Parametric and efficient macromodeling techniques for high-speed interconnects simulation

PhD students’ seminars
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Parametric and efficient macromodeling techniques for high-speed interconnects simulation

Agenda:
- high-speed interconnects simulation: *what? why? how?*
- standard macromodeling: *the Vector Fitting algorithm*
- Hot macromodeling research topics:
  - *parametric modeling*
  - *modeling of electrically long systems*
Electronic interconnects are very complex...

Airbus A380: 530 km of cables
Electronic interconnects are very complex...

Chip package (Courtesy of IBM)
...and nowadays work at very high speed

IBM next generation: 5 – 12 GHz clock
Far away from ideal wires!
They are transmission lines!

Electromagnetic effects can seriously compromise system performance and reliability!

Unless predicted with suitable simulation algorithms...
Simulation of systems with high-speed interconnects

1) Strongly nonlinear system

2) Broadband excitation

0 – 40 GHz

3) Partial differential eqs

\[ \begin{align*}
\nabla \times E &= -j\omega B \\
\nabla \times H &= j\omega D + J
\end{align*} \]

\[ \begin{align*}
\frac{d}{dz} V(z, j\omega) &= [R(\omega) + j\omega L(\omega)] I(z, j\omega) \\
-\frac{d}{dz} I(z, j\omega) &= [G(\omega) + j\omega C(\omega)] V(z, j\omega)
\end{align*} \]

\[ \dot{x}(t) = F(x(t)) \]
Simulation of systems with high-speed interconnects

Circuit simulators (eg SPICE)
- no general models for lines, connectors,...
- as many students... don’t like Maxwell’s equations ;-)
Simulation of systems with high-speed interconnects

Brute force approach: electromagnetic simulator

- computationally too expensive (way too)
- problems with circuit elements

\[
\begin{align*}
\nabla \times E &= -j\omega B \\
\nabla \times H &= j\omega D + J \\

\frac{d}{dz} V(z, j\omega) &= [R(\omega) + j\omega L(\omega)]I(z, j\omega) \\

\frac{d}{dz} I(z, j\omega) &= [G(\omega) + j\omega C(\omega)]V(z, j\omega)
\end{align*}
\]
The macromodeling approach

Macromodels:
- behavioral “black-box” models
- lowest possible number of equations (complexity reduction)
- compatible with any circuit simulator
Macromodeling via system identification

Measurement with VNA
EM simulation

\[
\begin{align*}
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \times H &= \frac{\partial D}{\partial t} + J
\end{align*}
\]

Frequency tables of transfer matrix \((S, Y, Z, \ldots)\)

Rational interpolation
Fitting
Identification

\[
H(s) = \frac{\sum_n Q_n s^n}{\sum_n R_n s^n}
\]


Macromodel compatible with any circuit simulator

\[
\dot{x}(t) = Ax(t) + Bw(t)
\]
Agenda:

- high-speed interconnects simulation: what? why? how?
- standard macromodeling: *the Vector Fitting algorithm*

Hot macromodeling research topics:

- *parametric modeling*
- *modeling of distributed systems*
Vector Fitting

Aim: finding the “right” model coefficients $Q_n$ and $r_n$ to minimize the error between the given samples and the model

$$H(j\omega_k) - \frac{\sum_n Q_n (j\omega_k)^n}{\sum_n r_n (j\omega_k)^n} \approx 0$$

Least squares

This optimization problem has two numerical issues:
Vector Fitting

Aim: finding the “right” model coefficients $Q_n$ and $r_n$ to minimize the error between the given samples and the model

$$H(j\omega_k) - \sum_n Q_n (j\omega_k)^n \approx 0$$

Least squares

This optimization problem has two numerical issues:

- NONLINEAR IN $r_n$
- ILL CONDITIONED

Large powers of frequency
How Vector Fitting tackles ill conditioning

- Use different “basis” functions for the numerator and denominator

\[
H(s) = \frac{\sum_n Q_n s^n}{\sum_n r_n s^n}
\]

\[
H(s) = \frac{Q'_0 + \sum_n Q'_n}{1 + \sum_n r'_n} \frac{1}{s - a_n}
\]

\[a_n\]  Common fixed poles
How Vector Fitting tackles the nonlinearity

\[
H(s_k) - \left( \sum_n \frac{Q_n}{s_k - a_n} + Q_0 \right) \approx 0
\]

\[
\sum_n \frac{r_n}{s_k - a_n} + 1
\]
How Vector Fitting tackles the nonlinearity

\[
\sum_{n} \frac{r_n}{s_k - a_n} + 1 \quad H(s_k) - \sum_{n} \frac{Q_n}{s_k - a_n} + Q_0 \quad \cong 0
\]
How Vector Fitting tackles the nonlinearity

\[
\sum_n \frac{r_n^{(i)}}{s_k - \alpha_n} + 1 - \frac{Q_n^{(i)}}{s_k - \alpha_n} + Q_0^{(i)} \approx 0
\]

Applied indirectly through poles relocation at each iteration

\[
a_n^{(i)} \rightarrow a_n^{(i+1)}
\]
How Vector Fitting tackles the nonlinearity

\[
\sum_n \frac{r_n^{(i)}}{s_k - a_n^{(i)}} + 1
\]

\[
H(s_k) - \sum_n \frac{Q_n^{(i)}}{s_k - a_n^{(i)}} + Q_{0}^{(i)} \approx 0
\]

- Linear least squares problem → robust and efficient solution via standard algorithms (MATLAB "\")
- Fast convergence (usually 3-4 iterations)
- The poles \( a_n \) approach the poles of the original system

\[
a_n^{(i)} \rightarrow p_n
\]
Vector Fitting outcome

- Final result: macromodel in poles&residues form

\[ H(s) = R_0 + \sum_n \frac{R_n}{s - p_n} \]
Example: stripline with launches

Data: measured S-parameters

Scattering matrix entries, magnitude

Scattering matrix entries, phase

Frequency [GHz]

S(1,1), data
S(1,1), model
S(2,1), data
S(2,1), model
Example: stripline with launches

Macromodel: 60 poles

Scattering matrix entries, magnitude

Scattering matrix entries, phase

Frequency [GHz]

S(1,1), data
S(1,1), model
S(2,1), data
S(2,1), model

40 GHz!
Example: Multichip Module to board connector

Total 10 electrical ports
Example: Multichip Module to board connector

Scattering matrix entries, magnitude (dB)

Scattering matrix entries, phase (degrees)

Frequency [GHz]

S(1,1), data
S(1,1), model

S(6,1), data
S(6,1), model
Example: Multichip Module to board connector

Macromodel: 4-poles

Error: 0.1%
Vector Fitting-Macromodel properties

👍 **Accuracy**
Good initial data $\Rightarrow$ small approximation errors

😊 **Stability**
All poles with negative real part

😀 **Passivity**
Interconnect components are always passive
The macromodel may not be passive
Macromodel Passivity

Systems composed by nonpassive models and arbitrary terminations may be unstable!

Port terminations:
\[ R = 50 \text{ m}\Omega \div 50 \Omega \]
\[ L = 1 \text{ nH} \]
\[ C = 1 \text{ pF} \]

Effects of passivity violation

System may become unstable!
Physical consistency of macromodels

In order to lead to consistent and trustworthy results, macromodels must retain the properties of the original system:

- *causality*
- *stability*
- *passivity*

**Important topic.** To learn more you can start from:

Agenda:

- high-speed interconnects simulation: *what? why? how?*

- standard macromodeling: *the Vector Fitting algorithm*

- Hot macromodeling research topics:
  - *parametric modeling*
  - *modeling of electrically long systems*
**Parametric macromodels: motivations**

**KEY ISSUE:** The model is valid only for one value!
**Parametric macromodels: motivations**

**KEY ISSUE:** The model is valid only for one value!

**SOLUTION:** A parameter dependent model, valid for the whole design range!
Parameterization of the macromodel

How to include the parameter in the macromodel?

\[ \hat{H}(s, \lambda) = \sum_{n} \frac{\lambda_n}{s - \lambda_n} p_n(\lambda) \]

