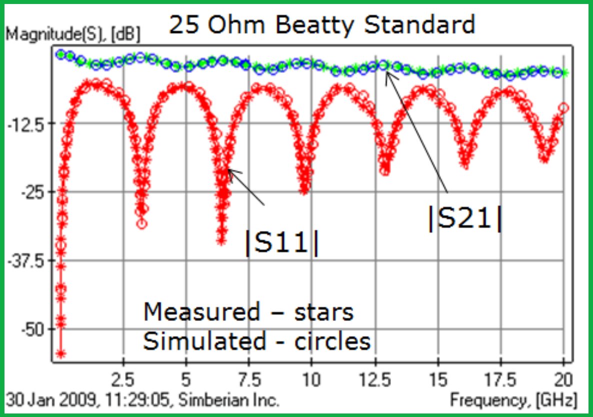
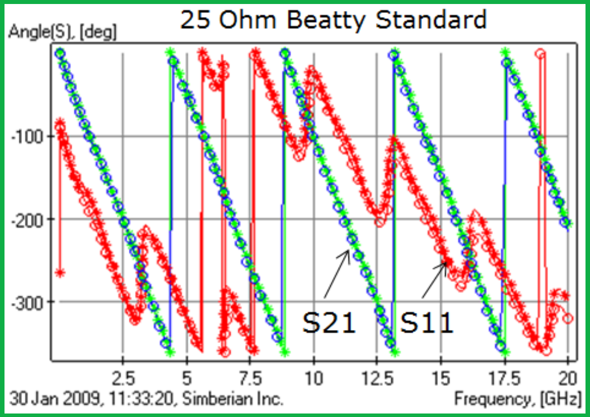
Getting Simulations to Match Measurements (simulation outlook)

Yuriy Shlepnev

Simberian Inc.

www.simberian.com





ANRITSU Signal Integrity Symposium, Santa Clara and Newport Beach, CA, July 2014

Anritsu envision : ensure

Simberian Electromagnetic Solutions

wildriver technology

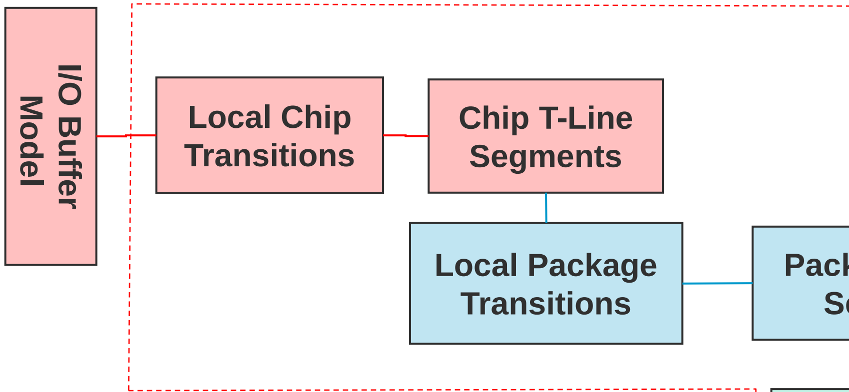
Outline

- Introduction
- Quality of S-parameter models
- Broadband material models
- Modeling discontinuities in isolation
- Validation and benchmarking
- Conclusion
- References and contacts

Introduction

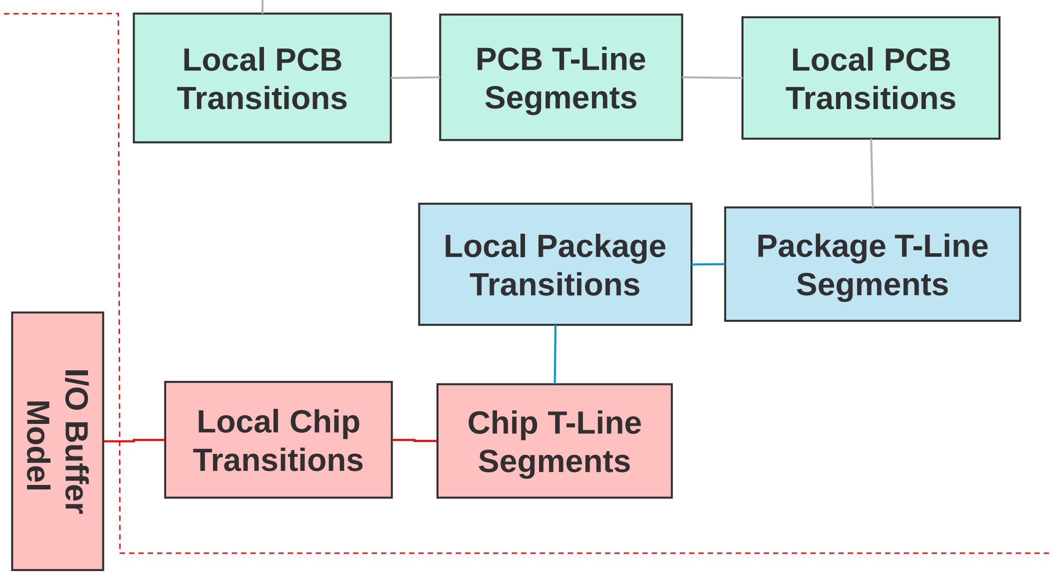
- 10G Ethernet is practically mainstream now, 25-50 G is coming out…
  - Spectrum of signals ranges from DC or MHz frequencies up to 20-50 GHz and beyond – no established methodologies to design predictable interconnects
  - Improper interconnect modeling may result in multiple re-spins or complete failure due to interconnects
- What is the best way to analyze such interconnects?
  - Electromagnetic analysis as a whole?
    - Suitable for EMC/EMI (radiation)
    - Inefficient for signal integrity analysis due to problem size and fine details
  - Decompositional electromagnetic analysis is the alternative
    - Divide into elements, build or get element models and unite
    - 2D, 3D, quasi-static or full-wave models can be used for the elements
    - **Fast and also accurate if some conditions are satisfied…**

Decompositional analysis of a channel



Connection of MULTIPORTS

Transmission lines (may be coupled) and mostly localizable via-holes, connectors, bond-wires, bumps and ball transitions



To enable pre- and post-layout de-compositional analysis that correlates with measurements:

1) Quality of all S-parameter models must be ensured

2) Simulation in isolation must be possible and coupling accounted

3) Material models identified

4) Models validated with manufacturing & measurements

4 conditions for design success!

(1) Quality of S-parameter models

- Multiports are usually described with S-parameter models
  - Produced by circuit or electromagnetic simulators, VNAs and TDNAs in forms of Touchstone or BB SPICE models
- Very often such models have issues and may be not suitable for consistent frequency and time domain analyses
  - S-parameter models must have sufficient bandwidth and satisfy passivity, reciprocity and causality conditions
- How to make sure that a model is suitable for analysis?
- The answer is the key element for design success

Common S-parameter model defects

- Model distortions due to
  - Measurement or simulation artifacts (passivity, causality, reciprocity)
  - Passivity and causality brut force “enforcements”
- Model bandwidth deficiency
  - S-parameter models are band-limited due to limited capabilities of solvers and measurement equipment (on both ends of spectrum)
- Model discreteness
  - Touchstone models are matrix elements at a set of frequencies
  - Interpolation and extrapolation of tabulated matrix elements may be necessary both for time and frequency domain analyses
- Human mistakes of model developers and users
- How to rate quality of the models?

