Multi-level Co-Simulation of Mixed Technology Microsystems

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***Abstract*- The advent of highly integrated technologies such as MEMS, MOEMS, nanometer scale integrated circuits, mixed signal systems on a chip (SoC), and opto-electronic communication networks, requires flexible, sophisticated and efficient simulation tools. It is only through system level simulation based on behavioral models that efficient design space exploration can be performed across both architectural and implementation choices. In this paper, we present our solution based on a multi-level co-simulation environment for mixed domain micro and nano systems.**

I. Background and Motivation

Beyond electronic devices, new MEMs, NEMs, optical, chemical and fluidic devices are becoming available for integration into mixed technology systems. However, these novel devices lack the supporting model generation, simulation, design and fabrication infrastructure that has developed over the past decades for silicon integrated circuits. Therefore, integrating them into the existing highly abstracted silicon CMOS design flow is problematic. For example, writing SPICE or even VHDL/Verilog analog models for devices where one only has 3D FEM simulation data is not only painstaking and error prone, it also fails to yield flexible parametric models that could be used in optimization or prediction tools.

The creation of simulation tools for multi-domain micro-systems systems is challenging because these systems span the physical domains of electronics, photonics, and mechanics, as well as multiple orders of magnitude in both time and length scales. The difficulties are compounded by the fact that computational performance and accuracy are directly related to the level of detail in the underlying models. Multi-domain micro-systems are currently simulated by point tools using component level models performed at the physical, or device, level.

Device level models focus on explicitly modeling the processes within the physical structure of a device such as electromagnetic fields, fluxes, mechanical stresses, and thermal gradients. These are typically described by partial differential equations in both space and time. Device-based tools are typically domain specific and computationally complex. In contrast, system-level tools are designed to include multiple domains and allow efficient system simulation, by modeling components by their functionality, or behavior, rather than their physical construction.

On the other hand, behavioral level models capture the above, mentioned distributed effects in terms of parameters, and the models focus on the relationships between these parameters and state variables (e.g., optical intensity, phase, current, voltage, displacement, or temperature) as a set of temporal linear or nonlinear differential equations in both space and time.

Therefore, one of the key requirements for integrating novel technologies into more traditional CAD flows is a methodology to extract abstract behavioral models from the lower level device models developed by the device designers. The second requirement is a robust simulation environment that can provide both simulation speed and fidelity. Meeting these two requirements will allow system designers to perform architectural design of novel technology for mainstream applications.

The rest of this paper is organized as follows. First we discuss our modeling methodology. Then we give an overview of our system level simulation environment where these ideas are being tested. Then we present an example system, an RF switch, illustrating the advantages of this approach.

II. Mixed Signal Multi-domain Modeling Methodology

The proposed methodology for the simulation of multi-domain, mixed signal systems can be described by three major tasks: system level description and modeling of the system, model abstraction of system components, and fast simulation algorithms.

A. *System Level Description and Modeling*

At the highest level, a system can be described as a set of component modules that are individually characterized and joined together by the mutual exchange of information. Each module processes some vector of input messages, updates its vector of internal state variables, and generates sets of output messages.

In our approach, we use a piece-wise linear paradigm to represent the discrete event signals in the system. At the system level, signals are linearized and, consequently, the transfer function for the elements in the component sub-systems can be obtained explicitly.

Using a discrete event simulator, each module's execution is based on the availability of new data values for its inputs. This allows each behavioral component model to be solved independently and consequently with the best possible strategy.

B. *Model Abstraction of System Components*

A state space description is typically used for the characterization of individual multi-domain components. A nodal description of the components is usually the final product of a discretization in time, space, or both of the physics based characterizations such as the ones used in Finite Element descriptions, EM analysis, or discrete and distributed electrical networks.

A wide range of linear and non-linear dynamic behaviors can be mapped to a state representation:

$$E\dot{x} = f(x) + Bu, \quad y = C^T x, \qquad (1)$$

Where $x \in \Re^n$ is the state vector, $u \in \mathfrak{R}^k$ is the input vector, $y \in \mathfrak{R}^m$ is the output vector, $B \in \mathfrak{R}^{nxk}$ is the input connectivity matrix, $E \in \mathfrak{R}^{nxn}$ is the energy storage matrix, $C^T \in \mathfrak{R}^{mxn}$ is the output scanning matrix, and $f(\cdot) \in \mathfrak{R}^n$ is a set of nonlinear functions.

Each component can be described as a network of linear and non-linear elements with ports defined as pairs of nodes between the elements.

