# Black-box macromodeling and its EMC applications

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**Abstract**. The main idea of black-box macromodeling is to approximate the dynamic behavior of complex systems in terms of low-complexity models or equivalent circuits. Such compact models can be derived through robust numerical algorithms, such as the Vector Fitting scheme, starting from frequency- or time-domain responses of the system, and without any specific knowledge of its internal structure. The excellent accuracy that can be achieved, combined with the reduced size of the models, has led to a widespread adoption of this approach in several electrical and electronic applications, allowing designers to perform numerical simulations at the system level with high efficiency. This paper reviews the basics of black-box macromodeling and illustrates several application scenarios that are relevant for the EMC community, including Signal and Power Integrity, lossy transmission line modeling, electromagnetic full-wave simulation, network equivalencing and transformer modeling.

## I. Introduction

Models are the fundamental tool that engineers use to understand, predict and design systems. This is true for all disciplines, including of course EMC. A model provides a mathematical description of how a system behaves or responds under prescribed excitations, and how different parts of a complex system interact with each other. When suitably validated through independent numerical simulation or direct measurement, a model can be reliably and consistently used for design, verification, and prediction.

But what is a model? Different answers to this question might be expected from engineers working in different application fields, on different problems, or even different aspects of the same problem. Maxwell's equations and Kirchhoff equations are models. But also a linear algebraic system of equations arising from a Finite Elements or Finite Differences discretization of Maxwell's equations is a model. A simplified equivalent circuit with RLC components describing a Power Distribution Network is also a model, as well as a detailed transistor-level description of a power amplifier or an I/O buffer.

First-principle models like Maxwell's equations and even their discretized versions are sometimes inadequate for the description of EMC problems and for their numerical simulation aimed at prediction or verification. Consider, as an example, the case of a Signal/Power Integrity (SPI) verification of a complete electronic system in a post-layout phase (see Figure 1). All signal and power degradation effects must be taken into account, including interconnect parasitics (both of signal and power distribution networks), relevant capacitive and inductive couplings between each pair of conductors, local and global resonances, dispersive and non-ideal material properties, strong nonlinear and dynamic effects of I/O circuits that drive/receive signals by drawing supply current from the power distribution network, and even the non-ideal characteristics of the Voltage Regulator Modules. Although suitably discretized Maxwell's equations (for the interconnect part) and Kirchhoff laws with device characteristics (for the device part) certainly hold true, a brute-force approach that combines these descriptions into a global system-level model for the entire structure will fail. The model is too complex to be realistically simulated on any computing hardware. A similar conclusion is reached for simulation of traditional power systems for generation, transmission and distribution of electrical power. For instance, the investigation of undesirable disturbance effects from power electronic converters on other system components cannot be simulated by a single, complete model obtained from first principles.

This is where "macromodeling" comes into play, sometimes under different denominations like "behavioral modeling", "reduced-order modeling", "black-box modeling", "surrogate modeling", and "network equivalencing" [1, 2]. The basic idea is simple: deriving a simpler model by reducing the complexity of an initial description through some approximation process, without compromising the ability of the final model to describe the phenomena that it is intended to represent. This simplification is performed through a mathematical process, whose only objective is accuracy-controlled complexity reduction. Not very different in fact from image or file compression algorithms that we daily use to reduce the size of and store our data.

This approach is quite different from "white-box", "topological", or "physics-based" modeling. The latter try to describe a dominant physical phenomenon with a simple circuit description, whose parameters are directly related to the geometry and materials of the structure. An example can be a loop inductance of a critical current return path, which is computed or parameterized based on the actual position and dimension of the conductors [3]. Black-box macromodeling aims at simplifying an initial and excessively complex model, in order to enable efficient numerical simulations, most often trading physical insight for simulation speed or even ability to perform simulations. White-box and black-box approaches are thus complementary, and no one should be preferred to the other. They are simply intended for different tasks.

In this article, we focus on linear black-box macromodeling, by discussing various approaches that are available for systems that are adequately described by linear equations (such as interconnect networks, transmission lines, filters), and for which both time and frequency domain descriptions are possible. In a companion article (this issue, page XX), the Authors focus on nonlinear macromodeling, with specific reference to I/O buffer modeling. Although the mathematical tools that are required are somewhat different, both applications

share the same objective of producing simple, reliable, and representative simulation models.

## II. Why black-box macromodeling?

With reference to EMC applications, there are several scenarios in which (linear) black-box macromodeling proves extremely useful. Some of these scenarios are itemized below.

**Order reduction**: a given large-size circuit can be reliably "compressed" by applying a projection or approximation process under controlled accuracy [4,5]: a smaller circuit is obtained, with nearly the same time and frequency-domain response as the larger original circuit. Runtime reduction of orders of magnitude is often possible using the reduced-order circuit (see Section III.A below).

**Modeling from measurements or field solver data**: starting from a set of tabulated responses available from measurements (e.g. scattering, admittance, or voltage transfer), it is possible to derive a black-box model that is ready for transient simulation; this model can be cast both in terms of state-space equations, or even synthesized as an equivalent circuit for SPICE or EMTP simulations [1]. The same process can be applied to extract a model from the results of a full-wave simulation. In fact, the macromodel derivation is agnostic about where these initial data come from: the measurement process can be replaced with a virtual measurement as offered by a field solver, which returns frequency or time responses by solving Maxwell's equations. Macromodeling can thus be applied as a post-processing step that translates the results of a field solver into a compact equivalent circuit (see Section III.B below). Most modern field solvers offer this post-processing capability, often transparently from the user.

**Hiding proprietary information**: a black-box model is defined by parameters that are measured or computed through a mathematical procedure; as such, no sensitive information on geometry or materials of the structure under investigation is disclosed. This feature intrinsically hides IP, therefore making black-box models excellent candidates to exchange information about electrical properties of devices between different vendors and companies, or even entire systems of components.

