Doctoral Dissertation
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Linear and Nonlinear Model Reduction for Large-scale Electronic Systems

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Summary

Development of modern electronic systems is highly dependent on numerical simulations to evaluate the overall performance and check design constraints. A system-level approach is essential with modern designs, where many components are tightly integrated in a small space: a feature that makes global simulations fundamental to check that performance is not degraded by spurious parasitic interactions among different components.

This thesis starts from an industrially relevant application, namely Power Integrity (PI) verification of multi-core microprocessors, to identify, formulate, and solve a number of open problems in model reduction of electronic systems. PI analysis represents an ideal testbench for Model Order Reduction (MOR) techniques, since it requires performing time-domain simulations of extremely large systems, with the aim of checking the impact of unwanted couplings that compromise the quality of power supply (power noise). These simulations are typically time-consuming because of their high complexity. Motivated by this problem, general results and numerical schemes are introduced herein to speed up simulations through MOR. Although these methods have broader applicability, they are demonstrated on relevant examples revolving around PI verification, with several benchmarks of real-world multi-core microprocessors provided by Intel Corporation. A detailed technological overview is given in the introductory chapter, providing a description of advanced Power Delivery Network (PDN) architectures with integrated voltage regulators.

Within a complex electronic system, different subsystems are modeled using different tools, because distributed components (such as interconnects) require full-wave analysis, whereas most functional blocks are naturally associated with a lumped circuit description (e.g. transistor-level). Therefore, a system-level simulation is naturally an interconnection of subsystem models coming from different sources. A direct approach to system-level simulation through a coupled EM-circuit solver to concurrently simulate the full system is not feasible due to excessive computational complexity, especially if individual components are modeled accurately using fundamental physical laws. In fact, simulation of advanced electronic systems typically leads to large-scale systems of differential equations, with thousands input/output signals and a much larger number of state variables. Consequently,

commercial transient solvers may require an excessive runtime to complete the simulation, thus constituting a bottleneck in the design cycle.

This thesis proposes reduced modeling methods to overcome several major limitations in system-level modeling and simulation flows. The main developments focus on a general topology of interconnected building blocks, which represent the various system parts. Depending on the nature of these blocks (linear, nonlinear or mixed), three main problems are considered.

The first problem addressed here is the formulation of robust MOR algorithms to reduce simulation complexity to make it affordable with low computational effort. A contribution in this sense is a structured MOR method, developed to reduce systems where a large linear network is connected with a nonlinear subsystem. Leveraging the linear/nonlinear decomposition in the system structure, a projection framework is applied to constrain the linear dynamics on a particular subspace. The latter is specifically designed to capture the behavior of the entire system, including the feedback contribution from the nonlinear subsystem. The proposed model reduction method can be efficiently applied to large-scale problems, with explicit guarantees regarding passivity and stability. This method enables transient simulation of microprocessor PDNs with a much smaller runtime compared to commercial solvers, with up to 1000× speedup.

Model reduction of weakly nonlinear systems is also addressed, with the aim of efficiently modeling nonlinear components characterized by an interconnected topology that is so complex that a linear/nonlinear decomposition is not feasible. A completely black-box, frequency-domain approach is taken to formulate a general nonlinear macromodeling algorithm that only requires input/output data measurable non-intrusively, i.e. without accessing the underlying system equations. In particular, an extension of the Vector Fitting algorithm is proposed to build nonlinear reduced models starting from the data that results from steady-state analysis of nonlinear systems (e.g. Harmonic Balance, X-parameters). The proposed algorithm relies on the concept of generalized transfer function defined within Volterra series theory, to build a reduced dynamical model in terms of a set differential equations. Although the model is learned from frequency-domain data, it is suitable for time-domain simulation and integration with SPICE solvers.

Besides fast simulation, another issue addressed herein is the reliability of system-level modeling flows, where a common practice is to combine reduced models of individual subsystems built through dedicated algorithms. In constructing the model, the reference structure is typically regarded as a *standalone* component. However, as reduced models of different subsystems interact in a system-level simulation, the response of the overall system might be much different from the exact one even if individual models seem to be accurate during model construction. This error magnification phenomenon arises from feedback and it might jeopardize the practical validity of a system-level assessment. A fundamental contribution of this thesis is a context-aware approach, whereby the target simulation environment is taken into

account when model accuracy is optimized. In particular, a suitable cost function is proposed to guide the optimization procedure so as to obtain a robust macromodel whose responses are accurate when inserted in the target interconnection.

The algorithms presented herein provide several novel solutions improving the state of the art, leading to models that are more robust and reliable, and enabling accelerated simulation of large-scale electronic systems. Numerical results demonstrate very efficient transient analyses of real-world systems, with dramatic speedup with respect to traditional approaches or commercial solvers. The proposed approaches are expected to become key enabling tools for the development of advanced computing technologies in the heterogeneous integration framework. The activity documented in this thesis led to 7 journal articles, 10 conference papers, two short abstracts, three *Best Student Paper Awards* and four *Travel Grants* to attend international conferences.