The advantage of this representation is that can be applied to a very wide set of descriptions independent on the nature of the type of energy signals being used. As we explain below this representation allows to describe the behavior of the component as a solution of a set of ordinary differential equations or more generally, as a set of partial nonlinear differential equations. This is the basic for analog solvers currently used as the workhorse for modeling in specific domains (e.g., SPICE for electronic circuits).

C. *Fast Simulation Algorithms*

Not only is it important to have a general representation of system components that can be applied to various physical domains, it is also essential to have a fast simulation methodology in order to provide the designer with a tool that can support effective design space exploration.

1. *Piecewise Linear Fast Simulation*

In previous work [1], we introduced our combined piecewise linear (PWL) and modified nodal analysis (MNA) approach for the fast simulation of multi-domain components. The use of a general PWL solver decreases the computational task and allows for a trade-off between accuracy and speed.

Instead of a typical analog treatment for the solution of equation (1) to find the behavior of the component, we characterize individual elements by piecewise linear stamps that can be switched during the operation of the component to account for localized nonlinear effects on the constituent elements. The convergence operation used in normal analog simulation is then being replaced by a search process in this piecewise linear algorithm. We proceed to explain this process more in detail

The linearization of the general set of nonlinear functions in the nodal representation, equation (1), for the component or subsystem function can be obtained through a multipoint Taylor expansion around a set of k points in the state space x where the function is differentiable:

$$f(x) \cong \sum_k \left(f(x_i) + f(x_i)^{'} (x - x_i) \right) sw_i(x) \qquad (2)$$

Where sw_i is a switch function that enables the i^{th}model of this function in the neighborhood of x_i

Substituting equation (2) in equation (1) gives a set of Ordinary Differential Equations (ODE) of order *n,* in vector form, that represents the piecewise linear equivalent of the device at time *t*. Additionally, this expression is in a nodal form that can be mapped directly to a MNA formulation. The relevance of this formulation is that it can include both multi-domain variables as well as non-linear elements. The additional complexity of order *n* for the ODE can be resolved using an appropriate variable change that reduces the expression to first order.

In order to increase the accuracy of the approximation we can increase, *k,* the number of piecewise linear models. This linear approximation of *f* is done for each of the elements that make up component.

The problem is then reduced to finding the set of *k* state values that effectively divide the domain of *f* into hyperlinear regions of operation. We use a triangulation approach, as shown in Figure 1, based on recursive decomposition of the function domain hyperspace into hypercubic regions of operation followed by a vertex index permutation approach for triangulation into hyperlinear regions of operation.

Figures 1(a) and (b) illustrate the case for three dimensions. After recursive decomposition of the space into cubes, each cube (in Figure 1(a)) represents an interval on the domain for a function of three variables ($F(u_1,u_2,u_3)$). In Figure 1(b), we show the tetrahedral triangulation of a single 3D cube, where each tetrahedron is a linear approximation of the function.

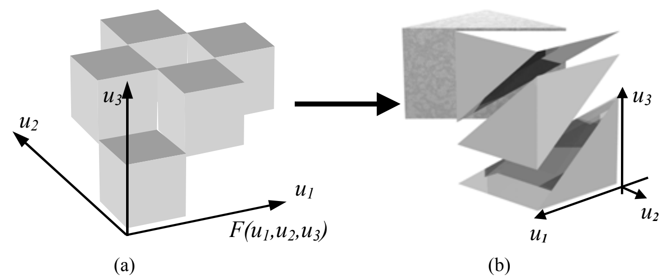

Figure 1: a) Function $F(u_1,u_2,u_3)$ decomposed into hypercubes b) Decomposition of cube into six tetrahedrons

The result of this element characterization is a model set composed of linear MNA stamps that can be added to form the snapshot of the system at the time of evaluation. The behavior of the component becomes the solution of the piecewise linear representation. The load of the evaluation resides in the search for the stamps of the nonlinear elements that corresponds to the hyper linear region of the component.

The advantage of this methodology is a complete control over the degree of resolution for the evaluation, which allows the user a trade-off accuracy/speed. Additionally, the underline MNA representation and explicit evaluation allows the natural blend of different energy types in the solution, if their representation is included in the overall description for the component.

2. *Model Order Reduction for Nonlinear Descriptions*

As an alternative to the previous approach we can accelerate the evaluation of the description in equation (1), by reducing the size of the representation itself. The cost of the evaluation of this expression resides in the degree of nonlinearity of the function set f (in terms of more iterations in an analog solver or a larger descriptor set in the PWL algorithm) and in the size N of the description itself (i.e., the number of nodes). Sizes of over 10,000 are typical of current component descriptions for a very accurate characterization. If an equivalent model can be obtained that closely matches the input/output behavior of the original description but whose order is greatly decreased, then a boost of the evaluation process can be achieved no matter what evaluation algorithm is finally used.

