

Macromodelling and its Applications to Signal and Power Integrity

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## Macromodelling and its Applications to Signal and Power Integrity

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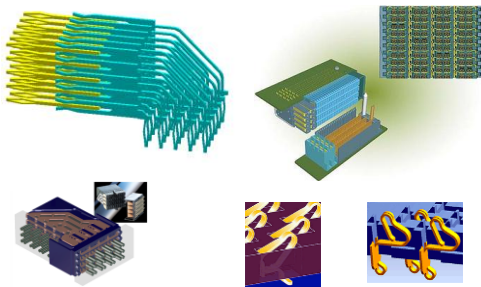
## Outline

- Simulation of terminated interconnects
  - Frequency and time-domain analysis
- Transient analysis
  - Convolution-based approaches
  - Direct circuit simulation (when possible)
  - Black-box passive macromodeling
- Black-box passive macromodeling
  - Rational curve fitting
  - Passivity enforcement
- An application example
  - Coupled signal-power integrity analysis of a real board
- Conclusions

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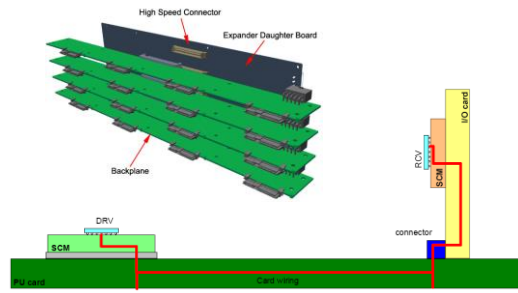
## Interconnects: showcase



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## Interconnects: showcase

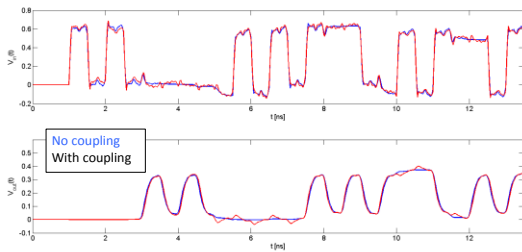
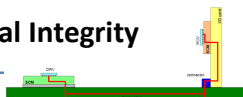


Courtesy D. Kaller, IBM Boeblingen, Germany

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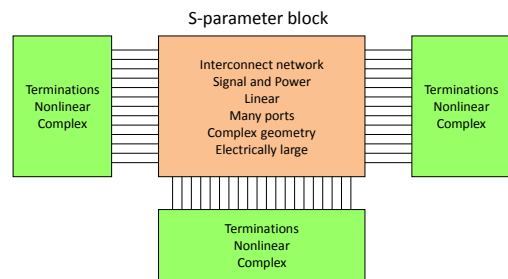
## Signal Integrity



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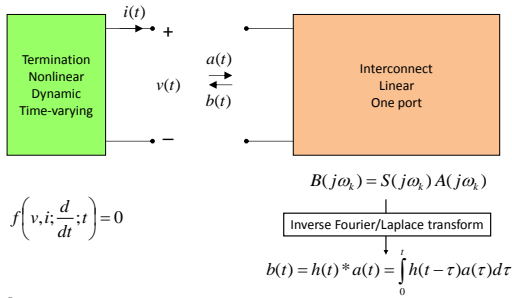
## The objective



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## Nonlinear terminations



$$f\left(v, i; \frac{d}{dt}; t\right) = 0$$

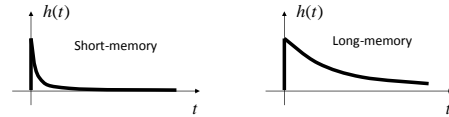
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## Discretizing convolution

$$b(t) = h(t) * a(t) = \int_0^t h(t-\tau)a(\tau)d\tau \quad b(t_k) \approx \sum_{m=0}^{k-1} a(t_m)\Delta h_\Delta(t_k - t_m)$$

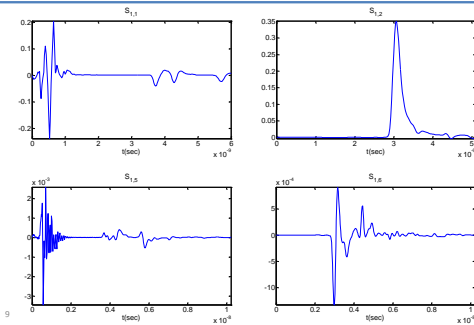
Memory: Number of non-vanishing time-samples in the impulse response



