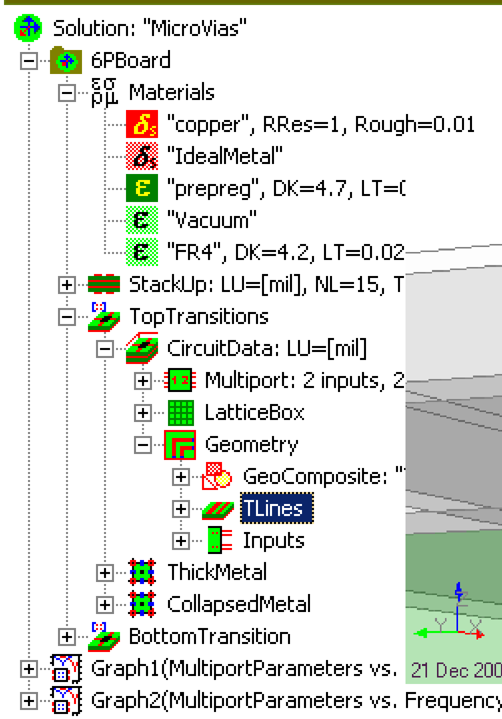
Reflections on S-parameter Quality

DesignCon IBIS Summit, Santa Clara, February 3, 2011



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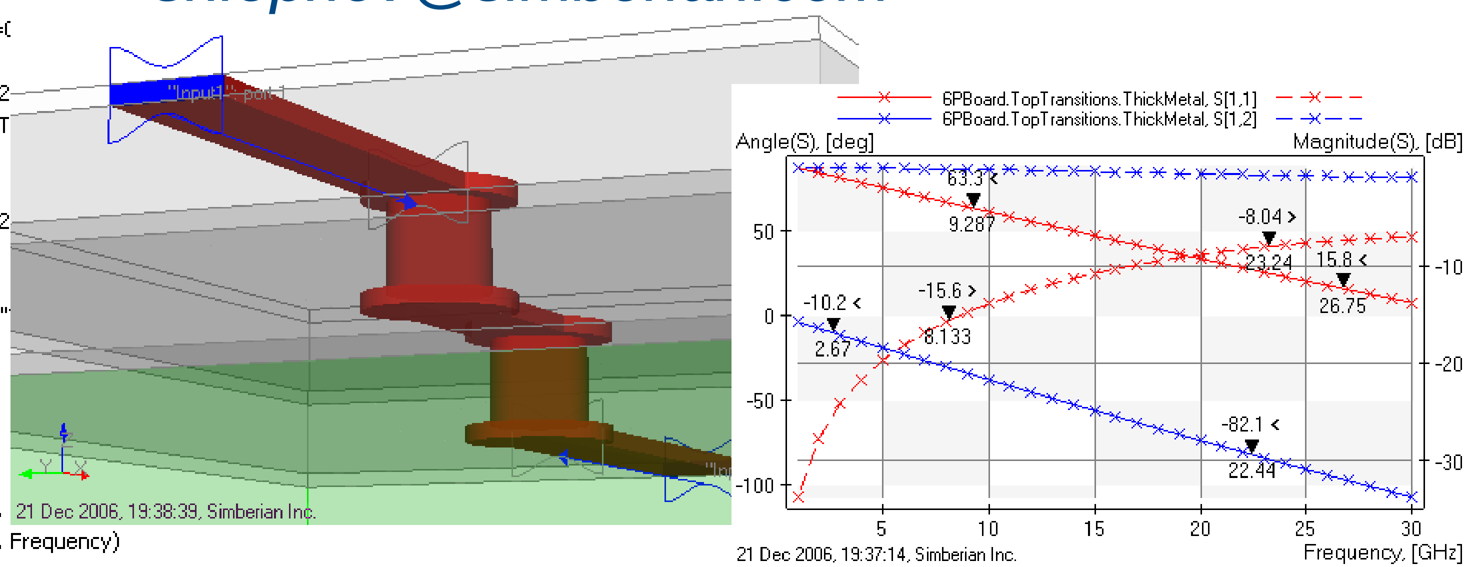


Outline

- Introduction
- Quality of S-parameter models
- Rational macro-models of S-parameters and final quality metric
- Examples
- Conclusion
- Contacts and resources

Introduction

- S-parameter models are becoming ubiquitous in design of multi-gigabit interconnects
  - Connectors, cables, PCBs, packages, backplanes, … ,any LTI-system in general can be characterized with S-parameters from DC to daylight
- Electromagnetic analysis or measurements are used to build S-parameter Touchstone models
- Very often such models have quality issues:
  - Reciprocity violations
  - Passivity and causality violations
  - Common sense violations
- And produce different time-domain and even frequency-domain responses in different solvers!

What are the major problems?

- Model bandwidth deficiency
  - S-parameter models are band-limited due to limited capabilities of solvers and measurement equipment
  - Model should include DC point or allow extrapolation, and high frequencies defined by the signal spectrum
- Model discreteness
  - S-parameter models are matrix elements at a set of frequencies
  - Interpolation or approximation of tabulated matrix elements may be necessary both for time and frequency domain analyses
- Model distortions due to
  - Measurement or simulation artifacts
  - Passivity violations and local “enforcements”
  - Causality violations and “enforcements”
- Human mistakes of model developers and users in general

Pristine models of interconnects

- Must have sufficient bandwidth matching signal spectrum
- Must be appropriately sampled to resolve all resonances
- Must be reciprocal (linear reciprocal materials used in PCBs)

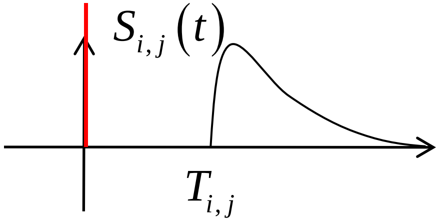
$$S_{i,j} = S_{j,i} \quad or \;\; S = S^t$$

- Must be passive (do not generate energy)

$P_{in} = \overline{a}^* \cdot \left[U - S^* S \right] \cdot \overline{a} \; \geq 0 \;\; \Rightarrow \;\; eigenvals\left[S^* \cdot S \right] \leq 1$ from DC to infinity!

- Have causal step or pulse response (response only after the excitation)

$$S_{i,j}\left(t\right) = 0, \;\; t < T_{ij}$$



What if models are not pristine?