Poles & residues form
Parameterization of the macromodel

Efficient parameterization: numerator and denominator coefficients

\[ H(s, \lambda) = \frac{\sum_n Q_n(\lambda)}{\sum_n r_n(\lambda)} s^n \]

\[ H(s, \lambda) = \frac{\sum_n \left( Q_{n0} + Q_{n1}\lambda + Q_{n2}\lambda^2 + \cdots \right)}{\sum_n \left( r_{n0} + r_{n1}\lambda + r_{n2}\lambda^2 + \cdots \right)} s^n \]
Macromodel identification

- Minimize the model-to-data error

\[ H(s_k, \lambda_l) - \sum_n \frac{(Q_n^0 + Q_n^1 \lambda_l + \cdots) s_k^n}{(r_n^0 + r_n^1 \lambda_l + \cdots) s_k^n} \approx 0 \]

- Iterative solution via linearized problems (generalization of Sanathanan Koerner algorithm)

\[ H(s_k, \lambda_l) - \frac{N^{(i)}(s_k, \lambda_l)}{D^{(i)}(s_k, \lambda_l)} \approx 0 \]
Macromodel identification

- Iterative solution via linearized problems (generalization of Sanathanan Koerner algorithm)

\[ \frac{D^{(i)}(s_k, \lambda_l) \cdot H(s_k, \lambda_l) - N^{(i)}(s_k, \lambda_l)}{D^{(i)}(s_k, \lambda_l)} \equiv 0 \]
Macromodel identification

- Iterative solution via linearized problems (generalization of Sanathanan Koerner algorithm)

\[ \begin{align*}
D^{(i)}(s_k, \lambda_l) &\quad H(s_k, \lambda_l) - N^{(i)}(s_k, \lambda_l) \\
\cong 0
\end{align*} \]

- Works with one or more parameters


Example: backdrilled via

Via connecting a microstrip and a stripline

MICROSTRIP
Port 1

STRIPLINE
Port 2

Model for the 2-port

VIA

STUB

Backdrilling
Example: backdrilled via

Via connecting a microstrip and a stripline

- Model for the 2-port
- Parameter: stub height $h$

Backdrilling
Example: backdrilled via

- **Polynomial model**
  - Order: 14
  - Degree: 3

Max error: $2.2 \times 10^{-2}$
Comp. time: 2.5 min

- **Black**: data
- **Red**: model (fitting)
- **Blue**: model (validation)
Example: backdrilled via

Polynomial model
Order: 14
Degree: 3

Max error: 2.2x10^{-2}
Comp. time: 2.5 min
Example: backdrilled via

Model poles

- Polynomial model
- Order: 14
- Degree: 3

Max error: $2.2 \times 10^{-2}$
Comp. time: 2.5 m

Stable: yes
RF device (courtesy of Infineon)

- Device for GSM and EDGE transceivers
- 7 ports (49 transfer function elements)
- Small signal scattering parameters 0-40 GHz
- Parameter: bias voltage VB 0.15-1 V

- Parametric macromodel generated with the algorithm described in:


RF device (courtesy of Infineon)

- Piecewise linear model
- Order: 6

Max error: $3.2 \times 10^{-3}$
Comp. time: 6 s

Black: data
Blue: model (validation)
RF device (courtesy of Infineon)

- Piecewise linear model
- Order: 6

Max error: 3.2x10^{-3}
Comp. time: 6 s

Stable: yes

Black: data
Red: model (fitting)
Blue: model (validation)
Agenda:

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Macromodels with delays

Fast simulation of long interconnects for Signal Integrity

If we apply Vector Fitting we get a lumped model with a huge number of poles

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

>1000 poles
Simulations too slow

Lumped model \(\rightarrow\) distributed model

\[ H(s) = H_\infty + \sum_n \frac{R_n}{s - p_n} + e^{-sT_m} \]
Rational approximation with delays

\[ S_{ij}(s) \approx \sum_{m=1}^{M} Q_{ij}^{(m)}(s) e^{-sT_m} \]

Propagation delays
Rational approximation with delays

\[ S_{ij}(s) \approx \sum_{m=1}^{M} Q^{(m)}_{ij}(s) e^{-sT_m} \]

\[ Q^{(m)}_{ij}(s) = \sum_{n} \frac{R^{(m)}_{ij,n}}{s - p^{(m)}_{ij,n}} + R^{(m)}_{ij,\infty} \]