Passivity, Reciprocity and Causality quality metrics introduced earlier in Simbeor software can be used for preliminary estimation of model quality

Model quality estimation with rational approximation in Simbeor software

- Accuracy of discrete S-parameters approximation with frequency-continuous macro-model, passive from DC to infinity

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

original tabulated data

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

- Can be used to estimate quality of the original data

$$Q = 100\cdot\max\left(1 - RMSE, 0\right)\%$$

Model Icon/Quality	Quality Metric	RMSE
- good	[99, 100]	[0, 0.01]
- acceptable	[90, 99)	(0.01, 0.1]
- inconclusive	[50, 90)	(0.1, 0.5]
- bad	[0, 50)	> 0.5
- uncertain	[0,100], not passive or not reciprocal	

Rational model can be used instead of the original data

Model bandwidth and sampling

- 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)

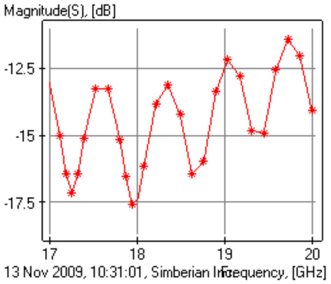
$$L < \frac{\lambda}{4} = \frac{c}{4 f_l \cdot \sqrt{\varepsilon_{eff}}} \Rightarrow f_l < \frac{c}{4L \cdot \sqrt{\varepsilon_{eff}}}$$

- 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 and data rate)

$$f_h > \frac{1}{2t_r} \qquad f_h > K \cdot f_{s1}$$

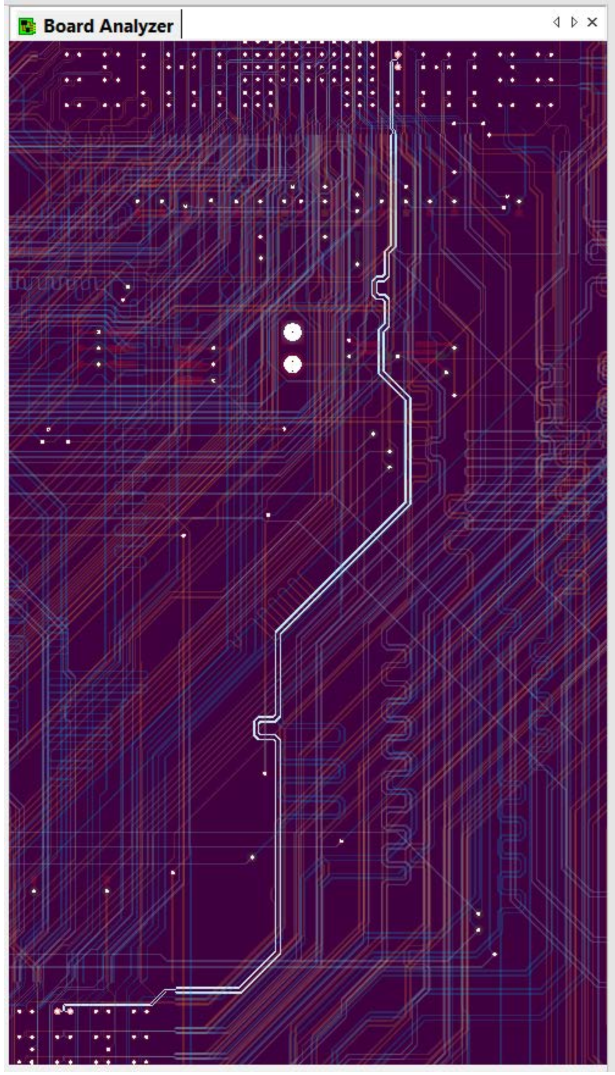
- The sampling is very important for DFT and convolution-based algorithms, but not so for algorithms based on the rational approximation
  - There must be 4-5 frequency point per each resonance
  - The electrical length of a system should not change more than quarter of wave-length between two consecutive points

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



(2) Broadband material models

- The largest part of interconnects are transmission line segments
- Models for transmission lines are usually constructed with a quasi-static or electromagnetic field solvers
  - T-lines with homogeneous dielectrics (strip lines) can be effectively analysed with quasi-static field solvers
  - T-lines with inhomogeneous dielectric may require analysis with a full-wave solver to account for the high-frequency dispersion
- Accuracy of transmission line models is mostly defined by **availability of broadband dielectric and conductor roughness models**
- This is another most important elements for design success



Common broadband material models

- **Common PCB dielectric models:**

Wideband Debye (aka Djordjevic-Sarkar or Swensson-Dermer):

$$\varepsilon(f) = \varepsilon_r(\infty) + \frac{\varepsilon_{rd}}{(m_2 - m_1)\cdot \ln(10)} \cdot \ln\left[\frac{10^{m2} + if}{10^{m1} + if}\right]$$

Continuous-spectrum model
Requires specification of DK and LT at one frequency point (2 parameters)

Multi-pole Debye:

$$\varepsilon(f) = \varepsilon(\infty) + \sum_{n=1}^{N} \frac{\Delta\varepsilon_n}{1 + i\dfrac{f}{fr_n}}$$

Requires specification of value at infinity and poles/residues or DK and LT at multiple frequency points (more than 2 parameters)

- **Common conductor surface roughness models:**

Modified Hammerstad (2 parameters):

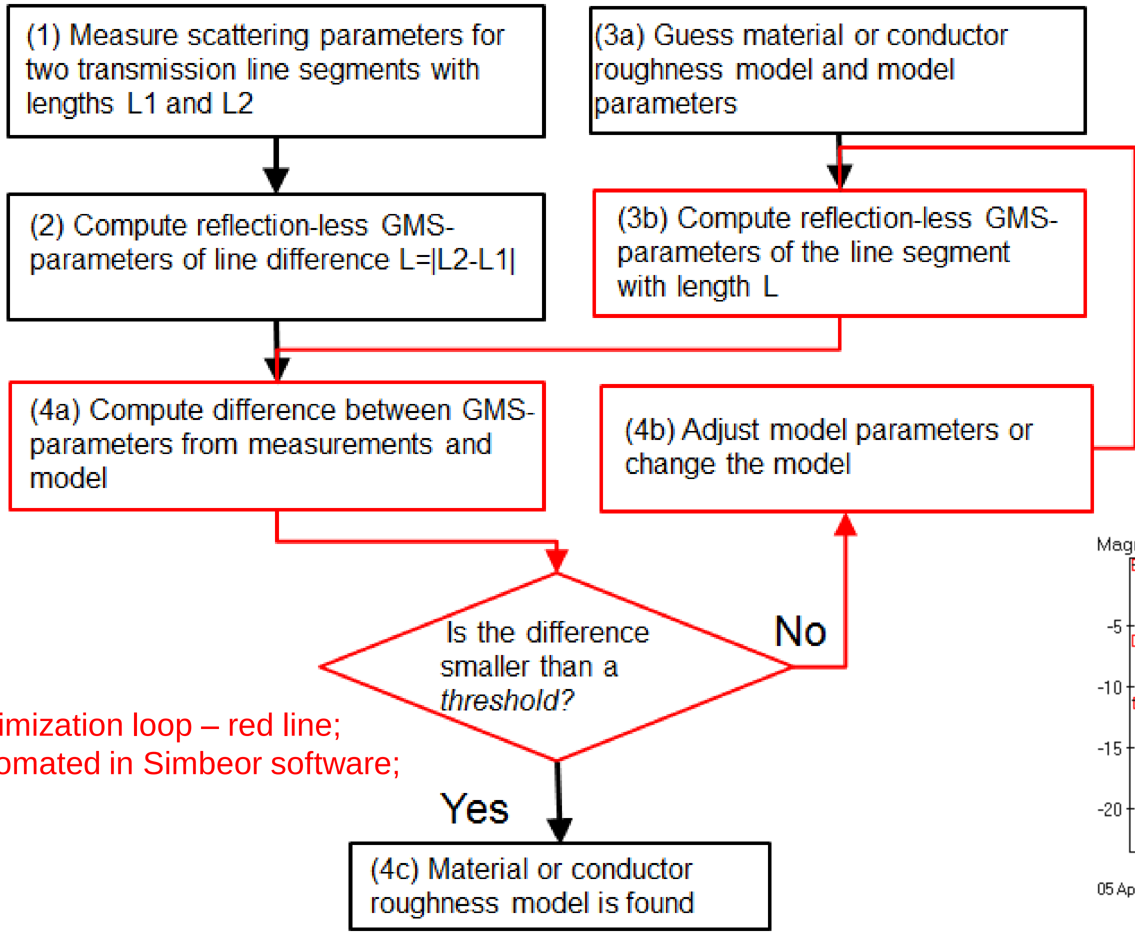
$$K_{rh} = 1 + \left(\frac{2}{\pi}\cdot \arctan\left[1.4\left(\frac{\Delta}{\delta}\right)^2\right]\right)\cdot (RF - 1)$$

