (1) with $u_o = 1$ V, $\tau = 70$ ps, and $T = 14$ ps (bandwidth $\approx$ 10 GHz). The resistor is $R = 100$ Ohm. The mesh for MEMS structure was generated and stored in the neutral format described in the previous section. The problem was solved using a full-wave time-domain integral-equation method [26]. It contained about 1000 triangles (approximately 1500 unknowns) and took approximately 1 minute of runtime on a 1 GHz PC.

Consider a macromodel of the system that includes MEMS resonator in series with 100 Ohm resistor. The input $u(t)$ to this system is the excitation voltage from the source V_s and the output $y(t)$ is the current I through the system. For identifying the continuous state-space system model of the form (2), we used `'pem'` and `'d2c'` functions in *MATLAB* system identification toolbox. The response $y(t)$ was well approximated with the 3rd order model, where noise component was set to zero. The model was implemented in VHDL-AMS as shown below and simulated using VHDL-AMS simulator *Hamster*[3]. The runtime was 0.2 s on 2.5 GHz PC. As one can see from Figure 5, macromodel simulation results match the results of full-wave EM simulation very well.

```
----- Macromodel of MEMS resonator ---
-------- in series with resistor -----
ENTITY macromodel IS
 PORT (TERMINAL a, b : ELECTRICAL);
END;
 ARCHITECTURE behav OF macromodel IS
 QUANTITY u ACROSS i THROUGH a TO b;
 QUANTITY x1,x2,x3: real;
 CONSTANT A11 : real := -4.929E11;
 .....
 CONSTANT C3 : real := -2.04e-8;
 CONSTANT D : real := 0.00518;
BEGIN
x1’dot == A11*x1+A12*x2+A13*x3+B1*u;
x2’dot == A21*x1+A22*x2+A23*x3+B2*u;
x3’dot == A31*x1+A32*x2+A33*x3+B3*u;
-i == C1*x1+C2*x2+C3*x3+D*u;
END ARCHITECTURE;

------ System description ----------
ENTITY system IS END;
ARCHITECTURE behav OF system IS
    TERMINAL n1: ELECTRICAL;
BEGIN
Vs: ENTITY gaussian_source (behav)
    GENERIC MAP (1.0,70.0E-12,14.0E-12)
    PORT MAP (n1,electrical_ground);
Mm: ENTITY macromodel (behav)
    PORT MAP (n1,electrical_ground);
END behav;
```

This example demonstrates that macromodels are an accurate and efficient way of simulating coupled circuit-electromagnetic systems in time-domain. Macromodels in general contain much fewer internal variables than full EM problems (in our example, 3 vs. 1500) and thus provide a significant simulation speedup. They are easy to implement in HDL and can be used in today's design flow.

4. Conclusions

In this paper, we described in detail the methodology of modeling and simulation of coupled circuit-electromagnetic effects using time-domain EM macromodels implemented in a hardware description language. This methodology fits well into electronic design flow existing today. Simulation of complete integrated circuit system can be carried out either entirely in HDL or in SPICE-type circuit simulator

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[3] Now part of *Simplorer*, trademark of *Ansoft Corp.*

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(using HDL-to-SPICE model compiler). We have also defined a circuit-EM contact interface and a neutral geometry meshing format that can be used by various electromagnetic solvers used in the design process.

For demonstration, we considered a simple coupled system (MEMS resonator connected to a lumped circuit) and showed that VHDL-AMS macromodel simulation results match full-wave EM results but take significantly less time to obtain. This shows that EM macromodeling is a very effective way to include circuit-electromagnetic effects into simulation. Implementing macromodels in a hardware description language allows one to use them in the current IC design flow.

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