Signal Integrity Tips and Techniques Using TDR, VNA and Modeling

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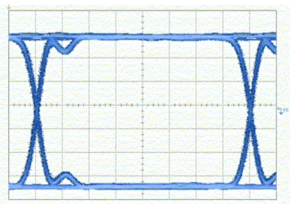
O.J. Danzy

KEYSIGHT TECHNOLOGIES

Simulation

KEYSIGHT TECHNOLOGIES

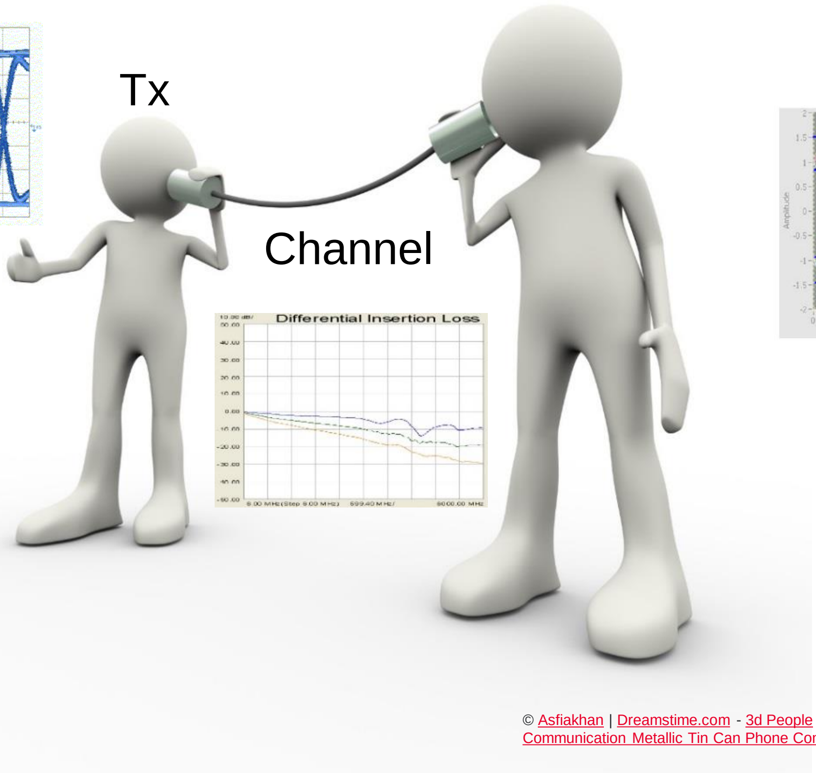
What is the Signal Integrity Challenge?

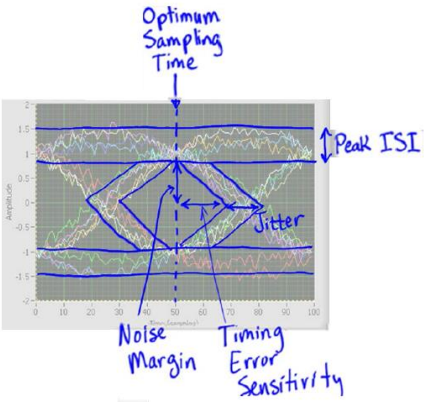


Rx

Tx

Channel

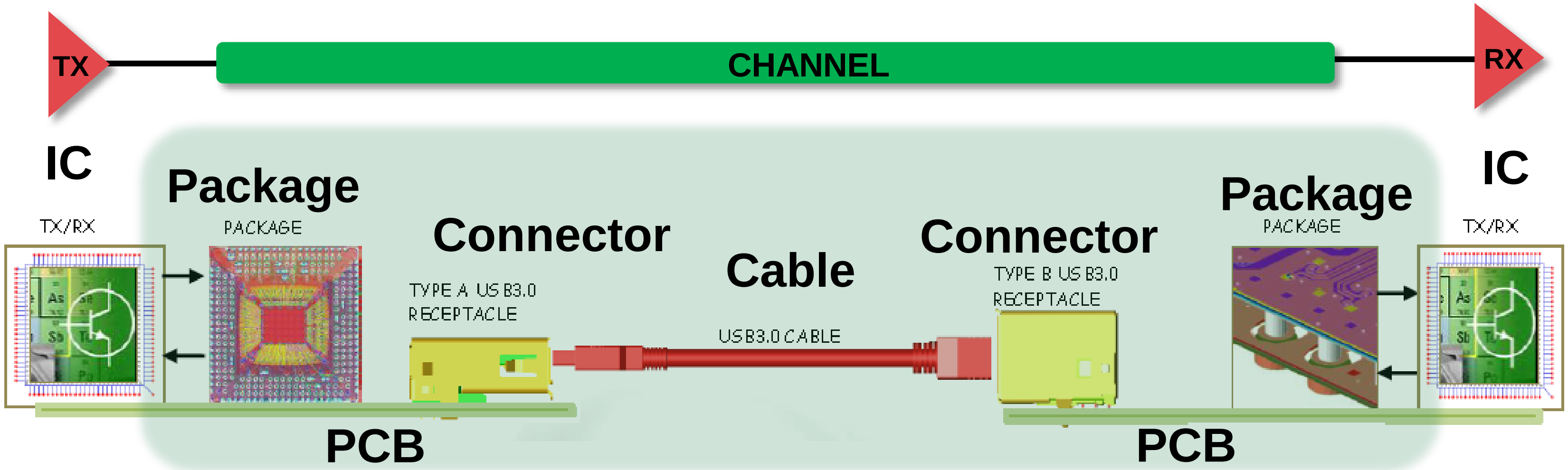


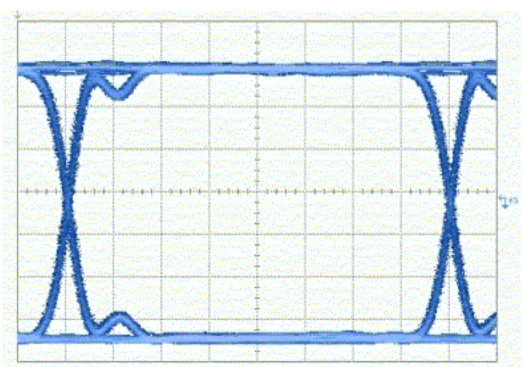


How does simulation help?

- Distributed Model of the Physical Channel
- Using simple simulations to interpret TDR, TDT, and S-Parameters:
  - Stub Z discontinuity
  - Series Z discontinuity
- Simulation + Measurement = Insight