Huray snowball (1-ball, 2 parameters):

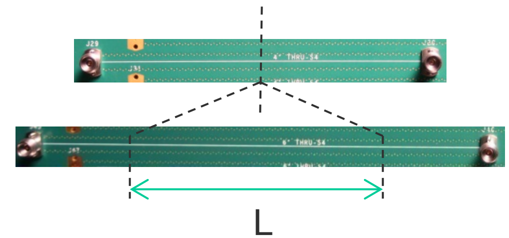
$$K_{rhu} = 1 + \left(\frac{N\cdot 4\pi \cdot r^2}{A_{hex}}\right) \Big/ \left(1 + \frac{\delta}{r} + \frac{\delta^2}{2\cdot r^2}\right)$$

- Parameters for the models are not available and must be identified

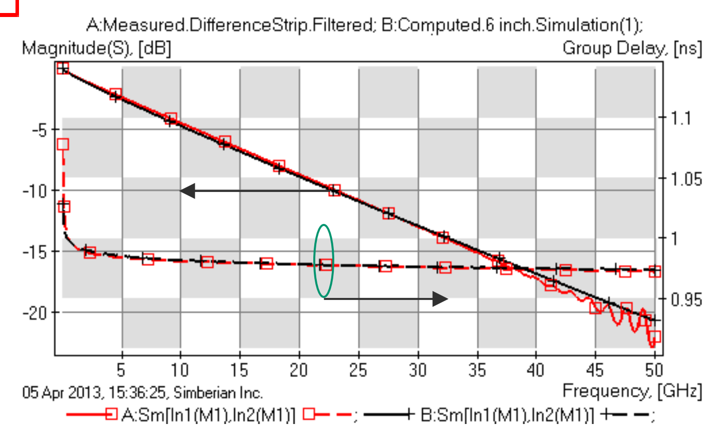
Material Model Identification with GMS-Parameters



Optimization loop – red line;
Automated in Simbeor software;

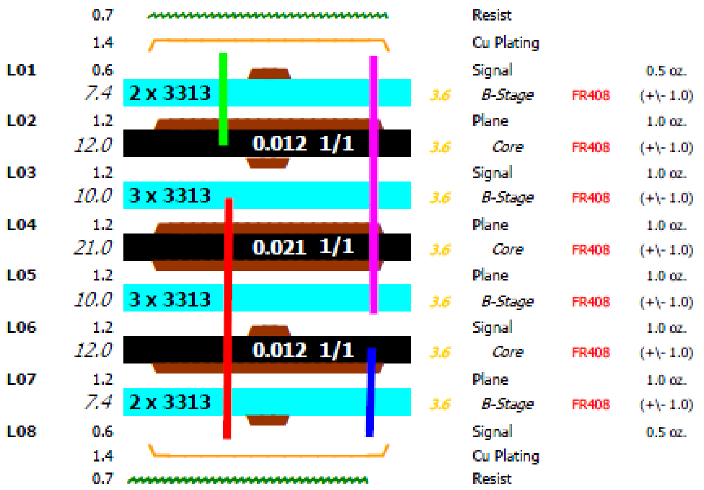


Applicable to dielectric and conductor roughness models;

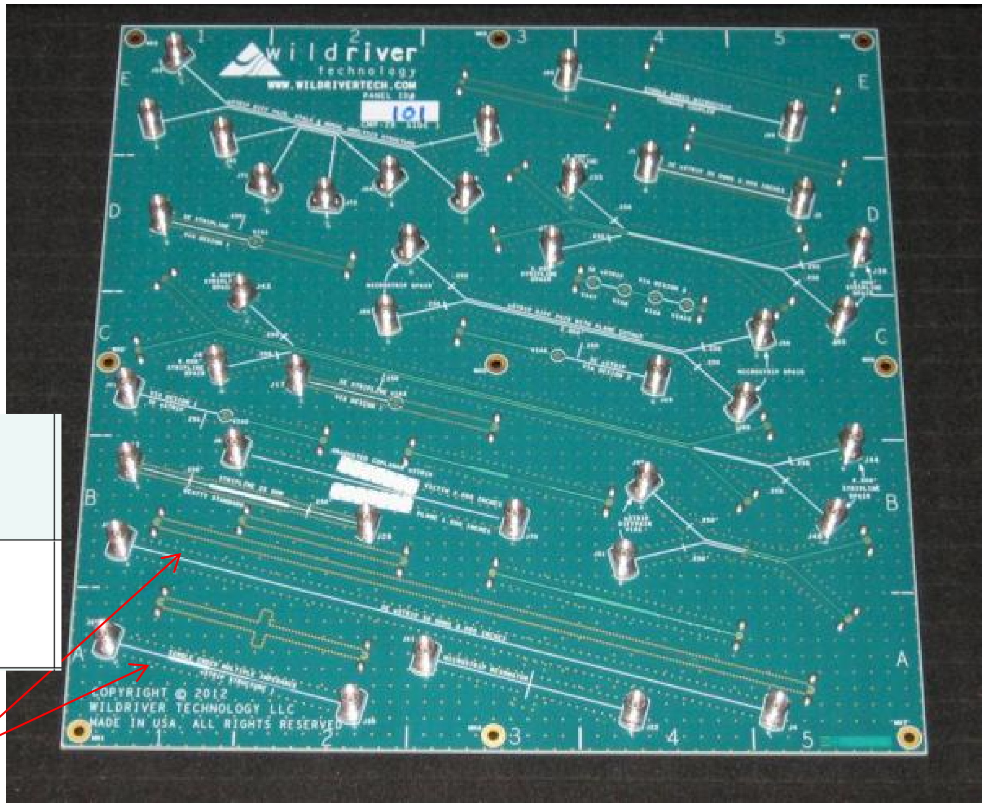


Simberian's USA patent #8577632 and patent pending #14/045,392

Example of dielectric identification with GMS-parameters in Simbeor software



CMP-28 validation board designed and investigated by Wild River Technology http://wildrivertech.com/

