S-PARAMETER QUALITY METRICS AND ANALYSIS TO MEASUREMENT CORRELATION

DesignCon 2015
Anritsu envision : ensure
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Anritsu envision : ensure

VNA Measurement S-Parameter Quality Metrics

S-Parameter Quality Metrics – Quality is important

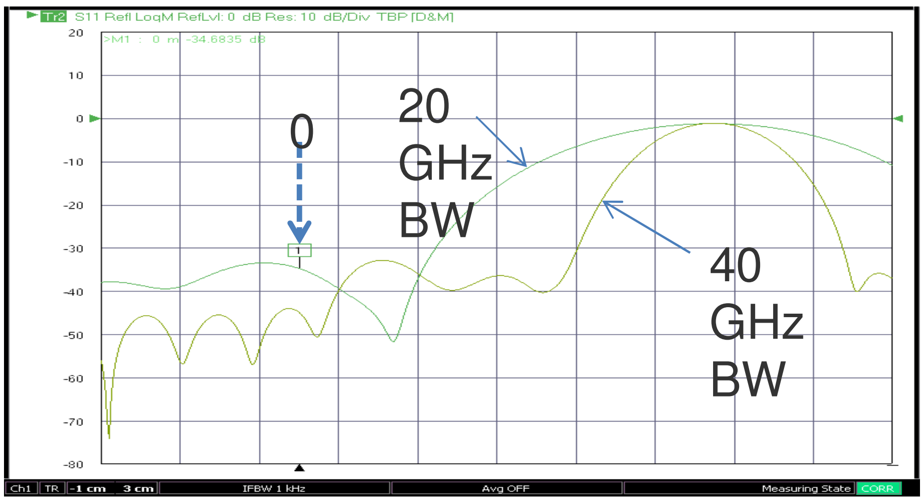
Anritsu envision : ensure

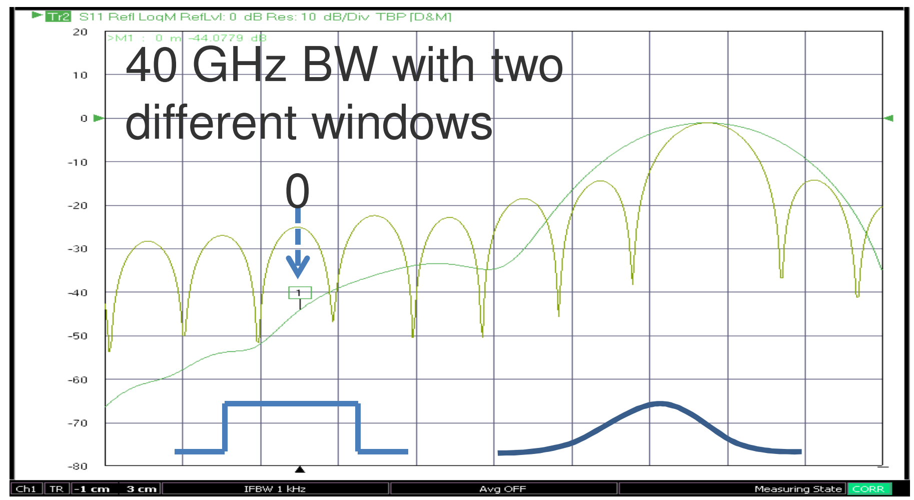
- **Reciprocity**
  - Forward and reverse transmission are equal in both Magnitude and Phase
  - VNA's have excellent Reciprocity because of the architecture
  - More of an issue for TDR's and scopes than VNA because of trigger jitter
- **Passivity**
  - The channel must be passive and have loss
  - Calibration, De-embedding and contact repeatability can effect passivity
  - Verify with high quality low loss thru - airline (not cal thru!)
- **Causality**
  - All VNA's have causality issues.
  - Incomplete DC to Daylight data will cause S-Parameters to be non-causal.
  - This shows up as output energy occurring before the input stimulus in the time domain
  - Verify with S-Parameter CCW rotation on a polar chart in the frequency domain or look for energy in the time domain for t<0

S-Parameter Metrics – Causality

Anritsu envision : ensure

- Basic causality is always *impacted* by available finite bandwidth.
- Note the signal levels for t<0.
- Bandwidth & Window Choices Affect Causality and Resolution



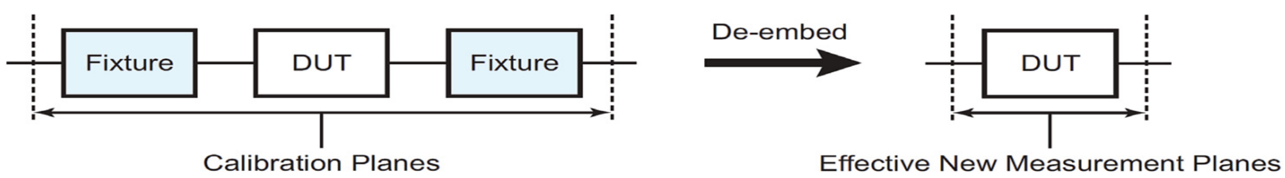


VNA BW (Frequency Span) effects causality

S-Parameter Metrics – Passivity

Anritsu envision : ensure

- Passivity problems occur when it appears a passive device has gain
- Receiver saturation issues can cause passivity issues during calibration or with the measurement
- De-embedding is often the problem. Small errors can cause large simulation errors.
- This is most prevalent in fixtures with high Insertion Loss and low Insertion Loss DUT's