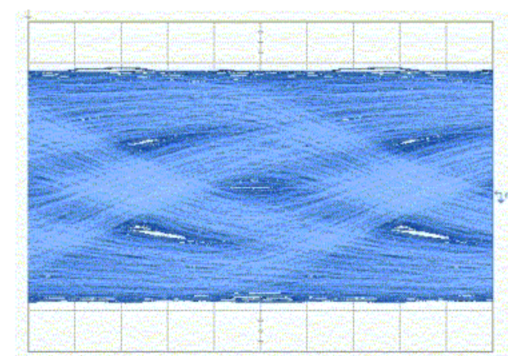
Example – SI Channel Degradation





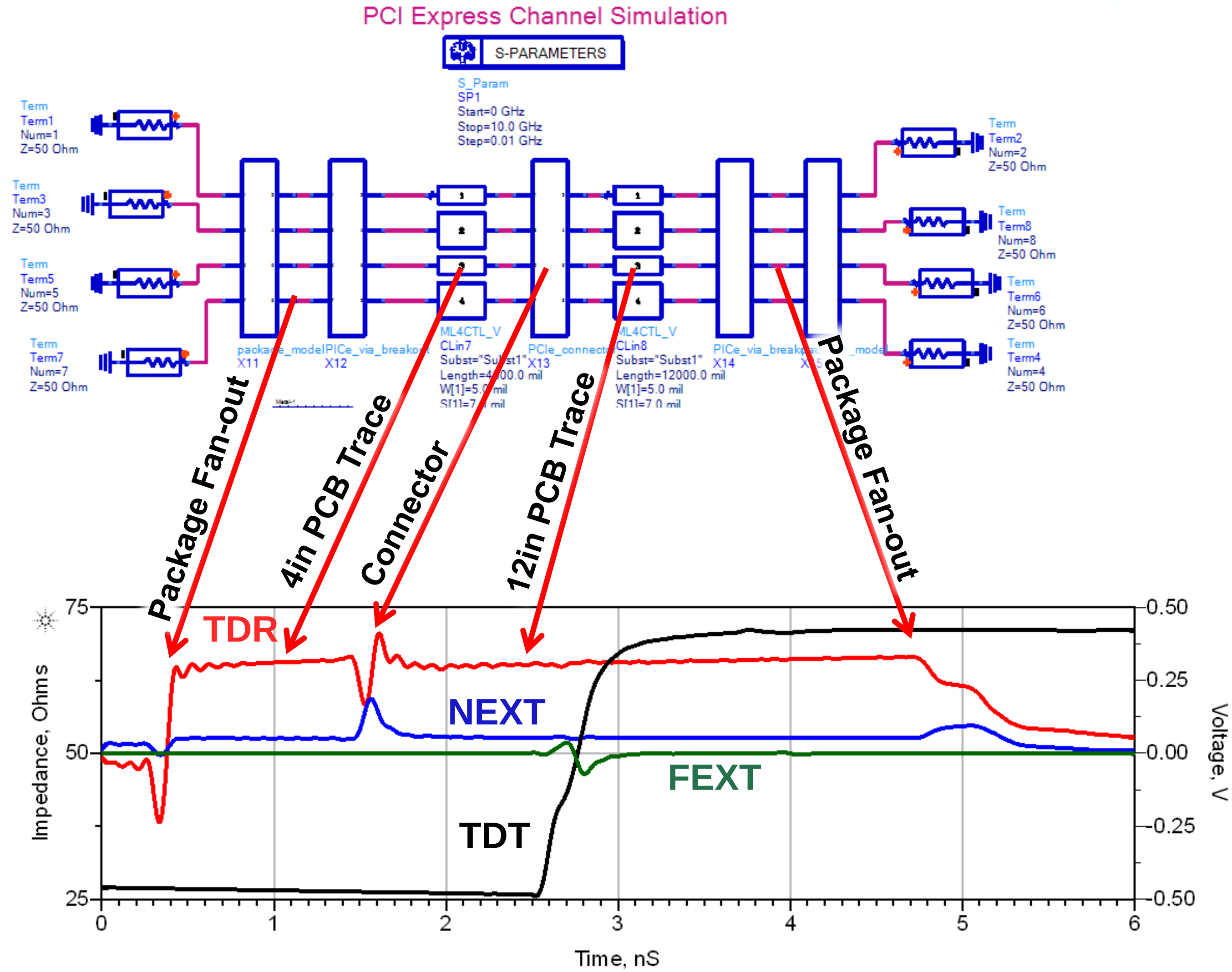
Non-Ideal TX Data

Channel Degradation

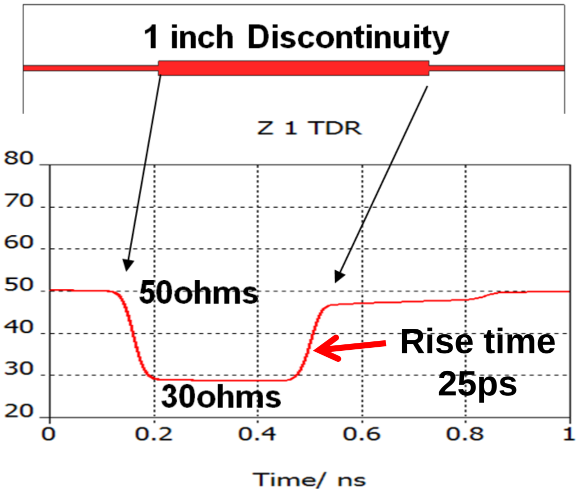


Corrupt Data at RX

Distributed Model of the Physical Channel



Impact of Rise Time on TDR

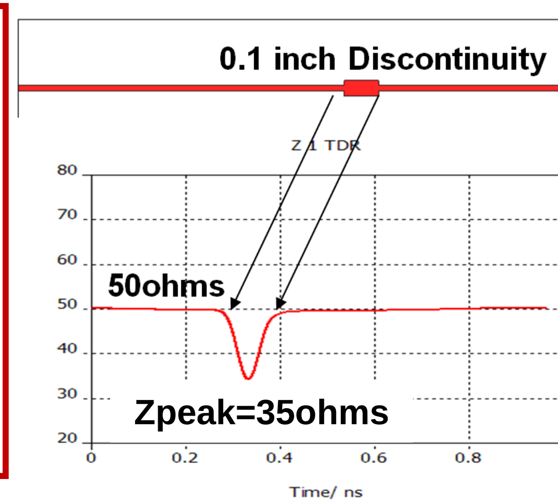


Reflection :

$$\Gamma = \frac{Z_{\Delta x} - Z_0}{Z_{\Delta x} + Z_0}$$

for small R :

$$Z = \sqrt{\frac{L}{C}}$$



Time Delay :

$$TD_{1inch} = vL$$

$$v = \frac{\sqrt{dK}}{12}\frac{ns}{mil}$$

Example FR4 :

$$= \frac{\sqrt{4}}{12}(100) \approx 17\,ps$$

$$< 25ps\ Rise\ time$$

Bit Rate	~1/10th Rise Time Feature Size	High Speed Feature Size
1 MBit	3 m (10 ft)	Matched Termination
10 MBit	30 cm (12 in)	T-Line Zo
100 MBit	3 cm (1.2 in)	Connector Zo
1 GBit	3 mm (120 mils)	Passive SMT Zo
5 GBit	0.6 mm (24 mils)	Via Zo
10 GBit	0.3 mm (12 mils)	Die, Package, PCB Co-sim
40 GBit	0.075 mm (6 mils)	Machining Tolerances

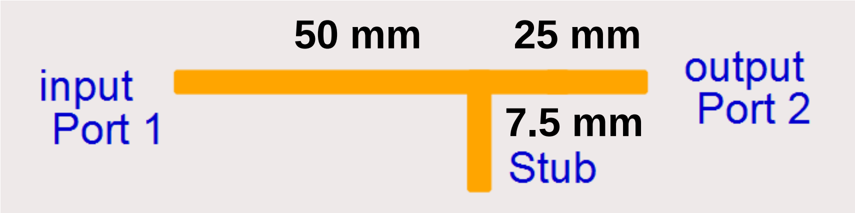
KEYSIGHT TECHNOLOGIES

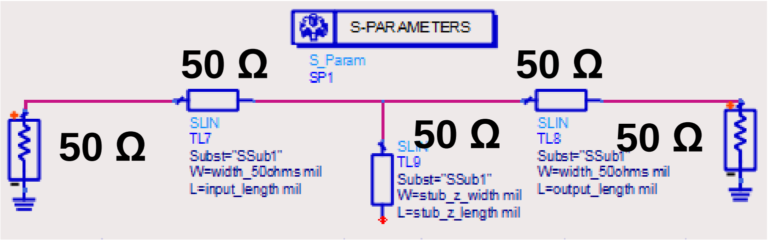
Use Simulation to Become an Expert on TDR/TDT

Simple simulations benefit analysis of TDR/TDT measurements.