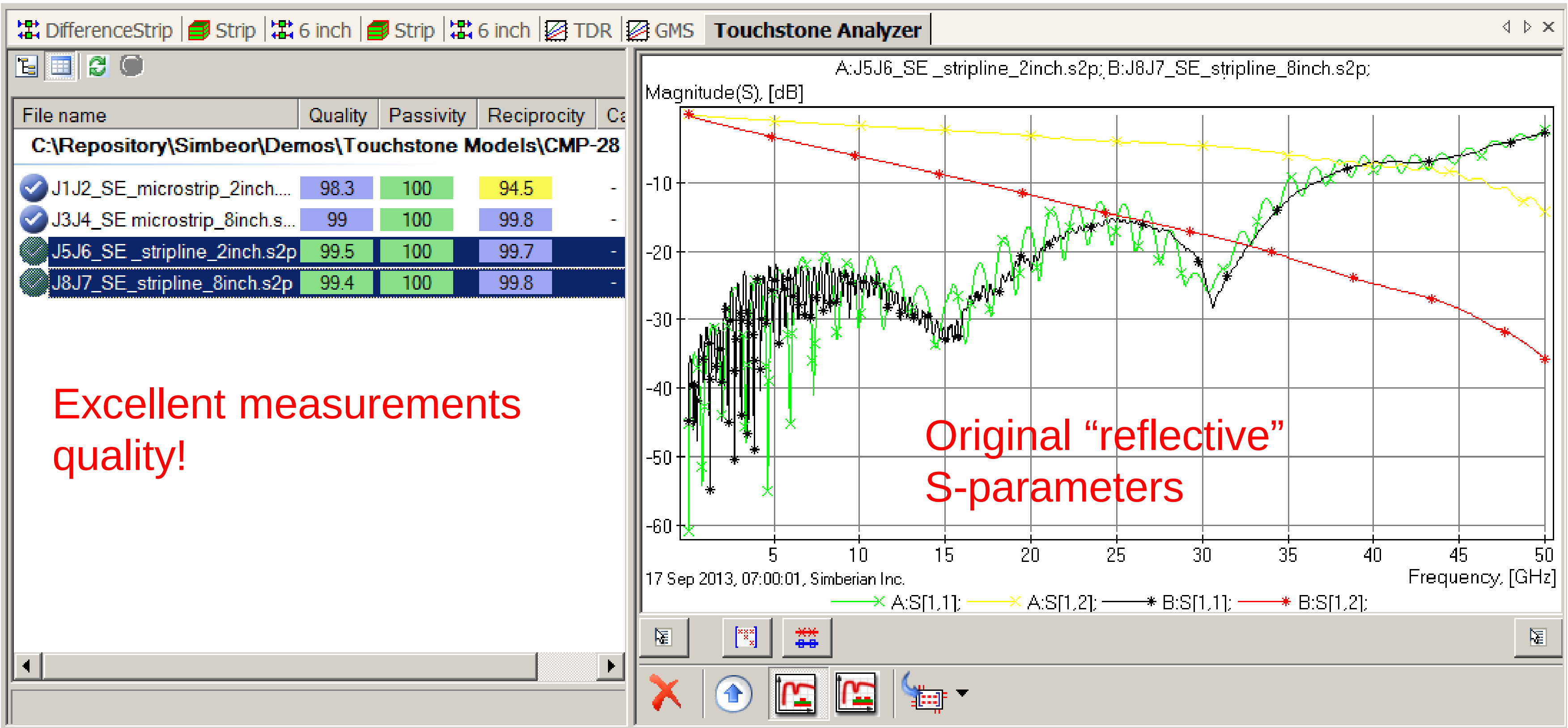


From Isola FR408 specifications

Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	3.69
	B. @ 1 GHz (HP4291A)	3.66
	C. @ 2 GHz (Bereskin Stripline)	3.67
	D. @ 5 GHz (Bereskin Stripline)	3.66
	E. @ 10 GHz (Bereskin Stripline)	3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	0.0094
	B. @ 1 GHz (HP4291A)	0.0117
	C. @ 2 GHz (Bereskin Stripline)	0.0120
	D. @ 5 GHz (Bereskin Stripline)	0.0127
	E. @ 10 GHz (Bereskin Stripline)	0.0125

10.5-11 mil wide strip lines,
Use measured S-parameters for 2 segments (2 inch and 8 inch)

Measured S-parameters for 2 and 8 inch segments

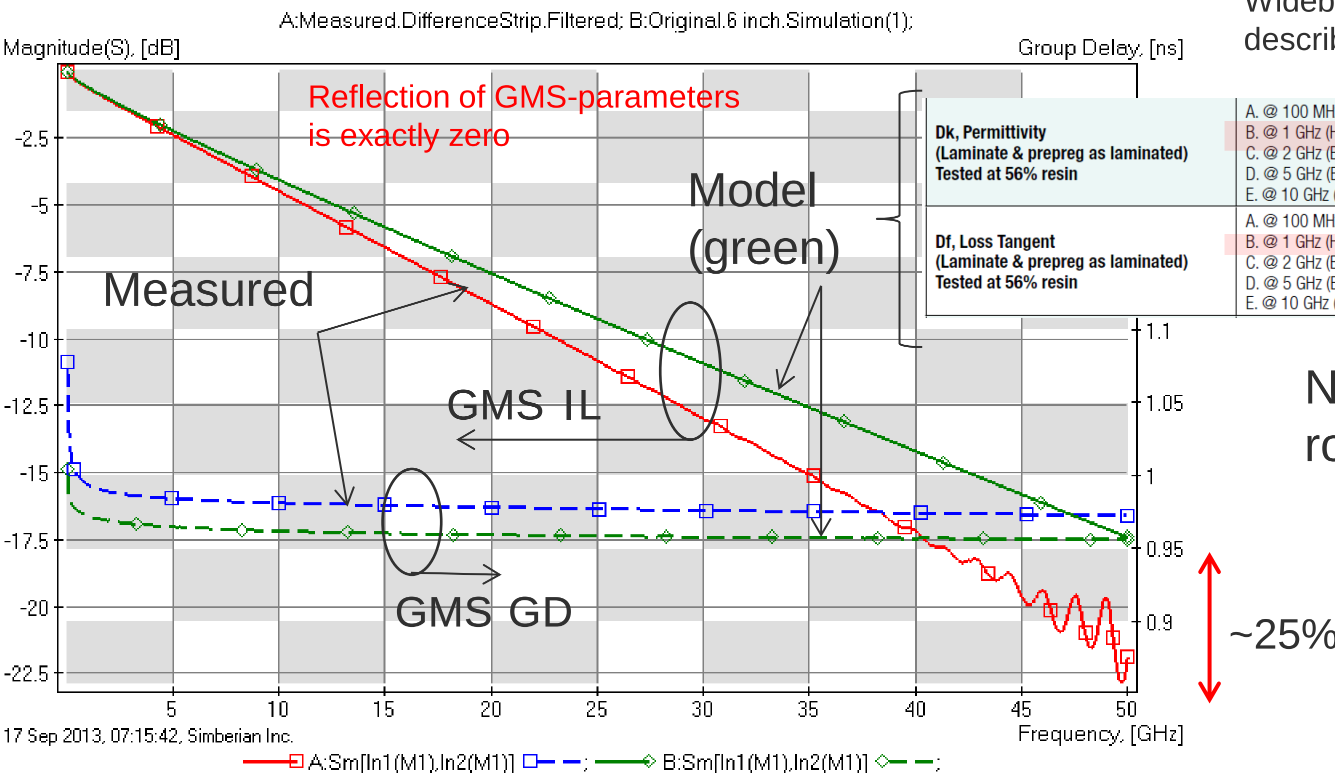


S-parameter and TDR analyses show that reflection-less GMS-parameters can be extracted from measured data

envision : ensure

Compare GMS-parameters with available material models

- The original model produces considerably lower insertion losses (GMS IL) above 5 GHz and smaller group delay (GMS GD) at all frequencies



Wideband Debye model can be described with just one Dk and LT

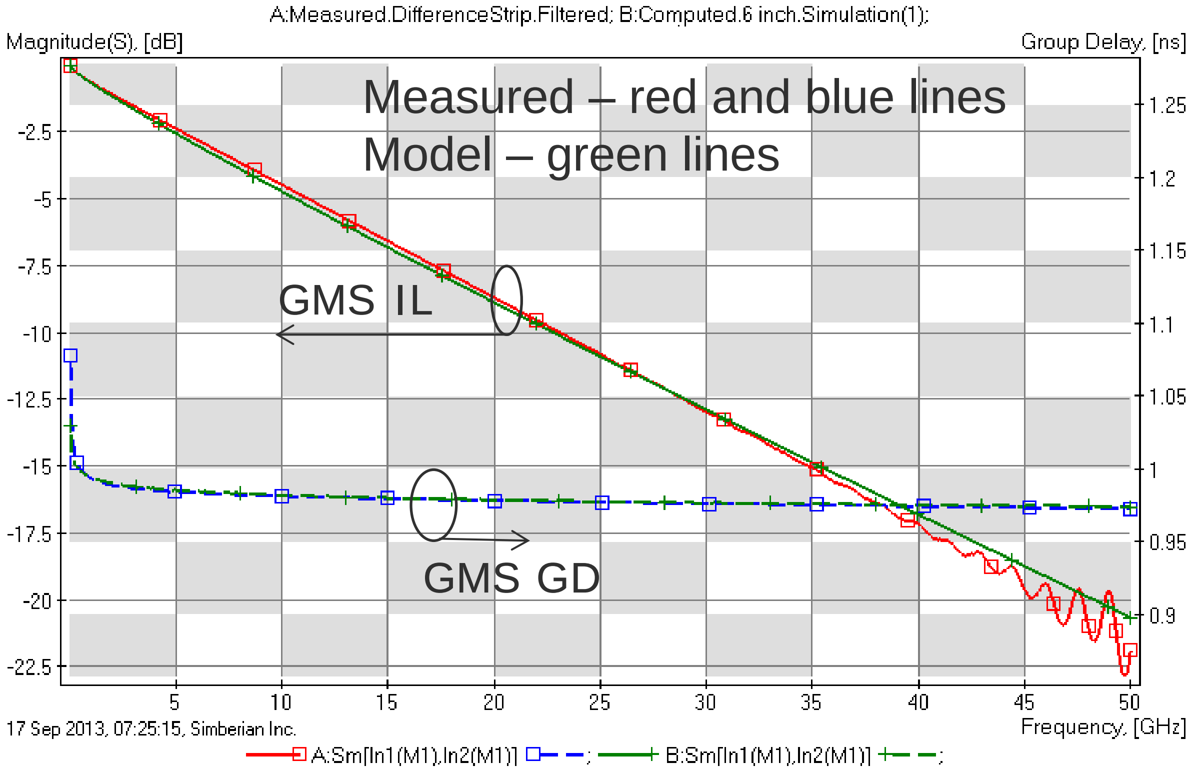
Dk, Permittivity (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	3.69
	B. @ 1 GHz (HP4291A)	3.66
	C. @ 2 GHz (Bereskin Stripline)	3.67
	D. @ 5 GHz (Bereskin Stripline)	3.66
	E. @ 10 GHz (Bereskin Stripline)	3.65
Df, Loss Tangent (Laminate & prepreg as laminated) Tested at 56% resin	A. @ 100 MHz (HP4285A)	0.0094
	B. @ 1 GHz (HP4291A)	0.0117
	C. @ 2 GHz (Bereskin Stripline)	0.0120
	D. @ 5 GHz (Bereskin Stripline)	0.0127
	E. @ 10 GHz (Bereskin Stripline)	0.0125

No model for roughness

Two options: 1) Increase Dk and LT in the dielectric model;
2) Increase Dk in dielectric model and model conductor roughness

Option 1: Increase Dk and LT in dielectric model (no conductor roughness)

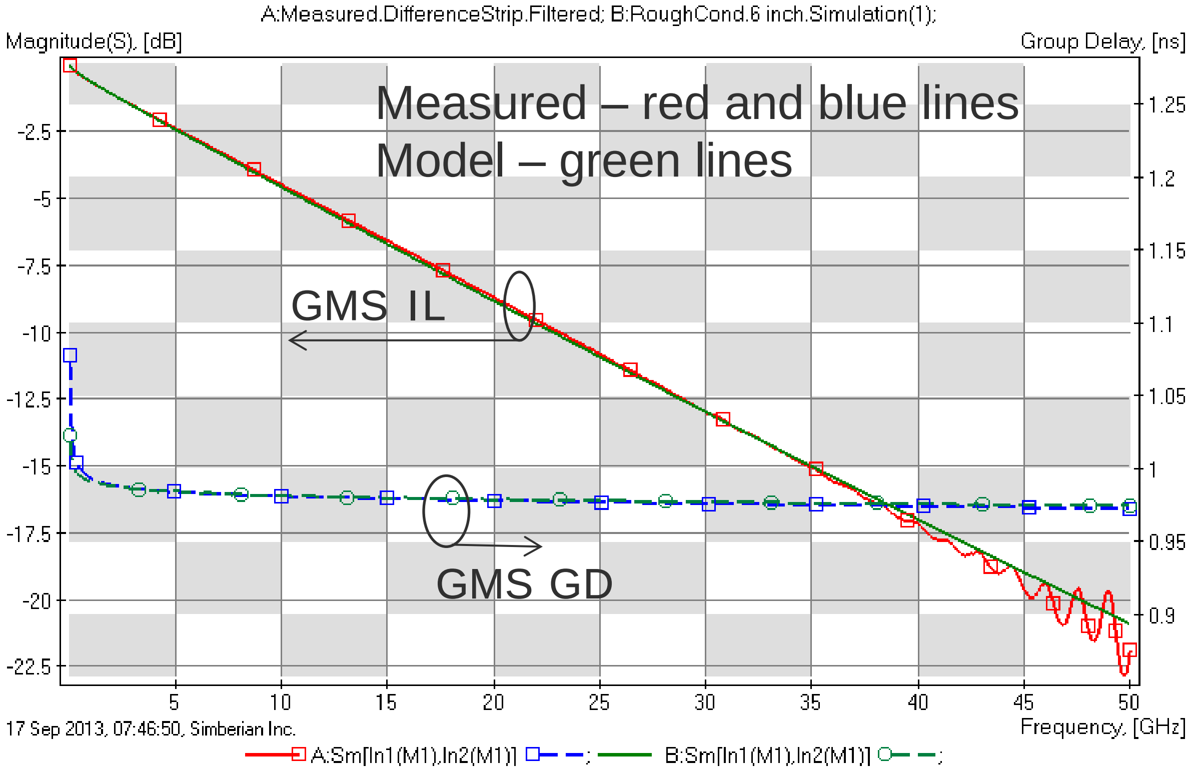
Good match with: Dk=3.83 (4.6% increase), LT=0.0138 (18% increase), Wideband Debye model



Good match, but what if conductors are actually rough?