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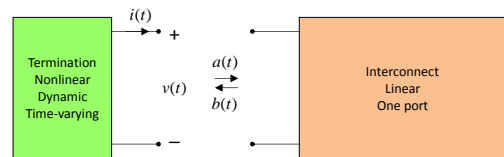
## An example: CPU-I/O channel



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## Direct convolution



$$f\left(v, i; \frac{d}{dt}; t\right) = 0$$

$$\left. \frac{dv}{dt} \right|_{t=t_k} \approx \frac{v(t_k) - v(t_{k-1})}{\Delta}$$

$$b(t_k) \approx \sum_{m=0}^{k-1} a(t_m)\Delta h_\Delta(t_k - t_m)$$

(e.g., backward Euler)

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## Direct convolution

$$F_k(v(t_k), i(t_k), v(t_{k-1}), i(t_{k-1})) = 0$$

Need nonlinear solver

$$b(t_k) \approx \sum_{m=0}^{k-1} a(t_m)\Delta h_\Delta(t_k - t_m)$$

Use many past samples

$$a(t_k) = \frac{1}{2} (Z_R^{-1/2} v(t_k) + Z_R^{1/2} i(t_k))$$

$$b(t_k) = \frac{1}{2} (Z_R^{-1/2} v(t_k) - Z_R^{1/2} i(t_k))$$

May be very slow due to long memory in convolution

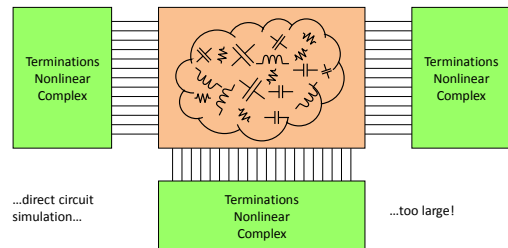
Very robust (when a good impulse response is available...)

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## Direct circuit simulation

If a circuit description of the interconnect is available...



...direct circuit simulation...

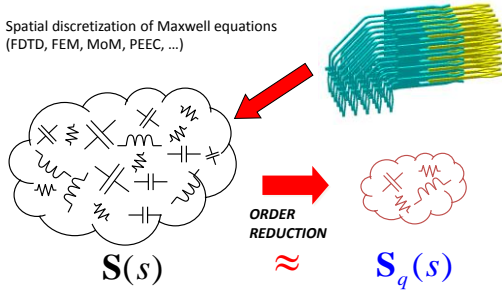
...too large!

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## Model Order Reduction

Spatial discretization of Maxwell equations (FDTD, FEM, MoM, PEEC, ...)

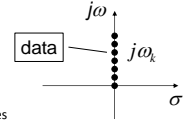


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## Black-Box Macromodeling

$$\mathbf{h}(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \mathbf{S}(j\omega) e^{j\omega t} d\omega$$



Parametric closed-form model fitting frequency samples

$$\mathbf{S}(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Macromodeling via rational function fitting  $s = j\omega_k$

Analytic inversion of Laplace transform

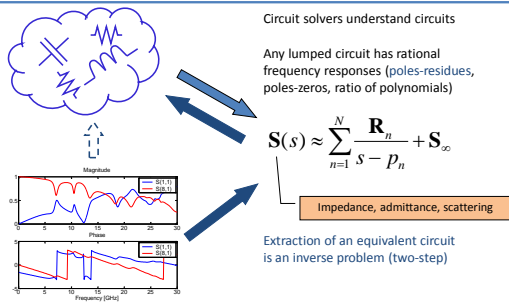
$$\mathbf{h}(t) \approx \sum_{n=1}^N \mathbf{R}_n \exp(p_n t) u(t) + \mathbf{S}_\infty \delta(t)$$

May be used directly in SPICE via equivalent circuit extraction

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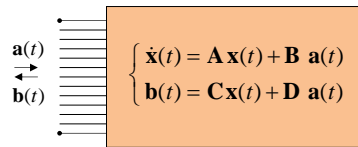
## Rational function fitting: why?