- Reciprocity, passivity and causality metrics was recently introduced for the model pre-qualification at DesignCon 2010 IBIS summit (references at the end)
- Models with low metrics must be discarded!
- Models that pass the quality metrics may still be not usable or mishandled by a system simulator
- The main reasons are band-limitedness, discreteness and brut force model fixing

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Computation of system response requires frequency-continuous models

TD

stimulus

$\bar{a}(t)$

pulse response matrix

$S(t)$

system response – time domain (TD)

$$\bar{b}(t)=\int_{-\infty}^{\infty} S(t-\tau)\cdot\bar{a}(\tau)\cdot d\tau$$

Fourier Transforms

FD

$\bar{a}(i\omega)$

stimulus

$S(i\omega)$

scattering matrix

$$\bar{b}(i\omega)=S(i\omega)\cdot\bar{a}(i\omega)$$

system response – frequency domain (FD)

$$S(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} S(i\omega)\cdot e^{i\omega t}\cdot d\omega,\quad S(t)\in R^{N\times N} \quad \Leftrightarrow \quad S(i\omega)=\int_{-\infty}^{\infty} S(t)\cdot e^{-i\omega t}\cdot dt,\quad S(i\omega)\in C^{N\times N}$$

For TD analysis we can either use Discrete Fourier Transforms (DFT) and convolution or approximate discrete S-parameters with frequency-continuous causal functions with analytical pulse response

Rational approximation of S-parameters is such frequency-continuous model

$$\bar{b} = S \cdot \bar{a},\quad S_{i,j} = \left.\frac{b_i}{a_j}\right|_{a_k=0\ k\neq j} \Rightarrow S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}} \left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r^*_{ij,n}}{i\omega - p^*_{ij,n}} \right) \right] \cdot e^{-s \cdot T_{ij}}$$

$$s = i\omega,\ d_{ij} - values\ at\ \infty,\ N_{ij} - number\ of\ poles,$$

$$r_{ij,n} - residues,\ p_{ij,n} - poles\ (real\ or\ complex), T_{ij} - optional\ delay$$

Continuous functions of frequency defined from DC to infinity

- Pulse response is analytical, real and delay-causal:

$$S_{i,j}(t) = 0,\ t < T_{ij}$$

$$S_{i,j}(t) = d_{ij}\delta(t - T_{ij}) + \sum_{n=1}^{N_{ij}} \left[r_{ij,n} \cdot \exp\left(p_{ij,n} \cdot (t - T_{ij}) \right) + r^*_{ij,n} \cdot \exp\left(p^*_{ij,n} \cdot (t - T_{ij}) \right) \right],\ t \geq T_{ij}$$

- Stable $\mathrm{Re}\left(p_{ij,n}\right) < 0$
- Passive if $eigenvals\left[S(\omega) \cdot S^*(\omega) \right] \leq 1\ \forall \omega,\ from\ 0\ to\ \infty$
- Reciprocal if $S_{i,j}(\omega) = S_{j,i}(\omega)$

May require enforcement

Bandwidth and sampling for rational approximation

- If no DC point, the lowest frequency in the sweep should be
  - Below the transition to skin-effect (1-50 MHz for PCB applications)
  - Below the first possible resonance in the system (important for cables, L is physical length)

$$L < \frac{\lambda}{4} = \frac{c}{4 f_l \cdot \sqrt{\varepsilon_{eff}}} \Rightarrow f_l < \frac{c}{4L \cdot \sqrt{\varepsilon_{eff}}}$$

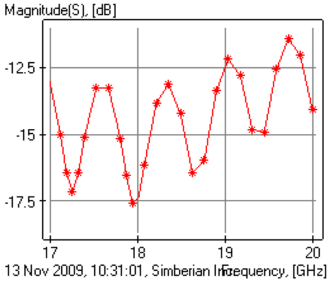
- The highest frequency in the sweep must be defined by the required resolution in time-domain or by spectrum of the signal (by rise time or data rate)

$$f_h > \frac{1}{2t_r}$$

- The sampling is very important for DFT and convolution-based algorithms, but not so for algorithms based on fitting

$$df < \frac{c}{4L \cdot \sqrt{\varepsilon_{eff}}}$$

  - There must be 4-5 frequency point per each resonance
  - The electrical length of a system should not change more than quarter of wave-length between two consecutive points



Rational approximation can be used for

- Compute time-domain response of a channel with a fast recursive convolution algorithm (exact solution for PWL signals)
- Improve quality of tabulated Touchstone models
  - Fix minor passivity and causality violations
  - Interpolate and extrapolate with guarantied passivity
- Produce broad-band SPICE macro-models
  - Smaller model size, stable analysis
  - Consistent frequency and time domain analyses in any solver
- Measure the original model quality with the Root Mean Square Error (RMSE) of the rational approximation:

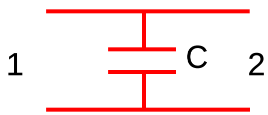
$$Q = 100 \cdot \max\left(1 - RMSE, 0\right)\% \qquad RMSE = \max_{i,j}\left[\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|S_{ij}(n) - S_{ij}(\omega_n)\right|^2}\right]$$

So, how to avoid bad S-parameters?

- Use reciprocity and passivity metrics for preliminary analysis
  - RQM and PQM metrics should be > 80%
- Use the rational model quality metric as the final measure
  - QM should be > 90%
- Otherwise discard the model
  - The main reason is we do not know what it originally was and should be – no information

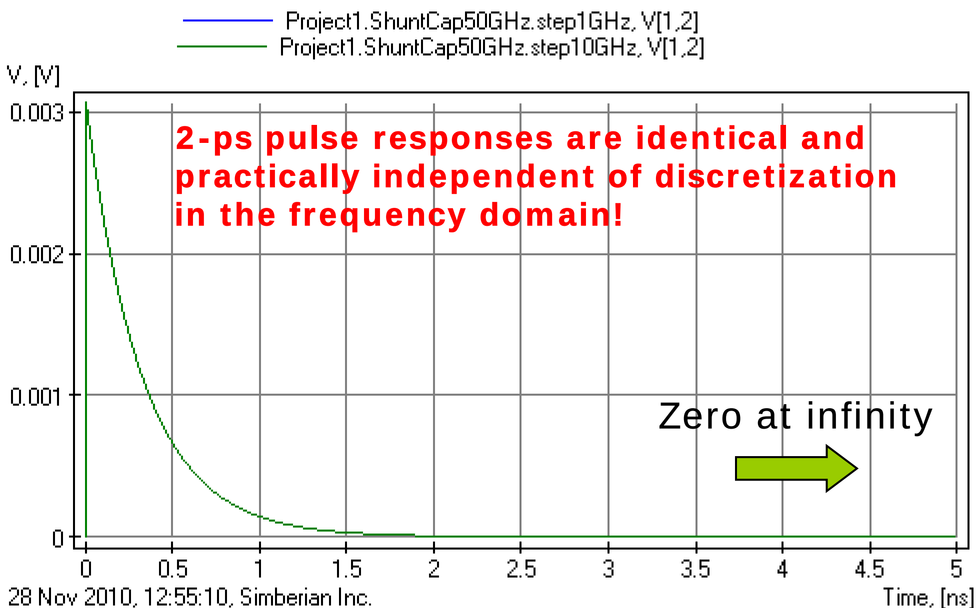
Example 1: Network with one real pole – shunt capacitor sampled up to 50 GHz