**Inclusion of frequency-dependent effects**: black-box macromodels are derived through robust mathematical algorithms, ensuring that any frequency-dependent effect is reproduced by the model equations; from a dispersive dielectric to a resonant cavity or a transmission line, macromodeling provides a unifying framework for describing complex frequency-dependent phenomena in terms of low-order linear Ordinary Differential Equations (ODE).

**Interpolation**: a set of tabulated scattering or admittance parameters describes the response of a system only at the frequencies where samples are available; a macromodel derived from these samples is a set of equations, whose AC

response can be computed at any arbitrary frequency (of course, within the modeling bandwidth). Thus, macromodels have an intrinsic interpolation capability.

**Fast time-domain simulation**: since macromodels can be cast as ODEs or as equivalent circuits, a direct simulation in time-domain is straightforward with off-the-shelf circuit solvers of the SPICE and EMTP class. Macromodels can also be cast in pole-residue form, which supports transient simulation based on recursive convolution [6,7]. This is by far the fastest possible transient simulation method, which is now implemented in all modern SPICE and EMTP engines.

## III. Macromodeling flows

Two main different types of macromodeling flows are available, depicted in Figures 2 and 3.

### III.A Macromodeling via Model Order Reduction

Let us consider Figure 2, where a "Model Order Reduction (MOR)" flow is discussed. The starting point is the physical structure under investigation. The first step translates a physical description into a first-principle electromagnetic model, by setting up ports (which define where we need to excite the system and where we need to observe its response) and appropriate boundary conditions for the fields. A spatial discretization is then applied; depending on the adopted strategy, the result is either a large-scale circuit description, e.g., as arising from a Partial Element Equivalent Circuit (PEEC) extraction [8], or a large-scale system of Differential Algebraic Equations (DAE's) or ODE's in case of a Finite Difference or Finite Element discretization (note that we are leaving the time variable continuous). The former PEEC circuit can be translated into a DAE system by applying a suitable circuit formulation such as Modified Nodal Analysis (MNA) [9]. The state vector $\boldsymbol{x}(t)$ includes all currents/voltages or electric/magnetic field coefficients arising from the discretization, so that its size $N$ can be very large (millions of unknowns).
The MOR approach reduces the size of the state vector by performing an approximate change of variable. The full set of unknowns is projected onto a smaller set $\boldsymbol{x}_q$ of size $q \ll N$ as $\boldsymbol{x} \approx \boldsymbol{V}_q \boldsymbol{x}_q$, where $\boldsymbol{V}_q$ is a "tall and thin" matrix with many more rows than columns. Since the change of variable is not invertible, we will never be able to recover the full set of unknowns from the small number of elements in $\boldsymbol{x}_q$: we are throwing away something. At the same time, a smaller number $q$ of equations is obtained from the original $N$ equations, by throwing away the equations that are unnecessary. Several consolidated MOR techniques exist [4,5,2] to determine particular changes of variable (i.e. matrices $\boldsymbol{V}_q$), and equation-reduction strategies so that the reduced model of size $q$ preserves the desired features of the original model responses. Some of these formulations lead to a passive model if the original model is passive [5]; some other techniques require a subsequent passivity check and enforcement stage (more on passivity in Section IV). Once a reduced order model is available, it can

be synthesized as a behavioral equivalent circuit [10,11,12], or even directly included in a SPICE deck, in case an interface is available. We should remark that this entire process, from geometry to SPICE netlist, can be fully automated. Figure 3 compares the frequency response of a reduced model to the corresponding full-size model of a transmission line network: accuracy is excellent, with almost 97% complexity reduction.

### III.B Macromodeling via rational function fitting

Figure 4 describes a different application setting, which requires a different macromodeling flow [1]. Here, we assume that the frequency responses $\boldsymbol{H}_k$ (e.g., the scattering parameters) of the structure under investigation are available at a prescribed set of frequencies $\omega_k$. The most typical scenario is to compute these samples using a commercial field solver, but the samples can come from any other source, like a direct measurement, a customer, a supplier, or a colleague. How can we derive an equivalent circuit from a finite number of frequency response samples?

Let us recall that the response of any lumped circuit (the form in which we would like to obtain our macromodel) is a rational function of the complex frequency $s = j\omega$. Such response can be cast in pole/zero form, as a ratio of polynomials in $s$, and in pole/residue form as in Figure 4, where the poles are denoted as $p_n$ and the corresponding residue (matrices) with $\boldsymbol{R}_n$. Once poles and residues are known, our model is ready. All we have to do is to determine poles and residues, making sure that the model response matches as closely as possible the available frequency samples, as $\boldsymbol{H}(j\omega_k) \approx \boldsymbol{H}_k$ for all $k$. This is a simple data fitting operation; since based on a rational function model form, the common denomination is rational function fitting.

A smart algorithm that is able to compute poles and residues reliably, by enforcing the above fitting condition, is the so-called Vector Fitting (VF) scheme [13,14]. This method is based on an iterative sequence of steps that, starting from an initial guess of the poles (yes, this guess can be almost arbitrary!), successively refines the estimate until the poles stabilize. Each step involves a linear least squares solution followed by an eigenvalue computation. The simplicity and the outstanding performance of VF made it the method of choice for black-box macromodeling since its introduction. Nowadays, practically all state-of-the-art field solvers and circuit solvers include some implementation of VF, either explicitly as an add-on tool, or hidden from the user. Figure 5 compares a VF model response of a package interconnect to the raw data samples from which the model was derived.

Once the model is available in pole/residue form, a so-called realization process constructs the associated system of ODE's in form of state-space equations. The latter can then be subject to a passivity check and enforcement, and subsequently synthesized as an equivalent circuit and/or interfaced with SPICE.