Propagation delays

Non-ideal effects like attenuation, dispersion,...
Rational approximation with delays

\[
S_{ij}(s) \approx \sum_{m=1}^{M} Q_{ij}^{(m)}(s) e^{-sT_m}
\]

\[
Q_{ij}^{(m)}(s) = \sum_{n} \frac{R_{ij,n}^{(m)}}{s - p_{ij,n}^{(m)}} + R_{ij,\infty}^{(m)}
\]
Delay estimation: the Gabor transform

Gaussian window

\[ W(\xi) = \pi^{-1/4} e^{-\xi^2 / 2} \]

“Basis function”

\[ W_{\omega,\tau}(\xi) = W(\xi - \omega) e^{-j\xi\tau} \]

\( \omega \)

\( \xi \) (frequency)
Delay estimation: the Gabor transform

\[ G(\omega, \tau) = \int_{-\infty}^{+\infty} H(j\xi) W_{\omega,\tau}(\xi) \, d\xi = \int_{-\infty}^{+\infty} H(j\xi) W(\xi - \omega) e^{j\xi\tau} \, d\xi \]

- Raw data
- Time (delay) localization
- Frequency localization

Example (measured stripline with launches)

\[ |S_{11}| \]

\[ \angle S_{11} \]

\[ |S_{13}| \]

\[ \angle S_{13} \]

Delay, \( \mu s \)

Frequency, MHz

Delay, \( \mu s \)

Frequency, MHz
DVF: Delayed Vector Fitting (scalar)

\[ H(s_k) - \sum_m \left( \sum_n \frac{R_{nm}}{s_k - p_n} + R_{m,\infty} \right) e^{-s_k T_m} \approx 0 \]
DVF: Delayed Vector Fitting (scalar)

\[ H(s_k) - \sum_{m} \frac{w_{nm}}{s_k - a_n} + w_{m,\infty} \approx 0 \]

\[ e^{-s_k T_m} \]

DVF: Delayed Vector Fitting (scalar)

\[ \sum_{n} \frac{r_n^{(i)}}{s_k - a_n} + r_\infty^{(i)} \]

\[ H(s_k) \sum_{m} \frac{w_{nm}^{(i)}}{s_k - a_n} + w_{m,\infty}^{(i)} \]

\[ e^{-s_k T_m} \approx 0 \]

Weight

Applied indirectly through poles relocation
(as in Vector Fitting)
DVF: Delayed Vector Fitting (scalar)

\[ a_n^{(i)} \rightarrow a_n^{(i+1)} \]

\[ \sum_n \frac{r_n^{(i)}}{s_k - a_n^{(i)}} + r_\infty^{(i)} + \sum_m \frac{w_{nm}^{(i)}}{s_k - a_m^{(i)}} + w_{m,\infty}^{(i)} e^{-s_k T_m} \cong 0 \]

- Again: solution via linear least square problems only
- Stability enforcement is possible
Example - IBM GX bus
Example - IBM GX bus

5 delays, 20 poles
RMS error ≈ 6E-3

1 delay, 15 poles
RMS error ≈ 5E-3

Using standard VF (no delays) a comparable model requires
N=110 poles

N=120 poles
Example - IBM GX bus

SPICE transient simulations
Input: single pulse (1 ns width, 100 ps rise/fall time)

Time required for SPICE simulations

VF 12.44 s
DVF 2.58 s
VF 9.16 s
DVF 1.84 s

Speedup factor = 5X
Conclusions

- Macromodeling
  - enables the solution of mixed fields-circuits problems
  - flexible: starting point can be measured data, simulated data,...
  - compatible: works with any circuits/equations solver
  - general: can be applied to any linear system

- Vector Fitting

- New macromodeling algorithms for:
  - Inclusion of design parameters in macromodels
  - Inclusion of distributed elements
Questions?
Thank you for your attention!
Bibliography
Interconnects analysis

Macromodeling

Stability, passivity, causality


Parametric macromodeling

Macromodeling with delays

For an interconnect of arbitrary shape:


Macromodeling with delays

For straight segments of transmission line only:
