Macromodeling of Connectors and Packages with a Large Number of Ports

MACROMODELING OF CONNECTORS AND PACKAGES WITH A LARGE NUMBER OF PORTS

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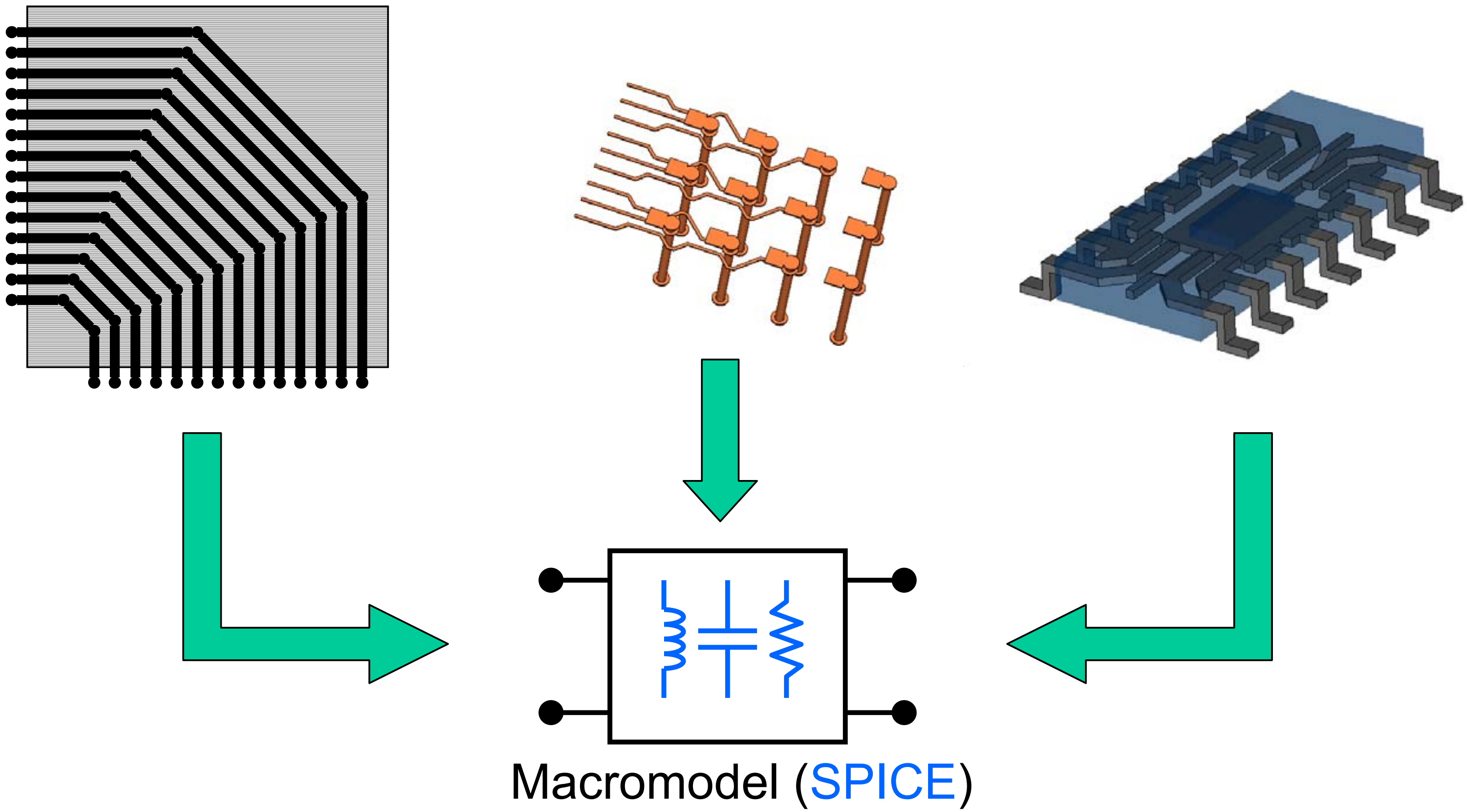
Motivations

Macromodeling of 3D interconnects for Signal Integrity assessment



Outline

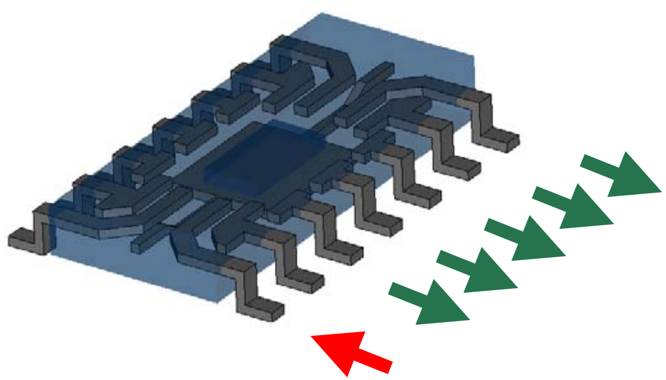
- Strategy
  1. Full-Wave transient simulation (FDTD, FIT,…)
  2. **Construction of a Macromodel**
  3. Synthesis of a SPICE equivalent
- **New macromodeling algorithm**
  - **Time-Domain Vector Fitting**
  - **Handling of many ports**
- Examples of package and connector modeling
  - Connectors with up to 84 ports

Strategy (1)

1. Structure characterization via 3D modeling

Conventional

Full-wave EM simulation
(standard time-domain field solver)



Input pulse

$\mathbf{x}(t)$ t – domain

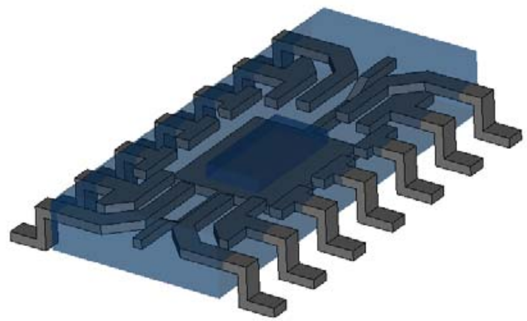
Output responses

$\mathbf{y}(t)$ t – domain

Transient scattering port characterization

Strategy (2)