## IV. Passivity, causality and stability

Electrical interconnects are passive, i.e., they are unable to generate energy [15]. It is then expected that interconnect models are also passive, in order to be

physically consistent. It turns out that enforcing passivity in a black-box model is not trivial, since the model parameters are obtained through numerical fitting. Due to the unavoidable (and intentional) numerical approximations, the reduced model might result non-passive. Simply ignoring the problem will not work, since it is known that a non-passive model may lead to unstable transient simulations [16], whereas the interconnection of passive models is theoretically guaranteed to remain stable. Model passivity is mandatory.

How can we enforce model passivity? First, we need to formulate a constraint that translates mathematically the concept of passivity. Then, we need to embed this constraint in the model construction. The model fitting process becomes thus a constrained fitting under passivity conditions. For the typical case of models in scattering form (for which the transfer function $\boldsymbol{H}(s)$ is a scattering matrix), the passivity conditions are listed in the inset [15, 17].

Condition 1 is related to stability and causality: a stable and causal model cannot have poles with a positive real part. Condition 2 implies that the impulse response $\boldsymbol{h}(t)$ is real-valued. Finally, condition 3 implies that the model does not generate any energy. This is easily understood if we consider a one-port system, whose scattering matrix $\boldsymbol{H}(s)$ is scalar and coincides with the reflection coefficient $\Gamma(s)$. We know that the reflection coefficient of a passive one-port must be less than one at any frequency, $|\Gamma(j\omega)| \leq 1$ for all $\omega$, otherwise the one-port returns more power than it receives. Condition 3 generalizes this to an arbitrary multi-port, where energy boundedness is expressed in terms of the singular values $\sigma_i$ of the scattering matrix (we recall that for any complex matrix $\boldsymbol{X}$, the singular values are defined as $\sigma_i\{\boldsymbol{X}\} = \sqrt{\lambda_i(\boldsymbol{X}^H\boldsymbol{X})}$, where $\lambda_i$ are the eigenvalues and superscript $^H$ denotes complex conjugate transpose). Singular values simply generalize the concept of magnitude to matrices. Figure 6 compares the singular values of a non-passive and a passive model of a connector, which in the latter case are uniformly less than one at all frequencies, whereas the non-passive model violates passivity conditions outside the modeling bandwidth (this is sufficient to destabilize SPICE simulations).

Most passivity enforcement schemes [18,19,20,21] start with an initial non-passive model and try to correct the model parameters (e.g., the residue matrices or directly the ODE coefficients) so that the singular values do not exceed one. In fact, the passive model of Figure 6 (bottom) was obtained by applying one of the leading passivity enforcement schemes [18] to the non-passive model (top). It is interesting to note that passivity conditions (see inset) include stability and causality as byproducts. Passivity is therefore the stronger and most important feature that a macromodel must have [22].

## V. EMC applications: a showcase

Applications of black-box macromodeling are unlimited, even crossing the boundaries of EMC [1]. In this section, we illustrate a few significant application scenarios for which macromodeling can be now considered as a standard approach.

**Full PCB modeling**. Figure 7 shows selected scattering responses of a full PCB structure, defined at both signal and power ports in order to include system

resonances and substrate coupling in a Signal and Power co-simulation flow [23]. The black-box model reproduces almost exactly the scattering responses obtained from a full-wave solver. Using the model in a SPICE simulation enables the direct computation of eye diagrams (Figure 8). This simulation can be set up to selectively include the possible different sources of signal degradation (crosstalk from nearby aggressor lines and/or core switching), in order to pinpoint where the design needs to be improved and optimized.

**Enhancing field solvers**. Rational function fitting can be integrated into frequency-domain field solver engines, in order to speed up frequency sweeps. Figure 9 shows how effective this integration can be. Only a few frequencies are directly computed by the solver. A rational fitting process is applied to predict the inter-sample behavior using a subset of computed samples, and the remaining samples are used to validate this prediction. Iteration of this process leads to an Adaptive Frequency Sampling loop [24] that produces a rational interpolation that is undistinguishable from the actual response, as could be computed with a fine resolution by the solver. Since the rational fitting time is negligible with respect to the time required for a single frequency computation by the solver, this process results in major CPU time savings.

**Enhancing field solvers (again)**. The predictive capabilities of black-box macromodels can be applied to stop the iterations of a time-domain field solver [25]. Once the system responses have been computed long enough, so that the available time samples include all information on the system dynamics, a Time-Domain Vector Fitting (TDVF) scheme [26] can be applied to predict the future transient evolution (Figure 10) via a macromodel. Validating this prediction by running the field solver for a few extra time steps ensures that the black-box model represents with good accuracy the original system. Automation of this process provides an accuracy-controlled criterion to terminate the solver run.

**Transmission lines**. One of the very first macromodeling applications was frequency-dependent modeling of transmission lines. These components are found in a wide range of applications, from high-speed electronics to high-voltage power systems. The runtime of time domain simulations can be greatly reduced by use of the traveling wave method, which requires to fit the line characteristic admittance and propagation operator with macromodels [27, 28]. Figure 11 reports the modeling of the propagation operator for a six-conductor high-voltage cable system. The model was obtained via the Universal Line Model scheme [28], where Vector Fitting is applied to modal components. The accuracy of the final approximation is seen to be excellent.

**Network equivalents**. Large systems such as a high-voltage grid can consist of hundreds of components. Simulation of local effects, e.g. the overvoltage resulting from the switching of a circuit breaker, can be very time consuming when all components are included in the system model. In many cases, the runtime can be greatly reduced by representing the adjacent system by a low-order macromodel. Figure 12 reports an example of simulating a three-phase short-circuit on one three-phase bus in the French 400 kV grid. The EMTP program was used for generating frequency domain samples for an admittance

terminal representation of the system adjacent to the faulted bus which was fitted using VF followed by passivity enforcement (top panel) [29]. The lower panel shows that the model can simulate the fault response with adequate accuracy. In this example, the CPU time for the simulation was reduced from 63.9 s to 4.7 s.