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## State-space realizations

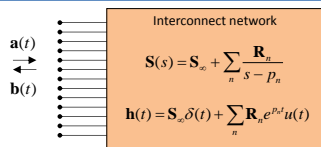


$$\mathbf{S}(s) \approx \sum_{n=1}^N \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty = \mathbf{D} + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

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## Recursive convolution



$$\mathbf{b}(t) = \mathbf{S}_\infty \mathbf{a}(t) + \sum_n \mathbf{R}_n \int_0^t e^{p_n(t-\tau)} \mathbf{a}(\tau) d\tau = \mathbf{S}_\infty \mathbf{a}(t) + \sum_n \mathbf{R}_n \tilde{\mathbf{b}}_n(t)$$

Requires only one sample in the past!

$$\tilde{\mathbf{b}}(t_k) \approx e^{p\Delta} \tilde{\mathbf{b}}(t_{k-1}) + \frac{1 - e^{p\Delta}}{p} \mathbf{a}(t_k) \leftarrow t_k = t_{k-1} + \Delta$$

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## Macromodel implementations

1. Synthesize an equivalent circuit in **SPICE format**  
No access to SPICE kernel  
Must use **standard circuit elements**
2. Direct **SPICE** implementation via recursive convolution  
**Laplace element**, most efficient
3. Other languages for mixed-signal analyses  
**Verilog-AMS, VHDL-AMS, ...**

**Equation-based**

Example: board with 13 ports →

	CPU time
Standard convolution	389 seconds
Equivalent circuit	180 seconds
Recursive convolution	5.8 seconds

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## Rational curve fitting

Model:  $S(s)$

3 alternative rational forms

$$\left\{ \begin{aligned} S(s) &= \frac{\alpha_0 + \alpha_1 s + \alpha_2 s^2 + \dots + \alpha_N s^N}{\beta_0 + \beta_1 s + \beta_2 s^2 + \dots + \beta_N s^N} \\ S(s) &= \sum_{n=1}^N \frac{R_n}{s - p_n} + S_\infty \\ S(s) &= S_\infty \frac{(s - z_1)(s - z_2) \dots (s - z_N)}{(s - p_1)(s - p_2) \dots (s - p_N)} \end{aligned} \right.$$

Fitting:  $S(j\omega_k) \approx \hat{S}(j\omega_k) = \hat{S}_k \quad k = 1, \dots, K$  Input data

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## Vector Fitting

$$\hat{S}(s) \approx S(s) = \frac{r_0 + \sum_{n=1}^N \frac{r_n}{s - q_n}}{c_0 + \sum_{n=1}^N \frac{c_n}{s - q_n}}$$

Input data

“starting poles” (arbitrary, as long as distinct)

Linearized (weighted) system: multiply by the denominator

$$\left[ c_0 + \sum_{n=1}^N \frac{c_n}{s - q_n} \right] \hat{S}(s) \approx r_0 + \sum_{n=1}^N \frac{r_n}{s - q_n} \quad s = j\omega_k, k = 1, \dots, K$$

The VF “weight function”  $w(s) = c_0 + \sum_{n=1}^N \frac{c_n}{s - q_n}$  Linear Least Squares system!

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## Vector Fitting

$$w(s) = c_0 + \sum_{n=1}^N \frac{c_n}{s - q_n} = \frac{c_0(s - q'_1)(s - q'_2) \dots (s - q'_N)}{(s - q_1)(s - q_2) \dots (s - q_N)}$$

“Pole relocation” process

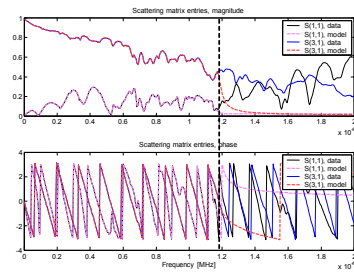
$$\{q_n\} \rightarrow \{q'_n\} \rightarrow \dots \rightarrow \{p_n\} \quad \text{“true poles”}$$

At convergence:  $w(s) \rightarrow \text{constant}$

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## High-speed connector, measured



Modeled up to 12 GHz

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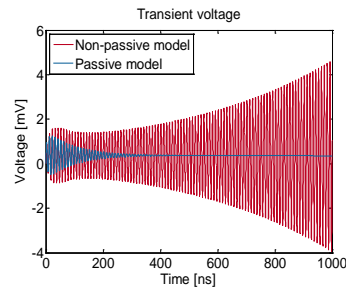
## Advanced VF formulations