- Having a wide range of extraction methods for de-embedding can be an advantage

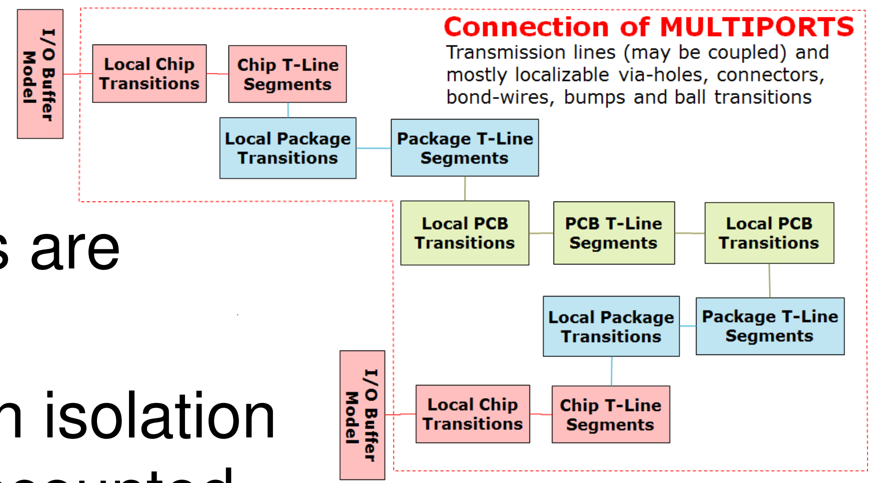
Analysis to Measurement Correlation

Introduction

- Design of PCB and packaging interconnects for data links running at bitrates 28-32 Gbps and beyond is a challenging problem:
  - It requires electromagnetic analysis over extremely broad frequency bandwidth from DC to 40-50 GHz
  - No frequency-continuous dielectric models available from manufactures
  - No conductor roughness models available from manufacturers
  - Boards are not manufactured as designed – large variations and manipulations by manufacturers
  - Making accurate measurements over this bandwidth is very difficult
- Is it possible to design interconnects and have acceptable analysis to measurement correlation from DC up to 40-50 GHz systematically?

Analysis correlates with measurements if…

1) Quality of S-parameter models is ensured
2) Broadband material models are identified or confirmed
3) Simulation of all elements in isolation is possible or coupling is accounted
4) Models are validated with measurements



4 elements of design success – see App Notes #2013_03, 2013_05, 2014_05 at http://www.simberian.com/AppNotes.php

(1) Quality of S-parameter models

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- 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
  - Bandwidth deficiency and discreteness
  - Model distortions leading to passivity, reciprocity and causality violations
- How to make sure that a model is suitable for analysis?
  - Use formal quality metrics…

Quality estimation theory is covered in webinar #1 at http://www.simberian.com/Webinars.php

Good S-parameter Models of Interconnects

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- Must have **sufficient bandwidth** matching signal spectrum
- Must be **appropriately sampled** to resolve all resonances
- Must be **passive** (do not generate energy)

$$P_{in} = \overline{a}^* \cdot \left[U - S^* S \right] \cdot \overline{a} \ \geq 0 \quad \Rightarrow \quad eigenvals\left[S^* \cdot S \right] \leq 1$$

Continuously from DC to infinity!

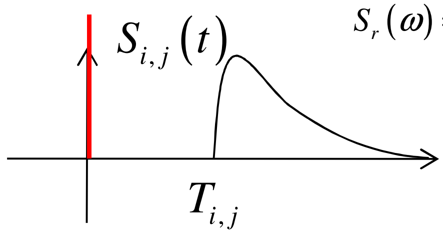
- Must be **reciprocal** (linear reciprocal materials used in PCBs)

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

- Must be **causal** (have causal step or impulse response or satisfy Kramers-Kronig relations)

$$S_r(\omega) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{S_i(\omega')}{\omega - \omega'} \cdot d\omega', \quad S_i(\omega) = \frac{-1}{\pi} PV \int_{-\infty}^{\infty} \frac{S_r(\omega')}{\omega - \omega'} \cdot d\omega'$$

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



Continuously from DC to infinity!

Preliminary Quality Metrics (0-100%)

First introduced at IBIS forum at DesignCon 2010

- Passivity Quality Measure:

$$PQM = \max\left[\frac{100}{N_{total}}\left(N_{total} - \sum_{n=1}^{N_{total}} PW_n\right), 0\right]\%$$

$$PW_n = 0 \text{ if } PM_n < 1.00001; \text{ otherwise } PW_n = \frac{PM_n - 1.00001}{0.1}$$

$$PM_n = \sqrt{\max\left[eigenvals\left(S^*(f_n)\cdot S(f_n)\right)\right]}$$

- Reciprocity Quality Measure:

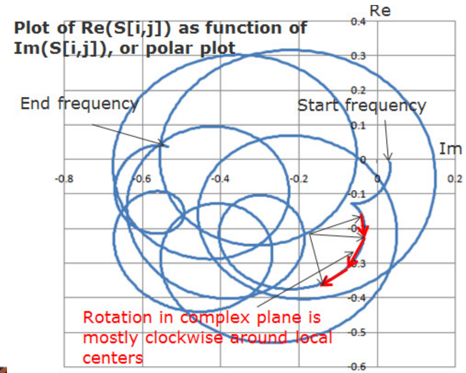
$$RQM = \max\left[\frac{100}{N_{total}}\left(N_{total} - \sum_{n=1}^{N_{total}} RW_n\right), 0\right]\%$$

$$RW_n = 0 \text{ if } RM_n < 10^{-6}; \text{ otherwise } RW_n = \frac{RM_n - 10^{-6}}{0.1}$$

$$RM_n = \frac{1}{N_s}\sum_{i,j}\left|S_{i,j}(f_n) - S_{j,i}(f_n)\right|$$

- Causality Quality Measure:

Minimal ratio of clockwise rotation measure to total rotation measure in %



Preliminary Quality Metrics

- Brackets for Passivity, Reciprocity and Causality quality metrics

Metric/Model Icon	- good	- acceptable	- inconclusive	- bad
Passivity	[100, 99.9]	(99.9, 99]	(99, 80]	(80, 0]
Reciprocity	[100, 99.9]	(99.9, 99]	(99, 80]	(80, 0]
Causality	[100, 80]	(80, 50]	(50, 0]	-----

For numerical models

Color code	Passivity (PQM)	Reciprocity (RQM)	Causality (CQM)
Green – good	[99.9, 100]	[99.9, 100]	[80, 100]
Blue – acceptable	[99, 99.9)	[99, 99.9)	[50, 80)
Yellow – inconclusive	[80, 99)	[80, 99)	[20, 50)
Red - bad	[0, 80)	[0, 80)	[0, 20)