**Power transformers.** The high-frequency terminal behavior of power transformers can be extremely difficult to predict through calculations alone. For studies of transient voltage transfer between windings and other high-frequency effects, a better approach is often to characterize the transformer behavior using frequency domain measurements. Figure 13 reports simulation results obtained for a three-phase three-winding transformer. Here, a nine-terminal admittance parameter model was extracted using admittance measurements followed by model extraction by Vector Fitting and passivity enforcement. In addition, the voltage transfer from the nine external terminals to eight internal points along one winding was measured and fitted using Vector Fitting. Figure 13 shows a very good agreement between the measured and simulated time domain responses on the internal points due to step voltage excitation to one of the transformer terminals.

## VI. Conclusions

This article presented a qualitative overview of black-box (linear) macromodeling approaches, together with a discussion on the main reasons why these techniques have become widespread in many scientific and engineering applications, including EMC. The literature on this subject is huge. The recent book [1] provides a general introduction to the theory of passive macromodeling, with a collection of the most important references. It is safe to state that, given the level of robustness and the versatility of state-of-the-art schemes, black-box macromodeling should now be regarded as one of the fundamental tools that an EMC engineer should have access to, in order to cope with the everincreasing complexity of electrical and electronic systems.

## VII. References


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## Biographies

**Stefano Grivet-Talocia** received the Laurea and the Ph.D. degrees in electronic engineering from Politecnico di Torino, Italy. From 1994 to 1996, he was with the NASA/Goddard Space Flight Center, Greenbelt, MD, USA. Currently, he is a Professor of Circuit Theory with Politecnico di Torino. His research interests are in passive macromodeling of lumped and distributed interconnect structures, model order reduction, modeling and simulation of fields, circuits, and their interaction, wavelets, time-frequency transforms, and their applications. He is author of more than 150 refereed journal and conference papers. He is co-recipient of the 2007 Best Paper Award of the IEEE Trans. Advanced Packaging. He received the IBM Shared University Research (SUR) Award in 2007, 2008 and 2009. Dr. Grivet-Talocia served as Associate Editor for the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY from 1999 to 2001. He is co-founder and President of IdemWorks.

**Bjørn Gustavsen** received the M.Sc. degree and the Dr.Ing. degree in Electrical Engineering from the Norwegian Institute of Technology (NTH) in Trondheim, Norway, in 1989 and 1993, respectively. Since 1994 he has been working at SINTEF Energy Research where he is currently Chief Scientist. His interests include simulation of electromagnetic transients and modeling of frequency dependent effects, including transmission lines, network equivalents and power transformers. He spent 1996 as a Visiting Researcher at the University of Toronto, Canada, and the summer of 1998 at the Manitoba HVDC Research Centre, Winnipeg, Canada. He was a Marie Curie Fellow at the University of Stuttgart, Germany, August 2001–August 2002. He is a Fellow of IEEE.

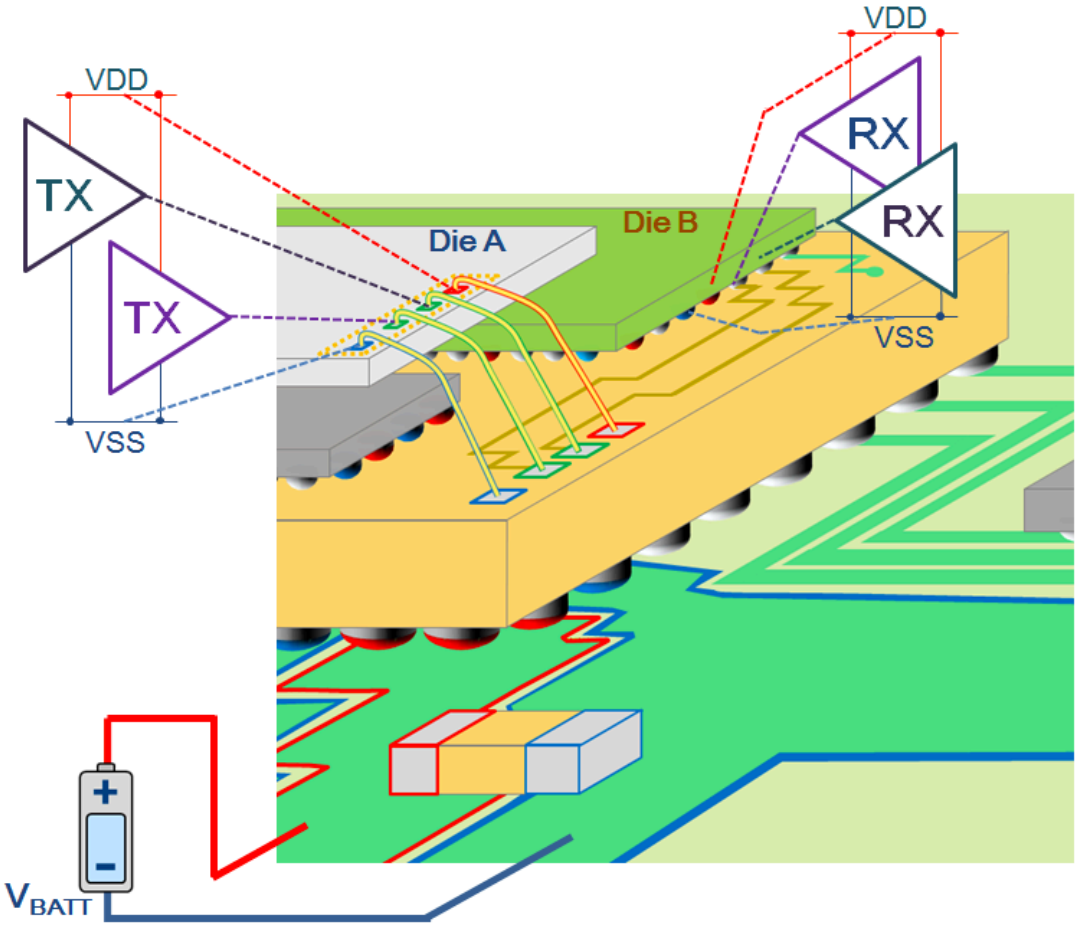


Figure 1: sketch of a Signal and Power distribution network on a chipb packageb board system