- 13 pF capacitance shunt to the ground

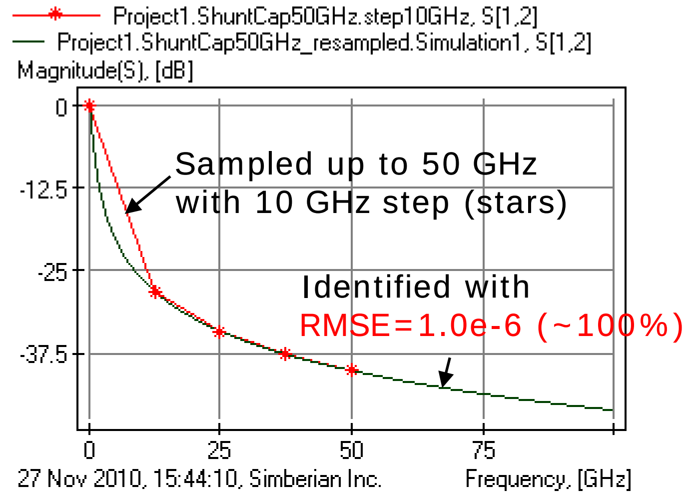


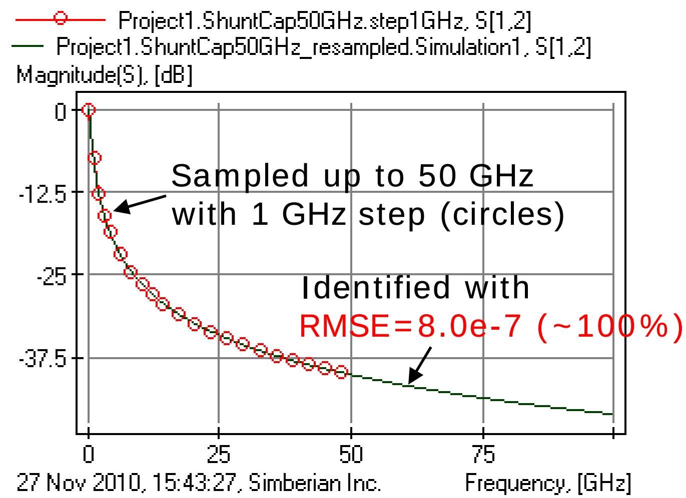
$$S_{1,2} = \frac{1}{1 + i\omega \cdot \frac{1}{2} C \cdot Z_0}$$

real pole at 489.707 MHz can be identified with just 5 frequency samples



No artifacts!





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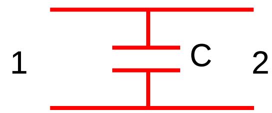
Example 1: Network with one real pole – shunt capacitor sampled up to 5 GHz

- 13 pF capacitance shunt to the ground



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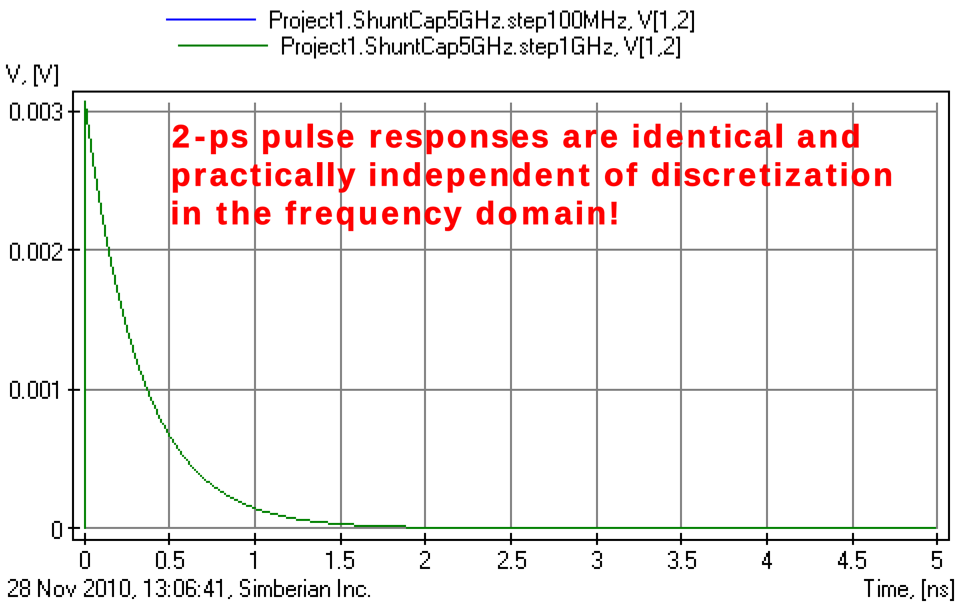
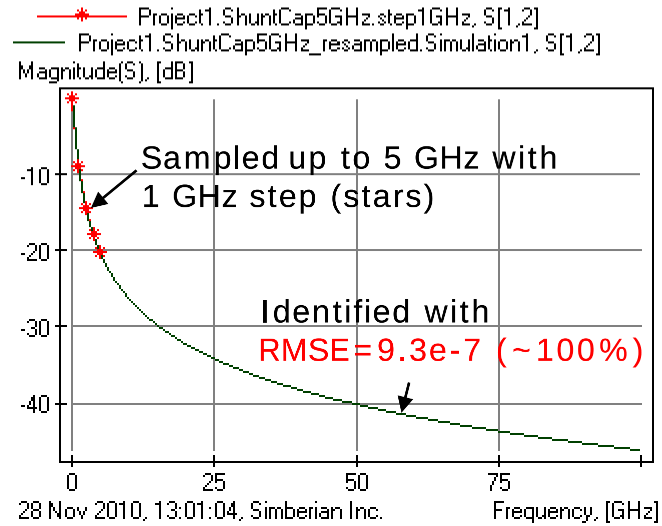
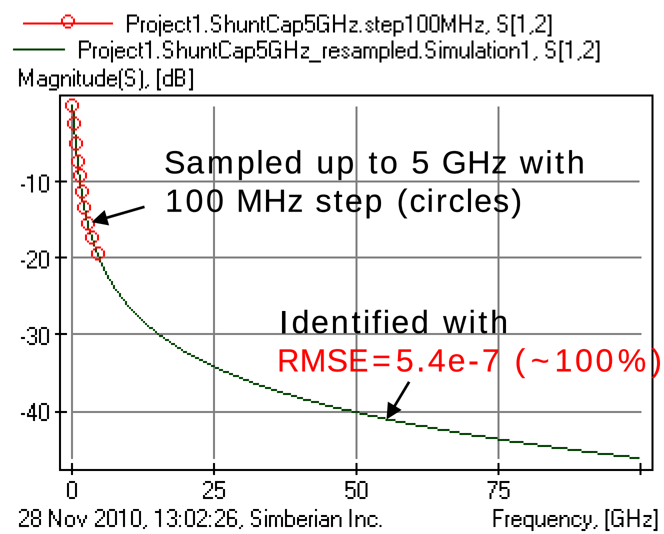


Still no artifacts!





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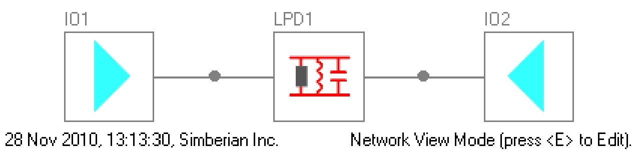
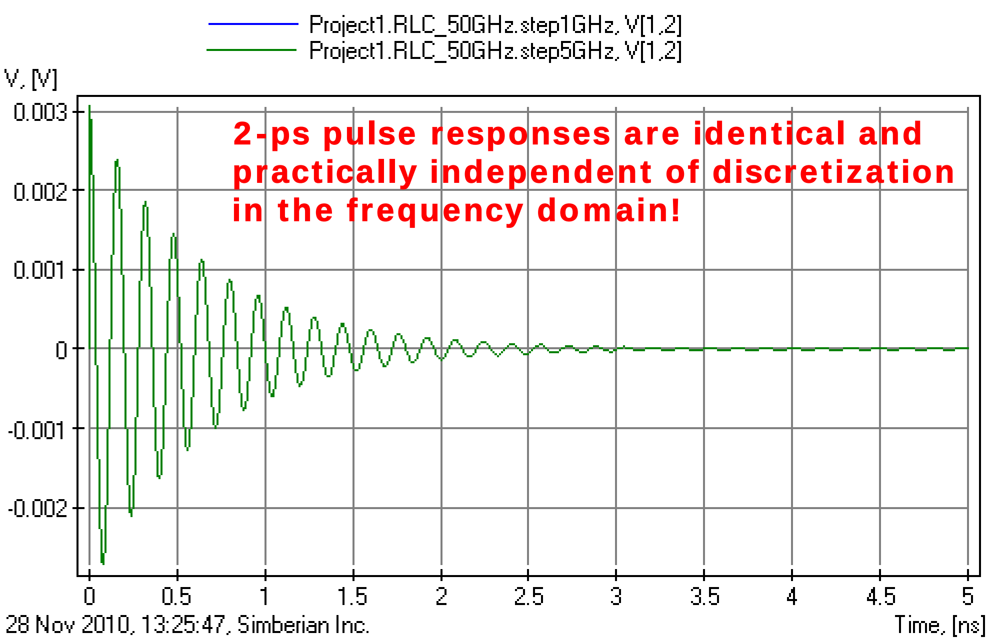
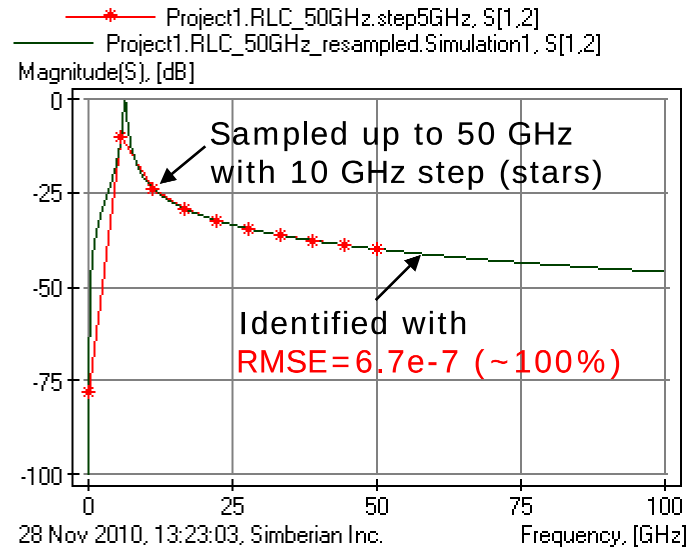
Example 2: Network with two complex poles – shunt RLC circuit sampled up to 50 GHz

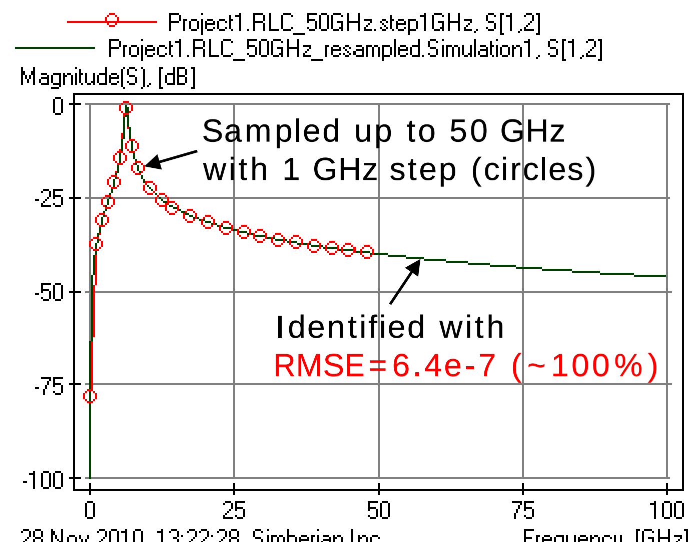
- Shunt tank: C=13 pF, L=50 pH, R=1 K



resonance at 6.24 GHz can be identified with 5 frequency samples

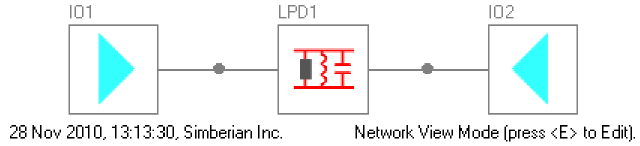






Example 2: Network with two complex poles – shunt RLC circuit sampled up to 5 GHz

