Tutorial lecture on Modeling and simulation of high-speed interconnects: approaches, challenges, and solutions

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Modeling and Simulation of High-Speed Interconnects: Approaches, Challenges and Solutions

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Complexity of electronic interconnects

Computer aided design techniques are essential for interconnects design.
Strong impact on:
- performance & reliability
- product time-to-market
- company revenues
- ... and so the relations with your boss... ;-)
A successful example... (stripline with launches)

**Data: measured S-parameters**

```
Frequency [GHz]  S(1,1), data  S(1,1), model  S(2,1), data  S(2,1), model
```

```
Scattering matrix entries, magnitude
```

```
Scattering matrix entries, phase
```

A successful example... (stripline with launches)

**Macromodel: 60 poles**

```
Frequency [GHz]  S(1,1), data  S(1,1), model  S(2,1), data  S(2,1), model
```

```
Scattering matrix entries, magnitude
```

```
Scattering matrix entries, phase
```
An example of failure... (courtesy of Nokia)

Three coupled lines

Scattering parameters from an electromagnetic simulation

Macromodel generation dramatically fails! But why? Where is the problem?

Computer Aided Design: always hassle-free?

Problems are not uncommon!

Examples:
- Simulator errors and warnings (“Convergence failure”, “Timestep too small”, “Malformed impulse response”,...)
- Data fitting problems
- Inaccurate simulation results

Such issues may strongly impair the design workflow!
- Increase product time-to-market
- Post-sale malfunctioning
- Trade performance for reliability
Reference scenario: interconnects simulation

**DATA** (Sampled S/Y/Z pars)

**MODEL** (Netlist, differential equations, poles/residues)

**AC Simulation**

**RESULTS** (Frequency-domain)

**RESULTS** (Time-domain)

---

Poor physical consistency is the cause!

A primary cause of these problems is a lack of physical consistency:

**Real device**

**BAD DATA**

**BAD MODELS**

**Perfect CAD Tool**

Garbage Out
Our goal

**UNDERSTAND**
What do these terms mean!

**HOW**
Violations can arise

**ISSUES**
How badly they can ruin my design

**BEST PRACTICES**
Rules to defeat them

---

**Benefits**

Actually, let us make them work for us, to improve our design workflow!

- **Measurement step**
  - Promptly detect inconsistencies & fix the measurement
  - ... before wasting hours/days in trying to get the design done!

- **Modeling step**
  - prevent modeling failures
  - maximize accuracy

- **Simulation step**
  - more accurate results
  - avoid convergence issues
Agenda

- Causality & stability of models
- Causality & stability of frequency data
- Passivity of models
- Passivity of frequency data

Causality/stability violation in a MODEL

\[ H(j\omega_k) \]

DATA (Sampled S/Y/Z pars)

AC Simulation

RESULTS (Frequency-domain)

Modeling tool

Transient Simulation

RESULTS (Time-domain)

MODEL

CAUSALITY/STABILITY VIOLATION
Causality: definition

- We consider a linear system (single input single output)
  \[ w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau \]
  \[
  \begin{array}{c c c}
    \text{IN} & x(t) & \text{OUT} \\
    \hline
    h(t) & \rightarrow \\
    \end{array}
  \]
  \[
  \begin{array}{c c c}
    \text{IN} & x(t) & \text{OUT} \\
    \hline
    h(t) & \rightarrow \\
    \end{array}
  \]

- Causality: “no output before the input”

- No anticipatory behavior
- All physical (real) systems are causal! (active, passive, nonlinear,...)

Causal system:

\[ h(t) = 0 \quad t < 0 \]
**Stability: definition**

- **BIBO Stability:** “if any Bounded Input leads to a Bounded Output”

\[ w(t) = \int_{-\infty}^{+\infty} h(\tau) x(t - \tau) d\tau \]

**Stability condition:**

\[ \int_{-\infty}^{+\infty} |h(t)| dt < \infty \]

---

**Causality and stability in Laplace domain**

- We apply the Laplace transform

\[ w(t) = \int_{-\infty}^{+\infty} h(\tau) x(t - \tau) d\tau \quad \xrightarrow{L} \quad W(s) = H(s)X(s) \]

- **Causality & stability condition** (for lumped systems):

  if all poles of \( H(s) \) lie in the left hand plane \( Re\{s\} < 0 \), then the system is stable and causal

  [Causality/stability violated!]
Causality/stability violations in MODELS

**How can causality/stability violations arise?**

- Causality/stability not enforced by modeling algorithm
- Noisy data
- Model order too large (estimation of redundant poles ill-conditioned)
- What happens when a model is not causal/stable?