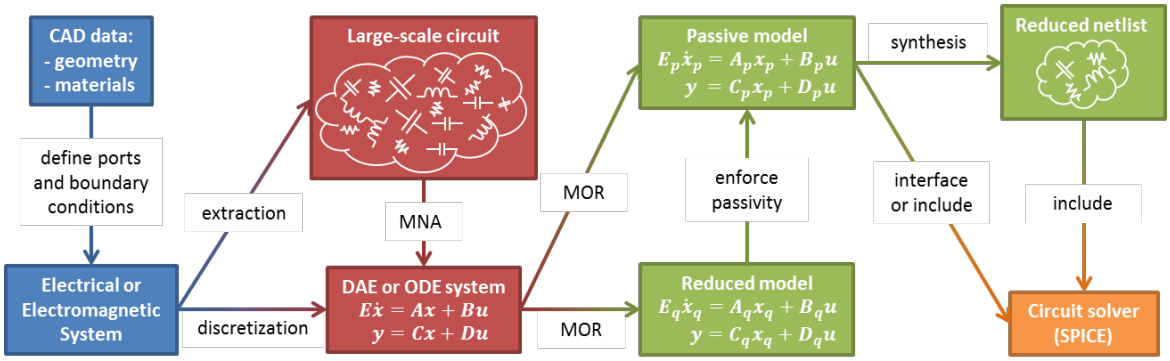


Figure 2: macromodeling flow based on Model Order Reduction (MOR).

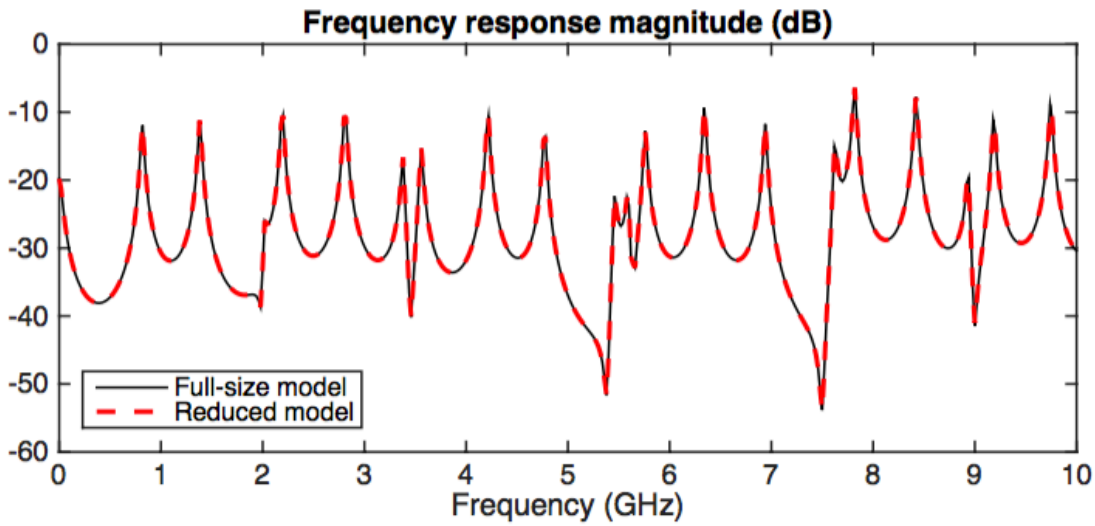


Figure 3: Frequency response of a 5b port discretized transmission line network ($N = 3906$ states) and its reducedb order model ($q = 130$ states).

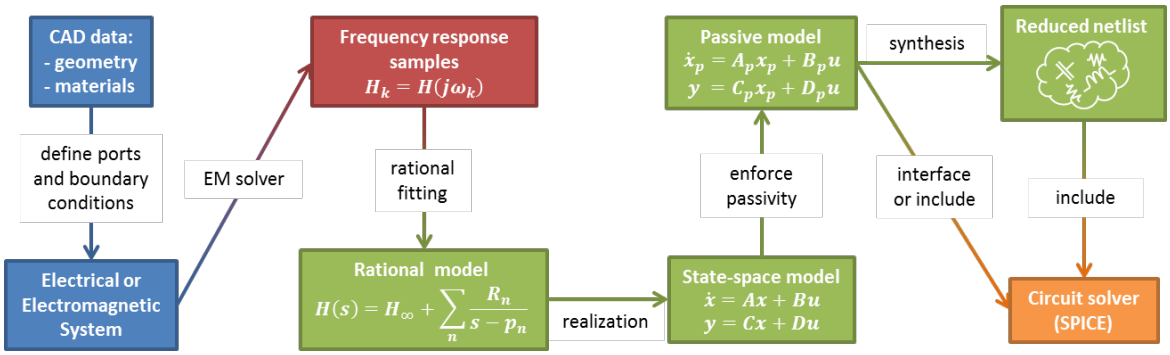


Figure 4: macromodeling flow based on frequencyb domain rational fitting.

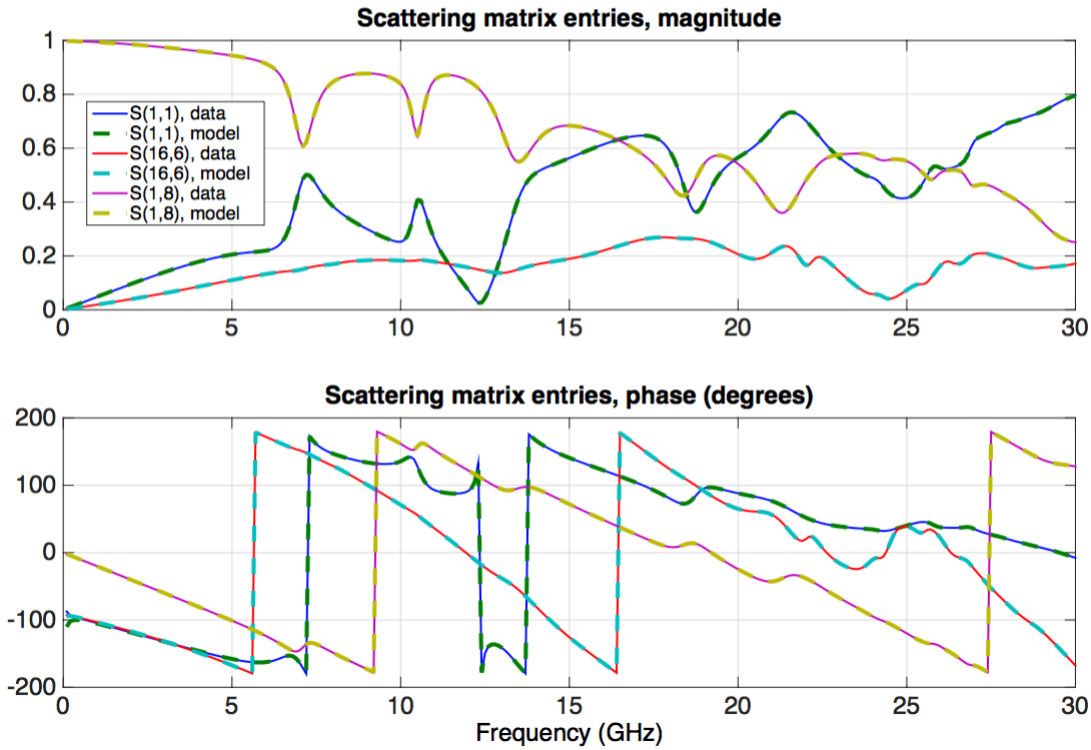


Figure 5: Scattering responses of a package interconnect from a field solver (solid lines) and corresponding response of a rational macromodel obtained by VF (dashed lines).

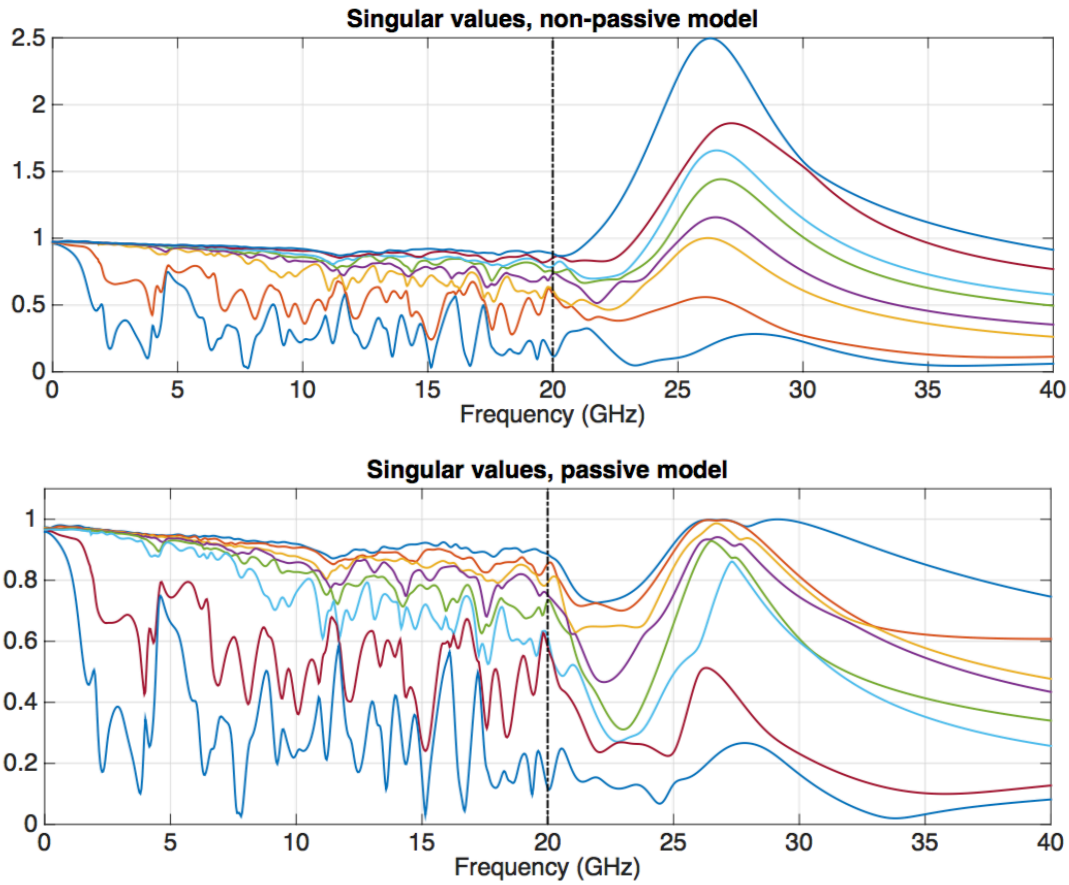


Figure 6: singular value (passivity) plot of a nonb passive model (top) and a passive model (bottom) of a PCB connector (modeling bandwidth: 20 GHz).