- Shunt tank: C=13 pF, L=50 pH, R=1 K



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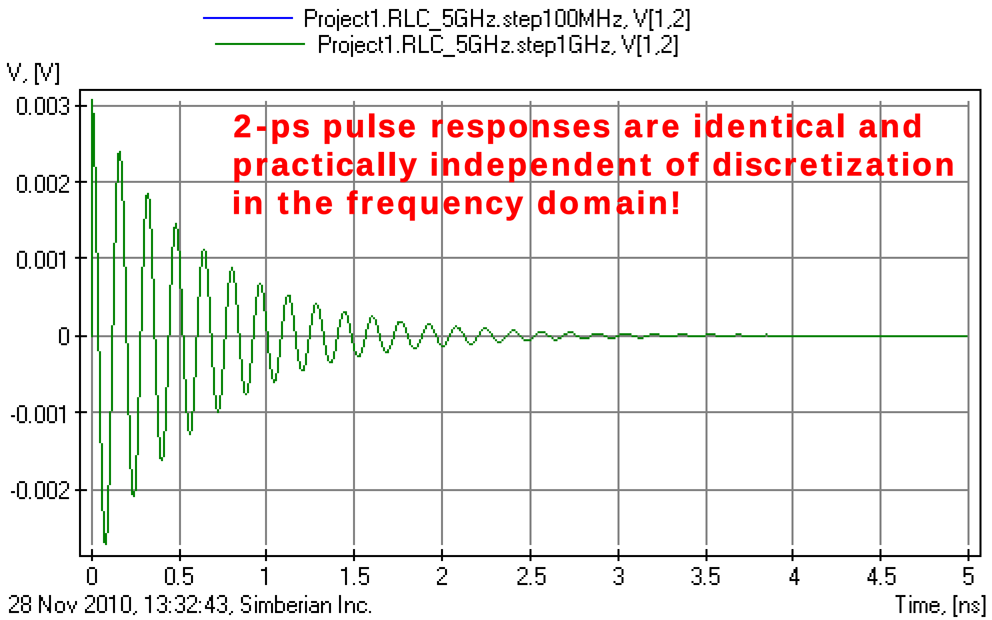
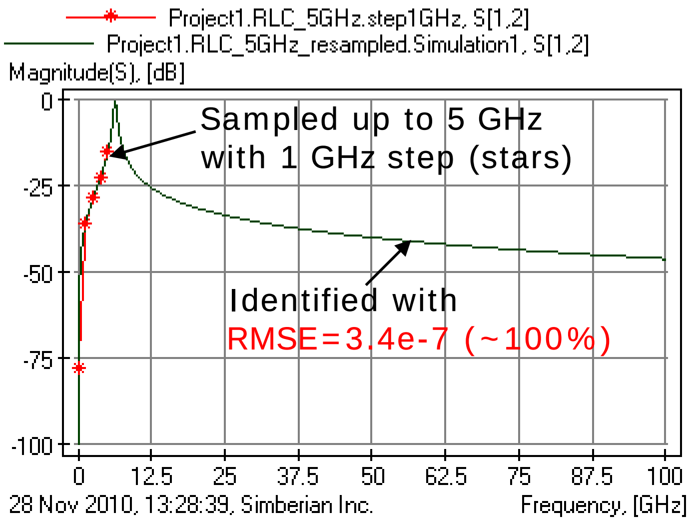
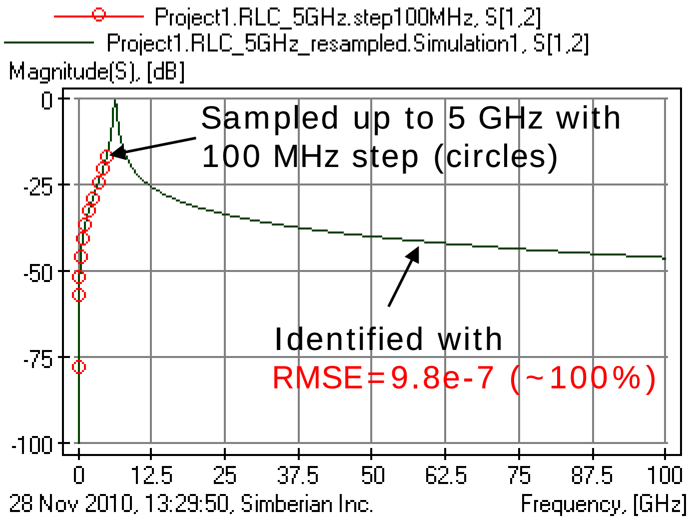
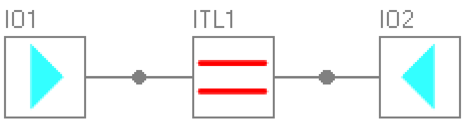






Example 3: Network with infinite number of poles – segment of ideal transmission line

- T-line segment: Zo=50 Ohm, Td=1 ns
  50 Ohm termination
- |S11| is exactly 0 from DC to infinity
- |S12| is exactly 1 from DC to infinity
- Phase is growing linearly
- Group Delay is exactly 1 ns from DC to infinity
- Such network is obviously non-physical
- We will try to sample and approximate |S21| over some frequency band and compare the step responses



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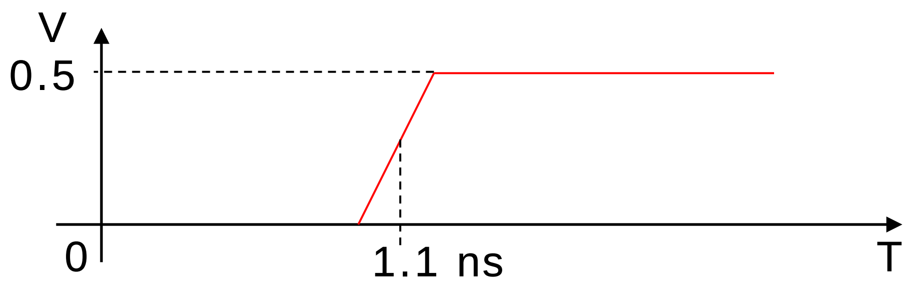
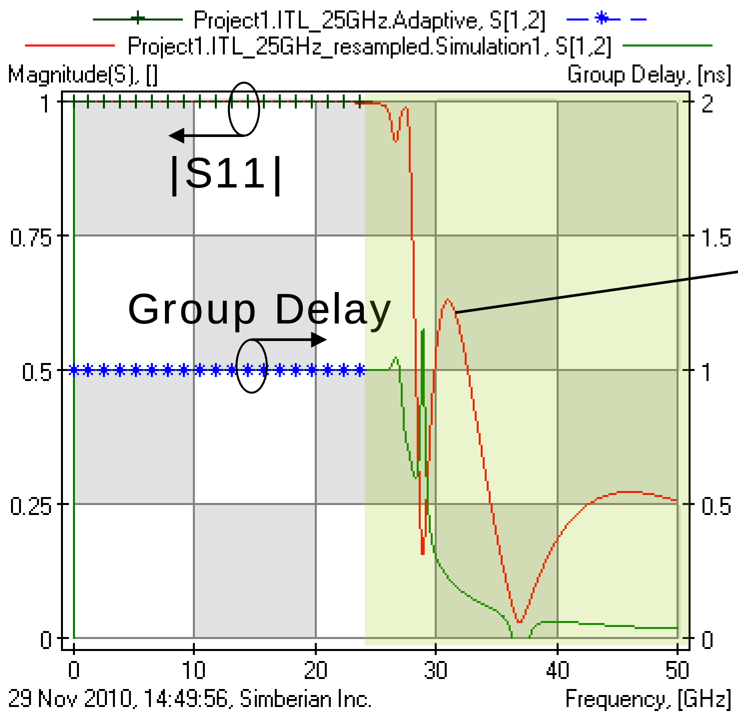
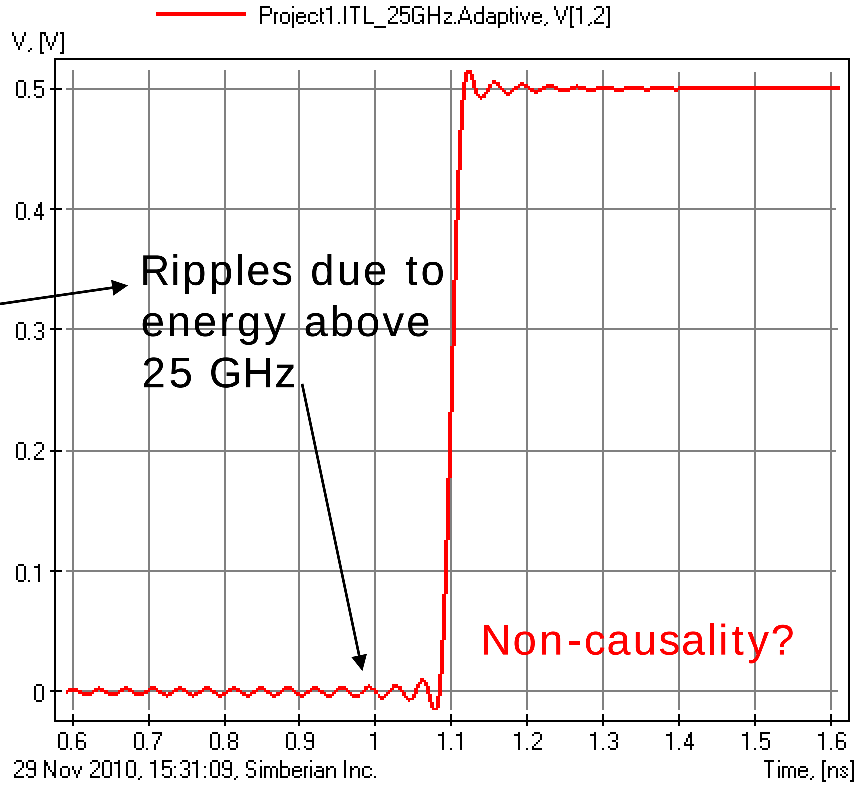
Exact response to 100 ps delayed step with 20 ps rise time (10-90%)