Causality/stability violations in MODELS: issues

Many commonly used theoretical results may be inappropriate! Example: Laplace transform

\[ H(s) = \int_{0}^{+\infty} h(t)e^{-st} \, dt \]

- The commonly used **one-sided** Laplace transform is not appropriate for possibly non-causal systems!
- Two-sided Laplace transform must be used!

\[ H(s) = \int_{-\infty}^{+\infty} h(t)e^{-st} \, dt \]

- More complicated... here avoided!
Causality/stability violations in MODELS: issues

Another example: which convolution formula?

\[ w(t) = \int_{0}^{t} h(\tau)x(t - \tau)d\tau \]

- OK only for causal systems! Otherwise integration must be performed from \(-\infty\) to \(+\infty\)

Time-domain circuit simulators based on the convolution formula may not support noncausal models!

Causality/stability violations in MODELS: issues

We consider those simulators that directly integrate the circuit differential equations:

\[ H(s) \rightarrow \dot{y}(t) = Ay(t) + Bx(t) \]

\[ y(0) = ? \]

*Initial condition*
Causality/stability violations in MODELS: issues

We consider those simulators that directly integrate the circuit differential equations:

\[ H(s) \rightarrow \dot{y}(t) = Ay(t) + Bx(t) \]

\[ y(0) = 0 \quad \text{Initial condition} \]

Wrong for non-causal models!!

Time-domain simulators based on integration of differential equations do not support noncausal models!

Causality/stability violations in MODELS: issues

Since all physical systems are causal, a non-causal model is for sure an approximation of the original system

\[ H(s) \rightarrow h(t) \]

Maybe a good approximation (small causality violation), but...
Causality/stability violations in MODELS: issues

Small causality violations can lead to large problems and inconsistencies!

- Negligible effect on the model transfer function $H(s)$
- But dramatic influence of the transient response!

Best practices

**Bottom line:** Noncausal/unstable models can lead to serious problems!

- Always enforce stability and causality during model construction (with any method):
  - Vector Fitting **OK**
  - Many order reduction methods **OK**
  - Safer than enforcing causality during circuit simulation

The original model must somehow be modified...
Best practices

**Bottom line:** Noncausal/unstable models can lead to serious problems!

- Always enforce stability and causality during model construction (with any method):
  - Vector Fitting **OK**
  - Many order reduction methods **OK**
- Safer than enforcing causality during circuit simulation

**SAFE WAY**

\[ H(s) \rightarrow \text{Causal Results} \]

No loss of accuracy!

---

**Causality/stability violation in DATA**

\[ H(j\omega_k) \rightarrow \text{AC Simulation} \rightarrow \text{RESULTS (Frequency-domain)} \]

**MODEL**

\[ H(s) \rightarrow \text{Transient Simulation} \rightarrow \text{RESULTS (Time-domain)} \]

**DATA**

(Sampled S/Y/Z pars)

**Modeling tool**

(Netlist, differential equations, poles/residues)
Causality in frequency domain

- We apply the Fourier transform
  \[ w(t) = \int_{-\infty}^{+\infty} h(\tau)x(t-\tau)d\tau \xrightarrow{F} W(j\omega) = H(j\omega)X(j\omega) \]

- This is mathematically correct only for stable systems

- Causality condition: the frequency response must satisfy the Kramers-Krönig dispersion relations (Hilbert transform)

\[ H(j\omega) = U(\omega) + jV(\omega) \]

\[ U(\omega) = \frac{1}{\pi} \text{pv} \int_{-\infty}^{+\infty} V(\omega') \frac{d\omega'}{\omega - \omega'} \]

\[ V(\omega) = -\frac{1}{\pi} \text{pv} \int_{-\infty}^{+\infty} U(\omega') \frac{d\omega'}{\omega - \omega'} \]

Causality violations in FREQUENCY DATA

- HOW can causality violations arise?

