



MACROMODELING OF CONNECTORS AND PACKAGES WITH A LARGE NUMBER OF PORTS

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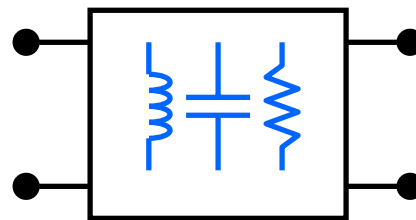
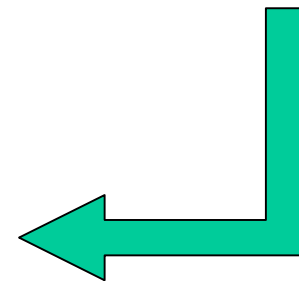
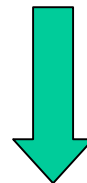
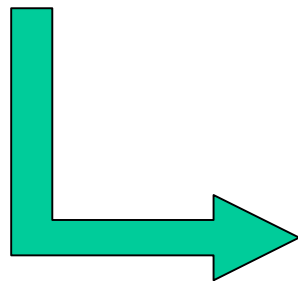
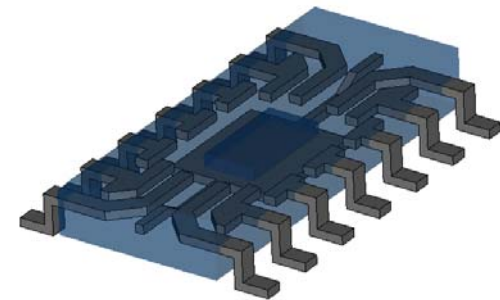
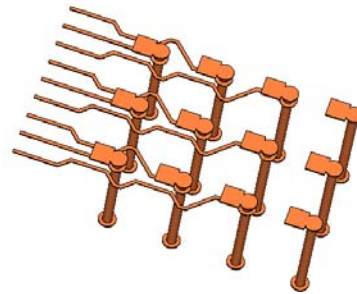
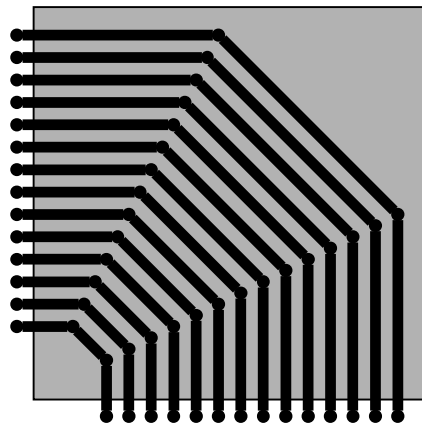
<http://www.eln.polito.it/research/emc>





Motivations

Macromodeling of 3D interconnects for Signal Integrity assessment



Macromodel (SPICE)



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

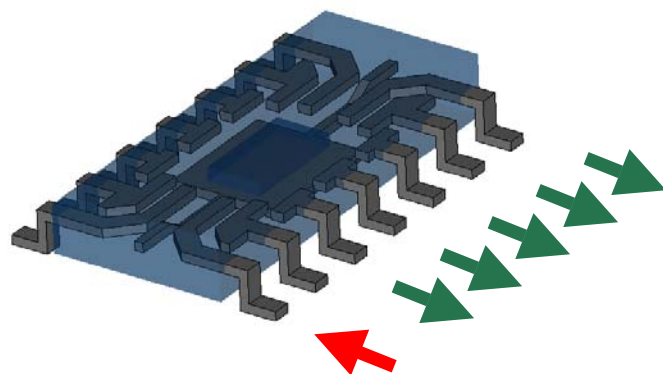


Strategy (1)

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

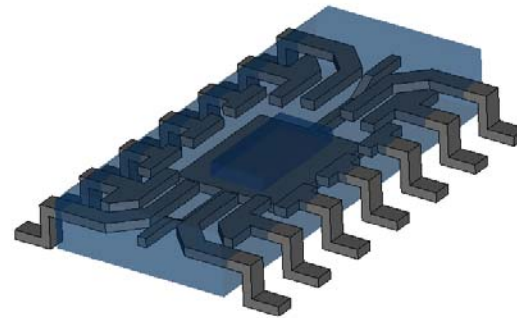
$\mathbf{y}(t)$ t – domain

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



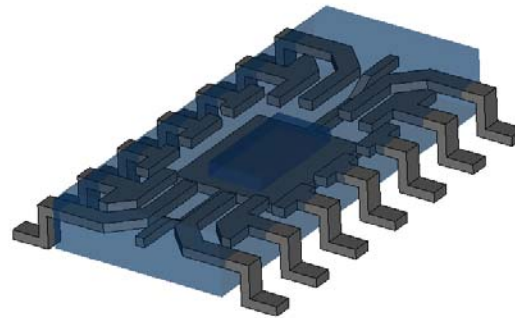
$$\mathbf{Y}(s) = \mathbf{H}(s) \mathbf{X}(s)$$