Option 2: Increase Dk and model conductor roughness (proper modeling)

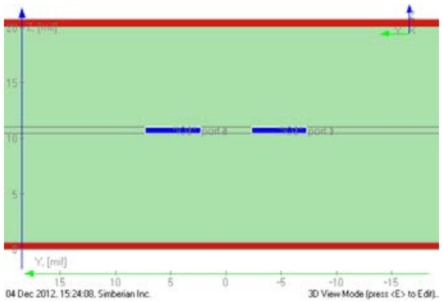
Dielectric: Dk=3.8 (3.8% increase), LT=0.0117 (no change), Wideband Debye model
Conductor: Modified Hammerstadt model with SR=0.32 um, RF=3.3



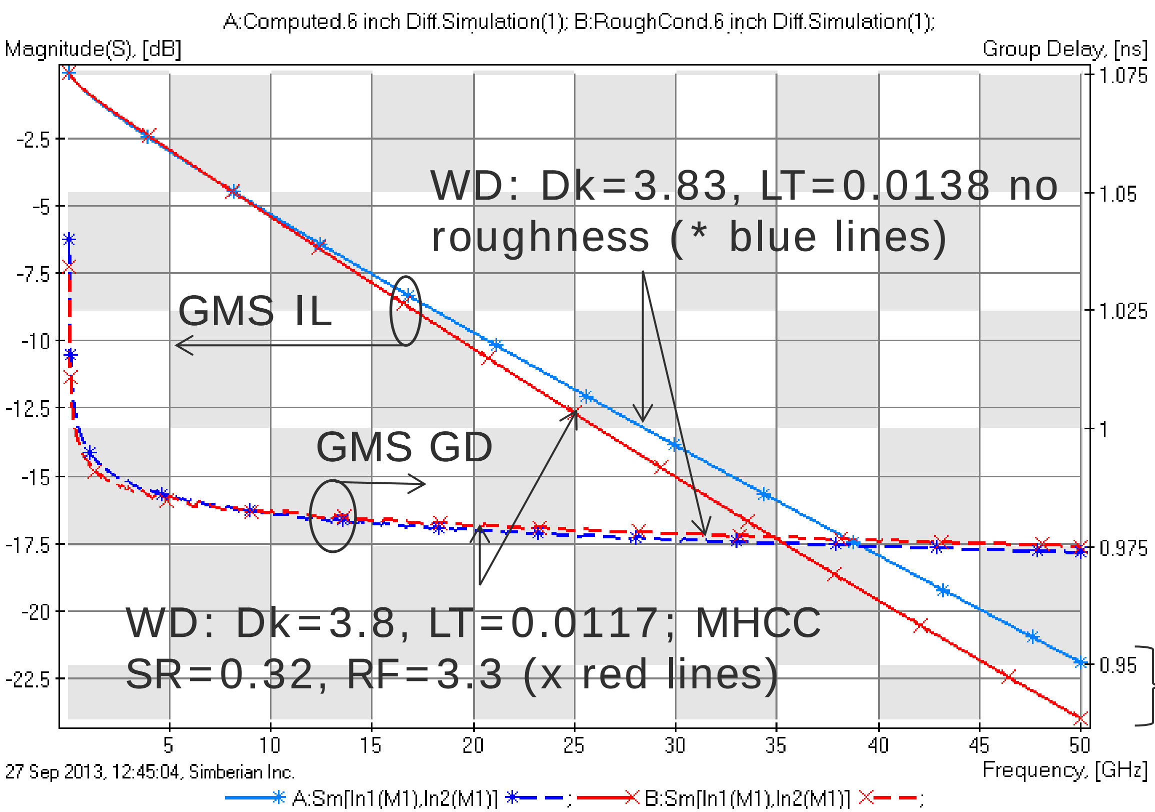
Excellent match and proper dispersion and loss separation!
This model is expected to work for strips with different widths

Can we use models for another cross-section?

- Differential 6 mil strips, 7.5 mil distance



GD is close, but the loss is different:



About 10% difference for medium-loss dielectric

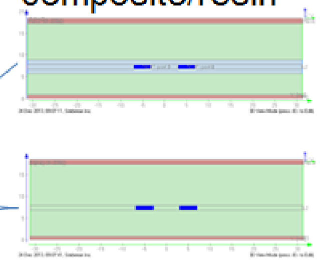
Which one is better?

Examples of practical material models identification with coupled lines

- Wideband Debye (WD) with dielectric and roughness losses:

Board Types / Model Parameters	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz
FR408HR with RTF copper, inhomogeneous	3.95/3.5 (3.66)	0.01/0.012 (0.0117)
FR408HR with RTF copper	3.76 (3.66)	0.012 (0.0117)
Megtron-6 with HVLP copper	3.69 (3.6)	0.0065 (0.002)
Megtron-6 with RTF copper	3.75 (3.6)	0.0083 (0.002)
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.011 (0.008)

composite/resin



- **Wideband Debye (WD) dielectric with loss tangent from specs and Modified Hammerstad model (MH) for conductor roughness losses:**

Board Types / Model Parameters	WD Dielectric Constant @ 1 GHz	WD Loss Tangent @ 1 GHz	MH Roughness (SR, rms) (um)	MH Roughness Factor (RF)
Megtron-6 with HVLP copper	3.64 (3.6)	0.002	0.38	3.15
Megtron-6 with RTF copper	3.72 (3.6)	0.002	0.37	4
Nelco N4000-13EPSI with RTF copper	3.425 (3.4)	0.008	0.49	2.3

Values from specifications are provided in brackets for comparison

See details at W. Beyene at all, Lessons learned: How to Make Predictable PCB Interconnects for Data Rates of 50 Gbps and Beyond, DesignCon2014