Model Order Reduction (MOR) techniques have been successfully used to obtain smaller versions of very large linear representation, and currently allow for the simulation of systems that otherwise would have unpractical memory and computational requirements [2]. For the nonlinear case however, there is no generally successful technique.

In contrast to current approaches for the generation of nonlinear compact models based on an assembly of piecewise linear models, we take a different tack. Our approach to nonlinear MOR is to consider the behavior of a dynamic nonlinear system as having two fundamental characteristics: a global behavioral "envelope" and a local behavior. The global behavior describes major transformations to the state of the system under external stimuli and the local behavior describes small perturbation responses. Local effects are captured by regions through a set of linear projections to a reduced state-space while global effects are captured by examining the non-commonalty among these projections. These "remainders" are used to build a modulation function that will generate the required dynamic changes in the common linear projection.

The advantage of the envelope representation for strongly nonlinear systems is that it simplifies the complexity of the model into a two-part problem. Depending on the complexity or cost of the behavioral separation procedure, it can be repeated recursively [3].

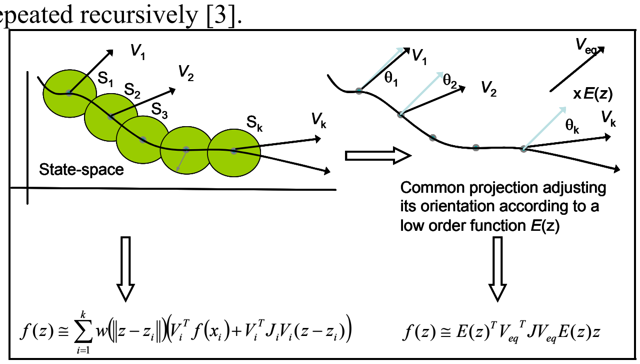

Figure 2, Envelope kernel, *E(z)*, modifying a linear model description of the nonlinear function *f(z)*

Current approaches for the generation of nonlinear compact models are based on the averaging of a set of piecewise linear models with individual projection bases (i.e., linear transformations that reduce the size of the system) as shown on the left side of Figure 2. In contrast, we extract a nonlinear function that modulates a common linear projection base, to account for its variation throughout the region of interest in the state-space, as shown on the right side of Figure 2. In the figure, we are representing the linear projections V_i as *2D* vectors for simplicity.

In our model, we consider that these variations can be described by a set of closed confining functions that depend on only a few parameters giving the desired envelope function.

III. Chatoyant: Mixed Signal Multi-Domain Simulation Environment

These ideas have been implemented in our mixed signal, multi-domain CAD tool, Chatoyant, that can be used to design and analyze complete mixed-technology micro-systems [1]. In Chatoyant, a user can perform end-to-end modeling of systems in which data signals are exchanged between the optical, mechanical and electronic domains. Systems can be designed by composing objects from the component library using a graphical user interface. The simulation of these multi-domain systems involves signals with different properties (e.g., voltage for electronics, force for mechanics and intensity for optics) and with varied dynamics.

IV. An Example: Simulation of a RF Mems Switch System

The RF MEMS device we model was designed and fabricated at the University of Michigan [4]. It is composed of electrostatic actuation plates and a capacitive plate suspended over a coplanar waveguide by spring meanders (Figure 3). This device works as an electrically switched shunt capacitor. With no voltage applied to the actuation pads, most of the RF signal can pass through the signal line. Applying a voltage to the actuation pads, results in an increase in the coupling capacitance between the signal line and the central capacitive plate. This lowers the impedance between the signal and ground, which effectively "shunts" the RF energy to ground and stops the RF propagation through the signal line [5]. The sensitivity of the device is directly related to the number of meanders in the spring assembly. Increasing the number of meanders lowers the required voltage for switch operation.

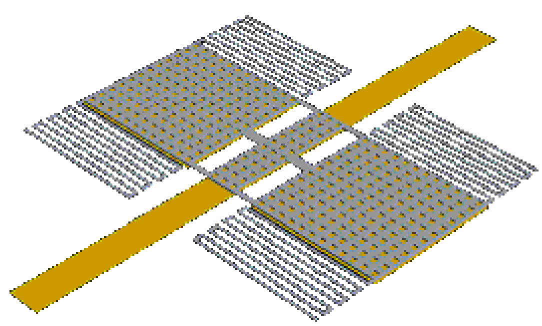

Figure 3: RF MEMS switch. Central signal trace is conditionally shunted to ground by central capacitive plate that is, in turn, controlled by meander springs and electrostatic actuators.