Example 3: Segment of ideal transmission line sampled up to 25 GHz

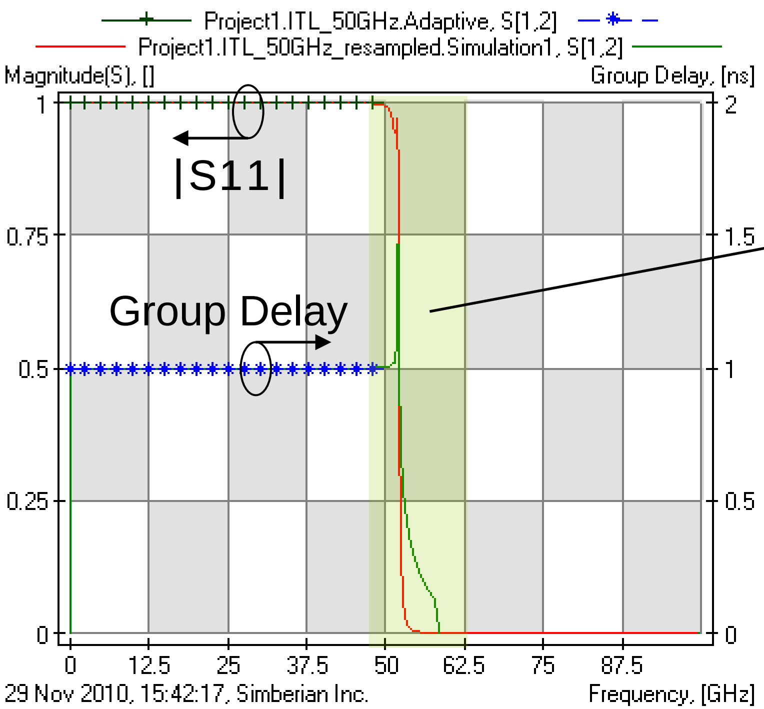
- Sampled with adaptive frequency sweep from 1 MHz to 25 GHz (628 samples) – stars and pluses on the left graph
- Approximated with rational macro-model with 100 poles (RMSE=0.0037, Q=99.63) – solid lines on left graph and TD graph

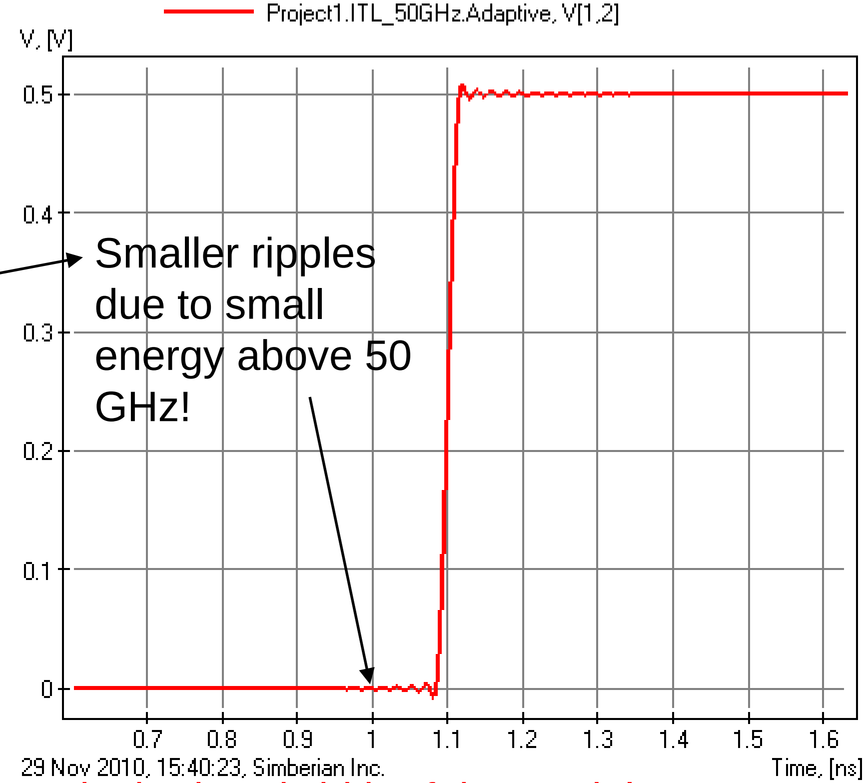




Example 3: Segment of ideal transmission line sampled up to 50 GHz

- Sampled with adaptive sweep from 1 MHz to 50 GHz (1278 samples) – stars and pluses on the left graph
- Approximated with rational macro-model with 190 poles (RMSE=0.0045, Q=99.55) – solid lines on left graph and TD graph





Spectrum of ramped step stimulus still exceeds the bandwidth of the model!

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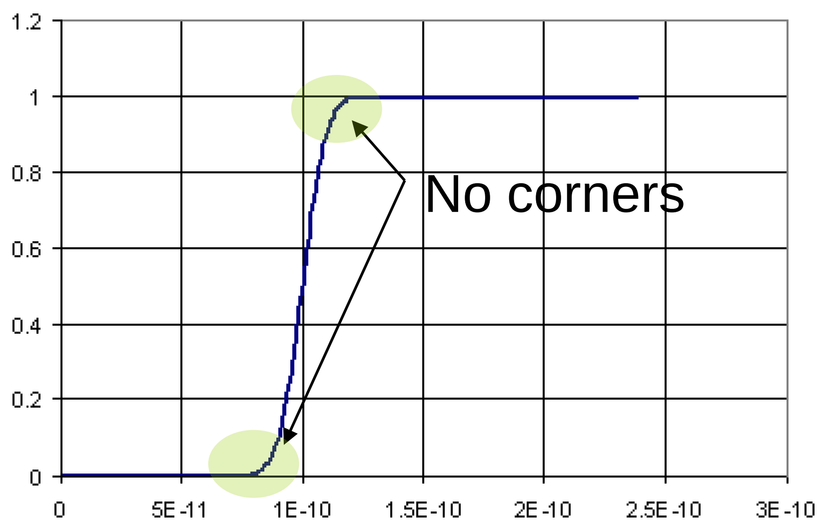
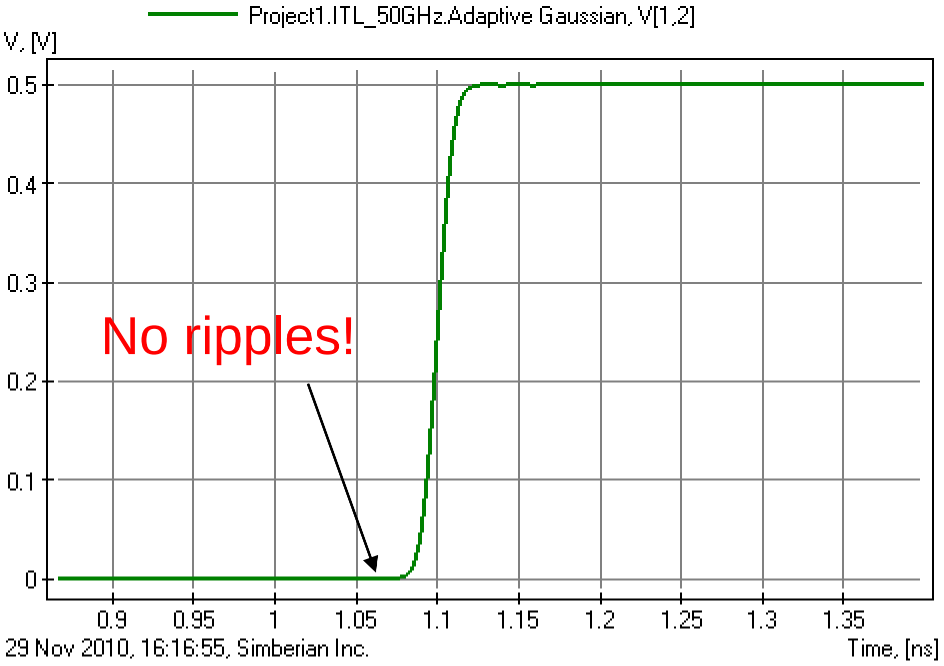
Example 3: Segment of ideal transmission line sampled up to 50 GHz