2. Synthesis of rational (lumped) macromodel



New

Input pulse

$\mathbf{x}(t)$ t – domain

Output responses

$\mathbf{y}(t)$ t – domain

$$\mathbf{Y}(s) = \mathbf{H}(s)\mathbf{X}(s)$$

$$\mathbf{H}(s) = \mathbf{H}_\infty + \sum_n \frac{\mathbf{R}_n}{s - p_n}$$

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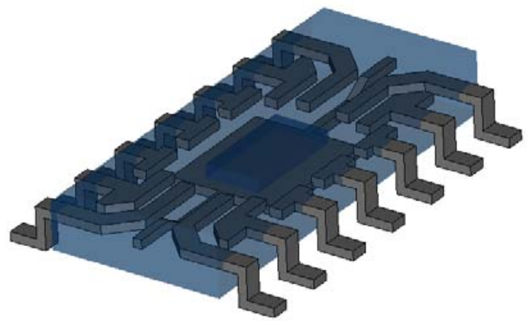
Strategy (3)

3. Synthesis of a SPICE subcircuit for system-level analysis

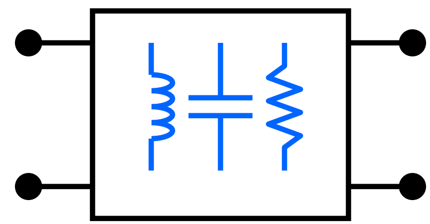


Conventional

$$\mathbf{Y}(s) = \mathbf{H}(s)\mathbf{X}(s)$$

$$\mathbf{H}(s) = \mathbf{H}_\infty + \sum_n \frac{\mathbf{R}_n}{s - p_n}$$

Circuit Synthesis



Macromodel (SPICE)

Time-Domain Vector Fitting (1)

Input pulse

$\mathbf{x}(t)$ t – domain

Output responses

$\mathbf{y}(t)$ t – domain

Transfer function

$$\mathbf{Y}(s) = \mathbf{H}(s)\mathbf{X}(s)$$

Rational approximation

$$\mathbf{H}(s) \approx \mathbf{H}_{\infty} + \sum_{n} \frac{\mathbf{R}_n}{s - p_n}$$

Unknowns:

- Poles p_n
- Residues $\mathbf{R}_n$
- Constant $\mathbf{H}_{\infty}$

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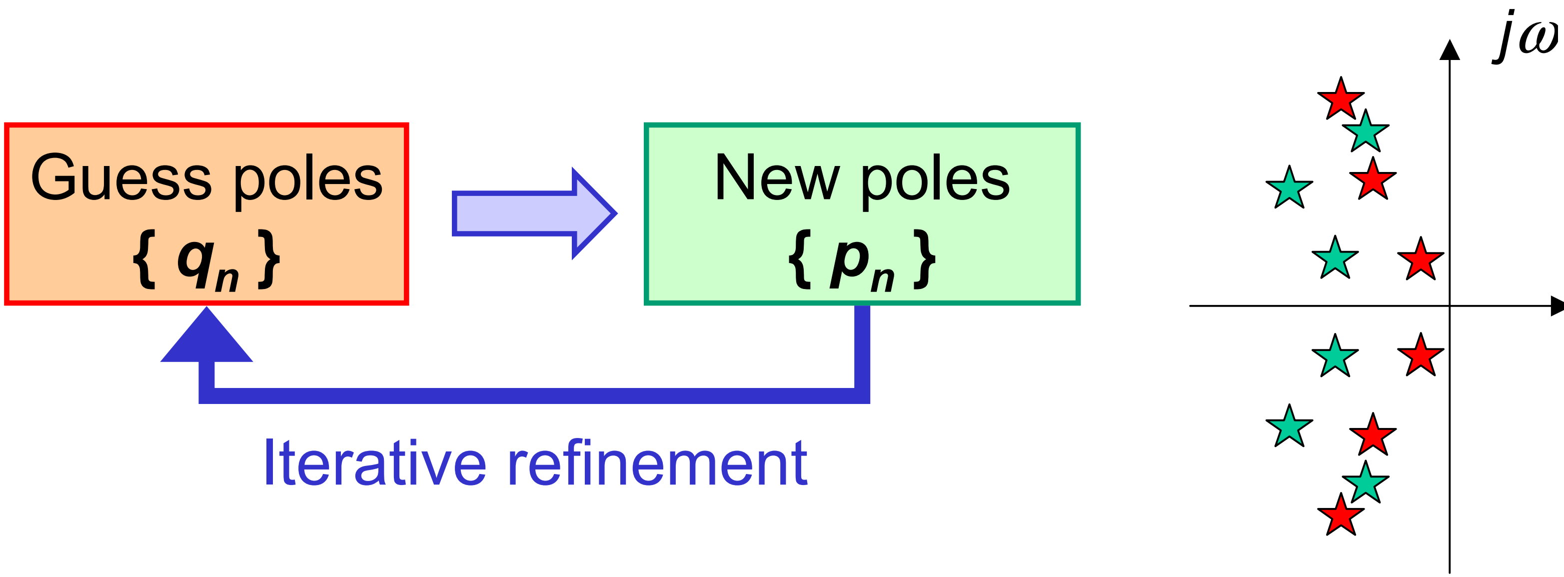
Time-Domain Vector Fitting (2)

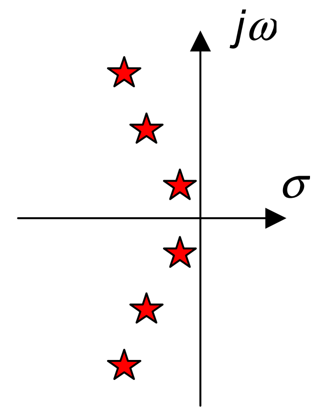
Step 1. Find the dominant poles via "relocation"



How to do it using time-domain data?

How to insure convergence to the right poles?

Time-Domain Vector Fitting (3)



1a. Start with initial poles: $\{ q_n \}$

1b. Define weight function: unknown $\{ k_n \}$

$$\sigma(s) = 1 + \sum_n \frac{k_n}{s - q_n}$$

Starting poles

1c. Assume the following condition

$$\sigma(s)\mathbf{H}(s) = a + \sum_n \frac{b_n}{s - q_n}$$

Poles of $\mathbf{H}(s)$ = Zeros of $\sigma(s)$

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Time-Domain Vector Fitting (4)

$$\sigma(s)\mathbf{H}(s) = a + \sum_n \frac{b_n}{s - q_n}$$

Apply the input pulse $\mathbf{X}(s)$

$$\sigma(s)\mathbf{Y}(s) = \left(a + \sum_n \frac{b_n}{s - q_n} \right) \mathbf{X}(s)$$

Compute inverse Laplace transform

$$\mathbf{y}(t) + \sum_n k_n \, \mathbf{y}_n(t) = a \, \mathbf{x}(t) + \sum_n b_n \, \mathbf{x}_n(t)$$

$$\mathbf{x}_n(t) = \int_0^t e^{q_n (t-\tau)} \mathbf{x}(\tau) d\tau$$

$$\mathbf{y}_n(t) = \int_0^t e^{q_n (t-\tau)} \mathbf{y}(\tau) d\tau$$

Low-pass filtered input and output signals

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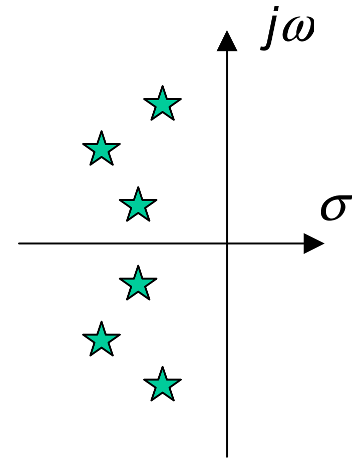
Time-Domain Vector Fitting (5)

1d. Solve a linear least squares system for k_n, a , b_n

$$\mathbf{y}(t)+\sum_n k_n\,\mathbf{y}_n(t)=a\,\mathbf{x}(t)+\sum_n b_n\,\mathbf{x}_n(t)$$

1e. Compute the zeros $\{\,\boldsymbol{p_n}\,\}$ of the auxiliary function

$$\sigma(s)=1+\sum_n \frac{k_n}{s-q_n}=\frac{\prod_n (s-p_n)}{\prod_n (s-q_n)}$$



These are the dominant poles!

S. Grivet-Talocia, "Package Macromodeling via Time-Domain Vector Fitting", *IEEE Microwave Wireless Comp. Lett.*, Nov. 2003

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Time-Domain Vector Fitting (6)

Step 2. Compute the residues

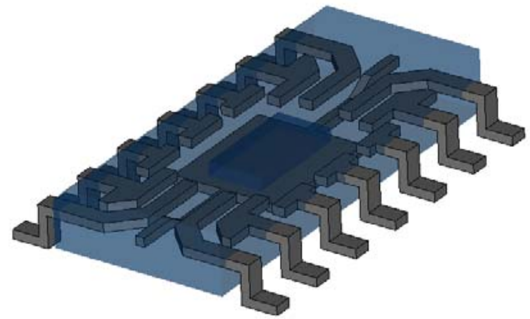
2a. Low-pass filter input signals with new poles

$$\tilde{\mathbf{x}}_n(t) = \int_0^t e^{p_n(t-\tau)}\mathbf{x}(\tau)\,d\tau$$

2b. Solve a linear least squares system for $\mathbf{R}_n$ and $\mathbf{H}_\infty$

$$\mathbf{y}(t) = \mathbf{H}_\infty\,\mathbf{x}(t) + \sum_n \mathbf{R}_n\,\tilde{\mathbf{x}}_n(t)$$

Time-Domain Vector Fitting: Summary



Ingredients for the construction of the macromodel:

- low-pass filtering

  ⇒ via recursive convolutions, fast and simple

- linear least squares

  ⇒ efficient, robust and simple

Handling many ports (1)

Key point: linear least squares system

Time-samples of all raw and filtered port responses

$$\mathbf{y}(t) + \sum_n k_n\, \mathbf{y}_n(t) = a\,\mathbf{x}(t) + \sum_n b_n\, \mathbf{x}_n(t)$$

Number of poles

Processing **all** responses may lead to a **large** system!

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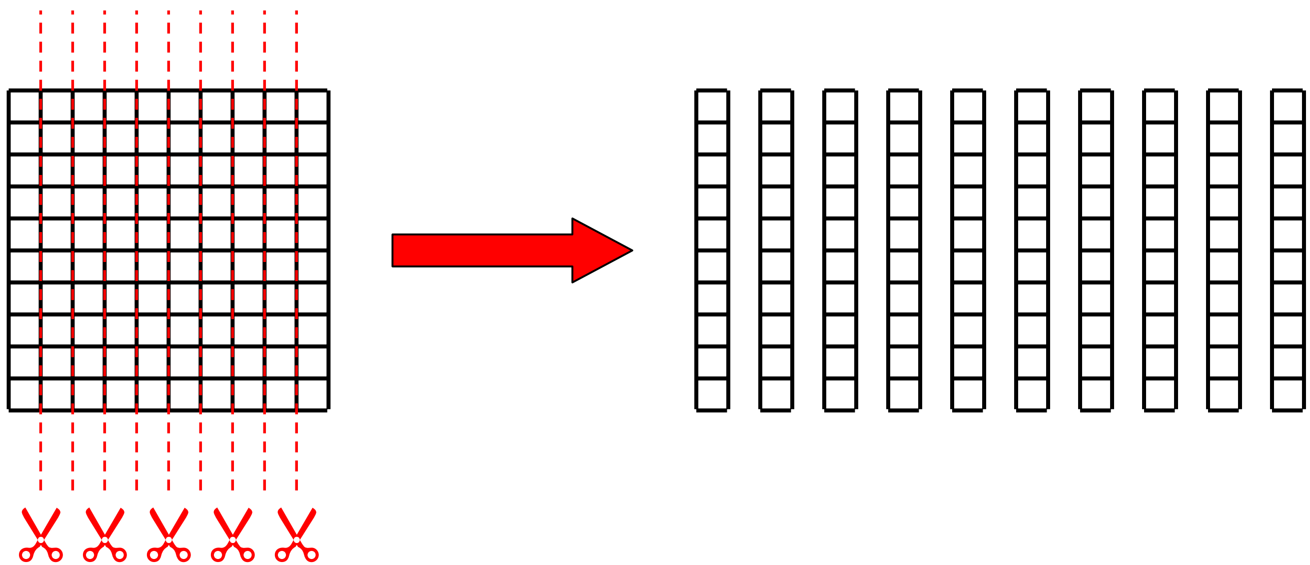
Handling many ports (2)

1. Split port responses into subsets

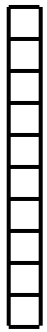
Transfer matrix $\mathbf{H}(s)$

Subsets $\{\mathbf{h}_k(s)\}$



Handling many ports (3)

2. Macromodel each subset via Time-Domain Vector Fitting



$$\mathbf{h}_k(s) \approx \mathbf{h}_{k,\infty} + \sum_n \frac{\mathbf{r}_{k,n}}{s - p_{k,n}}$$

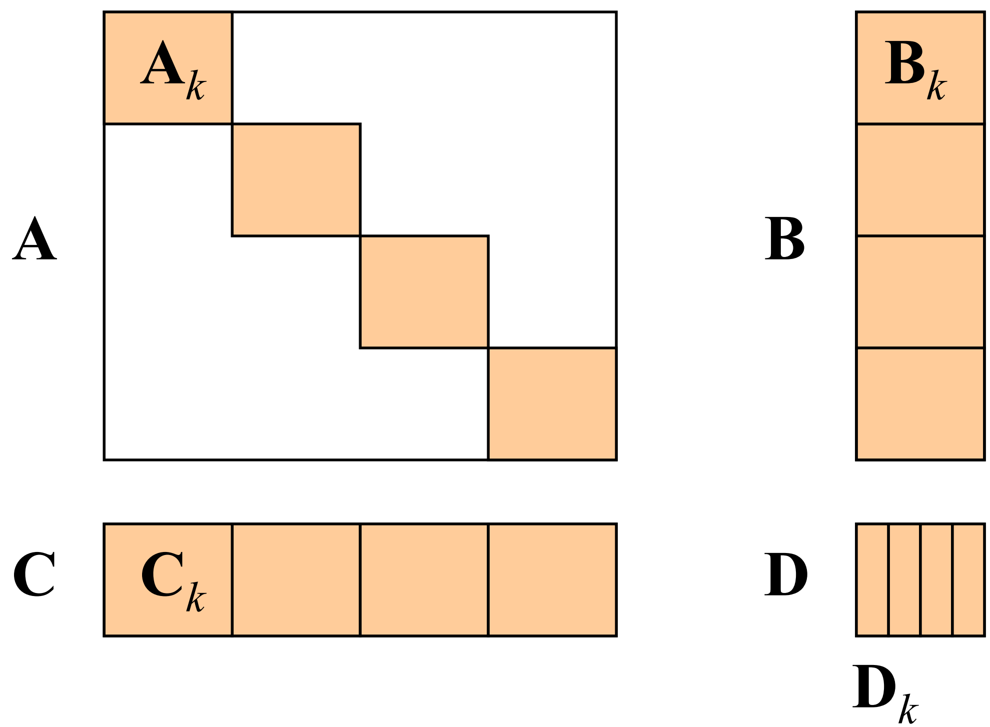
Partial state-space representation

$$\begin{cases} \dot{\mathbf{w}}_k = \mathbf{A}_k \mathbf{w}_k + \mathbf{B}_k \mathbf{x}_k \\ \mathbf{y}_k = \mathbf{C}_k \mathbf{w}_k + \mathbf{D}_k \mathbf{x}_k \end{cases}$$

Handling many ports (4)

4. Assemble all partial models into a global model

$$\begin{cases} \dot{\mathbf{w}} = \mathbf{A}\,\mathbf{w} + \mathbf{B}\,\mathbf{x} \\ \mathbf{y} = \mathbf{C}\,\mathbf{w} + \mathbf{D}\,\mathbf{x} \end{cases}$$



All matrices are sparse!

Passivity enforcement

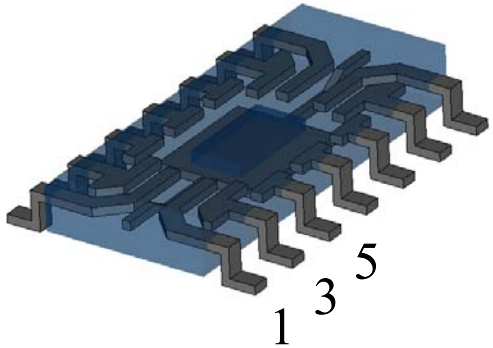
Macromodel passivity is enforced a-posteriori

Spectral perturbation of Hamiltonian matrices associated to the model

$$\begin{cases} \dot{\mathbf{w}} = \mathbf{A}\,\mathbf{w} + \mathbf{B}\;\mathbf{x} \\ \mathbf{y} = \mathbf{C}\,\mathbf{w} + \mathbf{D}\;\mathbf{x} \end{cases} \Rightarrow \begin{cases} \dot{\mathbf{w}} = \mathbf{A}\,\mathbf{w} + \mathbf{B}\;\mathbf{x} \\ \mathbf{y} = (\mathbf{C} + \Delta\mathbf{C})\,\mathbf{w} + \mathbf{D}\;\mathbf{x} \end{cases}$$

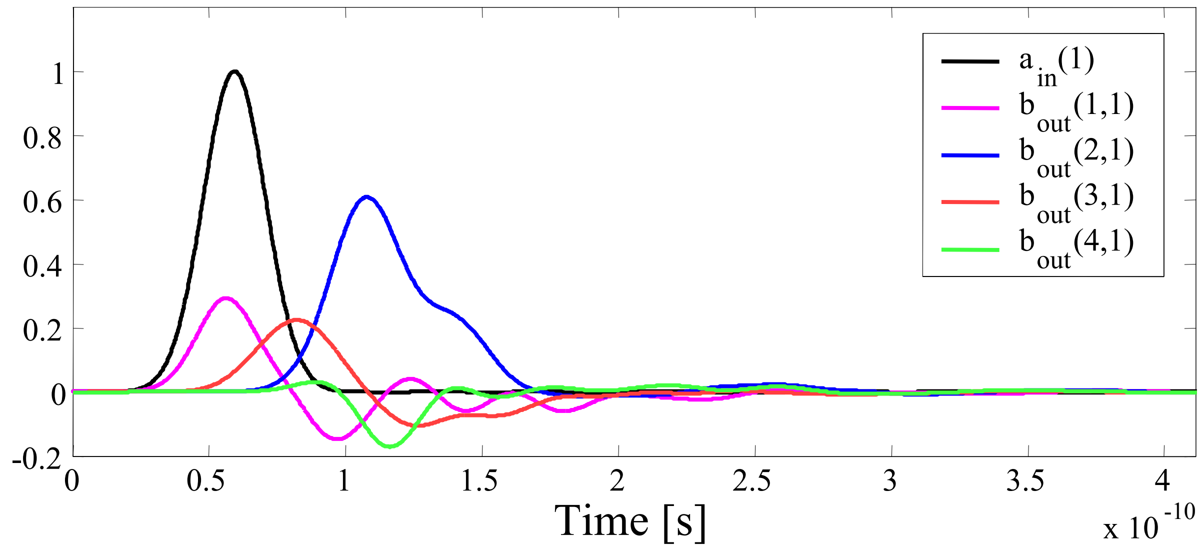
S. Grivet-Talocia, "Generation of Passive Macromodel from transient port responses", *Proc. EPEP'03, Princeton, NJ*, 27-29 Oct. 2003