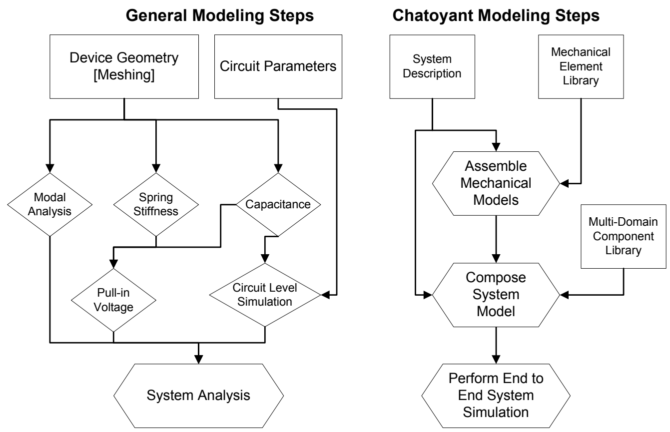

Figure 4: Comparison of RF-MEM system modeling flows, (left) traditional "ad hoc" approach, (right) system level approach

In general, in order to model the behavior of a MEM system, such as an RF switch, it is necessary to investigate its mechanical and electro-mechanical properties. As shown in Figure 4 on the left, analysis generally proceeds by first extracting the device geometry, using meshing, and then using that geometry in subsequent modeling steps. These include performing a modal analysis of the moving structures, extracting the stiffness properties of springs, determining electrostatic capacitance properties, etc. These results can then be used for electromechanical analyses such as determining the pull-in voltage and circuit level simulations. Finally, these analyses can be used together to understand the overall performance of the MEMS device as it would be used in a system. However, this understanding comes from the designer's expertise in correlating the results from these separate simulations.

In comparison, as shown on the right side of Figure 4, using a system level tool that follows the proposed methodology, the process is greatly simplified [5]. As illustrated, we can perform a system level simulation by assembling the components and then directly simulating the entire behavior of the switch in its environment. Starting with the system description, we assemble mechanical models by taking elements from the mechanical library (e.g., plates and beams) and mapping them into a global Cartesian coordinate system. The mechanical device models are then placed in a multi-domain environment together with components from other domains (e.g., electrical, optical). We then perform an end to end simulation of the entire system in a single simulation environment. In this case, the designer can explore design trade-offs directly and see the impacts of design decisions on system performance.

In this example we examine the behavior of the RF signal as the switch is actuated. We perform transient analyses of the mechanical switch coupled with the 40GHz input signal and observe the output of the switch (Figure 5). From this figure, we can see the operation of the switch and the response of the electrical signal. The magnitude of the signal envelope is attenuated by -29.57 dB, which agrees well with a HSPICE simulation. Of more interest, we can see the incremental attenuation of the signal as the switch is pulled down. The discrete amplitude values shown in the insert correspond to the time samples taken for the mechanical pull-in effect.

V. SUMMARY AND CONCLUSIONS

In this paper we have illustrated a methodology for the modeling and system level simulation of mixed signal, multi-domain systems. These systems are often based on new technologies where the only existing models are large physical descriptions. We have shown two techniques for abstracting behavioral models from these lower level models. Fast simulation of these systems can be achieved by using these abstract models in a multi-level simulator. We believe that only with the use of such a system level approach can we enable the integration of novel technologies into mainstream design flows.

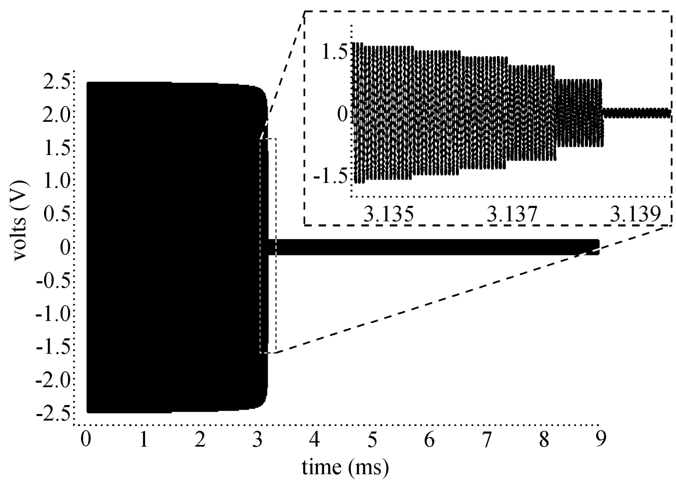

Figure 5: Simulated output voltage for a 5V P-P input sin wave at 40GHz during RF Switch actuation.

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