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



Strategy (3)

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

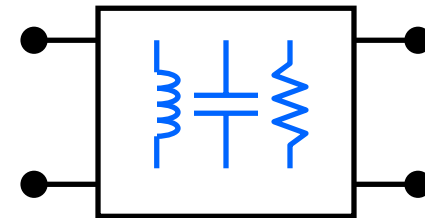
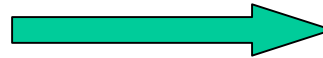


Conventional

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

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

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:

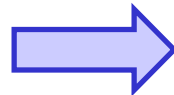
- Poles p_n
- Residues \mathbf{R}_n
- Constant \mathbf{H}_{∞}



Time-Domain Vector Fitting (2)

Step 1. Find the dominant poles via “relocation”

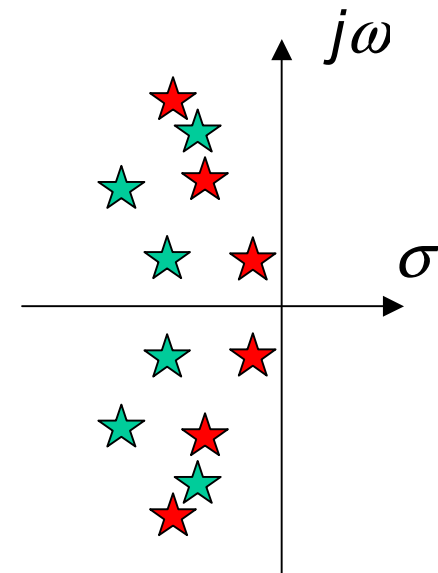
Guess poles
 $\{q_n\}$



New poles
 $\{p_n\}$



Iterative refinement



How to do it using time-domain data?

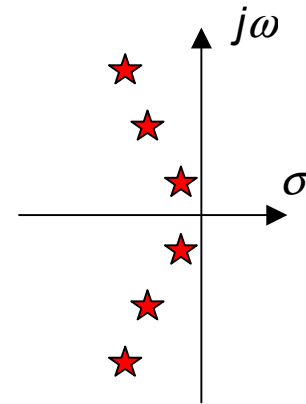
How to insure convergence to the right poles?



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 $\sigma(s)$



Time-Domain Vector Fitting (4)

$$\sigma(s)\mathbf{H}(s) = a + \sum_n \frac{b_n}{s - q_n} \quad \text{Apply the input pulse } \mathbf{X}(s)$$

$$\sigma(s)\mathbf{Y}(s) = \left(a + \sum_n \frac{b_n}{s - q_n} \right) \mathbf{X}(s) \quad \text{Compute inverse Laplace transform}$$

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

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

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

Low-pass filtered input and output signals



Time-Domain Vector Fitting (5)

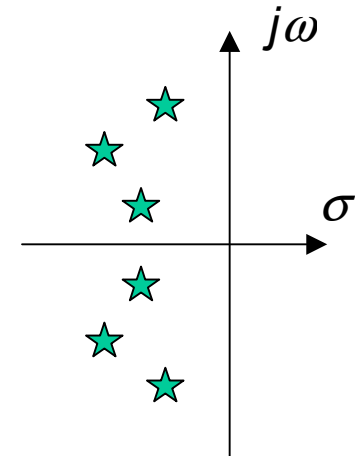
1d. Solve a linear least squares system for k_n , a , b_n

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

1e. Compute the zeros $\{p_n\}$ 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



Time-Domain Vector Fitting (6)

Step 2. Compute the residues

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

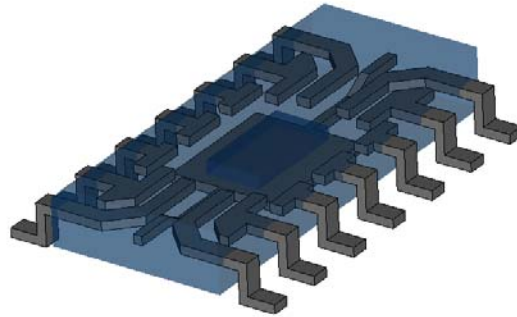
$$\tilde{\mathbf{x}}_n(t) = \int_0^t e^{p_n(t-\tau)} \mathbf{x}(\tau) d\tau$$

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

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



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!

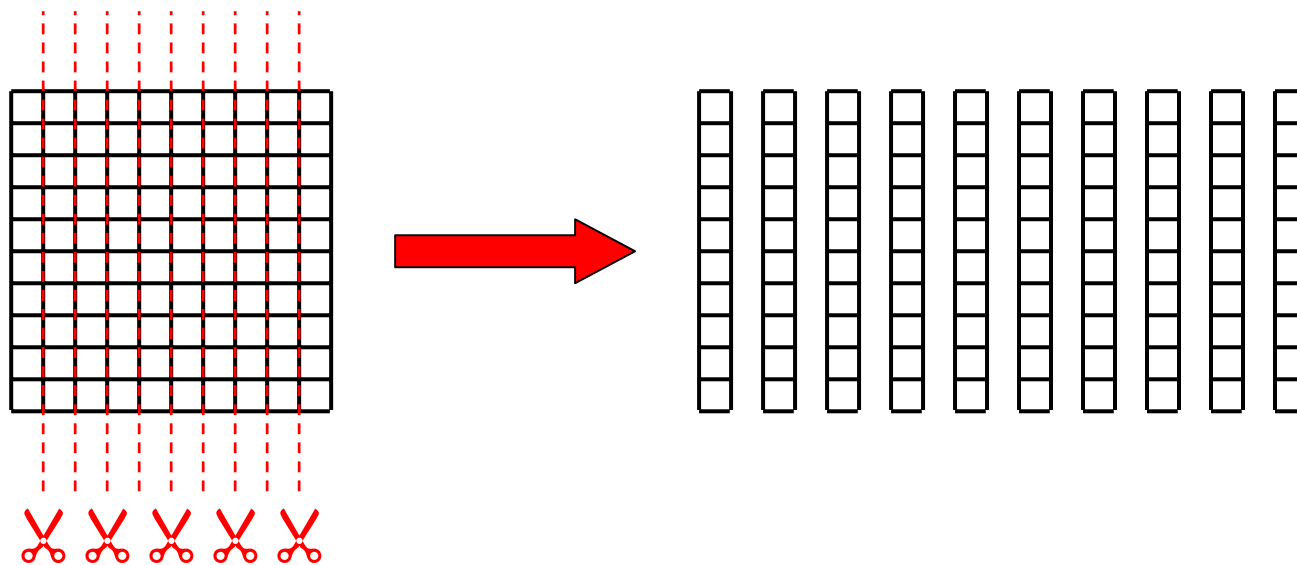


Handling many ports (2)

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

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

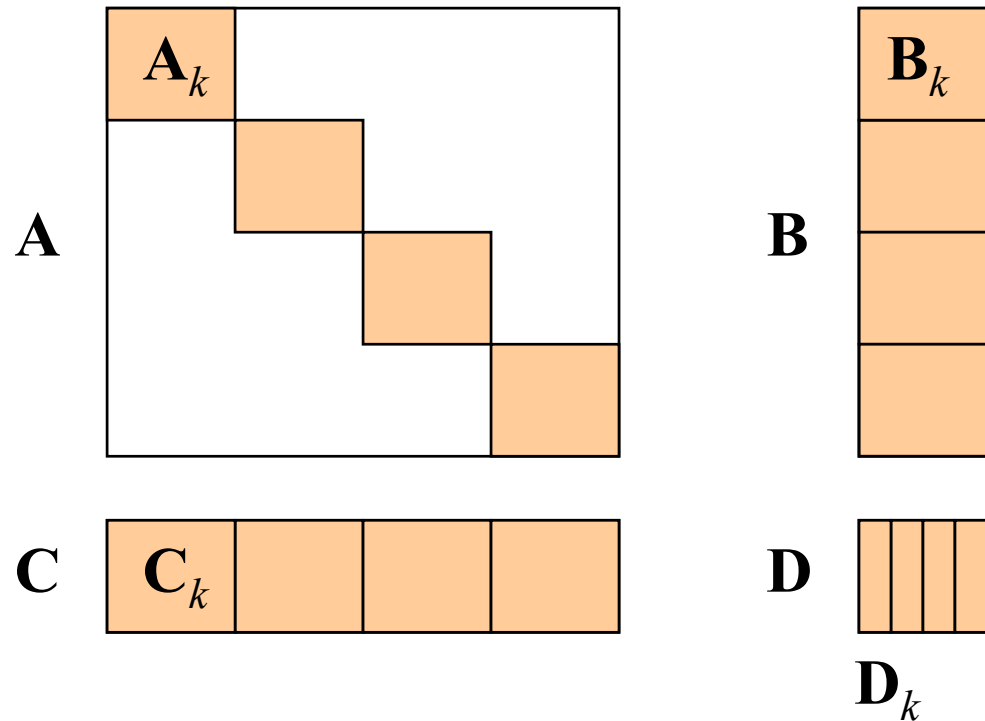


Handling many ports (4)