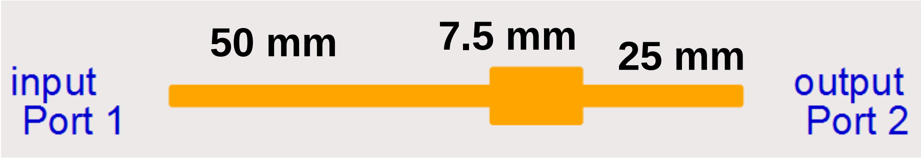
T-Line Model for Simulation

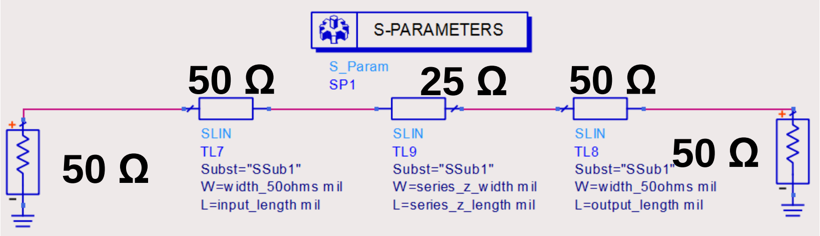
Stub Resonance





Series Resonance



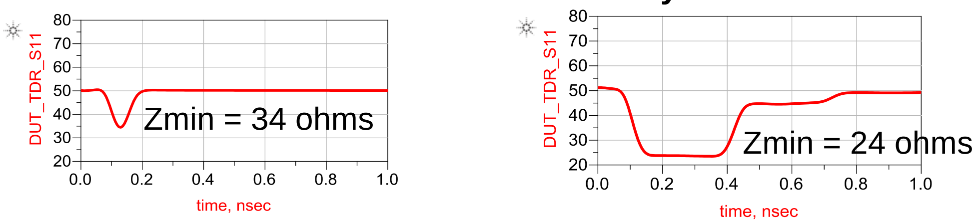


Fast Frequency Domain Sweep

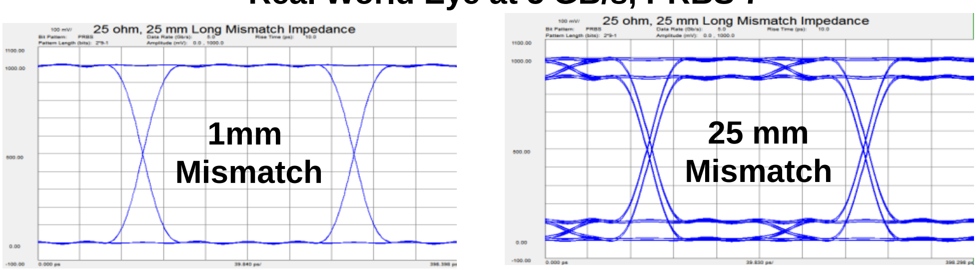
Series Impedance Discontinuity
Time and Frequency Domain Analysis

Physical Layout

Time Domain Reflectometry

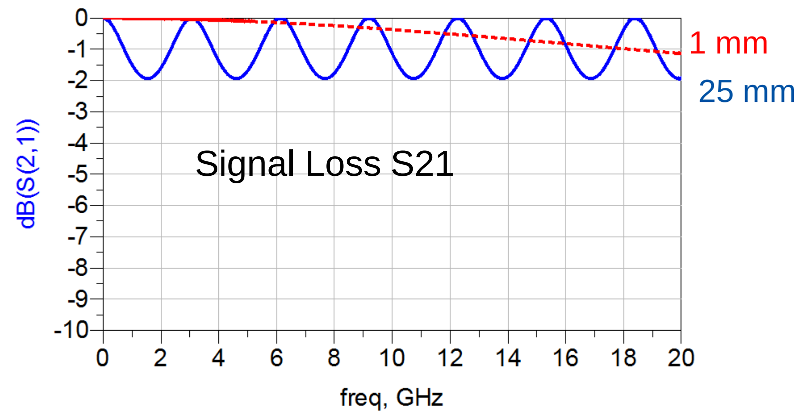


Real World Eye at 5 GB/s, PRBS 7



Frequency Domain Insertion Loss

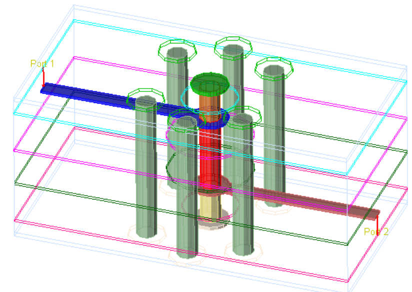
25 ohm Discontinuity with
Length from 25 mm to 1 mm



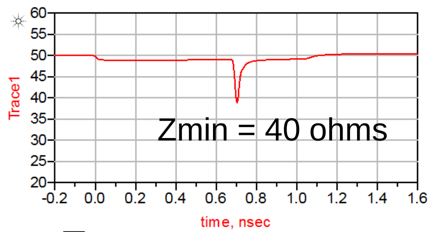
Stub Impedance Discontinuity
Time and Frequency Domain Analysis