- Numerical simulation: poor meshing, bad models or assumptions on material properties, inaccurate solver, human mistakes

- Measurement: Improper VNA calibration/de-embedding, human mistake, noise
Improper VNA calibration leading to causality violations

Example 1

Measurement in A:

At real device ports (in B):

Example 2

Measurement in A:

At real device ports (in B):
Causality/stability violation in DATA

\[ H(j\omega) \]

DATA
(Sampled S/Y/Z pars)

\[ H(s) \]

MODEL
(Netlist, differential equations, poles/residues)

AC Simulation

RESULTS
(Frequency-domain)

If transformed to the time-domain:

\[ h(t) \]

Non-physical (non-causal) results

CAUSALITY/STABILITY VIOLATION

Transient Simulation

RESULTS
(Time-domain)
Example (courtesy of Nokia)

Three coupled lines

$H(j\omega_k)$

$S_{11}$ real part

Frequency [GHz]

Non-causal EM simulation

$H(j\omega) = U(\omega) + jV(\omega)$

Computed with dispersion relations
Example (courtesy of Nokia)

Three coupled lines

Vector fitting fails... because of causality violations!

Even if the number of poles is increased up to 50, error does not decrease!

Courtesy of IdemWorks s.r.l.
Example (courtesy of Nokia)

Three coupled lines

Building model New using FDVF
Performing FDVF Model Generation ...

Iteration 1
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
RMS Error: 0.00498987   Max Dev: 0.0122055

.... [snip] ....

Iteration 15
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
RMS Error: 0.00385667   Max Dev: 0.0100463

Vector fitting fails... because of causality violations!

Explanation of Vector Fitting difficulties

Vector fitting is required to fulfill two requirements:

- **Accuracy**
  \[ H(j \omega_k) \rightarrow H(s) \]
  - **CONFLICTING REQUIREMENTS!**
  - **NO SOLUTION!**

- **Causality**
Causality/stability violation in DATA

\[ H(j\omega) \]

DATA
(Sampled S/Y/Z pars)

Modeling tool

Stability/causality is enforced

Inaccurate results!

INACCURATE!

MODEL
(Netlist, differential equations, poles/residues)

Transient Simulation

RESULTS
(Time-domain)

Causality/stability violation in DATA

\[ H(j\omega) \]

DATA
(Sampled S/Y/Z pars)

Modeling tool

Stability/causality NOT enforced

Divergent results
“Timestep too small”

NOT STABLE & CAUSAL!

MODEL
(Netlist, differential equations, poles/residues)

Transient Simulation

RESULTS
(Time-domain)
Causality/stability violation in DATA

The simulator must convert the frequency data to the time-domain. It will either:
- fit a macromodel \( \rightarrow \) convergence or accuracy issues
- find the impulse response \( h(t) \) and then do convolution \( \rightarrow \) the impulse response will be non-causal

Examples:

- CORRECT
- ANTICIPATION
- NON-CAUSAL PART
Dealing with a non-causal impulse response

The simulator may:
- do nothing → non-causal waveforms
  
  **Will you trust your results?**
  (may be critical for timing analysis)

- try to compensate the violation introducing a delay

**Accuracy/timings loss**

**h(t)**

**PART**

**ANTICIPATION**

**NON-CAUSAL**


Dealing with a non-causal impulse response

The simulator may:
- eliminate the non-causal part

**Accuracy loss**

**h(t)**

**PART**

**ANTICIPATION**

**NON-CAUSAL**


Hard to devise a causality-correction method that works well in all cases!

Causal frequency data → avoid any problem!
Causality/stability violation in DATA: conclusion

- Frequency data with causality/stability violations lead to a DEAD END!
- Simulation stability or accuracy is compromised!

Best practices

- Check your frequency data for causality violations
- Robust, fully-automated algorithms exist! See [1]

- Reject “bad” datasets and avoid wasting hours trying to get “good” results from them!
- Opportunity to improve your measurement or full-wave simulation process!