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

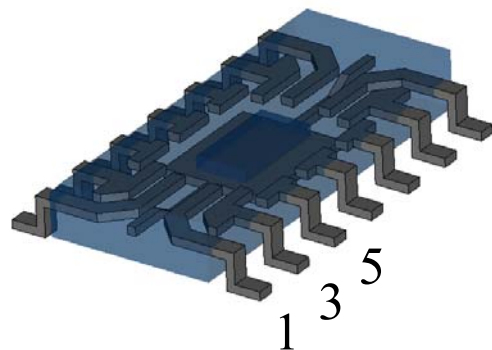
Spectral perturbation of Hamiltonian matrices associated to the model

$$\left\{ \begin{array}{l} \dot{\mathbf{w}} = \mathbf{A} \mathbf{w} + \mathbf{B} \mathbf{x} \\ \mathbf{y} = \mathbf{C} \mathbf{w} + \mathbf{D} \mathbf{x} \end{array} \right. \longrightarrow \left\{ \begin{array}{l} \dot{\mathbf{w}} = \mathbf{A} \mathbf{w} + \mathbf{B} \mathbf{x} \\ \mathbf{y} = (\mathbf{C} + \Delta\mathbf{C}) \mathbf{w} + \mathbf{D} \mathbf{x} \end{array} \right.$$