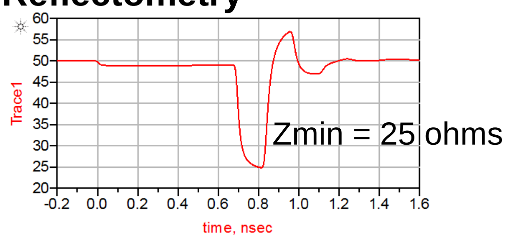
Physical Layout

L < Rising Edge | L > Rising Edge



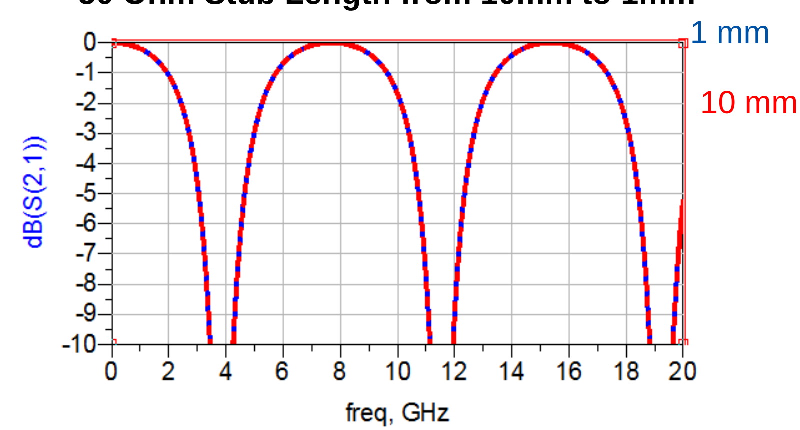
Time Domain Reflectometry



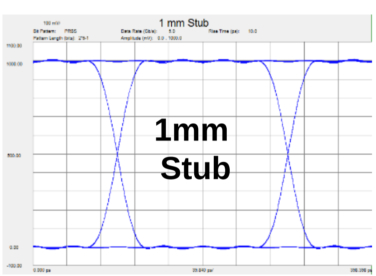


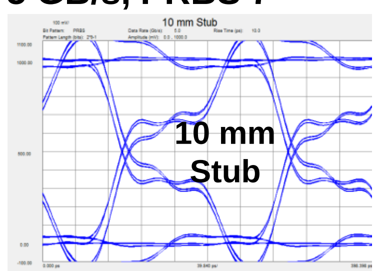
Frequency Domain Insertion Loss

50 Ohm Stub Length from 10mm to 1mm



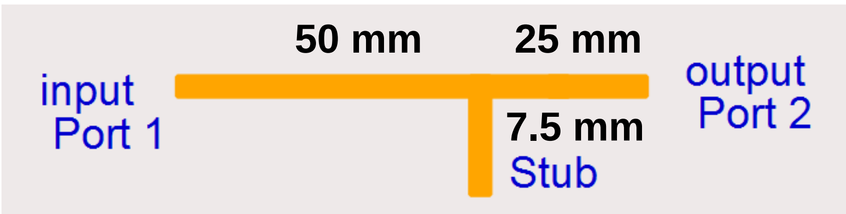
Real World Eye at 5 GB/s, PRBS 7

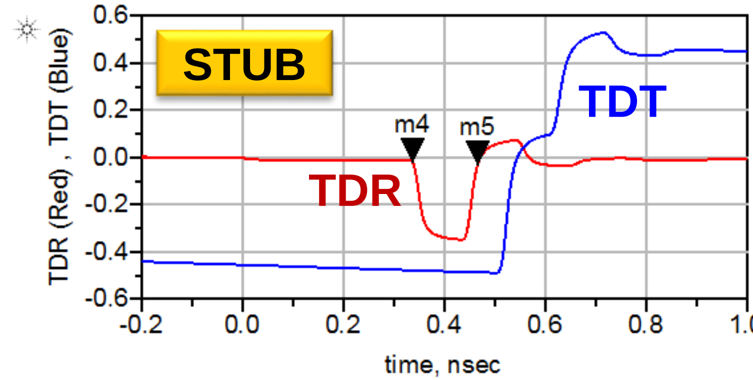




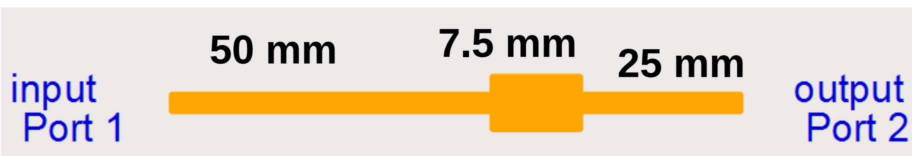
A Closer Look at TDR vs TDT

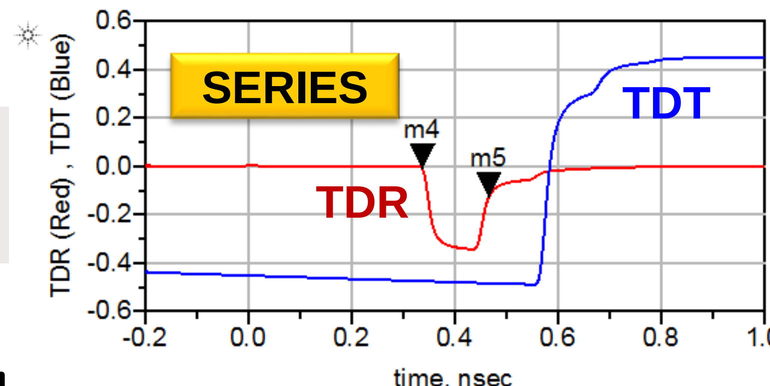
Stub Resonance





Series Resonance





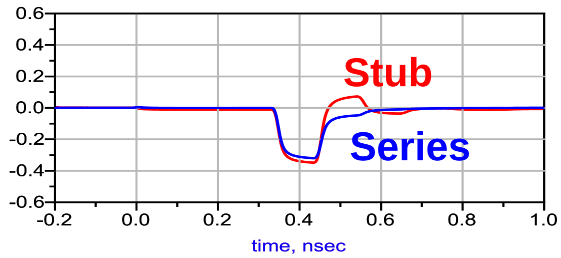
Excess C and L Calculations

$$C_{Total} = \frac{t_d}{Z_0} \qquad C = \frac{2\tau}{Z_0} = -\frac{2}{Z_0}\int_0^{+\infty} \text{reflected\_n} \cdot dt$$

$$L_{Total} = t_d Z_0 \qquad L = 2Z_0\tau = 2Z_0\int_0 \text{reflected\_n} \cdot dt$$

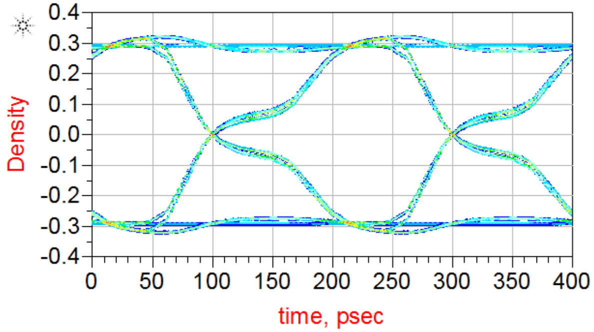
Integrate from Marker 4 to 5 to get Excess C = 1.4 pF

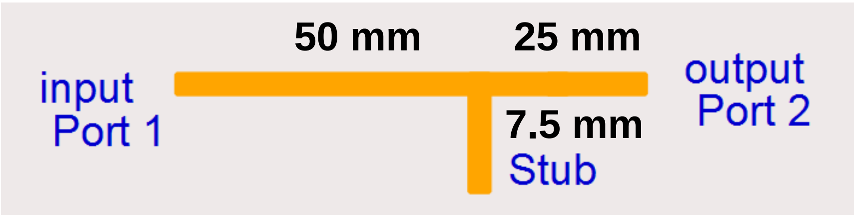
Why is the TDT different for the same delta Z change?