Another example: high-speed connector (courtesy of IBM)

- High performance connector
- Nine signal lines (18 ports)
- Scattering parameters computed with a field solver

Scattering matrix

\[ S_{11} \]

\[ S_{22} \]

\[ \cdots \]

\[ \cdots \]

\[ \text{S}_{11} \text{ is not causal!} \]

\[ \text{True} \]

\[ \text{Computed with dispersion relations} \]

\[ \text{Re}\{S_{11}\} \]

\[ \text{Frequency [GHz]} \]
$S_{22}$ is instead consistent

Computed with dispersion relations

Modeling is problematic...

Vector Fitting error: 0.16

Model is also strongly non passive
S_{11} modeling is very problematic!

After passivity enforcement...

Final model error: 0.02

S_{22} modeling instead ends successfully!
Causality violations pattern

- $S_{11}$, $S_{33}$, $S_{55}$... violate causality
- $S_{22}$, $S_{44}$, $S_{66}$... are instead OK

Odd ports

Even ports

Something got wrong in the de-embedding of odd numbered ports

Useful information to correct the S-parameters computation!

Passivity violation in a MODEL

MODEL $H(s)$

Modelling tool

$H(j\omega)$

AC Simulation

Transient Simulation

RESULTS (Time-domain)

RESULTS (Frequency-domain)

DATA (Sampled S/Y/Z pars)
Passivity: definition

- We consider a linear system (with \( N \) ports)

\[
\mathbf{w}(t) = \int_{-\infty}^{+\infty} \mathbf{h}(\tau) \mathbf{x}(t-\tau) d\tau
\]

- **Passivity**: “the system must absorb more energy than it generates”

- True for all interconnect elements (packages, lines, connectors,...)

---

Passivity conditions for transfer functions

- Scattering representation (similar conclusions for \( Z/Y \))

**Theorem**: \( \mathbf{H}(s) \) must be **bounded real**, that is:

1. \( \mathbf{H}(s^*) = \mathbf{H}^*(s) \)

To ensure a real-valued \( h(t) \)
Passivity conditions for transfer functions

\[ \begin{array}{ccc}
\text{IN} & H(s) & \text{OUT} \\
X(s) & H(s) & W(s) \\
\end{array} \]

- Scattering representation (similar conclusions for Z/Y)
- **Theorem:** \( H(s) \) must be **bounded real**, that is:

1. \( H(s^*) = H^*(s) \)
2. \( H^T(s)H(s) \leq I \) in \( \text{Re}\{s\} > 0 \)

**Singular values of \( S \) matrix bounded by 1 in \( \text{Re}\{s\} > 0 \)**

For lumped systems, no poles in right half plane

3. each element of \( H(s) \) be analytic in \( \text{Re}\{s\} > 0 \)
Relation to stability and causality

- Passivity
- Stability
- Causality

Stability and causality are prerequisites for passivity!
Relation to stability and causality

Passivity includes all physical consistency requirements

* and the system has no poles on the imaginary axis

Stability

Causality

Passivity


Application: passivity violations in MODELS

HOW can passivity violations arise?

- Passivity not enforced by modeling algorithm
- Approximation errors
- Common problem, especially for components with low losses (e.g. short interconnects, integrated inductors/capacitors,...)

What happens if a model is not passive??
Passivity violations in MODELS: issues

Neither passivity nor stability are guaranteed!

A **non passive** model, connected to **passive** loads may lead to an **unstable** circuit!

Example:

![Diagram](image)

Not passive

---

**Figure - Passivity plot**

![Graph](image)

**Courtesy of IdemWorks s.r.l.**
Destabilizing load

We can always find a passive load that makes the whole system unstable!

A pulse is applied to port 4

Transient simulation results

- Simulation slow-down!
- Simulation stops with "Timestep too small"
- Intermittent problem
- Is the simulator unreliable?
If model passivity is instead enforced...

Consistent results!