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

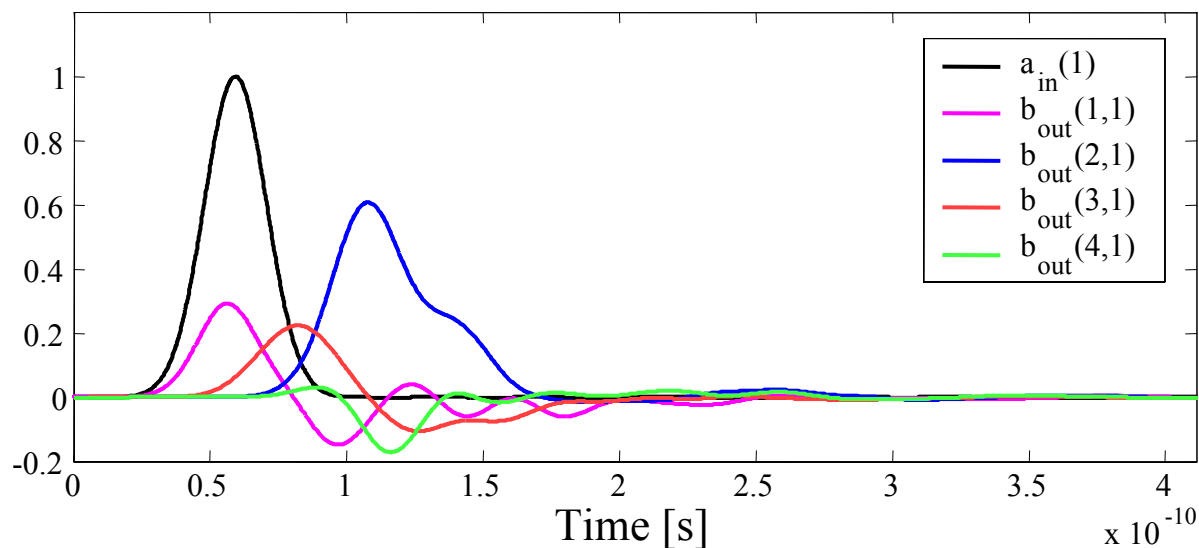


Example 1



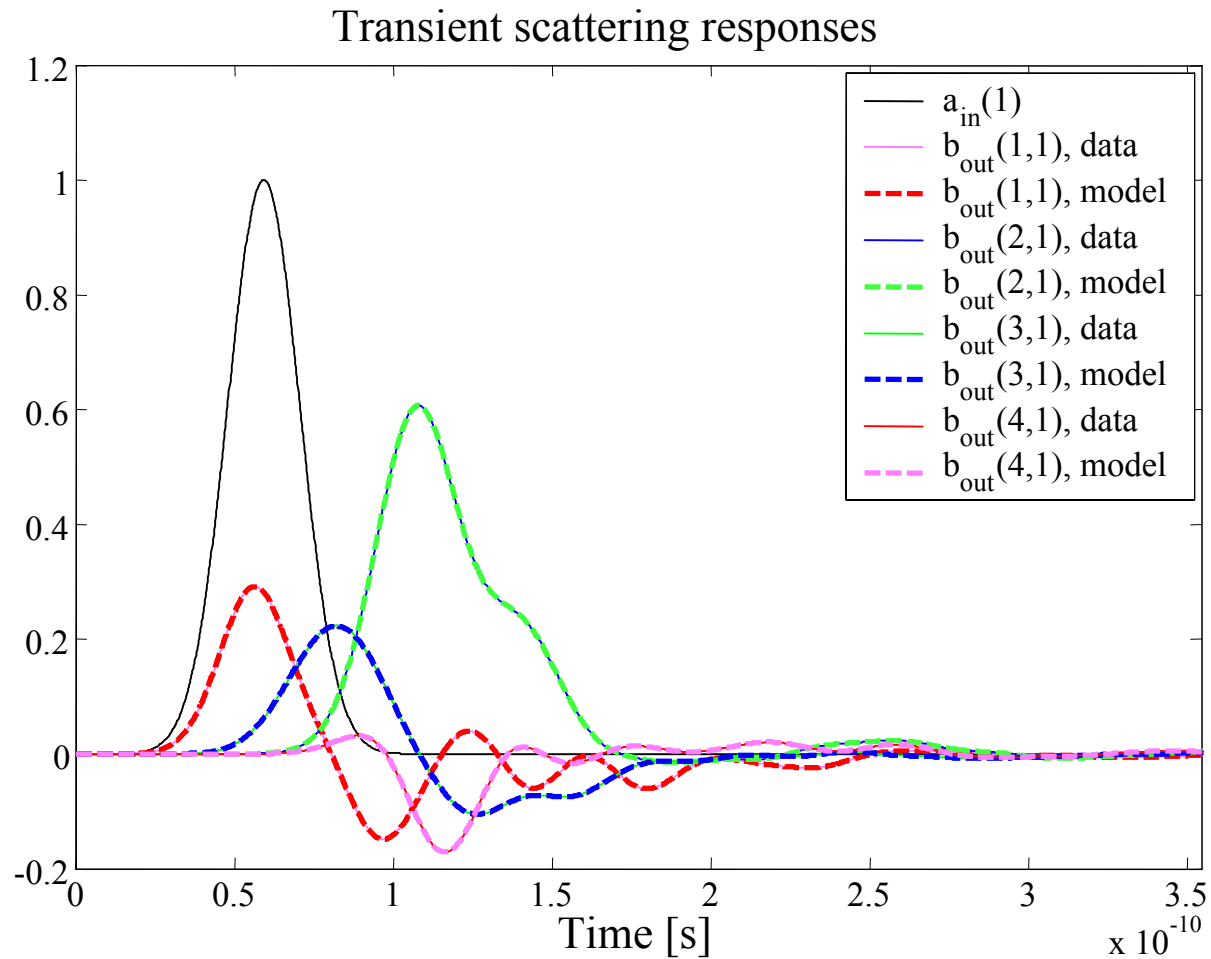
14-pin SOIC package
Simplified CAD for FDTD
Bandwidth: 40 GHz
50 Ω port terminations