Example 1

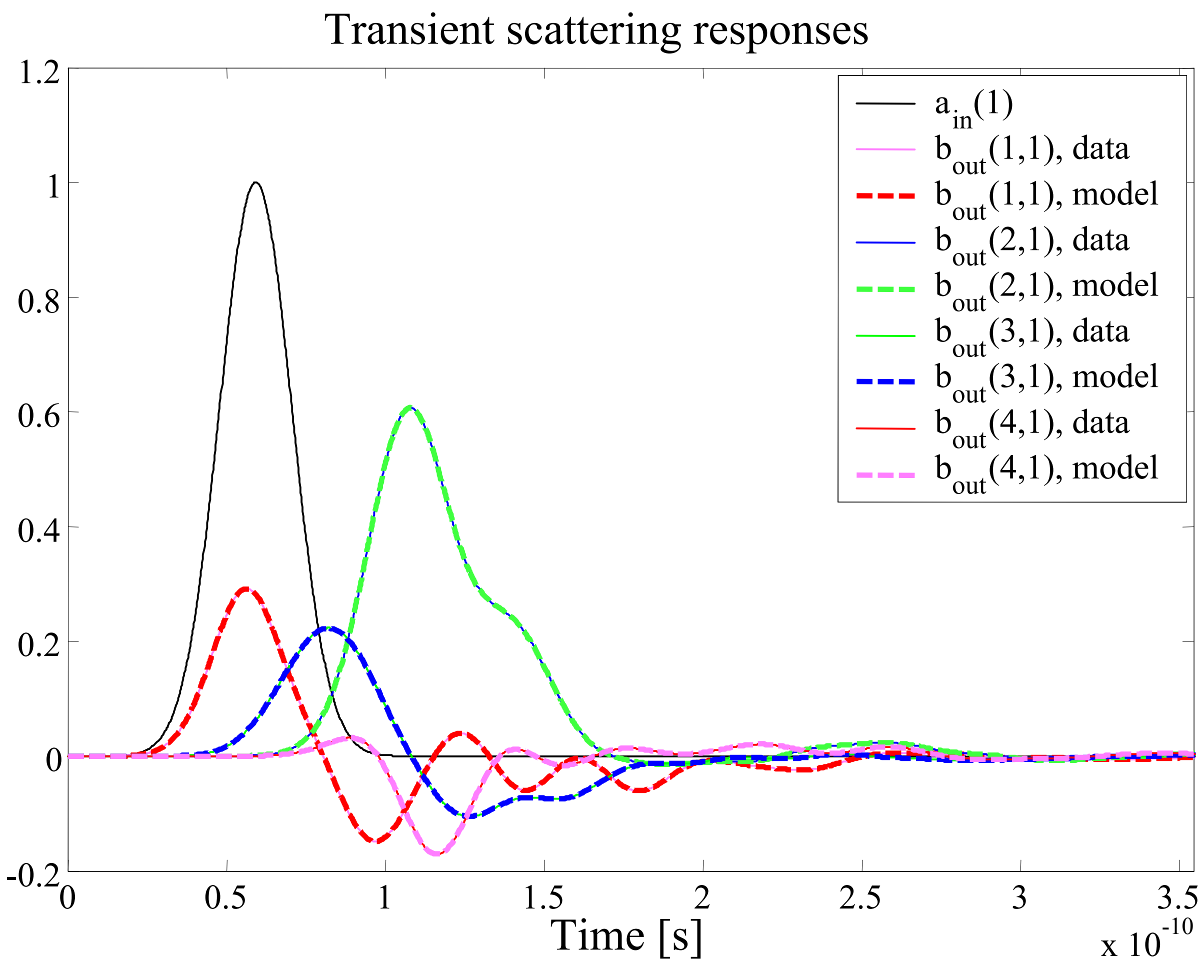


- 14-pin SOIC package
- Simplified CAD for FDTD
- Bandwidth: 40 GHz
- 50 Ω port terminations

FDTD transient scattering responses



Example 1: macromodel accuracy



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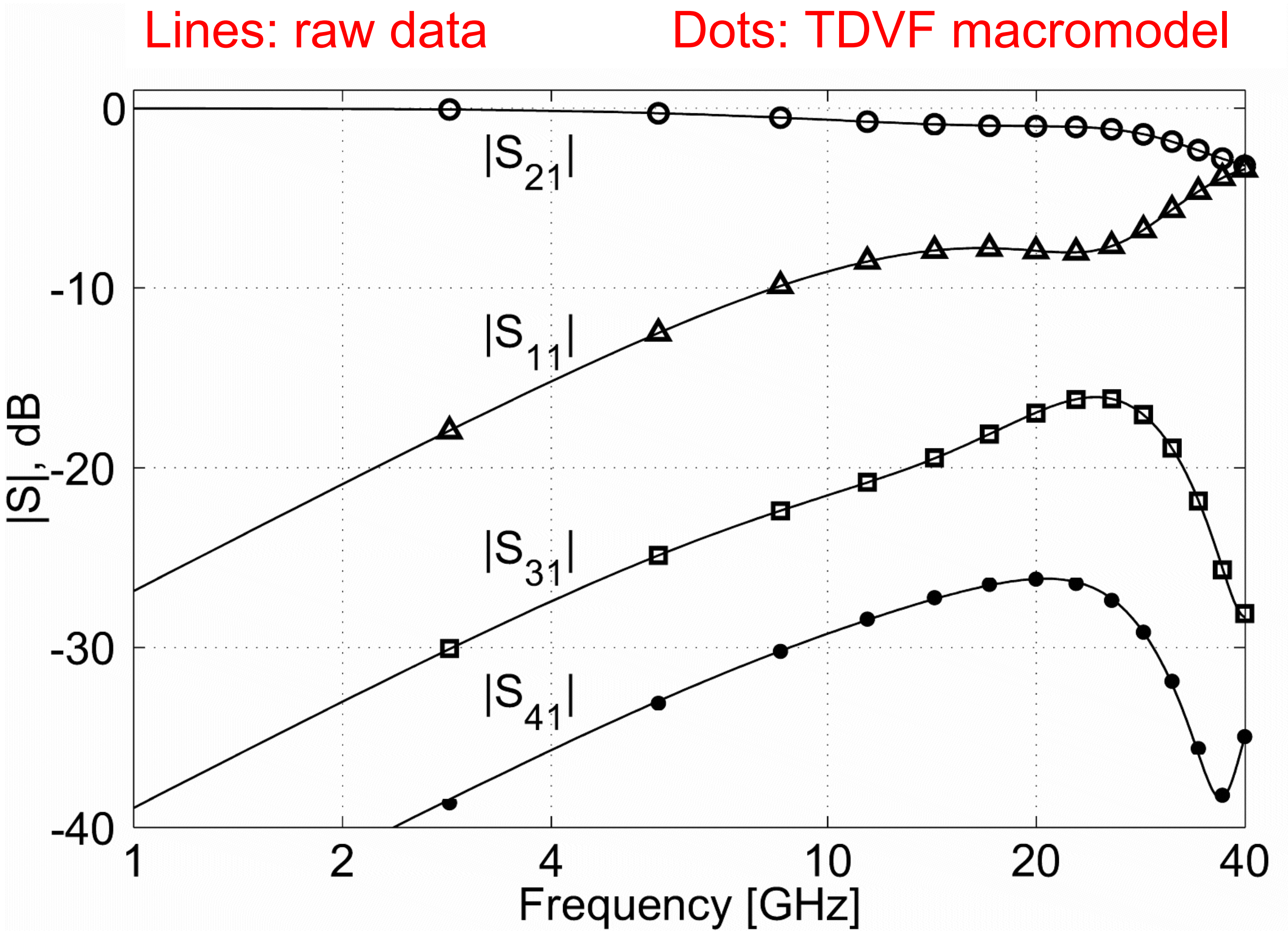
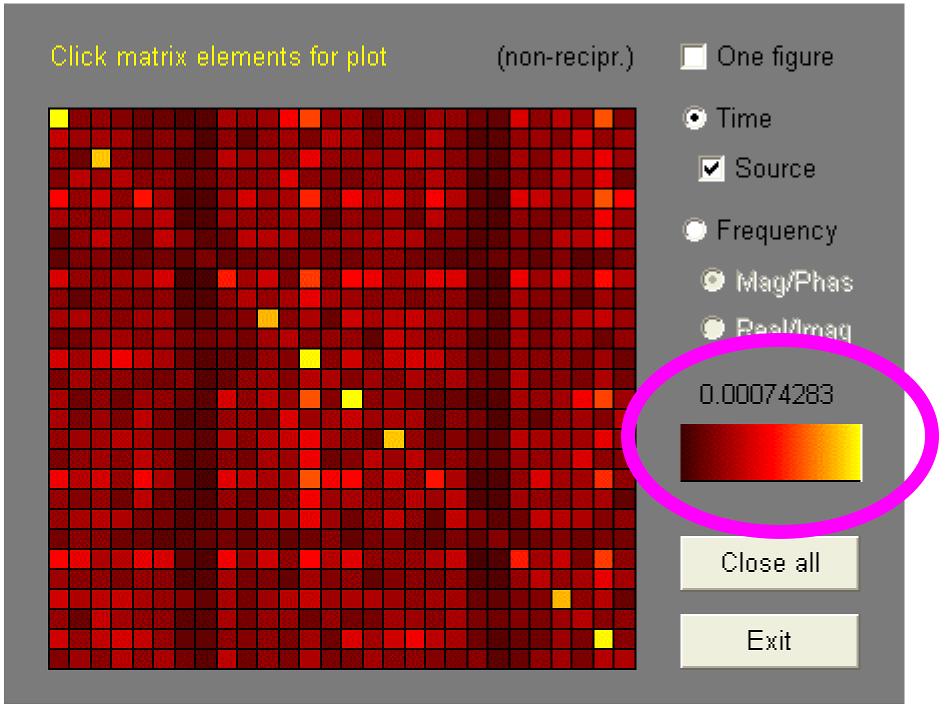
Example 1: macromodel accuracy



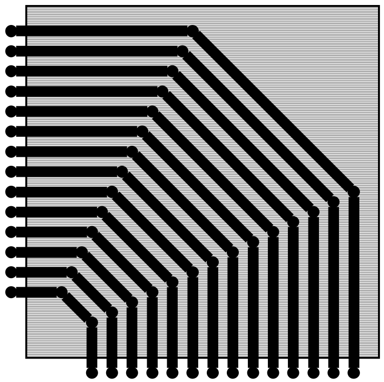
Example 1: macromodel accuracy

Maximum deviation between model and data for all 28x28 responses



Largest:
0.00074

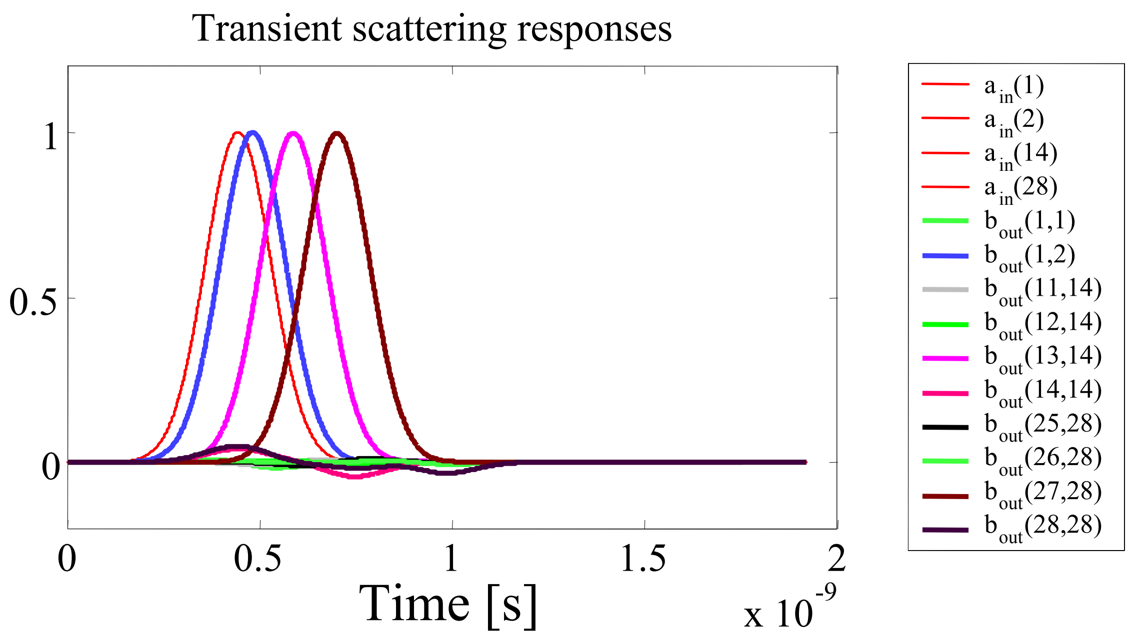
Example 2: 42-pin connector



3x14 pins, 84 ports

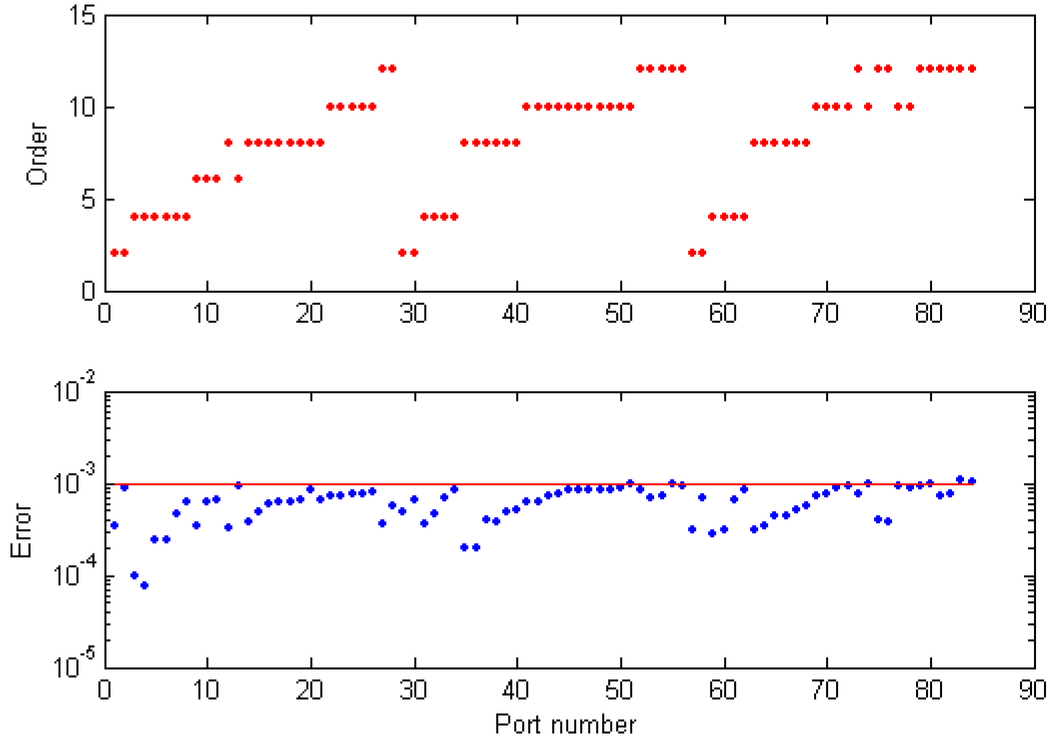
Characterized via FIT

(CST Microwave Studio 4)