Gaussian step stimulus with 20 ps rise time (10-90%)
Spectrum: -20 dB at 44 GHz and -40 dB at 62 GHz

Gaussian Step (ideal step filtered with the Gaussian filter)



Rational Macro-Model Response



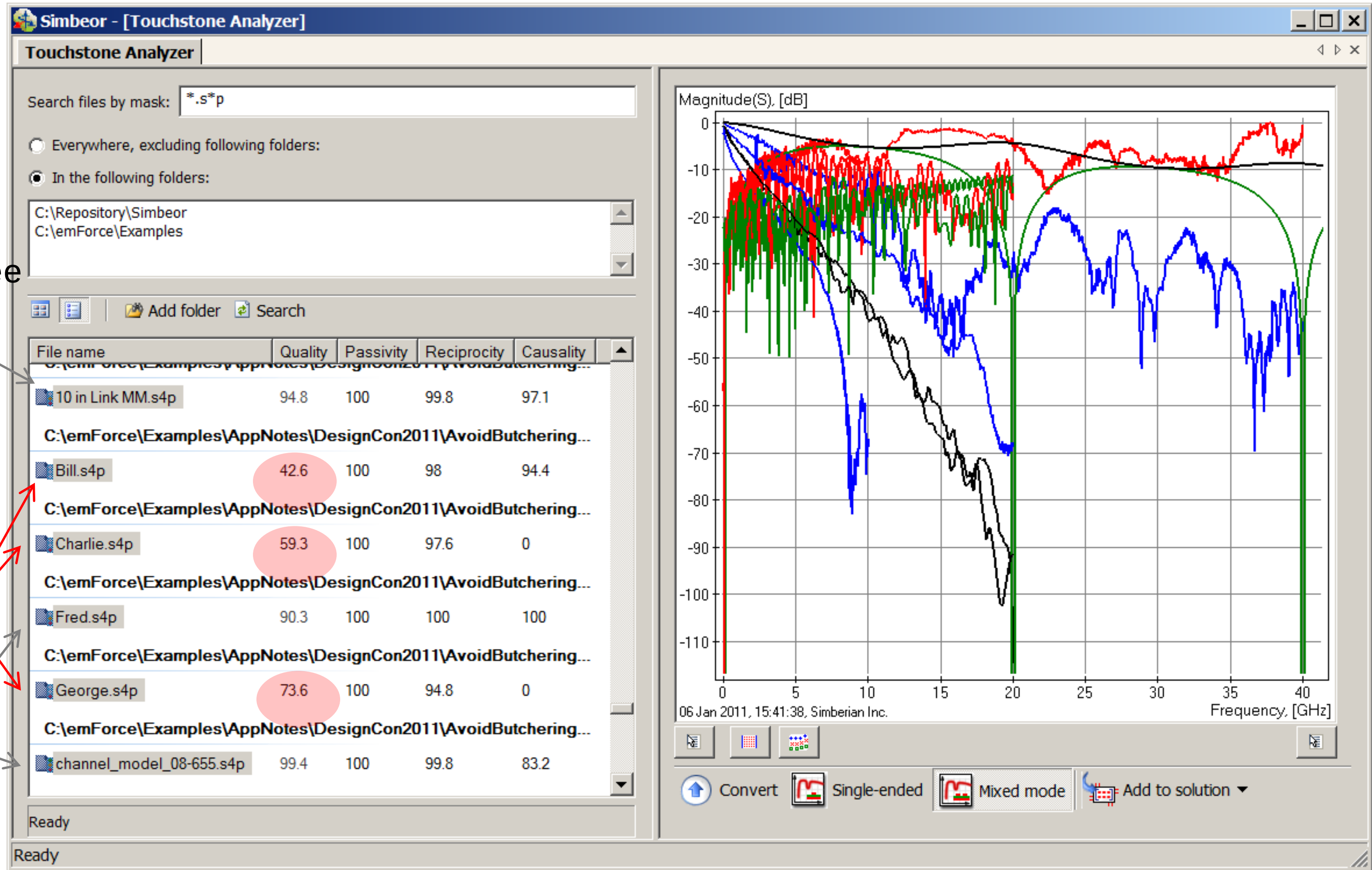
No ripples in the computed time-domain response – model bandwidth matches the excitation spectrum!

Practical examples from panel TP-T3

Acceptable (see next slides)