Summary on material models

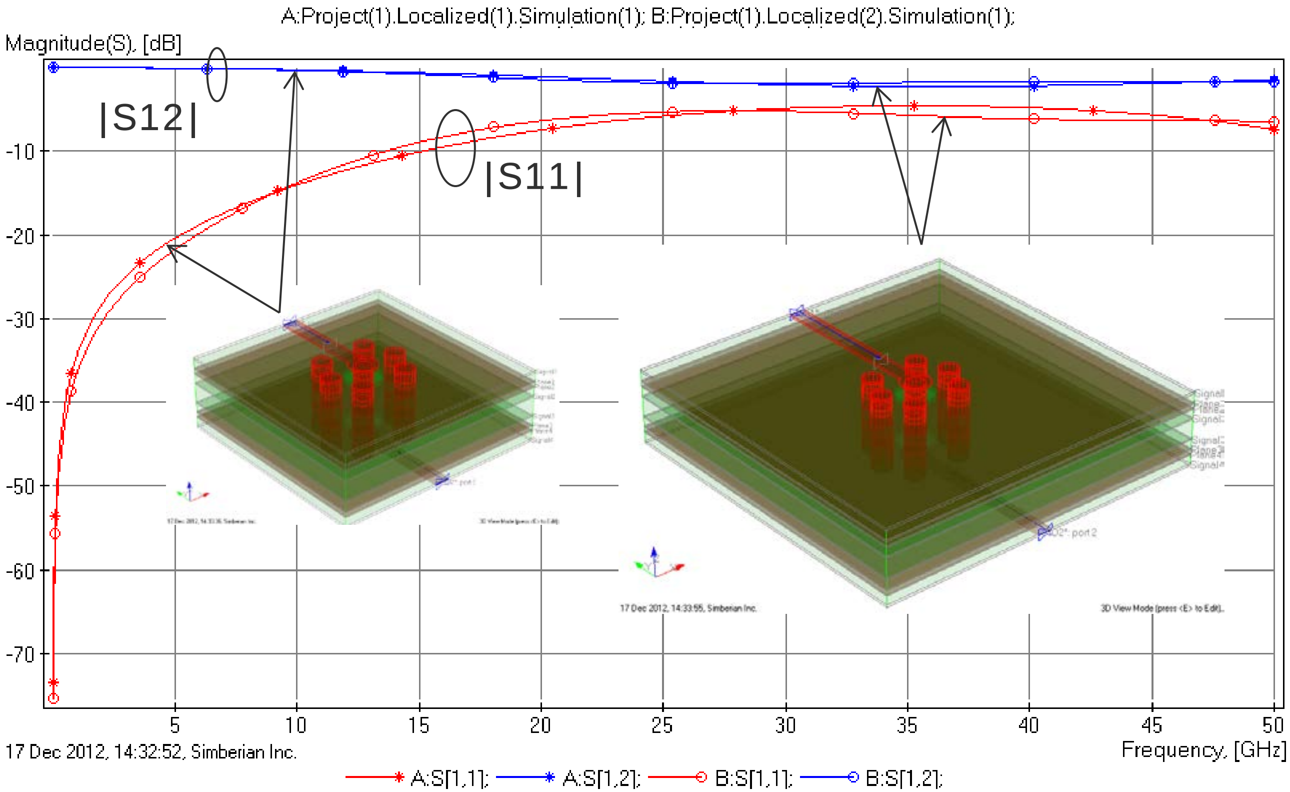
- Both dielectric and conductor roughness models require procedure to identify or confirm parameters of broadband models
- Provided example illustrates typical situation and importance of the dielectric and conductor roughness models identification
- Proper separation of loss and dispersion effects between dielectric and conductor models is very important, but not easy task
  - Without proper roughness model dielectric models become dependent on strip width and cross-section
- In addition, PCB dielectrics are inhomogeneous and exhibit anisotropy and fiber-weave effect

(3) Modeling discontinuities in isolation

- A channel is typically composed with transmission lines of different types and transitions (vias, launches, connectors,…)
- The transitions may be reflective due to physical differences in cross-sections of the connected lines
  - The reflections cause additional losses and resonances and, thus, unwanted signal degradation
- The effect of the transitions can be accounted for with models built with a full-wave 3D analysis
- If such analysis is possible in isolation from the rest of the board up to a target frequency, the structure is called localizable
- **Only localizable transitions must be used to design predictable interconnects – this is one of the most important elements for design success**

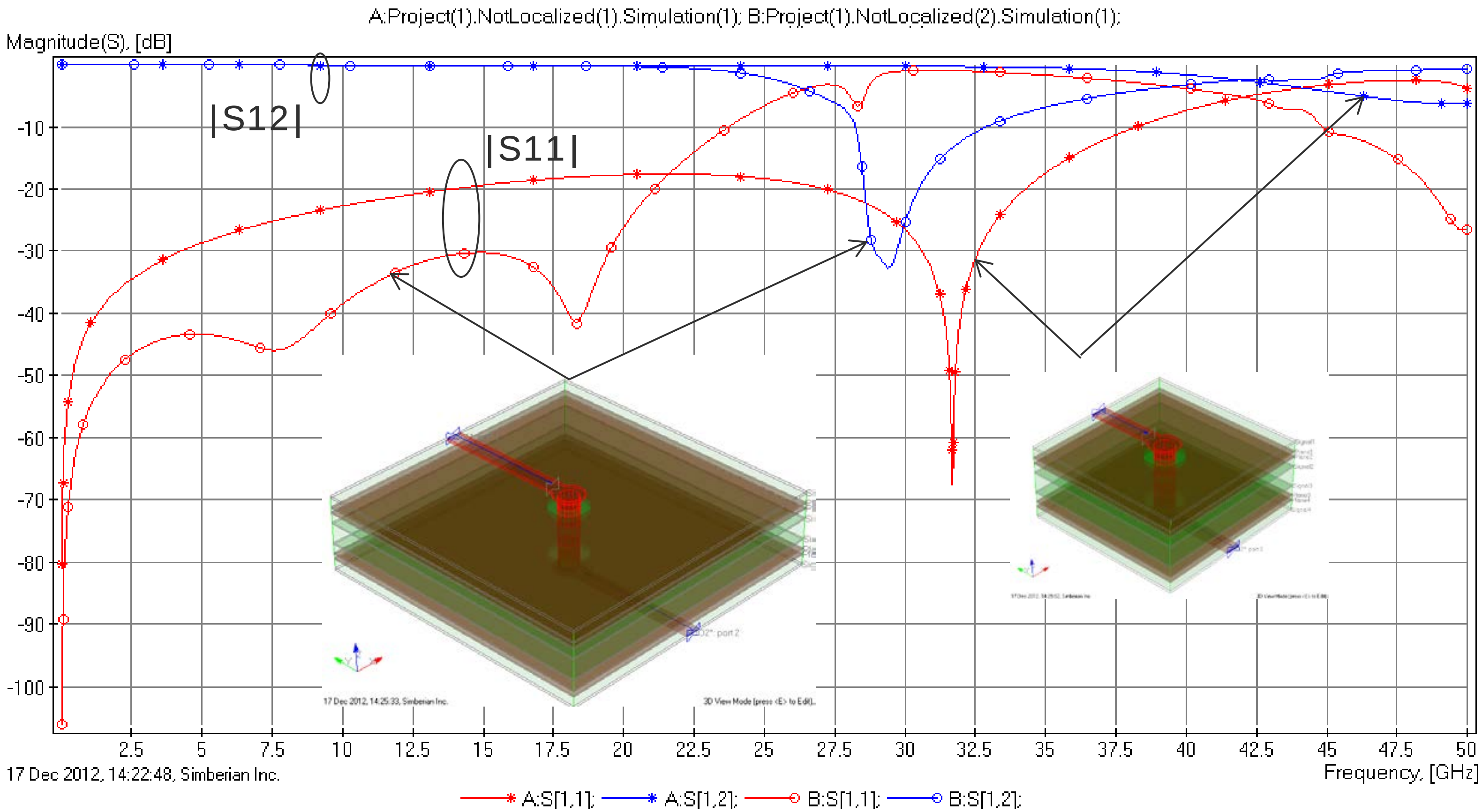
How estimate the localization?