Example of preliminary quality evaluation in Simbeor Touchstone Analyzer

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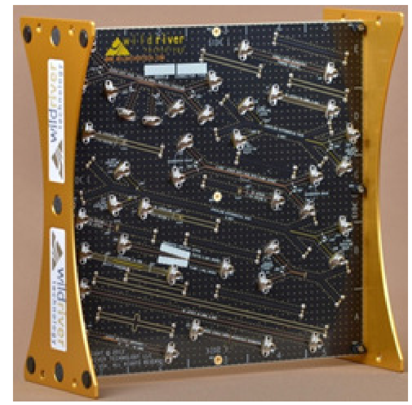
Touchstone Analyzer

File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone_Files\2ndcal_d...				
Cal_Thru_3p74ns_p1_p2.s2p	-	100	99.8	99.9
Cal_Thru_3p74ns_p3_p4.s2p	-	100	99.6	99.9
cmp28_mstrp_diff_2inch_J38J37J34J33.s4p	-	100	99.8	71.4
cmp28_mstrp_diff_6inch_J46J45J42J41.s4p	-	100	99.8	73.1
cmp28_mstrp_diff_gnd_cutout_J59J60J55J56.s4p	-	100	99.8	89.7
cmp28_mstrp_diff_xtalk_J57J58J53J54.s4p	-	100	99.8	55.6
cmp28_mstrp_diff_xtalk_J57J64J53J72.s4p	-	100	99.9	77.2
cmp28_mstrp_diff_xtalk_J57J71J53J61.s4p	-	100	99.9	66.2
cmp28_mstrp_diff_xtalk_J57J72J53J64.s4p	-	100	99.9	67.8
cmp28_mstrp_diff_xtalk_J64J72J58J54.s4p	-	100	99.9	67.9
cmp28_mstrp_diff_xtalk_J71J58J61J54.s4p	-	100	99.9	66.9
cmp28_mstrp_diff_xtalk_J71J72J61J64.s4p	-	100	99.7	50
cmp28_mstrp_diff_xtalk_J72J58J64J54.s4p	-	100	99.9	63.6
cmp28_strpl_diff_2inch_J39J40J35J36.s4p	-	100	99.8	77.3
cmp28_strpl_diff_6inch_J47J48J43J44.s4p	-	100	99.9	78.3
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone_Files\3rdcal_v				
Cal_Thru_3p74ns_p1_p2_vias.s2p	-	100	99.4	99.9
Cal_Thru_3p74ns_p1_p2_vias_rpt.s2p	-	100	99.2	99.9
Cal_Thru_3p74ns_p3_p4_vias.s2p	-	100	99.5	100
cmp28_mstrp_diff_vias_J49J50J51J52.s4p	-	100	99.8	87.8
cmp28_mstrp_via_capacitive_p1J19_p2J20.s2p	-	100	99.2	94.8
cmp28_mstrp_via_inductive_p1J15_p2J16.s2p	-	100	99.6	96.6
cmp28_strpl_via_backdrilled_p1J14_p2J13.s2p	-	100	99.4	88
cmp28_strpl_via_capacitive_p1J18_p2J17.s2p	-	100	99.7	95.8

S-parameters measured for CMP-28 Channel Modeling Platform by Wild River Technology (from CMP-28 Simbeor Kit)



Touchstone Analyzer

File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone_Files\1stcal_sin...				
cmp28_gnd_voids_p1J74_p2J75.s2p	-	100	99.4	93.1
cmp28_graduated_coplanar_p1J70_p2J69.s2p	-	100	99.5	84.4
cmp28_mstrp_2in_p1J1_p2J2.s2p	-	100	99.7	82.3
cmp28_mstrp_8inch_p1J4_p2J3.s2p	-	100	99.8	82.5
cmp28_mstrp_Beatty_25ohm_p1J25_p2J26.s2p	-	100	99.4	98.3
cmp28_mstrp_multiZ_p1J31_p2J32.s2p	-	100	99.3	98.5
cmp28_mstrp_p1J30_p2J29.s2p	-	100	99.8	98.6
cmp28_mstrp_resonator_p1J22_p2J22.s2p	-	100	99.7	99.4
cmp28_mstrp_whiskers_p1J68_p2J67.s2p	-	100	99.8	94
cmp28_strpl_2in_50ohm_p1J6_p2J5.s2p	-	100	99.1	82.3
cmp28_strpl_2in_Capacitive_p1J10_p2J09.s2p	-	100	99.5	93.8
cmp28_strpl_2in_Inductive_p1J12_p2J11.s2p	-	100	99.4	84.6
cmp28_strpl_8inch_p1J7_p2J8.s2p	-	100	99.7	74.7
cmp28_strpl_Beatty_25ohm_p1J28_p2J27.s2p	-	100	99.4	95.5
cmp28_strpl_resonator_p1J23_p2J24.s2p	-	100	99.4	98
cmp28_via_pathology_p1J65_p2J66.s2p	-	100	99.8	97.5

Live Demo…
Estimate quality
Plot S-parameters

Final model quality estimation with the rational approximation

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

$$RMSE = \max_{i,j}\left[\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left|S_{ij}(n) - S_{ij}(\omega_n)\right|^2}\right] \qquad S_{i,j}(i\omega) = \left[d_{ij} + \sum_{n=1}^{N_{ij}}\left(\frac{r_{ij,n}}{i\omega - p_{ij,n}} + \frac{r^*_{ij,n}}{i\omega - p^*_{ij,n}}\right)\right]\cdot e^{-s\cdot T_{ij}}$$

original tabulated data — *rational approximation*

- Is 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 for FD and TD analysis instead of the original data

Example of FINAL quality evaluation in Simbeor Touchstone Analyzer

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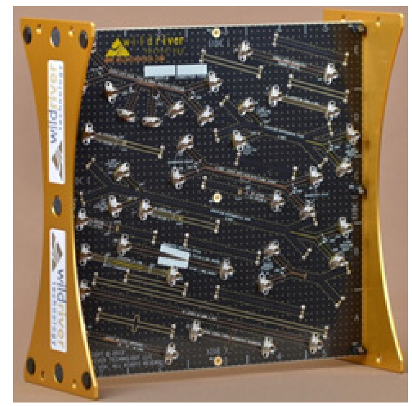
Touchstone Analyzer

File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone_Files\2nd...				
cmp28_mstrp_diff_2inch_J38J37J34J33.s4p	99.5	100	99.8	-
cmp28_mstrp_diff_6inch_J46J45J42J41.s4p	99.6	100	99.8	-
cmp28_mstrp_diff_gnd_cutout_J59J60J55J56.s4p	99.5	100	99.8	
cmp28_mstrp_diff_xtalk_J57J58J53J54.s4p	99.5	100	99.8	
cmp28_mstrp_diff_xtalk_J57J64J53J72.s4p	99.6	100	99.9	
cmp28_mstrp_diff_xtalk_J57J71J53J61.s4p	99.6	100	99.9	
cmp28_mstrp_diff_xtalk_J57J72J53J64.s4p	99.6	100	99.9	
cmp28_mstrp_diff_xtalk_J64J72J58J54.s4p	99.5	100	99.9	
cmp28_mstrp_diff_xtalk_J71J58J61J54.s4p	99.5	100	99.9	
cmp28_mstrp_diff_xtalk_J71J72J61J64.s4p	99.5	100	99.7	
cmp28_mstrp_diff_xtalk_J72J58J64J54.s4p	99.6	100	99.9	
cmp28_strpl_diff_2inch_J39J40J35J36.s4p	99.5	100	99.8	
cmp28_strpl_diff_6inch_J47J48J43J44.s4p	99.3	100	99.9	
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone				
Cal_Thru_3p74ns_p1_p2_vias.s2p	96.5	100	99.4	
Cal_Thru_3p74ns_p1_p2_vias_rpt.s2p	96.8	100	99.2	
Cal_Thru_3p74ns_p3_p4_vias.s2p	97	100	99.5	
cmp28_mstrp_diff_vias_J49J50J51J52.s4p	98.9	100	99.8	
cmp28_mstrp_via_capacitive_p1J19_p2J20.s2p	99.6	100	99.2	
cmp28_mstrp_via_inductive_p1J15_p2J16.s2p	98.3	100	99.6	
cmp28_strpl_via_backdrilled_p1J14_p2J13.s2p	97.7	100	99.4	
cmp28_strpl_via_capacitive_p1J18_p2J17.s2p	93.4	100	99.7	

S-parameters measured for CMP-28 Channel Modeling Platform by Wild River Technology (from CMP-28 Simbeor Kit)

Touchstone Analyzer

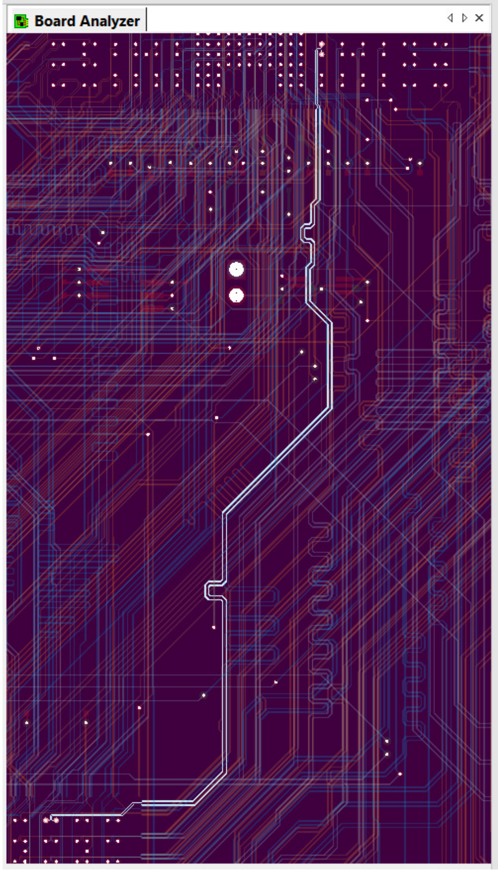
File name	Quality	Passivity	Reciprocity	Causality
C:\Repository\Simbeor\CMP-28_Simbeor_Kit_Rev4\CMP-28_Rev4\Touchstone_Files\1stc...				
cmp28_gnd_voids_p1J74_p2J75.s2p	99.5	100	99.4	-
cmp28_graduated_coplanar_p1J70_p2J69.s2p	99.7	100	99.5	-
cmp28_mstrp_2in_p1J1_p2J2.s2p	99.5	100	99.7	-
cmp28_mstrp_8inch_p1J4_p2J3.s2p	99.7	100	99.8	-
cmp28_mstrp_Beatty_25ohm_p1J25_p2J26.s2p	99.6	100	99.4	-
cmp28_mstrp_multiZ_p1J31_p2J32.s2p	99.6	100	99.3	-
cmp28_mstrp_p1J30_p2J29.s2p	99.6	100	99.8	-
cmp28_mstrp_resonator_p1J22_p2J22.s2p	99.7	100	99.7	-
cmp28_mstrp_whiskers_p1J68_p2J67.s2p	99.5	100	99.8	-
cmp28_strpl_2in_50ohm_p1J6_p2J5.s2p	99.6	100	99.1	-
cmp28_strpl_2in_Capacitive_p1J10_p2J09.s2p	99.5	100	99.5	-
cmp28_strpl_2in_Inductive_p1J12_p2J11.s2p	99.5	100	99.4	-
cmp28_strpl_8inch_p1J7_p2J8.s2p	99.6	100	99.7	-
cmp28_strpl_Beatty_25ohm_p1J28_p2J27.s2p	99.7	100	99.4	-
cmp28_strpl_resonator_p1J23_p2J24.s2p	99.6	100	99.4	-
cmp28_via_pathology_p1J65_p2J66.s2p	99.6	100	99.8	-



Live Demo…
Build RCM
Estimate quality
Compute TDR

(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
  - Strip lines can be effectively analysed with quasi-static field solvers
  - Microstrip or CPW 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**



PCB/Packaging material models

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

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):

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

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

Material model identification with GMS-parameters

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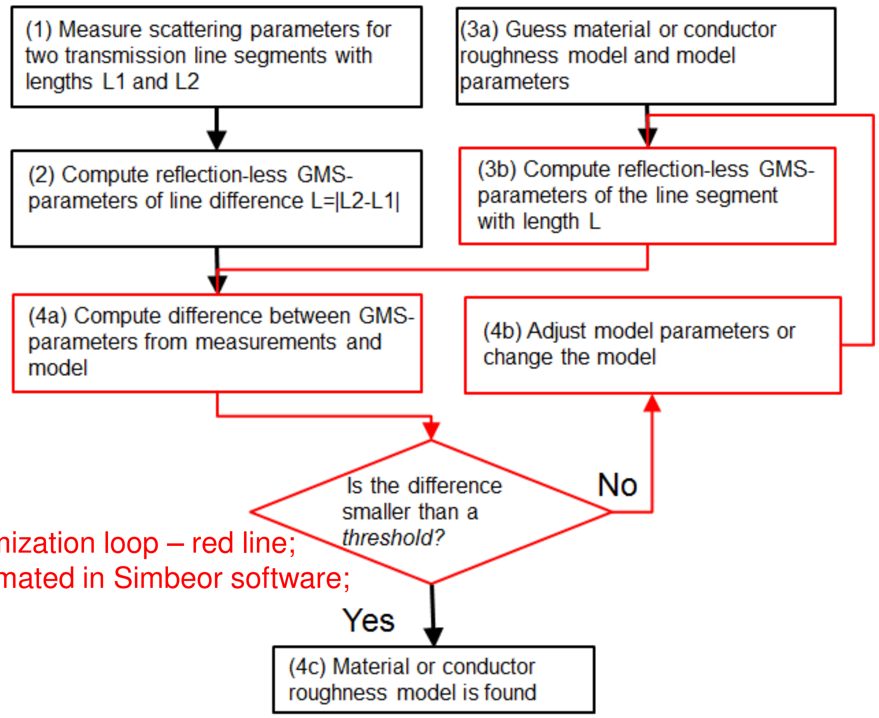
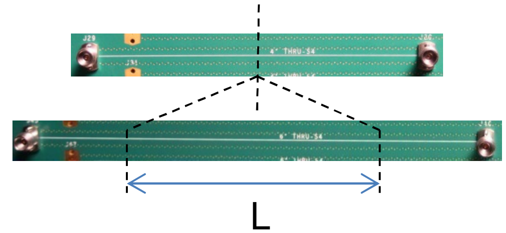
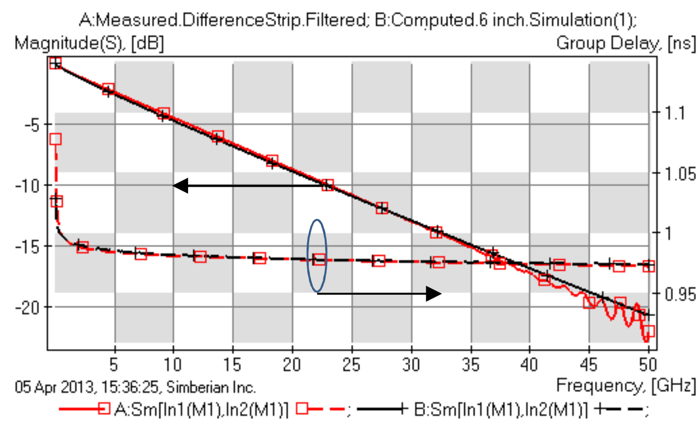


Optimization loop – red line;
Automated in Simbeor software;

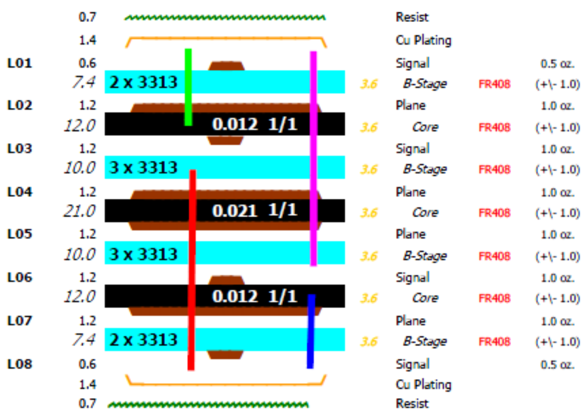


Applicable to dielectric and conductor roughness models;

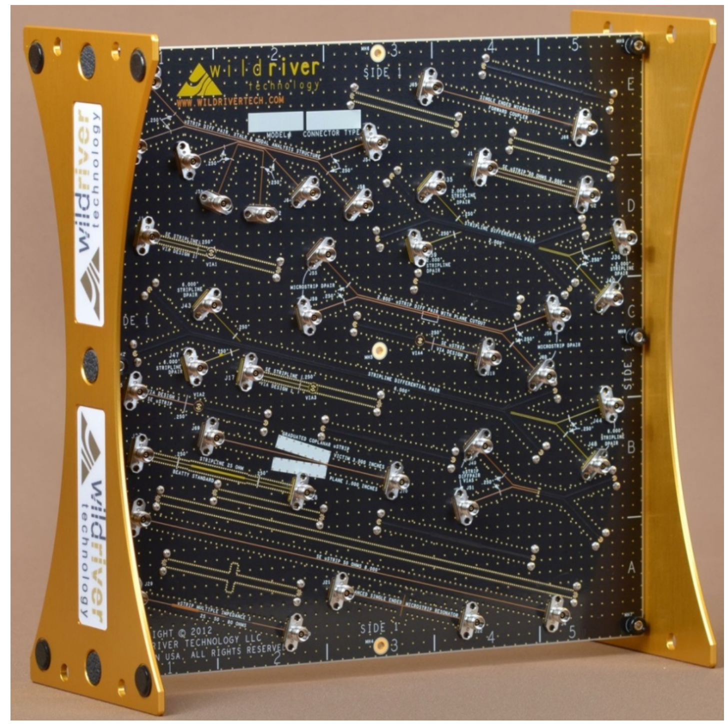


See App Notes #2014_02 and 2014_03 for details on identification with GMS-parameters at http://www.simberian.com/AppNotes.php and webinar #2 at http://www.simberian.com/Webinars.php

Example of material model identification



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



From Isola FR408HR specifications

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

Use measured S-parameters for 2 strip (10.5 mil wide) and micro-strip (13.5 mil wide) segments (2 and 8 inch long); Confirm with differential segments;

Models identified with strip line

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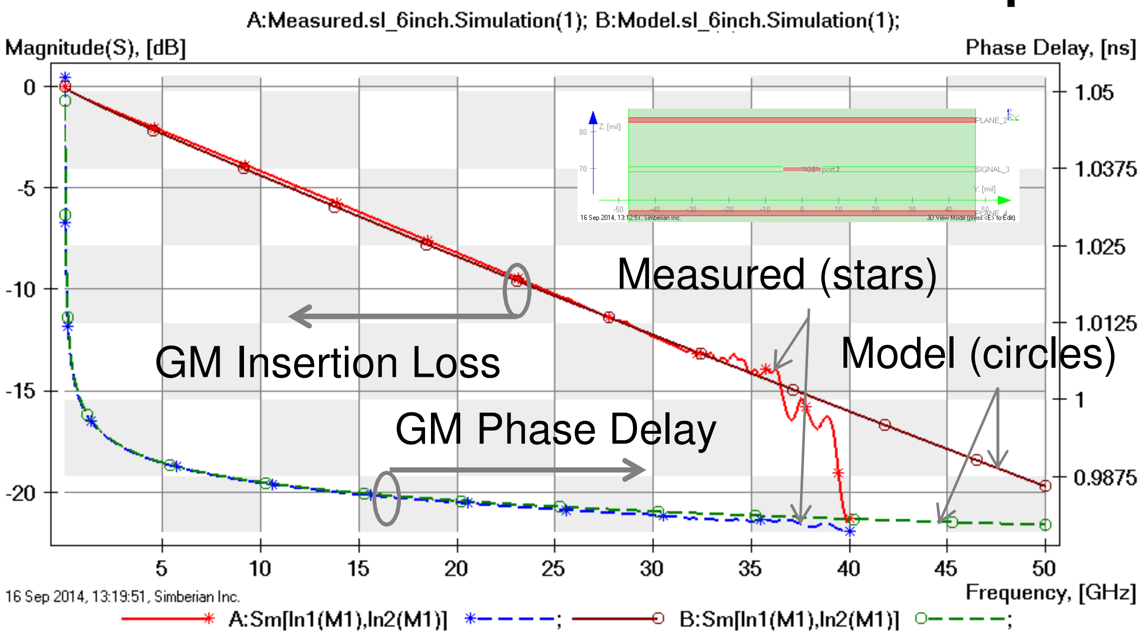

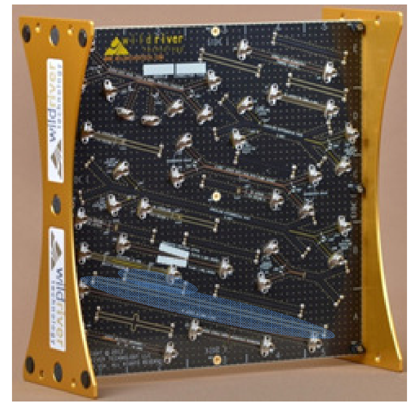

GM - Generalized Modal (reflection-less);

About 35 GHz useful bandwidth from the measured data due to mechanical differences;

GMS parameters computed from S-parameters measured for 2 and 8 inch strip line segments (red and blue lines) and modeled for 6 inch strip line segment (brown and green lines):
FR408HR model: Wideband Debye, Dk=3.815 (3.66), LT=0.0117 @ 1 GHz;
Conductor roughness model: Modified Hammerstad, SR=0.4 um, RF=2;

Models are usable up to 50 GHz!

Models identified with micro-strip line

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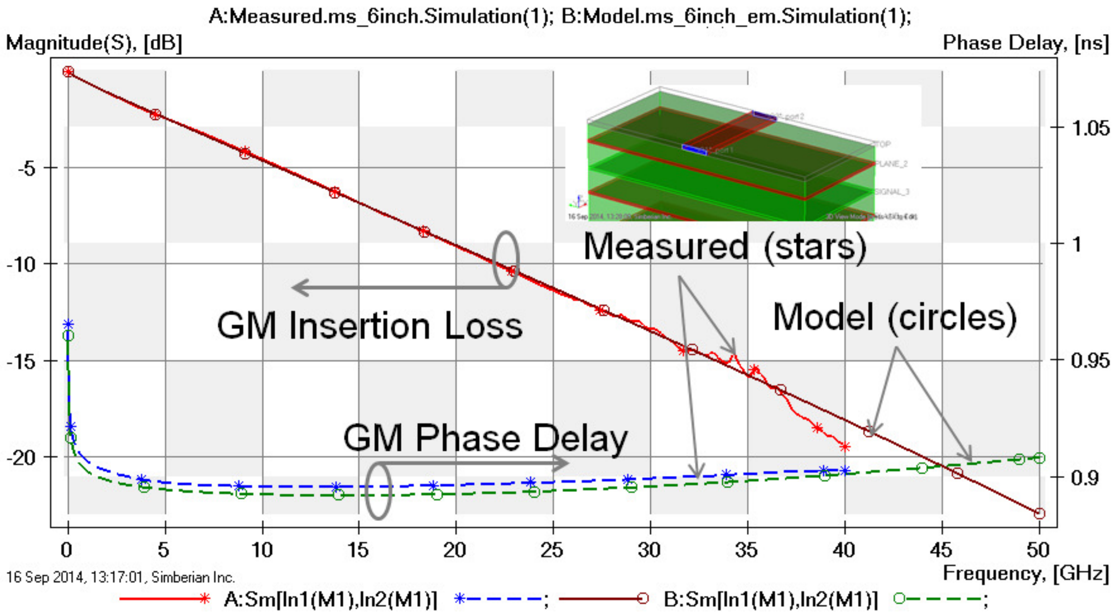

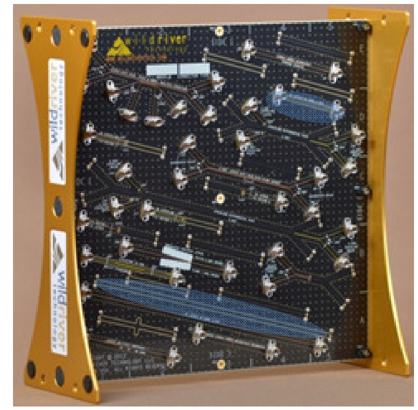

GM - Generalized Modal (reflection-less);

About 35 GHz useful bandwidth from the measured data due to mechanical differences;

GMS parameters computed from S-parameters measured for 2 and 8 inch micro-strip line segments (red and blue lines) and modeled for 6 inch micro-strip line segment (brown and green lines):
FR408HR model: Wideband Debye, Dk=3.815 (3.66), LT=0.0117 @ 1 GHz (same as for strip);
Taiyo solder mask model: Wideband Debye, Dk=3.85 (3.9), LT=0.02 @ 1 GHz;
Conductor roughness model: Modified Hammerstad, SR=0.4 um, RF=3.5;

Models are usable up to 50 GHz!

