MACROMODELING
OF CONNECTORS AND PACKAGES
WITH A LARGE NUMBER OF PORTS

Flavio Canavero
Politecnico di Torino, Italy

canavero@polito.it

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

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

Input pulse
\( x(t) \) t – domain

Output responses
\( y(t) \) t – domain

Transient scattering port characterization

Conventional
2. Synthesis of rational (lumped) macromodel

\[ Y(s) = H(s)X(s) \]

\[ H(s) = H_\infty + \sum_{n} \frac{R_n}{s - p_n} \]
3. Synthesis of a SPICE subcircuit for system-level analysis

\[ Y(s) = H(s)X(s) \]

\[ H(s) = H_\infty + \sum^n_n \frac{R_n}{s - p_n} \]

Circuit Synthesis

Macromodel (SPICE)
Time-Domain Vector Fitting (1)

Input pulse: \( x(t) \)  
\[ t \text{ – domain} \]

Output responses: \( y(t) \)  
\[ t \text{ – domain} \]

Transfer function:
\[ Y(s) = H(s)X(s) \]

Rational approximation:
\[ H(s) \approx H_\infty + \sum_n \frac{R_n}{s - p_n} \]

Unknowns:
- Poles: \( p_n \)
- Residues: \( R_n \)
- Constant: \( H_\infty \)
Step 1. Find the dominant poles via “relocation”

Guess poles \( \{ q_n \} \) \[\text{Iterative refinement}\] New poles \( \{ p_n \} \)

How to do it using time-domain data?
How to insure convergence to the right poles?
1a. Start with initial poles: \( \{ q_n \} \)

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

\[
\sigma(s) = 1 + \sum_{n} \frac{k_n}{s - q_n}
\]

1c. Assume the following condition

\[
\sigma(s)H(s) = a + \sum_{n} \frac{b_n}{s - q_n}
\]

Poles of \( H(s) \) = Zeros of \( \sigma(s) \)
Time-Domain Vector Fitting (4)

\[ \sigma(s)H(s) = a + \sum_{n} \frac{b_n}{s - q_n} \]

Apply the input pulse \( X(s) \)

\[ \sigma(s)Y(s) = \left( a + \sum_{n} \frac{b_n}{s - q_n} \right) X(s) \]

Compute inverse Laplace transform

**Low-pass filtered input and output signals**

\[ y(t) + \sum_{n} k_n y_n(t) = a \ x(t) + \sum_{n} b_n \ x_n(t) \]

\[ x_n(t) = \int_{0}^{t} e^{q_n(t-\tau)} x(\tau) d\tau \]

\[ y_n(t) = \int_{0}^{t} e^{q_n(t-\tau)} y(\tau) d\tau \]
Time-Domain Vector Fitting (5)

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

$$y(t) + \sum_n k_n y_n(t) = a x(t) + \sum_n b_n x_n(t)$$

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

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

These are the dominant poles!

Time-Domain Vector Fitting (6)

Step 2. Compute the residues

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

\[ \tilde{x}_n(t) = \int_{0}^{t} e^{p_n(t-\tau)} x(\tau) d\tau \]

2b. Solve a linear least squares system for \( R_n \) and \( H_\infty \)

\[ y(t) = H_\infty x(t) + \sum_{n} R_n \tilde{x}_n(t) \]
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

\[ y(t) + \sum_{n} k_n y_n(t) = a x(t) + \sum_{n} b_n x_n(t) \]

Number of poles

Processing all responses may lead to a large system!
Handling many ports (2)

1. Split port responses into subsets

Transfer matrix $H(s)$  \hspace{1cm}  Subsets $\{h_k(s)\}$
Handling many ports (3)

2. Macromodel each subset via Time-Domain Vector Fitting

\[ h_k(s) \approx h_{k,\infty} + \sum_n \frac{r_{k,n}}{s - p_{k,n}} \]

Partial state-space representation

\[
\begin{align*}
\dot{w}_k &= A_k \ w_k + B_k \ x_k \\
y_k &= C_k \ w_k + D_k \ x_k
\end{align*}
\]
4. Assemble all partial models into a global model

\[
\begin{align*}
\dot{w} &= Aw + Bx \\
y &= Cw + Dx
\end{align*}
\]

All matrices are sparse!
Passivity enforcement

Macromodel passivity is enforced a-posteriori

Spectral perturbation of Hamiltonian matrices associated to the model

\[
\begin{align*}
\dot{w} &= Aw + Bx \\
y &= Cw + Dx
\end{align*}
\]

\[
\begin{align*}
\dot{w} &= Aw + Bx \\
y &= (C + \Delta C)w + Dx
\end{align*}
\]

Example 1

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

FDTD transient scattering responses

- Time [s]
- a_{in}^{(1)}
- b_{out}^{(1,1)}
- b_{out}^{(2,1)}
- b_{out}^{(3,1)}
- b_{out}^{(4,1)}
Example 1: macromodel accuracy

Transient scattering responses

- $a_{in}(1)$
- $b_{out}(1,1)$, data
- $b_{out}(1,1)$, model
- $b_{out}(2,1)$, data
- $b_{out}(2,1)$, model
- $b_{out}(3,1)$, data
- $b_{out}(3,1)$, model
- $b_{out}(4,1)$, data
- $b_{out}(4,1)$, model

Time [s] vs. $x \times 10^{-10}$
Example 1: macromodel accuracy

Lines: raw data
Dots: TDVF macromodel

|S_{21}| dB
|S_{11}| dB
|S_{31}| dB
|S_{41}| dB

Frequency [GHz]

F. Canavero, EDAPS 2003 Workshop, Daejeon, Korea
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

Transient scattering responses - transmitted

- $a_{in}(2)$
- $a_{in}(14)$
- $a_{in}(28)$
- $b_{out}(1,2)$, data
- $b_{out}(1,2)$, model
- $b_{out}(13,14)$, data
- $b_{out}(13,14)$, model
- $b_{out}(27,28)$, data
- $b_{out}(27,28)$, model

Time [s] x 10^{-9}
Example 2: macromodel accuracy

Transient scattering responses - Xtalk

- $b_{out}(19,22)$, data
- $b_{out}(19,22)$, model
- $b_{out}(20,22)$, data
- $b_{out}(20,22)$, model
- $b_{out}(25,28)$, data
- $b_{out}(25,28)$, model
- $b_{out}(26,28)$, data
- $b_{out}(26,28)$, model
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*