FDTD transient scattering responses



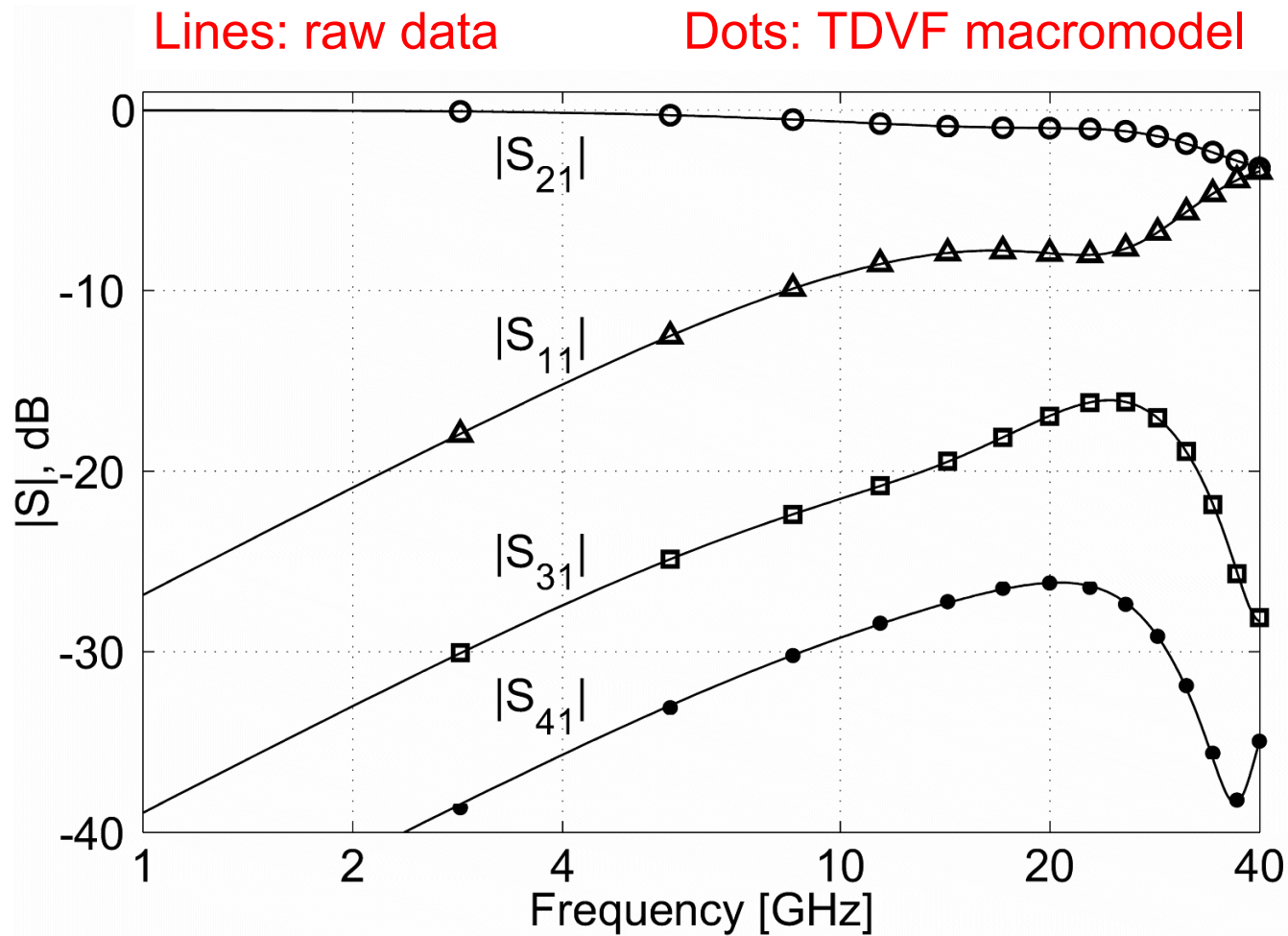


Example 1: macromodel accuracy





Example 1: macromodel accuracy





Example 1: macromodel accuracy

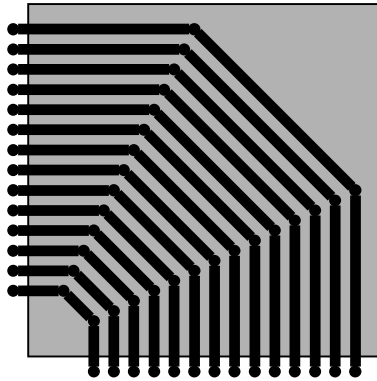
Maximum deviation between model and data for all 28x28 responses



Largest:
0.00074



Example 2: 42-pin connector

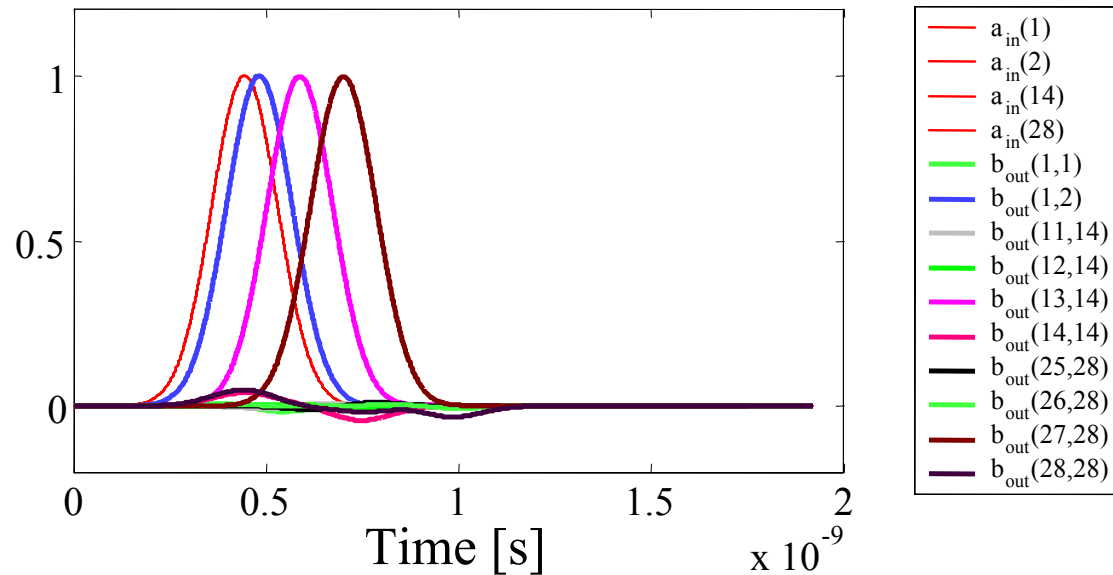


3x14 pins, 84 ports

Characterized via FIT

(CST Microwave Studio 4)

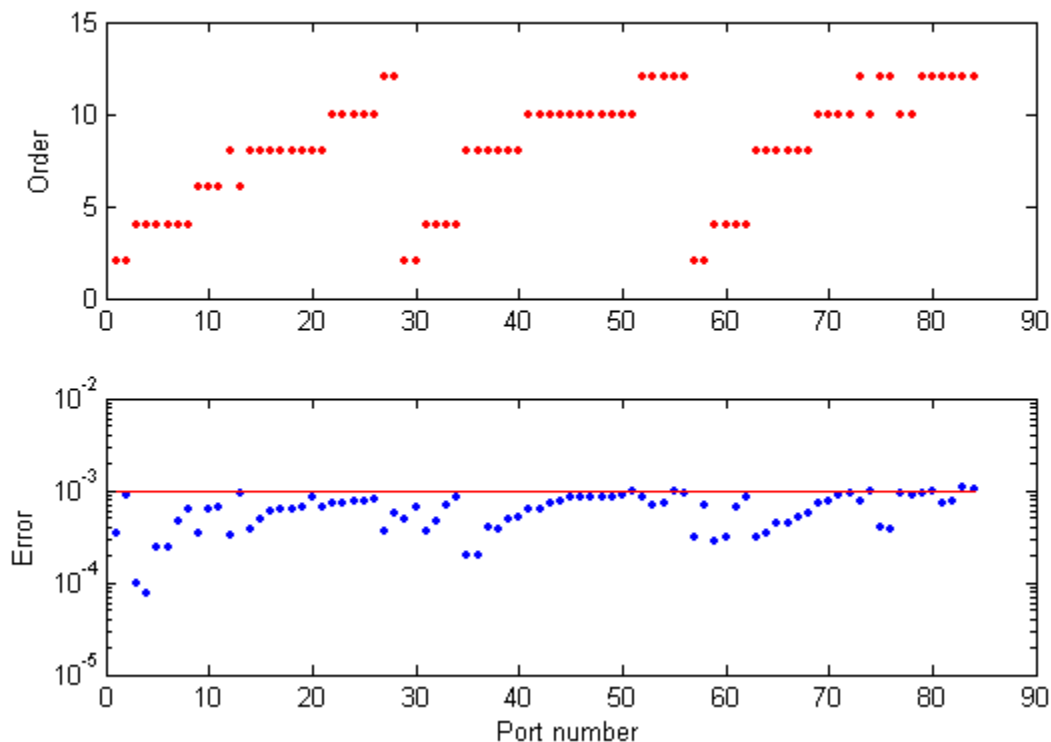
Transient scattering responses





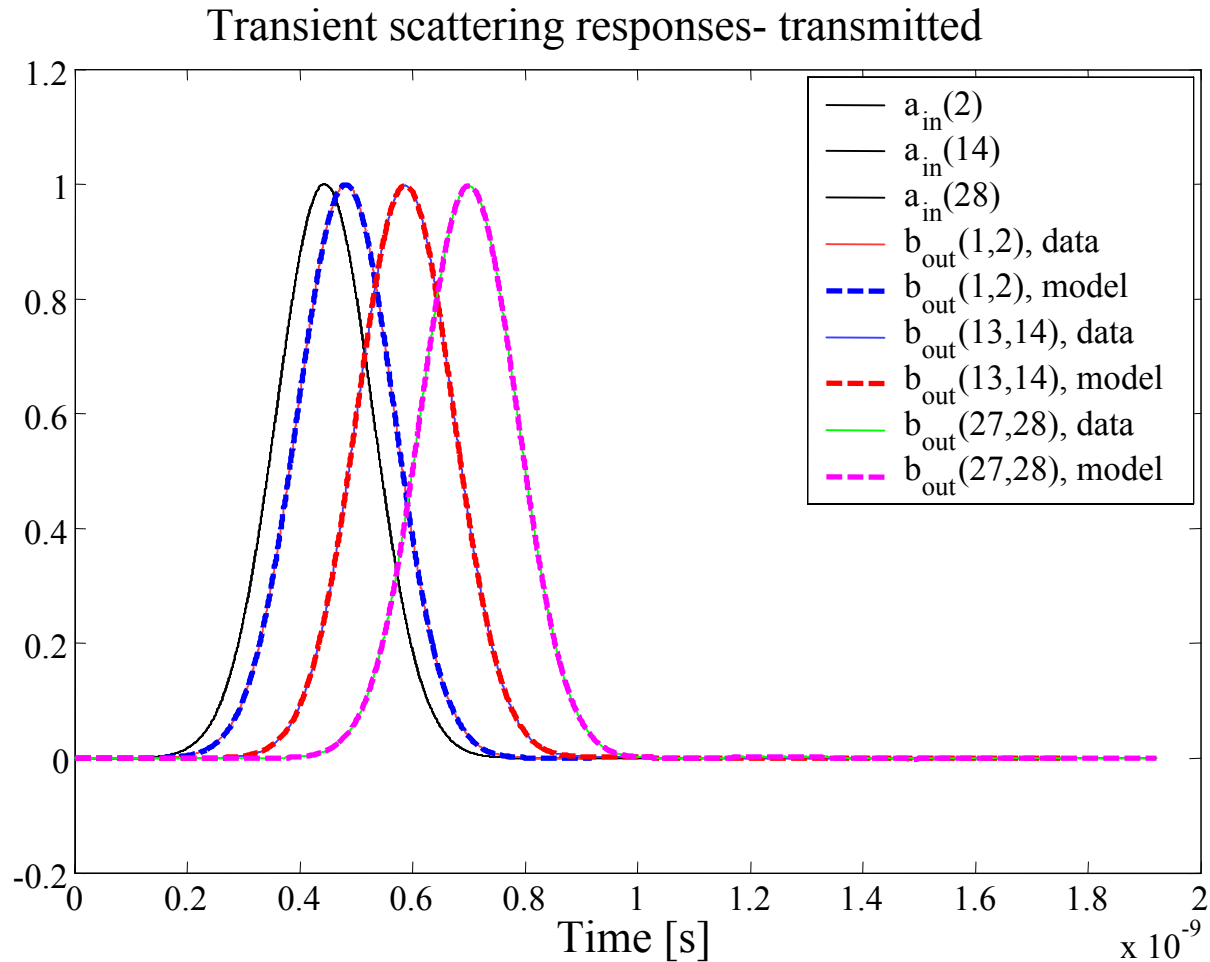
Example 2: model order selection

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