(3) Modeling discontinuities in isolation

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- 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**

See how to check the localization at App Notes #2013_03, 2013_05 at http://www.simberian.com/AppNotes.php

(4) Benchmarking or validation

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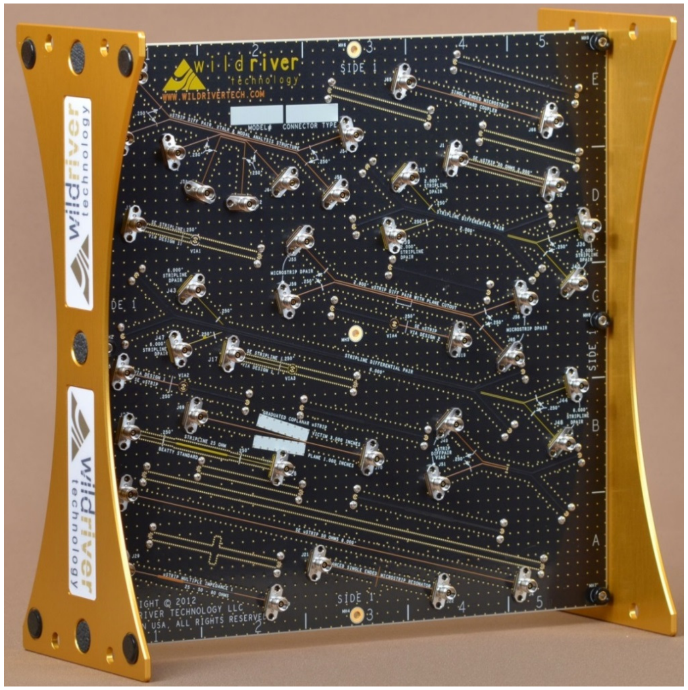
- How to make sure that simulation works? – Build validation boards!
- Controlled board manufacturing is the key for success
  - Fiber type, resin content, copper roughness must be strictly specified or fixed!!!
  - Identify all manufacturing adjustments: stackup, etching compensation,…
- Include a set 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 measurements and compare both magnitude and phase (or group delay) of all S-parameters and optionally TDR and eye diagram

See more at: Y. Shlepnev, **Sink or swim at 28 Gbps**, The PCB Design Magazine, October 2014, p. 12-23.

Validation platforms simplify process

- CMP-28/32 Channel Modeling Platform was developed by Wild River Technology to promote systematic approach to interconnect analysis to measurement validation up to 40/50 GHz or up to 28/32 Gbps
  - **Contains 27 micro-strip and strip-line interconnect structures** equipped with 2.92 mm (CMP-28) and 2.4 mm (CMP-32) connectors and can be used to validate signal integrity simulators or measurement technique



Complete description of CMP-28/32 platforms with all results is available at
http://www.simberian.com/Presentations/CMP-28_Simbeor_Kit_Guide.pdf

Demo of validation with Simbeor

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1. Measure and ensure quality of S-parameters (done)
2. Get all stackup and geometry adjustments from manufacturer or do cross-sectioning (done)
3. Identify or confirm material models (done)
4. Load board design and do post-layout analysis with or without connectors/launches

Example of validation

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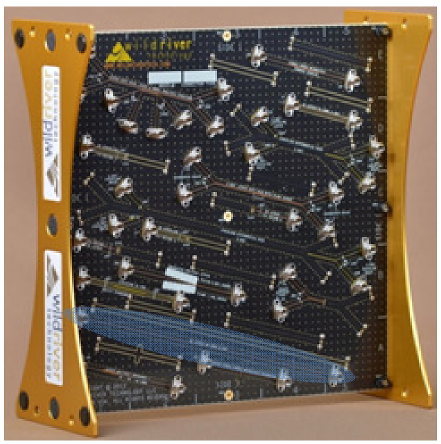
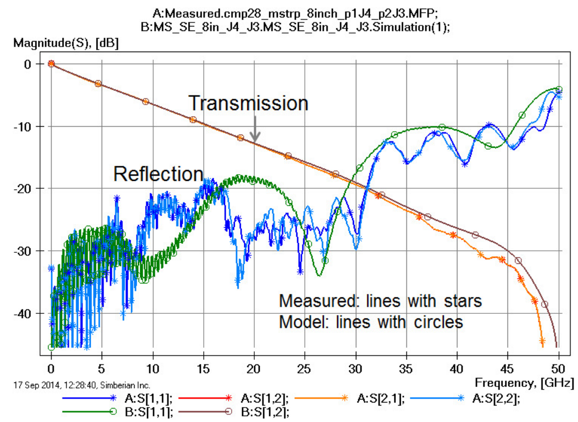
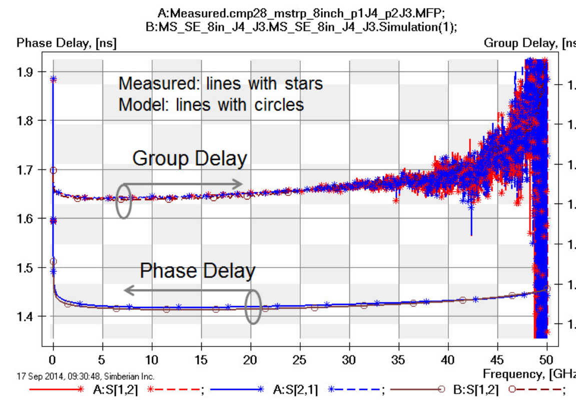
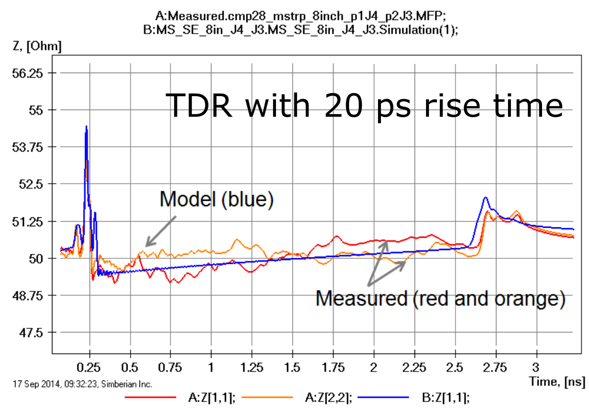
8-inch micro-strip line segment with launches and connectors