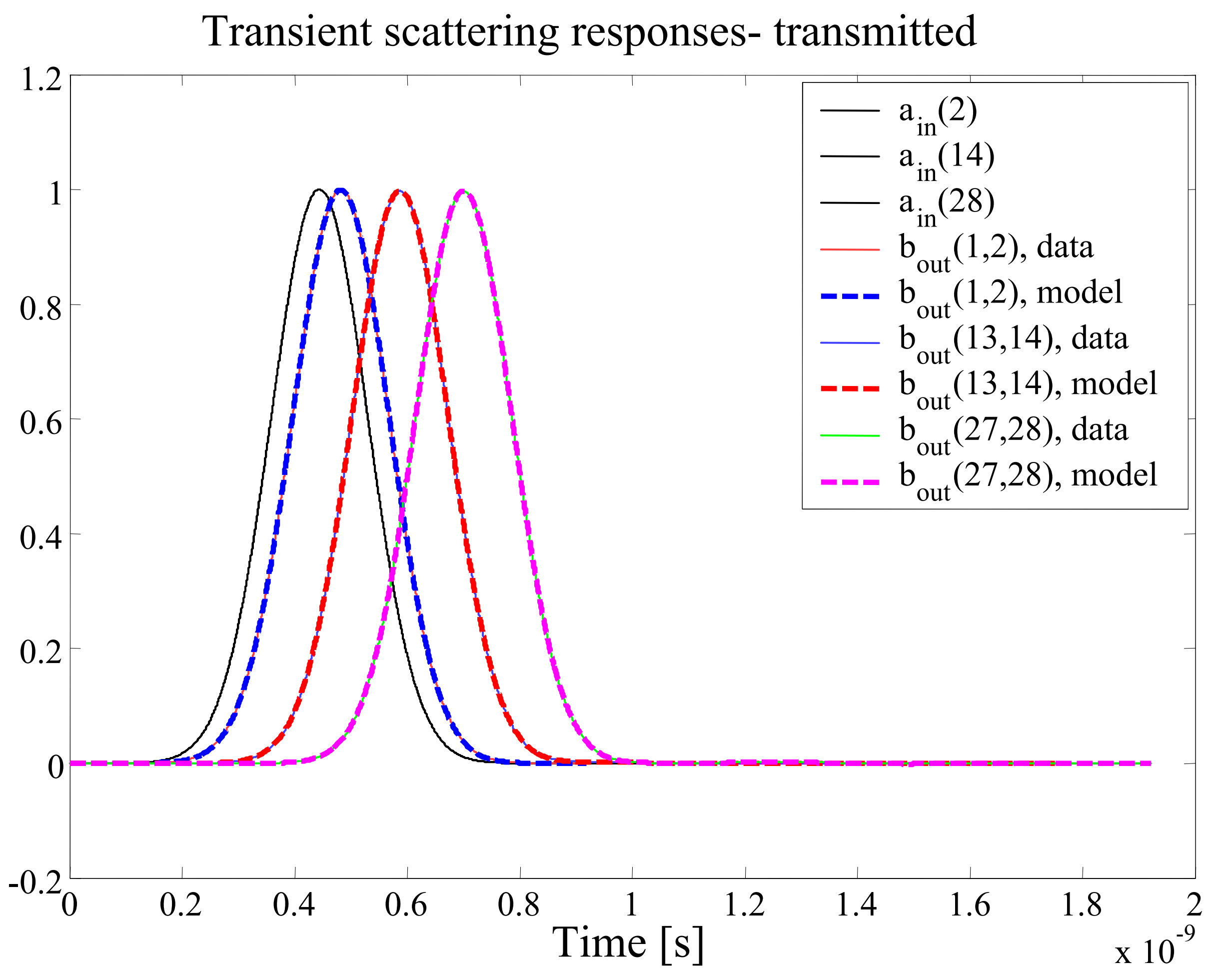


Example 2: model order selection

Automatic (iterative) order selection on each of the 84 subsets of port responses (reduced model complexity)



Example 2: macromodel accuracy



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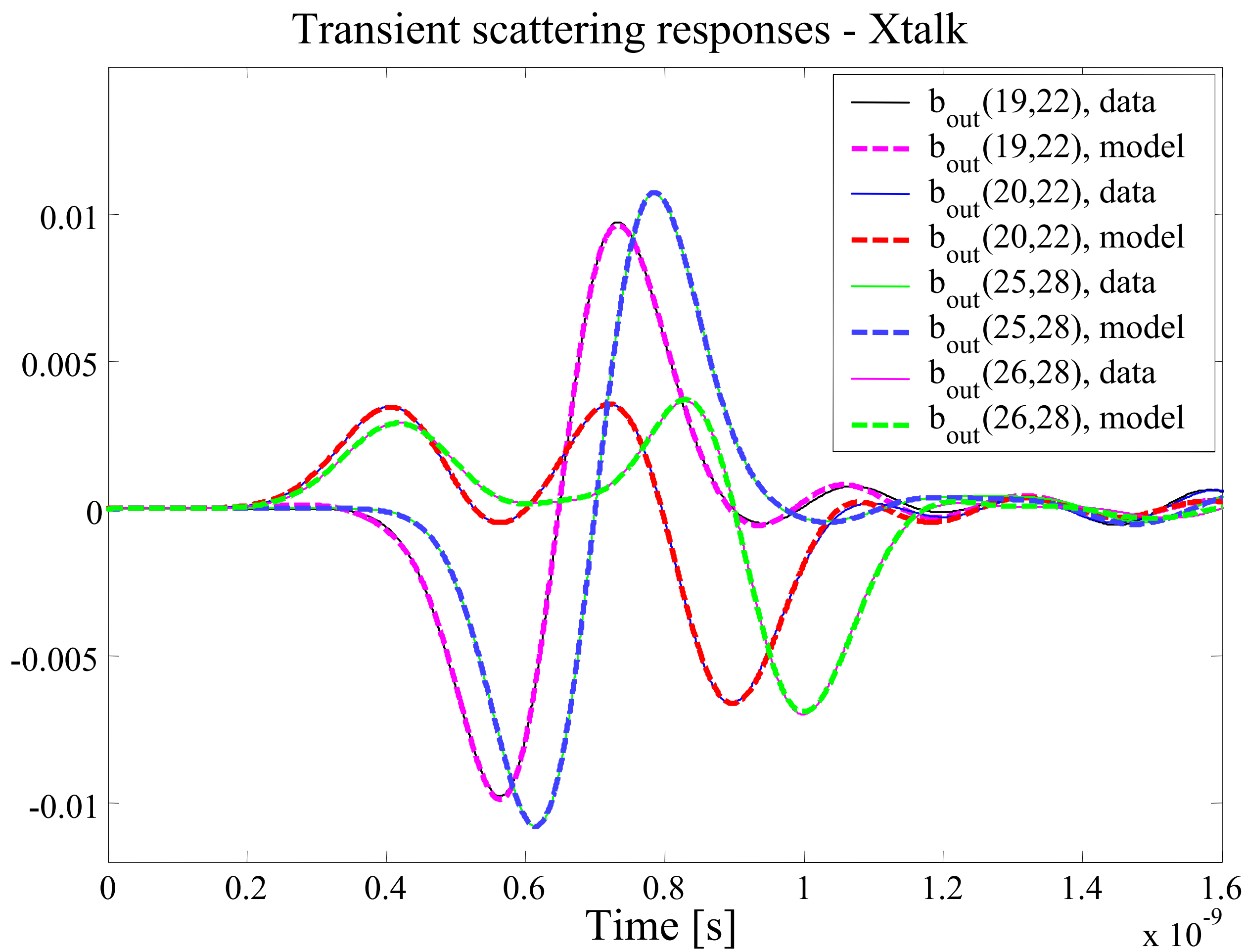
Example 2: macromodel accuracy



Conclusions

New **Time-Domain Vector Fitting** algorithm

Macromodeling of linear interconnect structures

- Known via transient port responses (EM simulation)
- Characterized by a possibly large number of ports
- Simple, fast, robust, accurate
- Passivity easily enforced a-posteriori using a Hamiltonian-matrix perturbation approach

Macromodels ready-to-use for SPICE simulations