Best practices

- Use passive models for passive components!
- If a given model violates passivity, compensate the violation with one of the well-established methods (see references at the end):
  - convex optimization
  - Hamiltonian matrices
  - linear and quadratic programming
- If violations are large, compensate violations with discretion! Or take the safe way: redo the model
Passivity violation in the DATA

**Passivity Violation**

\[ H(j\omega) \]

**DATA**
(Sampled S/Y/Z pars)

**Modeling tool**

\[ H(s) \]

**MODEL**
(Netlist, differential equations, poles/residues)

**AC Simulation**

\[ ? \]

**RESULTS**
(Frequency-domain)

**Transient Simulation**

\[ ? \]

**RESULTS**
(Time-domain)

---

Passivity in frequency domain

**Passivity conditions (frequency domain):**

1) \[ H(-j\omega) = H^*(j\omega) \]

2) \[ H^H(j\omega)H(j\omega) \leq I \]

3) Check if \( H(j\omega) \) is causal
   (i.e. check dispersion relations)

- Mind the third condition!
- Allow for a complete passivity check for tabulated data

Passivity violations in FREQUENCY DATA

HOW can passivity violations arise?

- **Numerical simulation**: poor meshing, bad models or assumptions on material properties, inaccurate solver, human mistakes

- **Measurement**: Improper VNA calibration/de-embedding, human mistake, noise

What happens if starting frequency data are not passive?

---

Example: passive vs non-passive data

For this PCB coupled lines, two different measurements were performed

- Improper calibration
- S-parameters measured with VNA

Non-passive dataset

Passive dataset
**Example: passive vs non-passive data**

![Graph showing the comparison between passive and non-passive data for magnitude and phase.](image)
Example: passive vs non-passive data

One dataset violates passivity

Passive data

Non-passive data

\[ H(s) \]  \[ H(s) \]

Vector Fitting

Passivity Enforcement

?
**Example: passive vs non-passive data**

<table>
<thead>
<tr>
<th>Vector Fitting model order</th>
<th>Non-passive data</th>
<th>Passive data</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Example: passive vs non-passive data**

<table>
<thead>
<tr>
<th>Vector Fitting model order</th>
<th>Passivity not enforced</th>
<th>Non-passive data</th>
<th>Passive data</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model is not passive!
Example: passive vs non-passive data

<table>
<thead>
<tr>
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<td>0.020</td>
<td>0.11</td>
</tr>
<tr>
<td>18</td>
<td>0.017</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Passive & accurate!
Passivity violation in the DATA

\[ H(j\omega_k) \]

(Sampled S/Y/Z pars)

Transient Simulation

Convolution-based

RESULTS
(Time-domain)

Convolution simulation setup

- The coupled lines (represented by the Touchstone file) are connected to a destabilizing load

All ports loaded with

- 1.3 Ohm
- 1.9 kOhm
- 4.18 nH

A 1mA current pulse is applied to port 4

The same analysis is repeated with the **passive S-parameters**
Convolution simulation

At t~0.93 us simulation breakdown (timestep too small)

Convolution simulation (passivity enforcement ON)

No breakdown
Convolution simulation (passivity enforcement ON)

The enforcement of large passivity violations may compromise accuracy! Double check or redo the measurement!

Best practices

- If you have a dataset with significant passivity violations, you will have to renounce to either:
  - accuracy (will you trust your results?)
  - model passivity (simulations may diverge!)

- Promptly scan your measured/simulated data for passivity violations! For an algorithm, see [1]
- And reject “bad” datasets!

Conclusion

- Comprehensive overview of causality, stability & passivity and their interrelations

- Impact of physical consistency violations on modeling and simulation tasks
  - models with violations → divergent simulations!
  - data with violations → either inaccurate models or unstable simulations

- When consistency is preserved → Accuracy, speed and reliability of CAD tools is maximized!

Conclusion

- Being aware of the importance of physical consistency can improve the design workflow significantly!
Conclusion

- Problems can be fixed right away!
- Physical consistency checks greatly help to identify the real source of the problems!

![Diagram showing the process of measurement, modeling, and simulation with wasted time indicated: 1h and >1 day.]

Thank you!
Bibliography: high-speed interconnects


Bibliography: Vector Fitting

Bibliography: passivity enforcement


Bibliography: transmission lines macromodeling

Bibliography: delay-based macromodeling


Bibliography: multivariate macromodeling

Bibliography: stability, passivity and causality