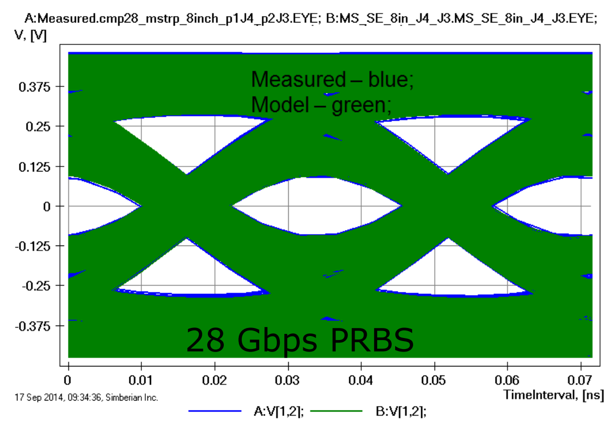


Trace width is reduced by 1 mil



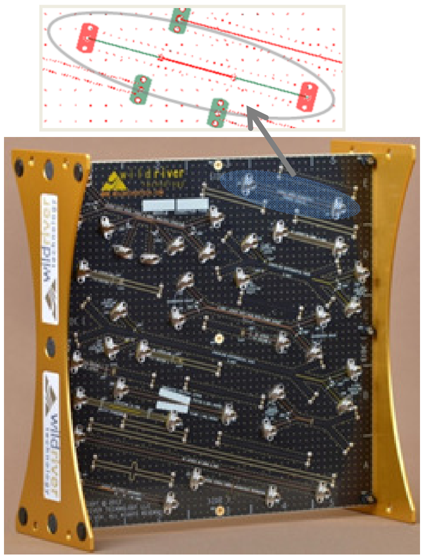




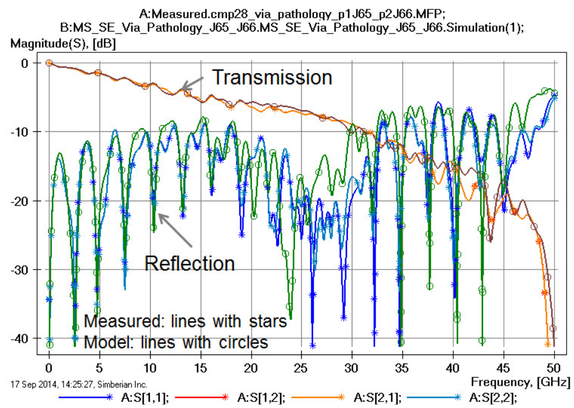


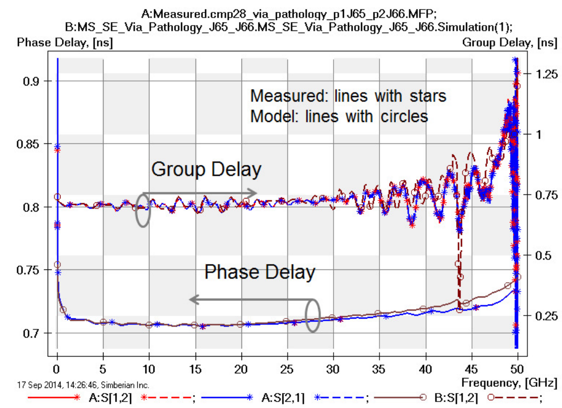
Example of validation

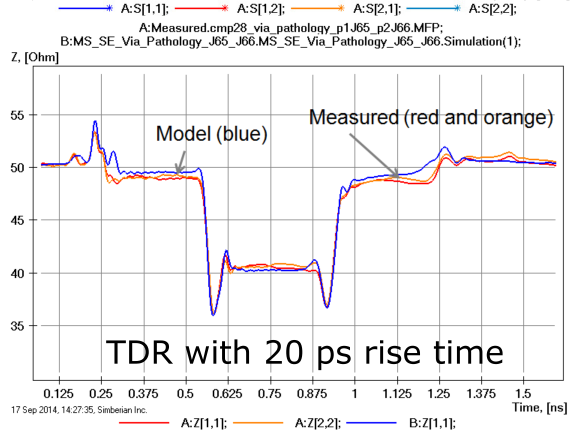
Micro-strip line segment with 2 capacitive vias with connectors and launches

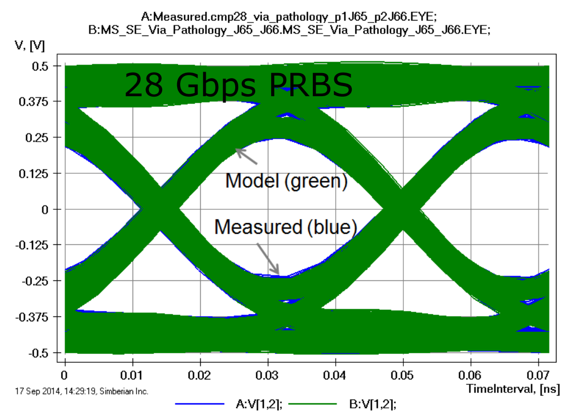


Both narrow and wider sections widths are reduced by 1mil









What if simulation does not match measurements?

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- 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…

Further 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
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