- Time-domain Vector Fitting
  - Processes time samples instead of frequency samples
- Orthonormal Vector Fitting
  - Further improvement in matrix conditioning using orthonormal rational functions
- Z-domain (orthonormal) Vector Fitting
  - Works on discrete-time/frequency systems
- Fast Vector Fitting
  - Uses smart QR decomposition (compressions) for systems with many ports
- Eigenvalue-based Vector Fitting
  - Possibly with relative error minimization, for improved robustness
- Multivariate/Parameterized Vector Fitting
  - Allows closed-form inclusion of geometry-material parameters in the macromodel equations
- Delayed Vector Fitting
  - Uses modified basis functions for representing propagation delays in closed form
- Parallel Vector Fitting
  - For multicore hardware architectures: close to ideal speedups, almost real-time modeling

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## Passivity: why?



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## Passivity conditions (scattering)

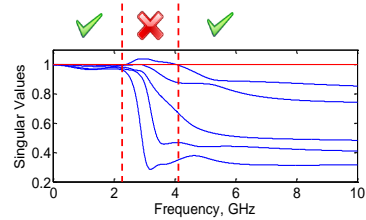
- $S(-j\omega) = S^*(j\omega)$   
 Guarantees real-valued impulse response.  
 Always assumed by construction
- $\|S(j\omega)\| \leq 1$  or  $\max_i \sigma_i\{S(j\omega)\} \leq 1$   
 Energy condition: structure must not amplify signals.  
 Sometimes called simply "passivity" condition
- $S(j\omega)$  is causal  
 No anticipatory behavior in time-domain.  
 Note: causality is a prerequisite for passivity!  
 Guaranteed if macromodel is stable.

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## Passivity constraints (scattering)

$$S(s) \text{ is passive} \Leftrightarrow \{ \text{singular values of } S(j\omega) \} \leq 1, \forall \omega$$



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## Passivity violations: why?

- Data from measurement
  - Improper calibration and de-embedding, human mistakes
  - Measurement noise
- Data from simulation
  - Poor meshing
  - Inaccurate solver
  - Bad models or assumptions on material properties
  - Poor data post-processing algorithms
  - Putting together results from two solvers
- Macromodel
  - Approximation errors in Vector Fitting
  - May be critical out-of-band, where no data sample is available

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## Passivity enforcement

- Generate a **new passive macromodel**
- Apply **small correction** to preserve accuracy
  - original dataset should be passive
  - original macromodel should be accurate
  - (usually) preserve poles

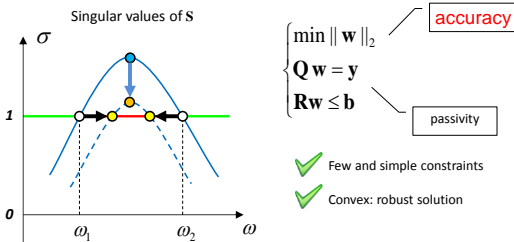
$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases} \rightarrow \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x} + \mathbf{D}\mathbf{a} \end{cases}$$

$$\Delta\mathbf{S} = \Delta\mathbf{C}(\mathbf{s}\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

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## Model Perturbation



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## A case study: coupled Signal/Power Integrity

This case study courtesy of

- Georgia Institute of Technology, Atlanta GA, USA
- E-System Design, Inc.
  - Provided field solver **Sphinx**
- Politecnico di Torino
- IdemWorks s.r.l.
  - Provided passive macromodeling tool **IdEM**



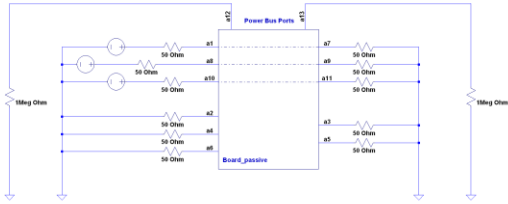
www.e-systemdesign.com  
www.idemworks.com

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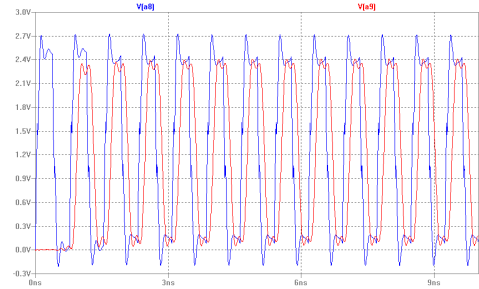
### SPICE: excitation on signal lines