- Change simulation area or simulate with different boundary conditions and observe changes
- Example of conditionally localized structure



Example of non-localizable via

- Change of simulation area size causes huge differences in reflection and insertion loss – unpredictable “pathological” structure

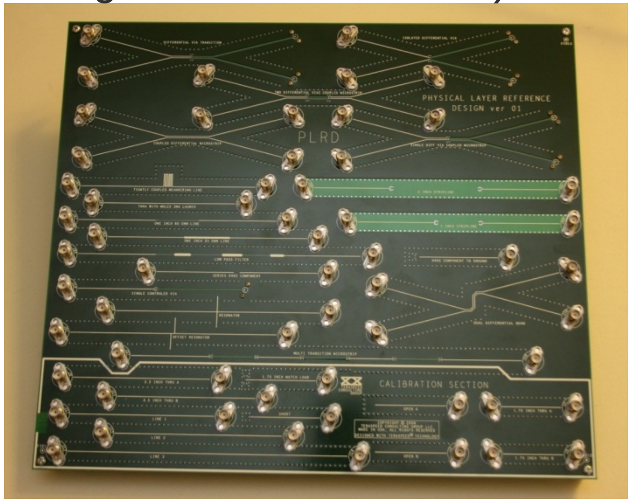


(4) Benchmarking or validation

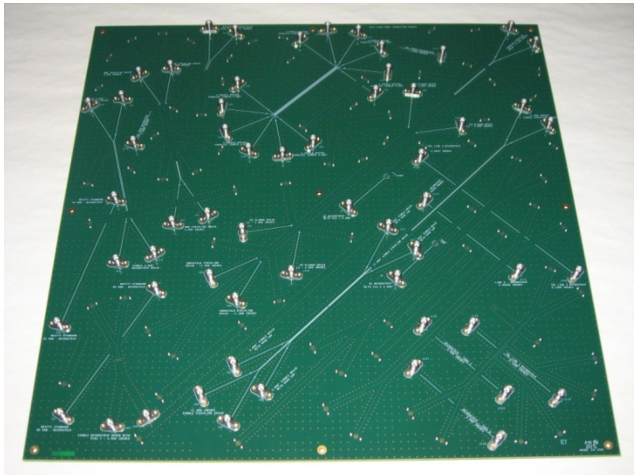
- How to make sure that simulation works? – Build validation boards!
- Controlled board manufacturing is the key for success
  - Fiber type, resin content, copper roughness must be strictly specified or fixed!!!
- Include a set of structures to identify one material model at a time
  - Solder mask, core and prepreg, resin and glass, roughness, plating,…
- Include a set of structures to identify accuracy for transmission lines and typical discontinuities
  - Use identified material models for all structures on the board consistently
  - No tweaking - discrepancies should be investigated
- Use VNA/TDNA measurements and compare both magnitude and phase (or group delay) of all S-parameters

Examples of validation boards

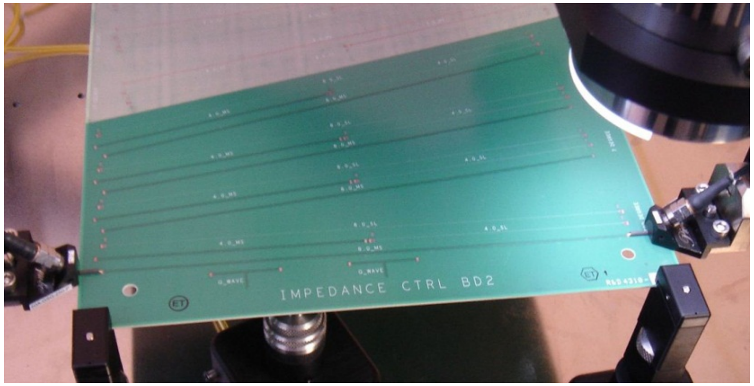
PLRD-1 (Teraspeed Consulting, DesignCon 2009, 2010)



CMP-08 (Wild River Technology & Teraspeed Consulting, DesignCon 2011)



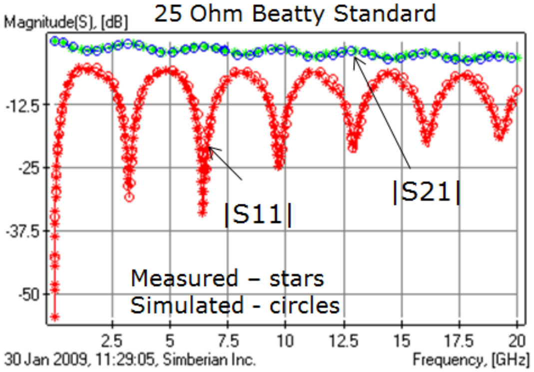
Isola, EMC 2011, DesignCon 2012

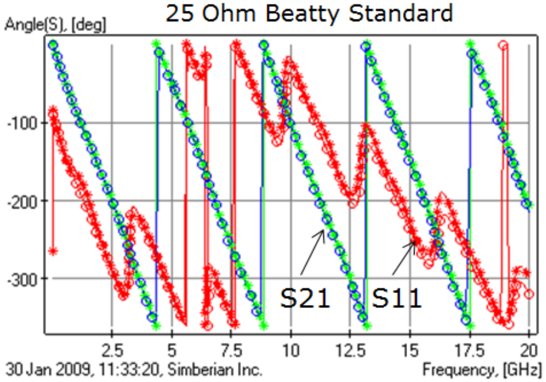


CMP-28, Wild River Technology, DesignCon 2012

What does “VALIDATION” mean?

- Validation – independent checking or proving the validity or accuracy of manufacturing, models and measurements (performed by disinterested parties);
- Statistical analysis can be used to quantify PCB/package manufacturing and allow sensitivity analysis:
  - Brist, G., “*Design Optimization of Single-Ended and Differential Impedance PCB Transmission Lines*,” PCB West Conference Proceedings, 2004
- Simple visual assessment of simulation to measurement correlation may be acceptable, but depends on experience of who is looking
- Feature Selective Validation (FSV) method can be used to formalize simulation to measurement correlation:
  - A. P. Duffy et al., “Feature selective validation (FSV) for validation of computational electromagnetics (CEM). part I-the FSV method,” Electromagnetic Compatibility, IEEE Transactions on, vol. 48, no. 3, pp. 449–459, 2006.
  - A. Orlandi et al., “Feature selective validation (FSV) for validation of computational electromagnetics (CEM). part II- assessment of FSV performance,” Electromagnetic Compatibility, IEEE Transactions on, vol. 48, no. 3, pp. 460–467, 2006.
  - Standard IEEE, “IEEE 1597.1 Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations.” Jun-2008.





Conclusion & Questions

What if measurements do not match simulations? – TROUBLESHOOT!

- Verify quality metrics of the measured S-parameters
  - Discard and re-measure if quality is not acceptable
- Verify localization property of the link path (referencing and topology)
  - Re-design non-localized elements
  - Verify model ports if all elements are localized
- Validate or identify material models
- Control manufacturing or verify geometry (build or use validation boards)
  - Cross-section t-lines and vias, do sensitivity analysis
- Other things to check: model convergence, TDR spectrum, de-embedding…

Contact and resources

- Yuriy Shlepnev, Simberian Inc., www.simberian.com
  shlepnev@simberian.com
  Tel: 206-409-2368
- **Webinars on decompositional analysis, S-parameters quality and material identification http://www.simberian.com/Webinars.php**
- Simberian web site and contacts www.simberian.com
- Demo-videos http://www.simberian.com/ScreenCasts.php
- App notes http://www.simberian.com/AppNotes.php
- Technical papers http://kb.simberian.com/Publications.php
- Presentations http://kb.simberian.com/Presentations.php
- Download Simbeor® from www.simberian.com and try it on your problems for 15 days

Simberian
Electromagnetic Solutions