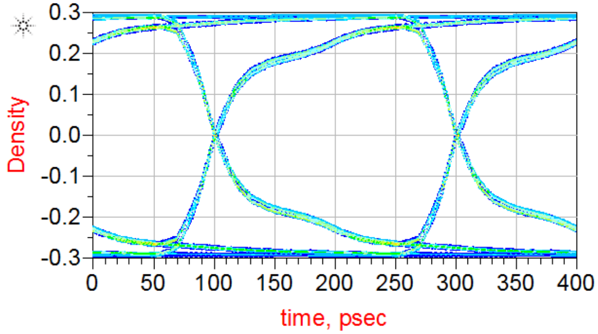
Excess C is 1.4 pF and Z~ 26 ohms

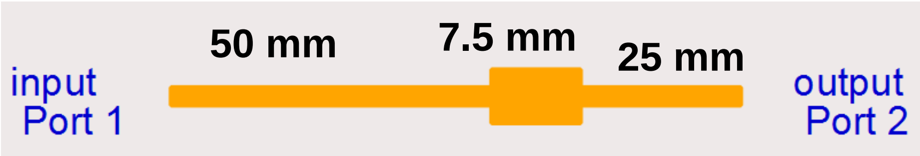
Stub Resonance



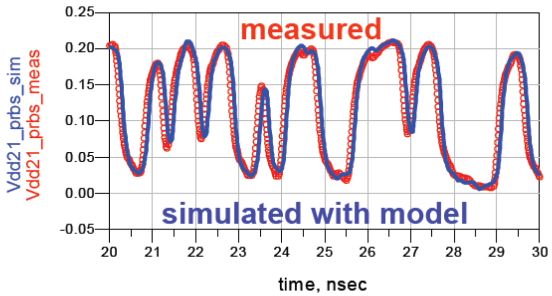


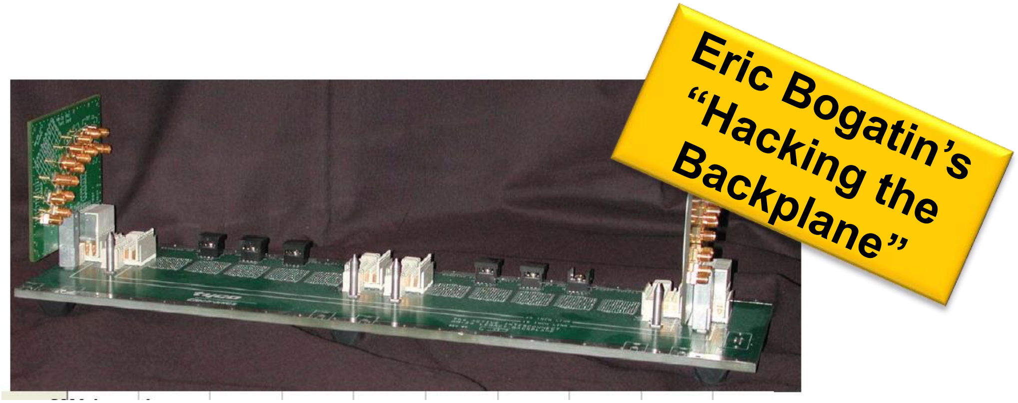
Series Resonance



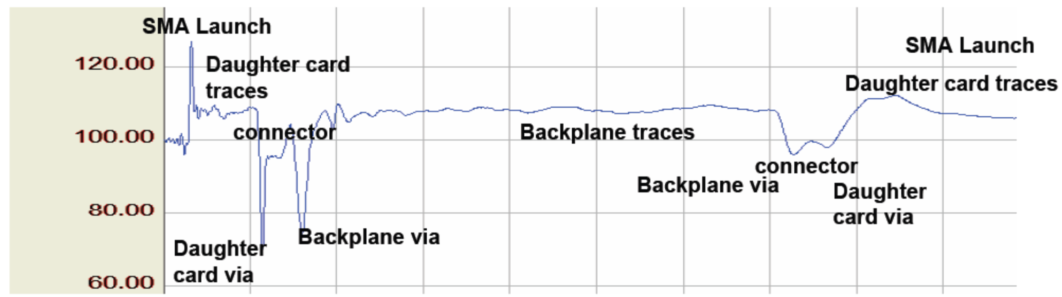


Measurement Based T-Line Model for Debugging the Channel – Virtual Lab

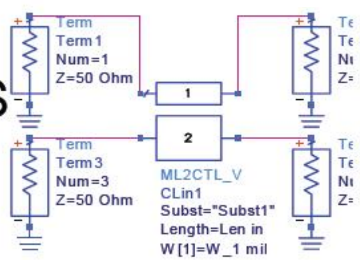


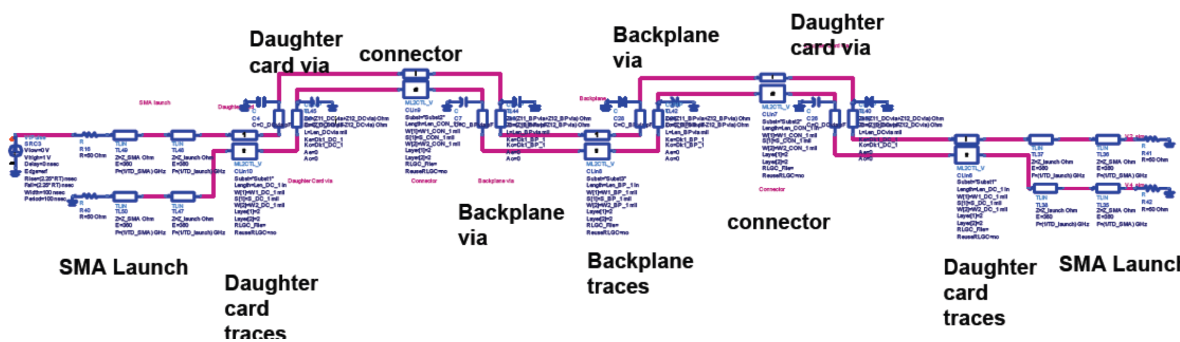


TDR/TDT

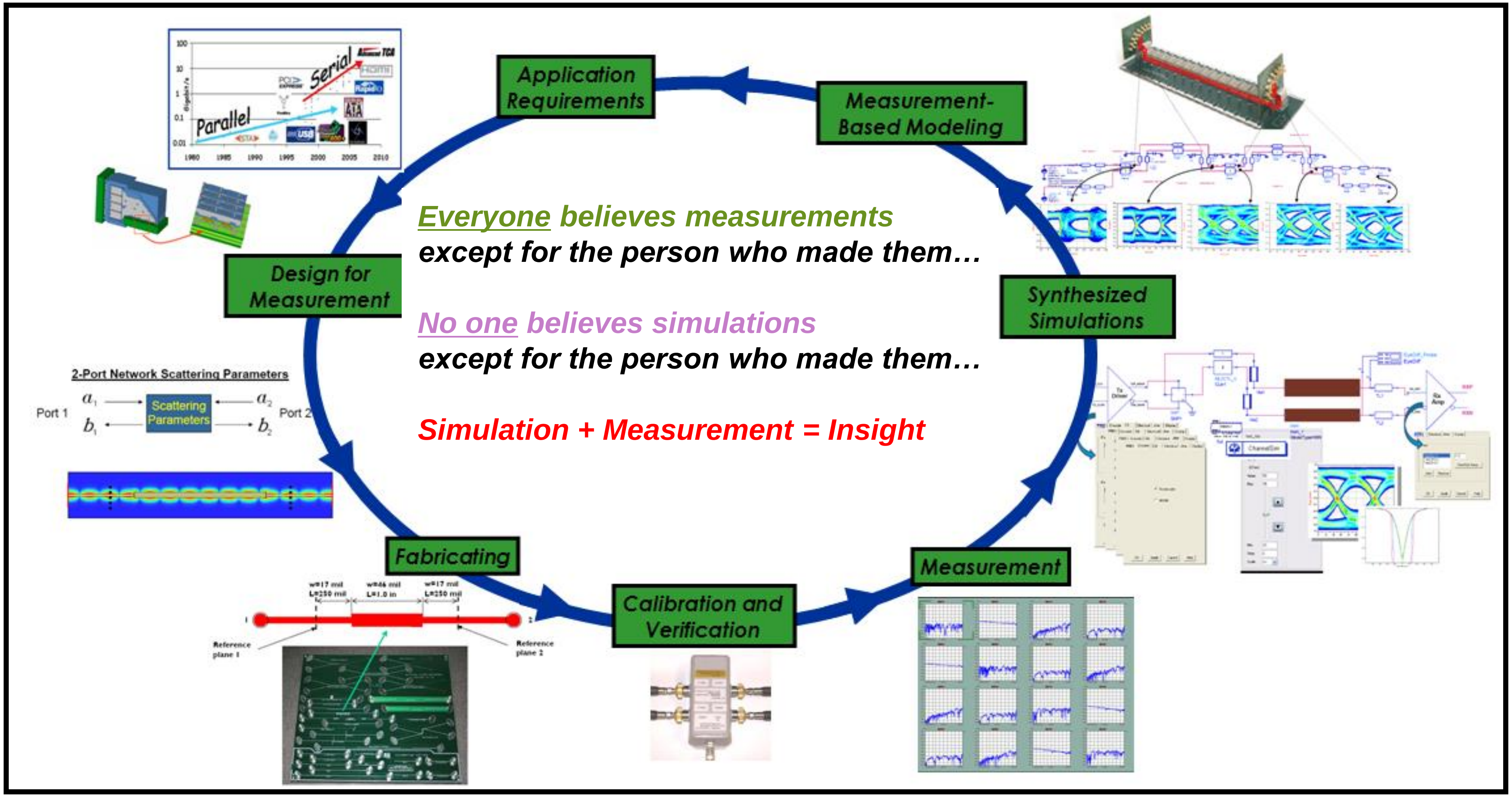


ADS





Solving the Problem with
Pre-Layout, Post-Layout, Measurement



Measurement

Agenda, “Finding the Causes of EMI and How TDR can Help”

– How do high speed serial designs typically cause EMI?

– In high speed serial designs, where do common currents come from?

– A quick overview of the DUT evaluated

– How can TDR Help address the EMI issue?

What Causes EMI?

- Of course, there are many potential causes of EMI but in high-speed serial designs one of the largest sources of EMI is radiation (that gets out of the box) from **common currents generated by a differential data channel**.
- The differential channel ideally has no common currents but it takes only a very small common signal to create an EMI issue.
- As a rule of thumb, to pass an FCC certification test the maximum allowable common signal on an external twisted pair should be < 10 mV at 1 GHz.

Agenda

– How do high speed serial designs typically cause EMI?

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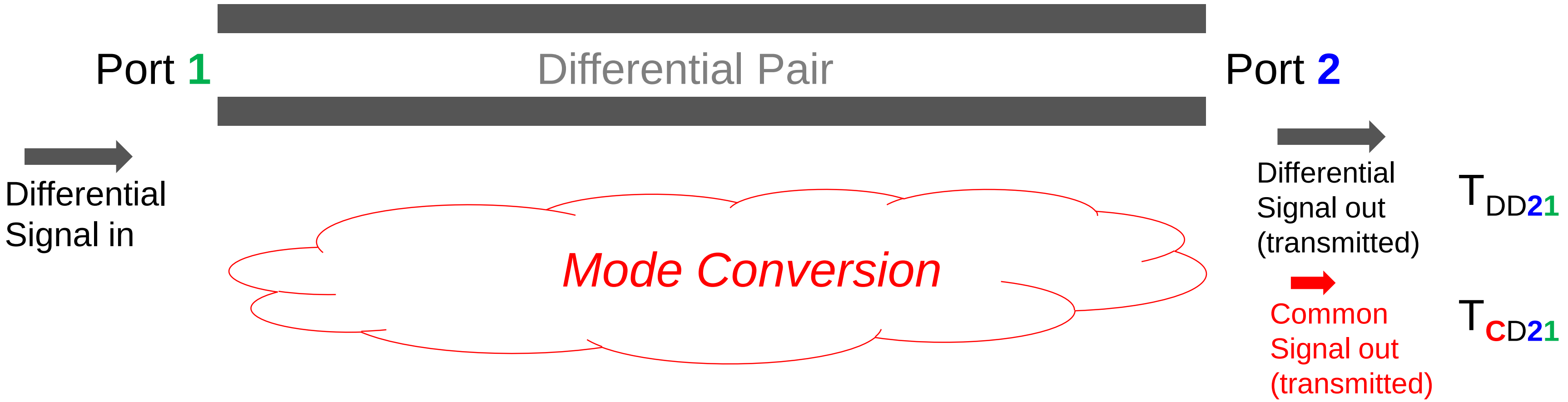
Where do the common currents come from?

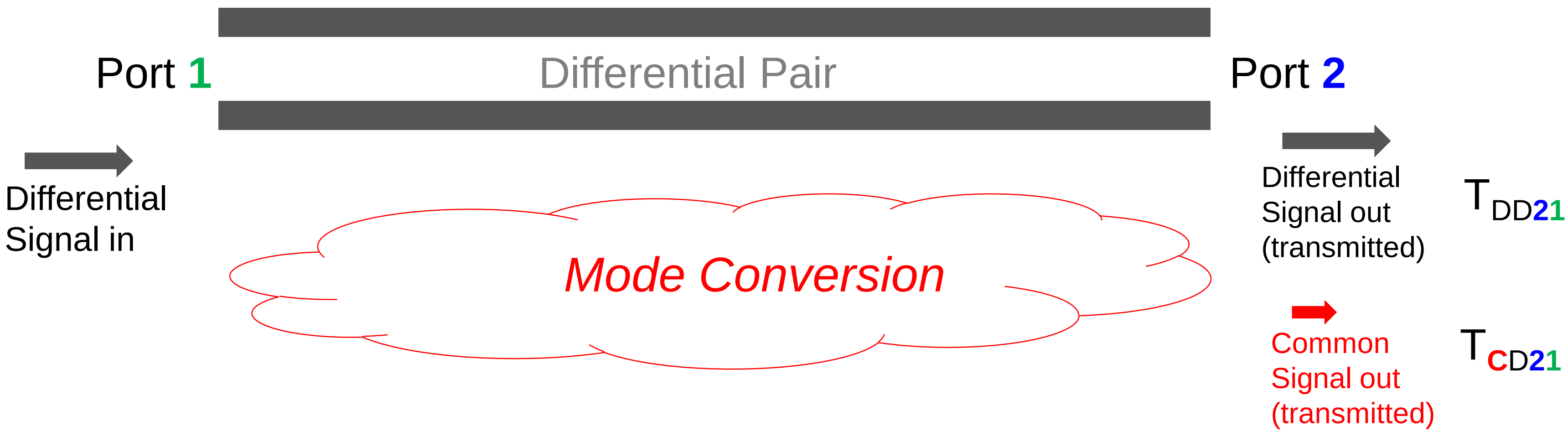


In theory, if the drivers produce a perfect differential signal (no common component) and the differential signal passes through a perfect differential channel, there will be NO common signal generated.

In practice that is NEVER the case!

Assuming the driver is perfect and we consider just the channel, any asymmetry in a coupled differential channel will convert some of the differential signal into a common signal. This is known as “Mode Conversion”.

What Causes Mode Conversion in the Channel?



ANY asymmetries in the coupled lines can cause mode conversion:

- Non-equal line widths
- Non-equal line lengths
- Different "local" effective dielectric constants (even due to the glass weave in the laminate)
- A discontinuity in the ground plane

Let's look at a real example

Agenda

– How do high speed serial designs typically cause EMI?

– In high speed serial designs, where do common currents come from?

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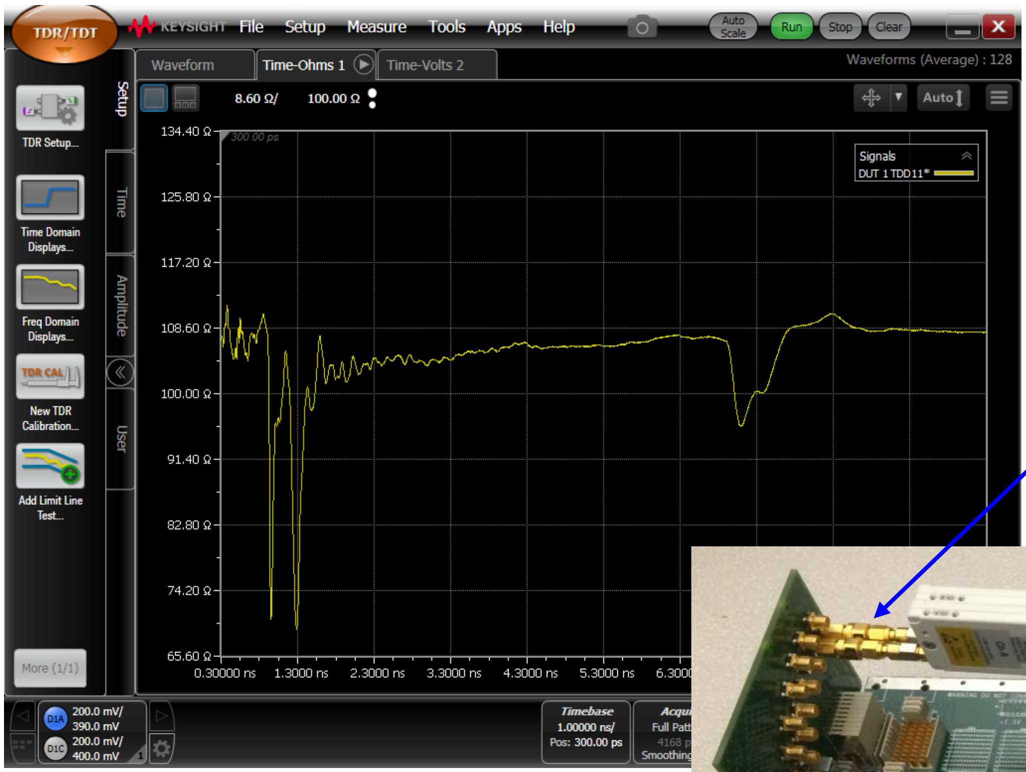
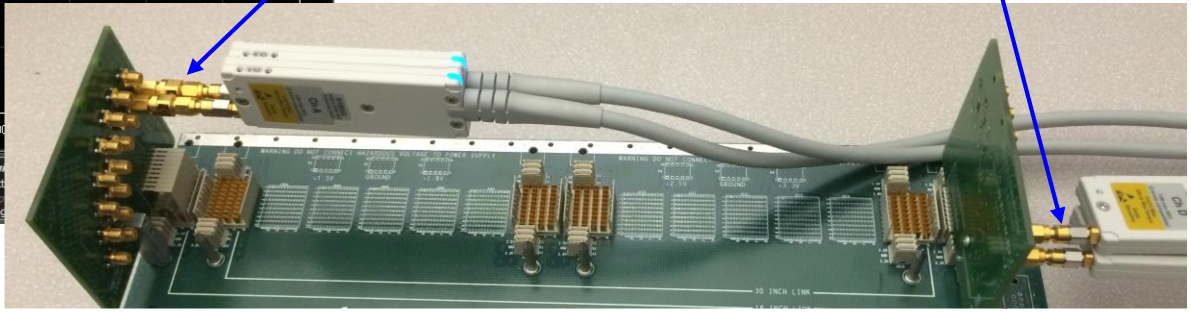
Using TDR to evaluate the channel:





TDR remote heads enable connecting directly to the DUT without the need for cables

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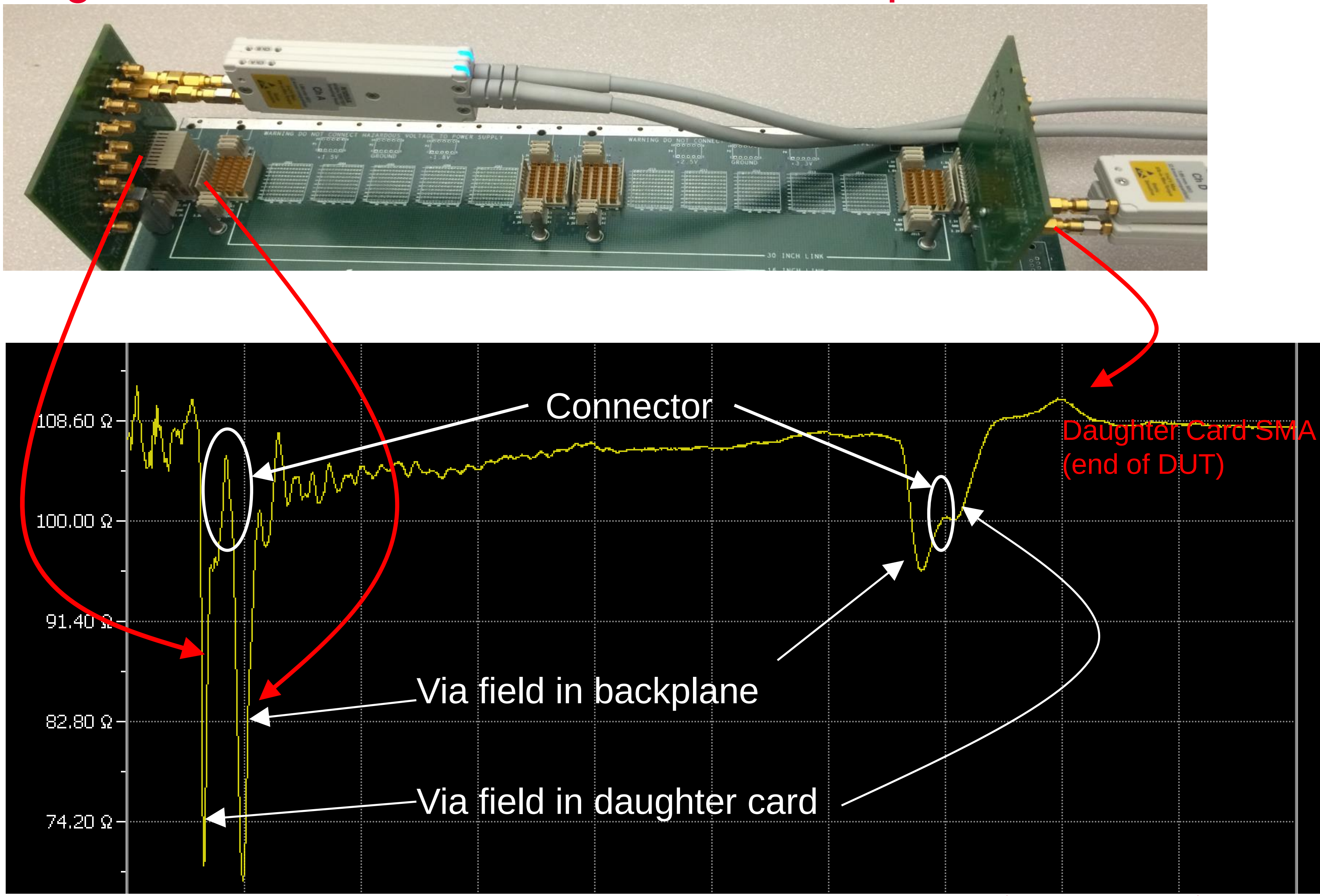
Using TDR to evaluate the channel: A quick look at the DUT



KEYSIGHT TECHNOLOGIES

Agenda

– How do high speed serial designs typically cause EMI?

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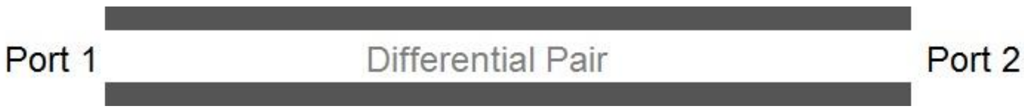
How can TDR help find the source of EMI issues?

Part 1: Is there mode conversion?

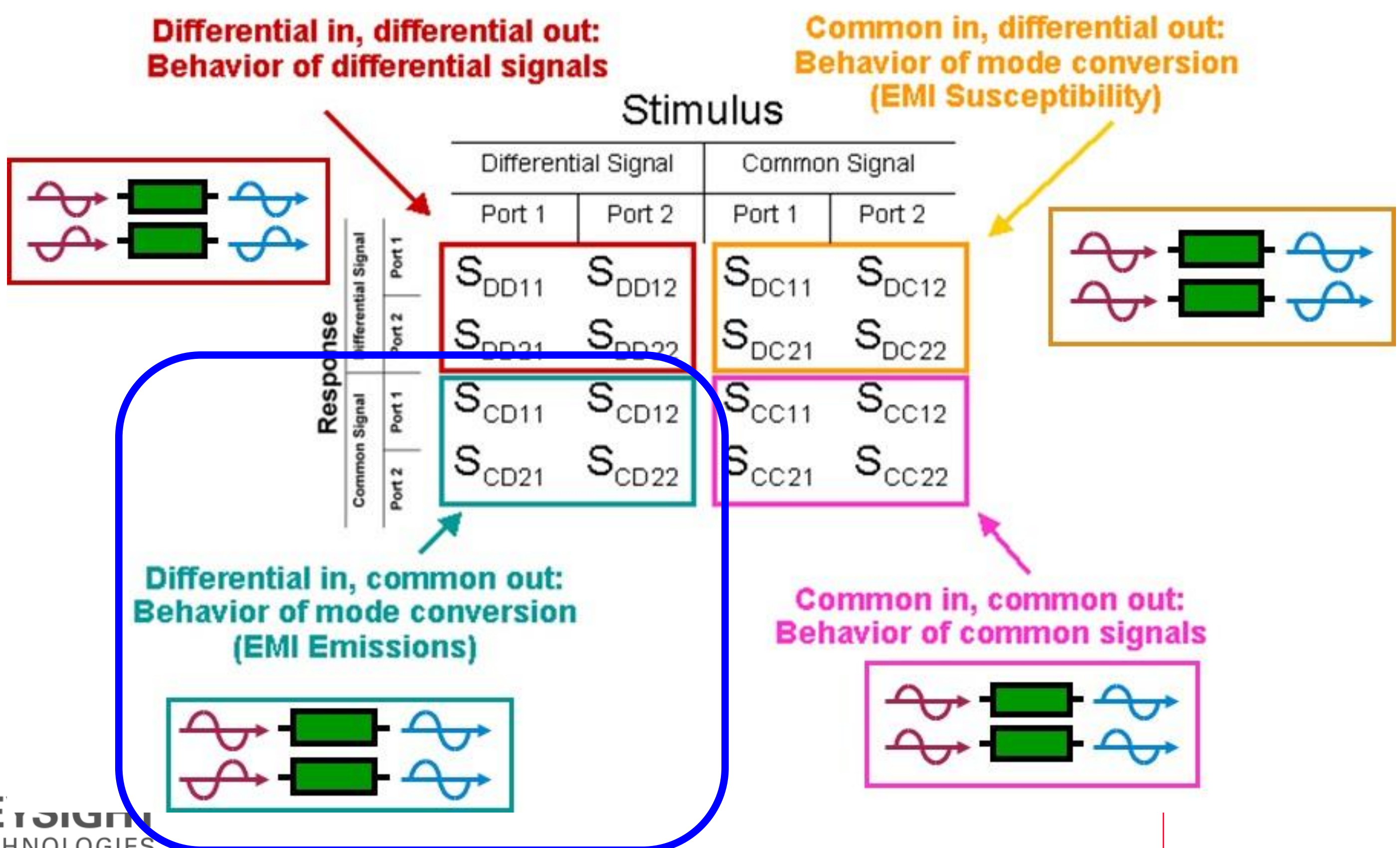
Start with a quick review of S-parameter terms



Stimulus (in)

S_{CD21}

Response (out)



How can TDR help find the source of EMI issues?

Part 1: Is there mode conversion?

Port 1 | Differential Pair | Port 2

Differential Signal in

Differential Signal out (transmitted) T_{DD21}

Common Signal out (transmitted) T_{CD21}

Similar – but not exactly the same – signal velocity

How can TDR help find the source of EMI issues?