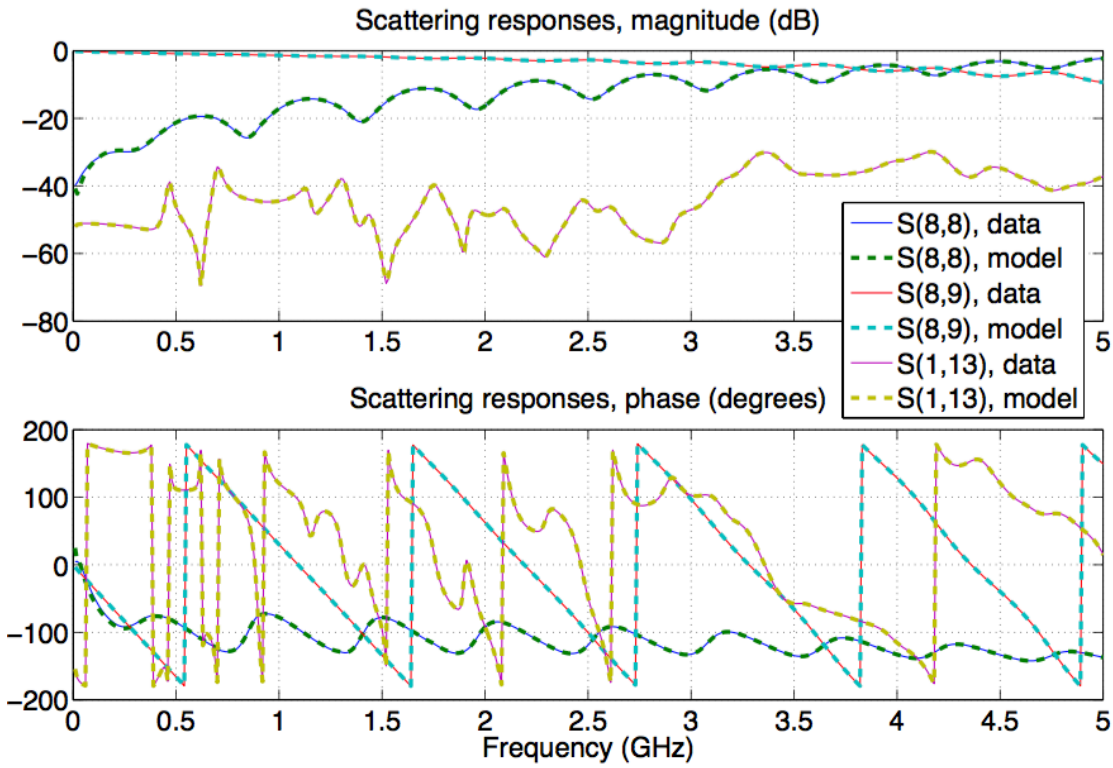


Figure 7: full PCB modeling; comparing selected scattering responses of a passive macromodel to the corresponding responses from a frequency-domain field solver (courtesy of Prof. Madhavan Swaminathan, Georgia Institute of Technology, USA and E-System Design, Inc.).

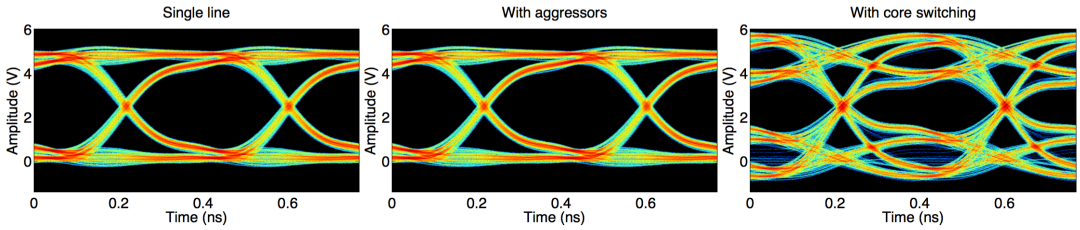


Figure 8: computed eye diagrams of a PCB interconnect link (left: isolated link; middle: with nearby aggressor lines switching; right: with core switching enabled).

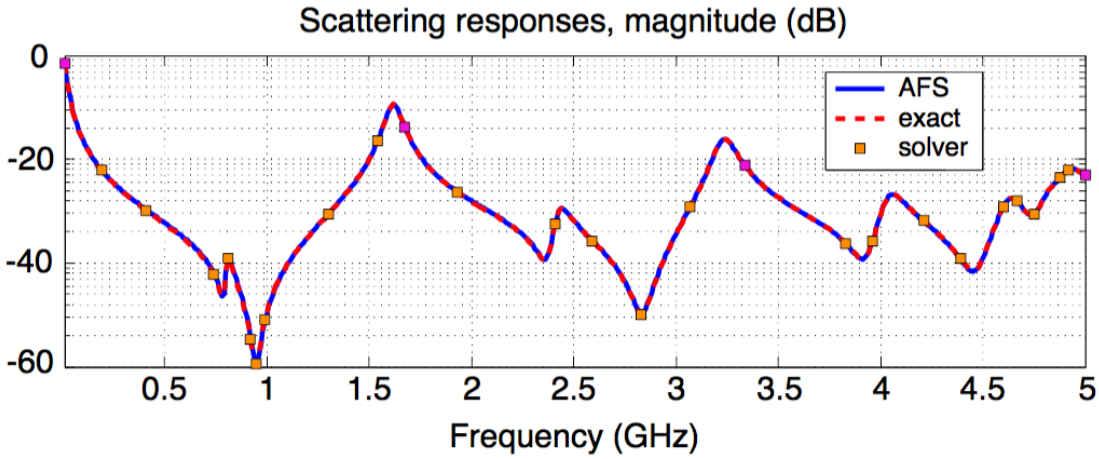


Figure 9: embedding a macromodel-based rational interpolation into an Adaptive Frequency Sampling loop to speed up a frequency sweep of a field solver.

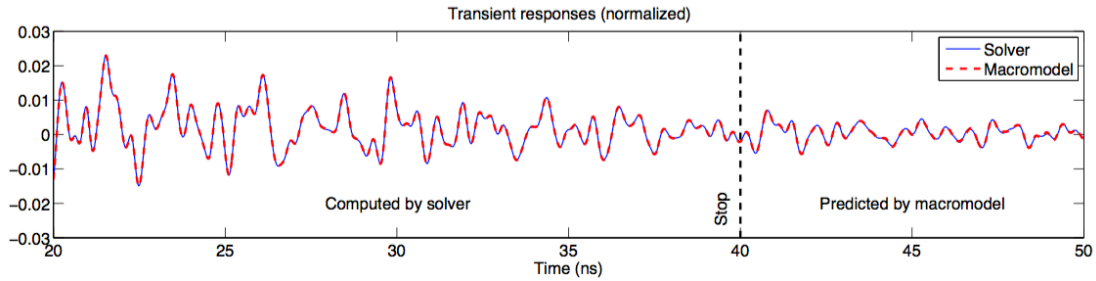


Figure 10: Stopping a transient solver through a macromodel-based prediction.

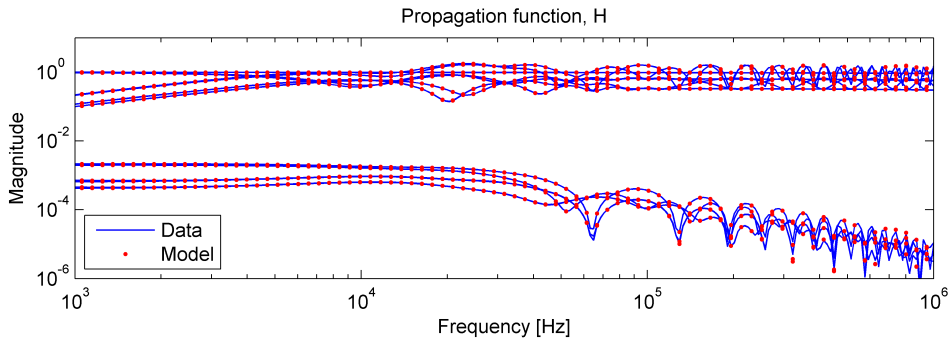


Figure 11: Delayed-rational model of transmission line propagation operator.

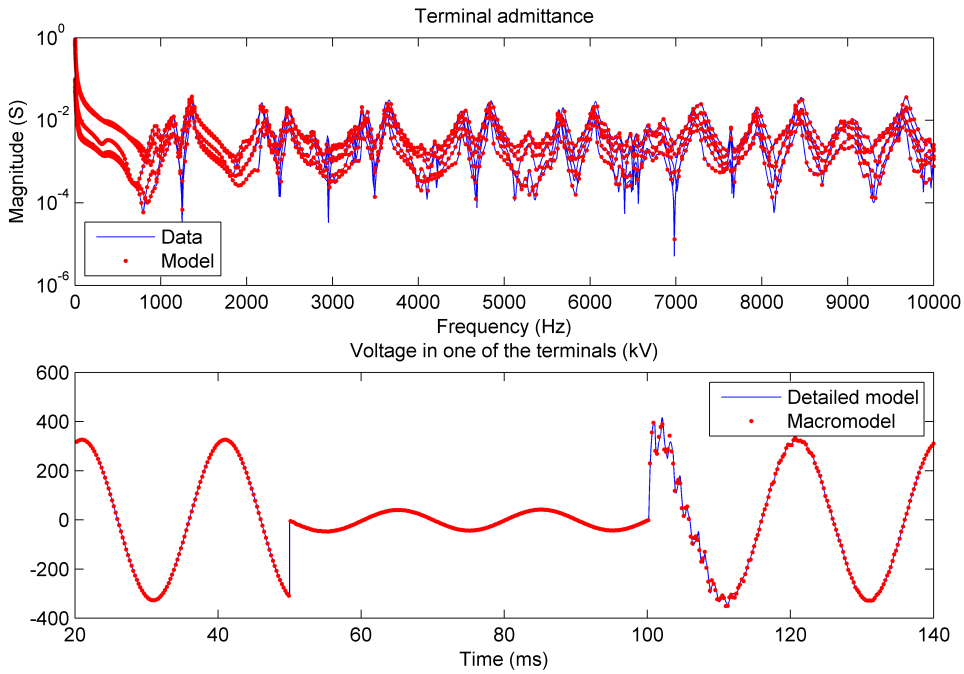


Figure 12: Network equivalencing of high-voltage grid with respect to a three-phase bus. Top: Fitted terminal admittance matrix. Bottom: time domain simulation of system response to shortb circuit application.

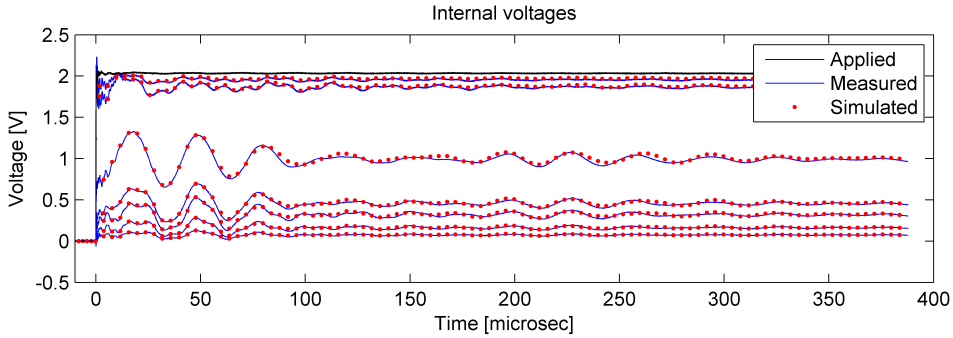


Figure 13: Wideb band modeling of power transformer. Voltages on internal points along winding. "Applied" denotes the excitation voltage used in the test.

Inset [Section IV]

Passivity conditions (scattering)

1. $H(s)$ regular for $\Re(s) > 0$
2. $H^*(s) = H(s^*)$
3. $\sigma_i\{H(s)\} \leq 1$ for $\Re(s) > 0$

*: complex conjugate operator
$\sigma_i$: singular values of matrix $H(s)$