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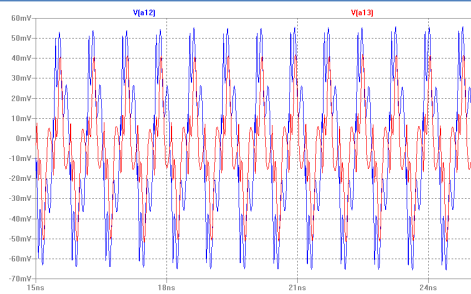
### Response on a signal line, 1.3GHz



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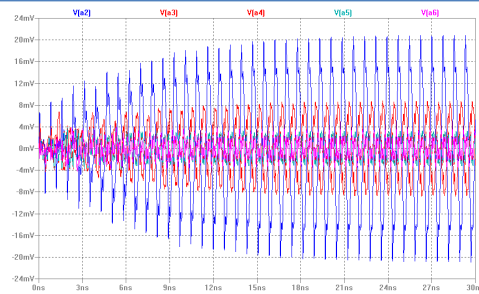
### Coupling to power ports, 1.3GHz



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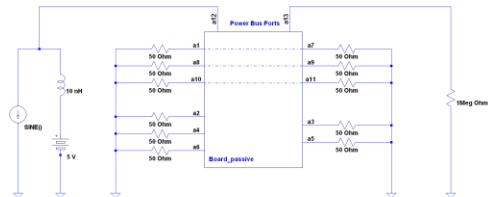
### Xtalk and substrate coupling, 1.3GHz



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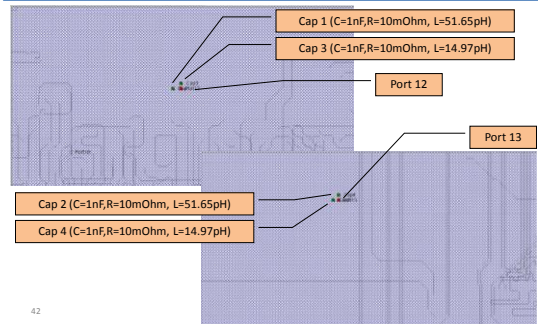
### SPICE: excitation on PDN (core switching)



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### Decoupling capacitors

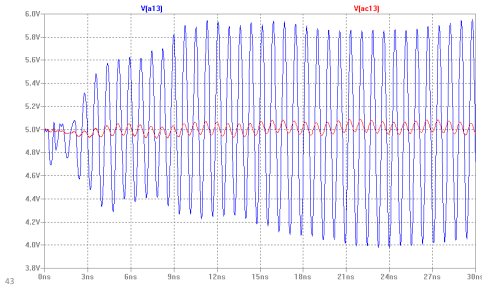


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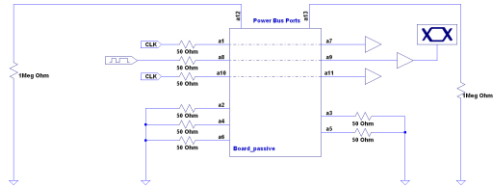


## PDN response

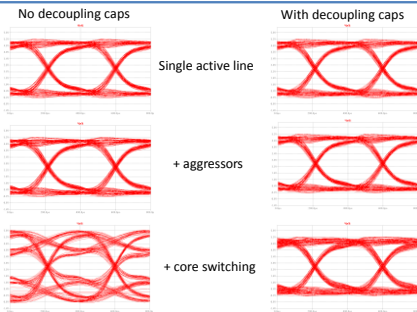
Port 13: With and Without Caps



## Eye diagram simulation: setup



## Eye diagram results, 2.6 Gb/s



## „Signal Integrity Summary“

- **Application:**
  - Fast numerical assessment of Signal and Power Integrity problems during early design stages
- **Problems:**
  - Mixing time-domain circuit-level models (NL) with frequency-domain description of interconnect networks, complexity, efficiency
- **Solution:**
  - Rational black-box macromodeling + smart implementation
  - Key enabling factors for fast system-level simulation, design optimization, what-if analyses