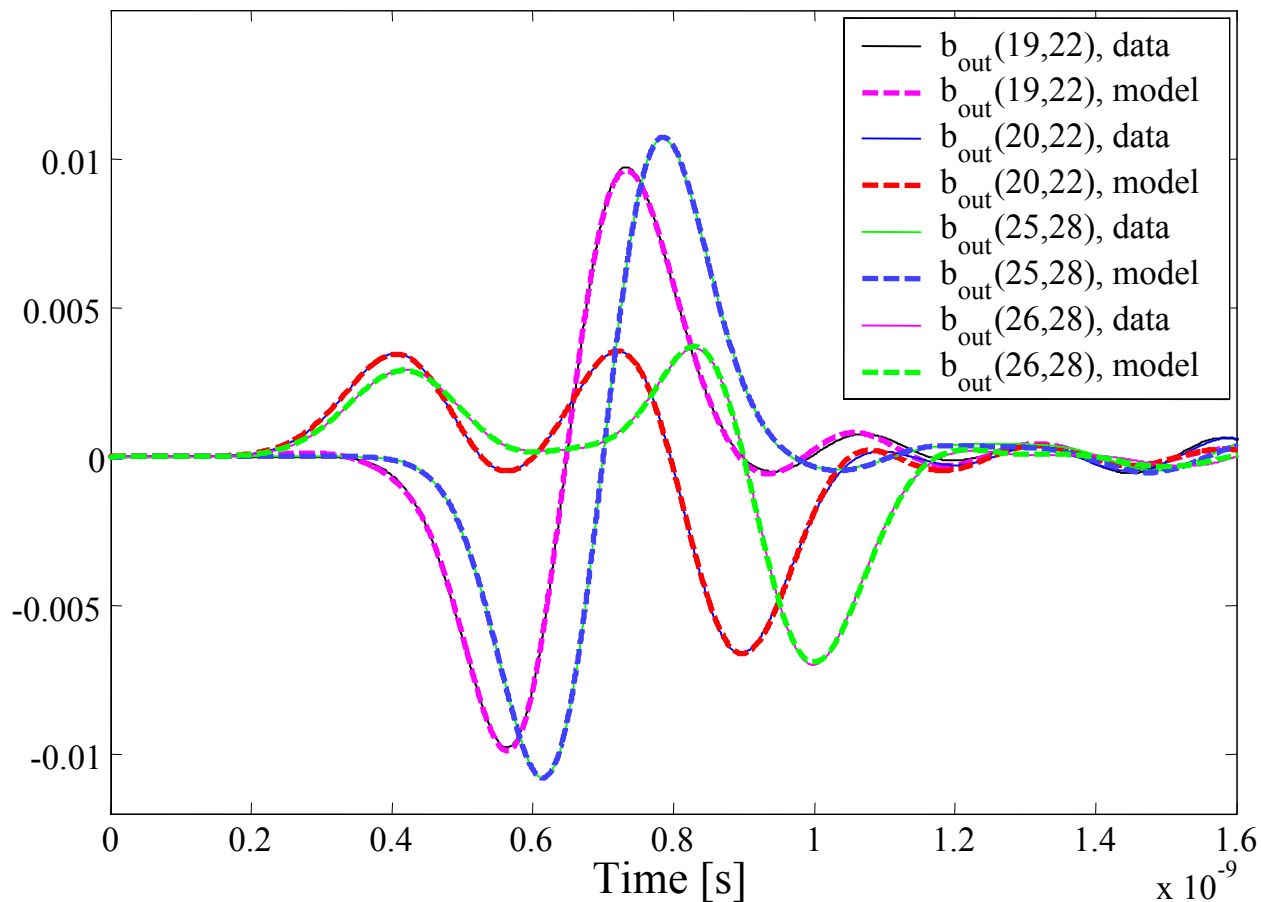
Example 2: macromodel accuracy





Example 2: macromodel accuracy

Transient scattering responses - Xtalk





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