Discard

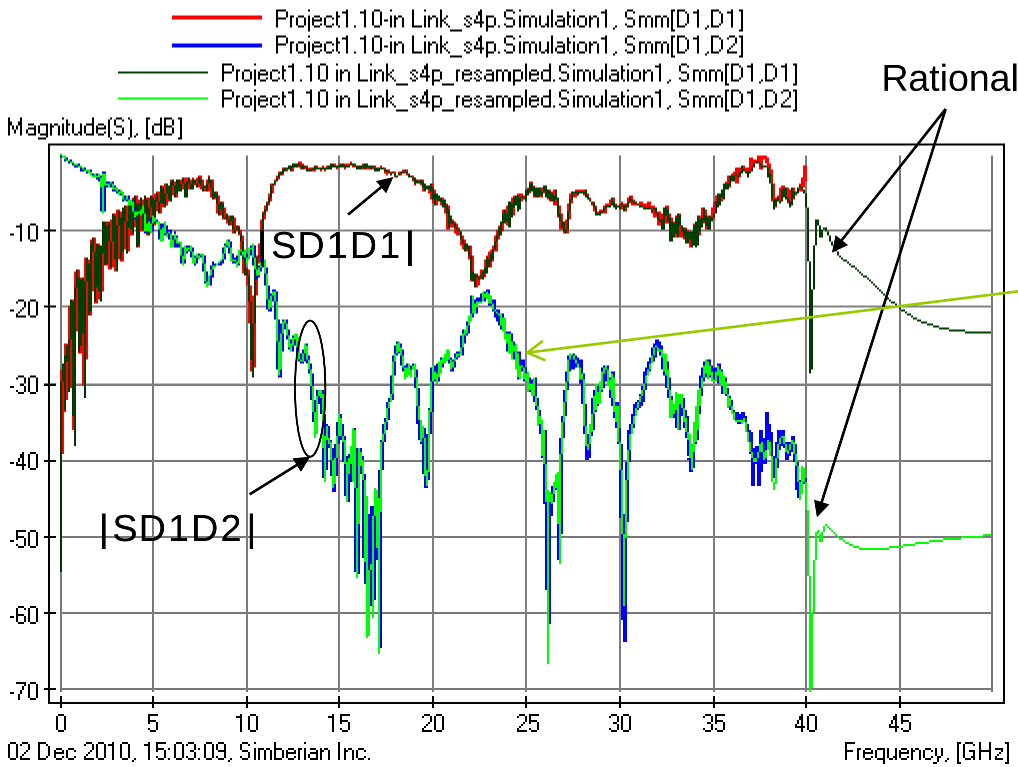
Acceptable



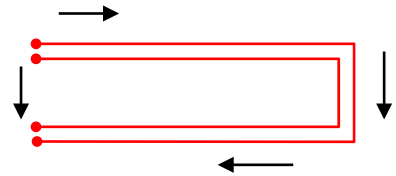
Common sense analysis of system response may be also useful

Acceptable Measured Model Example: U-shaped 10-in differential link

- Model supplied by Peter Pupalaikis (LeCroy), 2001 points from 0 to 40 GHz
- 4 by 4 S-matrix is approximated with rational macro-model with 300-400 poles per element, max RMSE=0.055, Q=94.5%

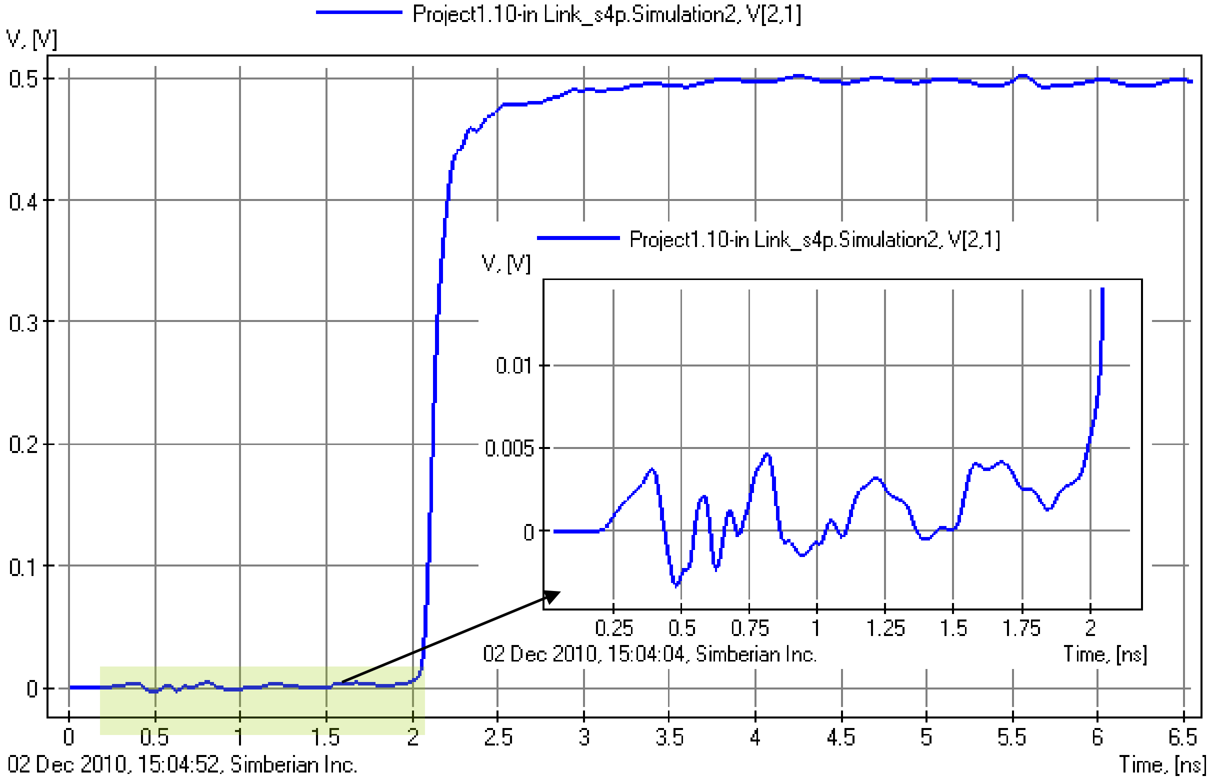


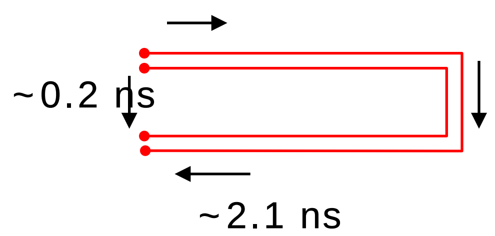
There is transmission along the traces and additional pad-to-pad transmission at all frequencies



Acceptable Measured Model Example: U-shaped differential link TDT

- 40 ps 10-90% Gaussian step response (-20 dB at 22 GHz, -40 dB at 31 GHz)





- The response shows clearly that there are “shortcuts” in the system
- Any “causality enforcement” may be erroneous for such cases!

Conclusion

- Models must be appropriately sampled over the bandwidth matching the signal spectrum
- Reciprocity, passivity and causality of interconnect component models must be verified before use
  - Both measured and computational models may have severe problems and not acceptable for any analysis
- Rational macro-models with controlled accuracy over the model frequency band can be used to
  - Do consistent frequency and time domain analyses
  - Estimate quality of the tabulated models
- Bad models with small quality metrics must be discarded

Contact and resources

- Yuriy Shlepnev, Simberian Inc.
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  Tel: 206-409-2368
- Free version of software used to plot and estimate quality of S-parameters is available at www.simberian.com
- To learn more on S-parameters quality see the following presentations (also available on request):
  - Y. Shlepnev, Quality Metrics for S-parameter Models, DesignCon 2010 IBIS Summit, Santa Clara, February 4, 2010
  - H. Barnes, Y. Shlepnev, J. Nadolny, T. Dagostino, S. McMorrow, Quality of High Frequency Measurements: Practical Examples, Theoretical Foundations, and Successful Techniques that Work Past the 40GHz Realm, DesignCon 2010, Santa Clara, February 1, 2010.
  - E. Bogatin, B. Kirk, M. Jenkins,Y. Shlepnev, M. Steinberger, How to Avoid Butchering S-Parameters, DesignCon 2011