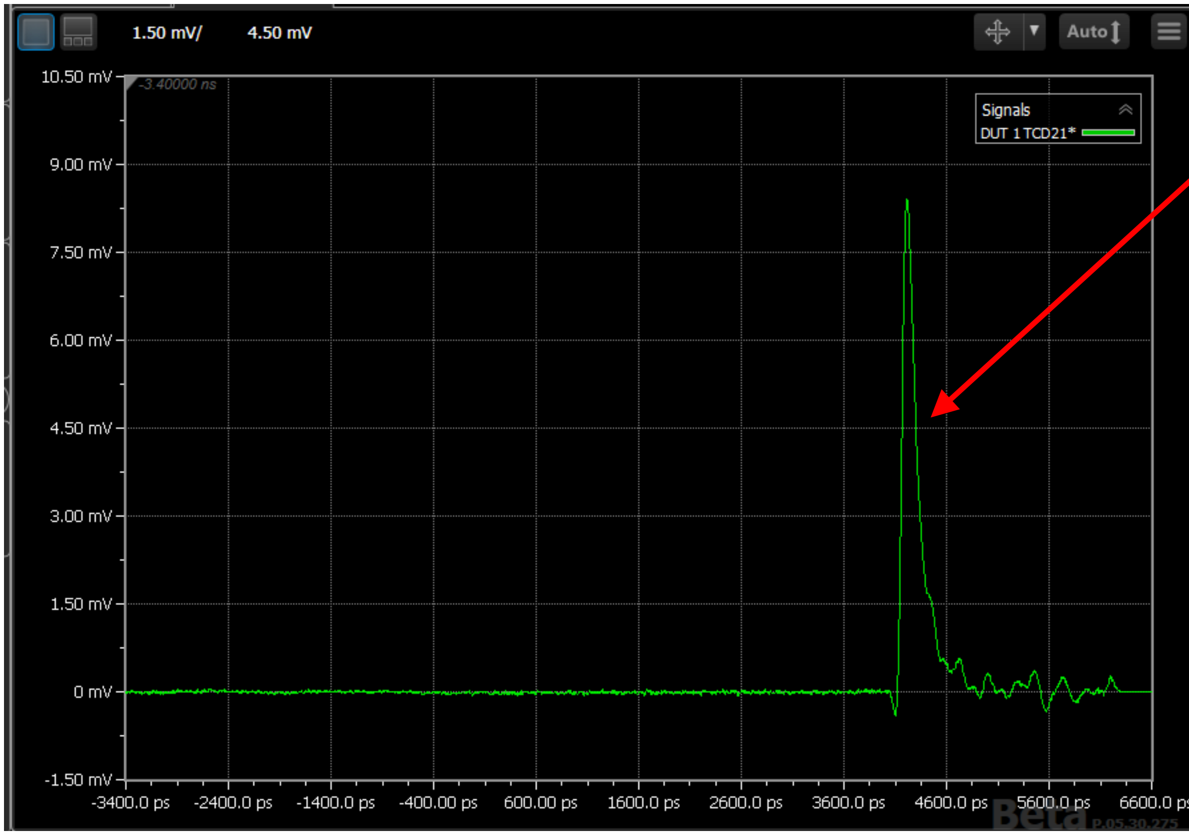
Part 1: Is there mode conversion? TDT

Port 1

Differential Pair

Port 2

Differential Signal in



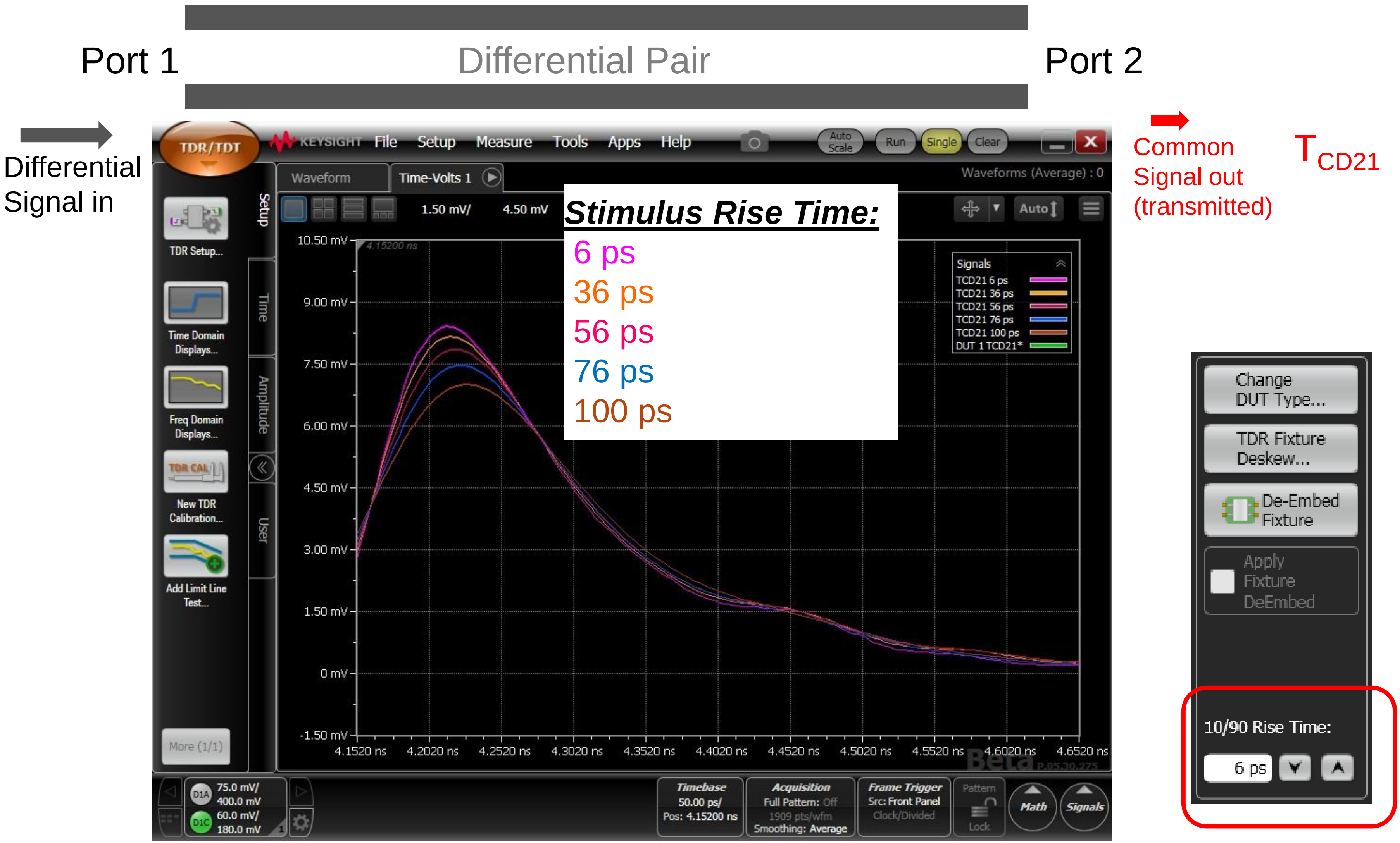
Common Signal out (transmitted)

T_{CD21}

KEYSIGHT TECHNOLOGIES

How can TDR help find the source of EMI issues?

Part 1: Is there mode conversion? How dependent is it on edge speed?



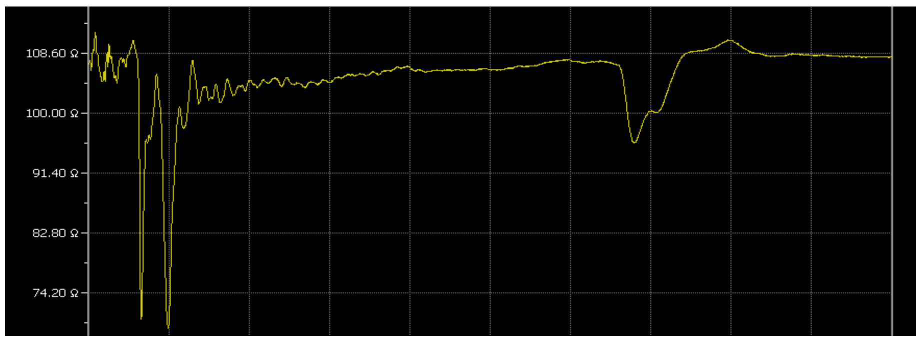
How can TDR help find the source of EMI issues?

Part 2: There is mode conversion; what is causing it?

Port 1 Differential Pair Port 2

Differential Signal in

Differential Reflection T_{DD11}



Differential Signal out (transmitted) T_{DD21}

This shows the position and magnitude of differential reflections

Common Signal out (reflected) T_{CD11}

Mode Conversion

Common Signal out (transmitted) T_{CD21}

Remember, velocities are similar

KEYSIGHT TECHNOLOGIES

How can TDR help find the source of EMI issues?

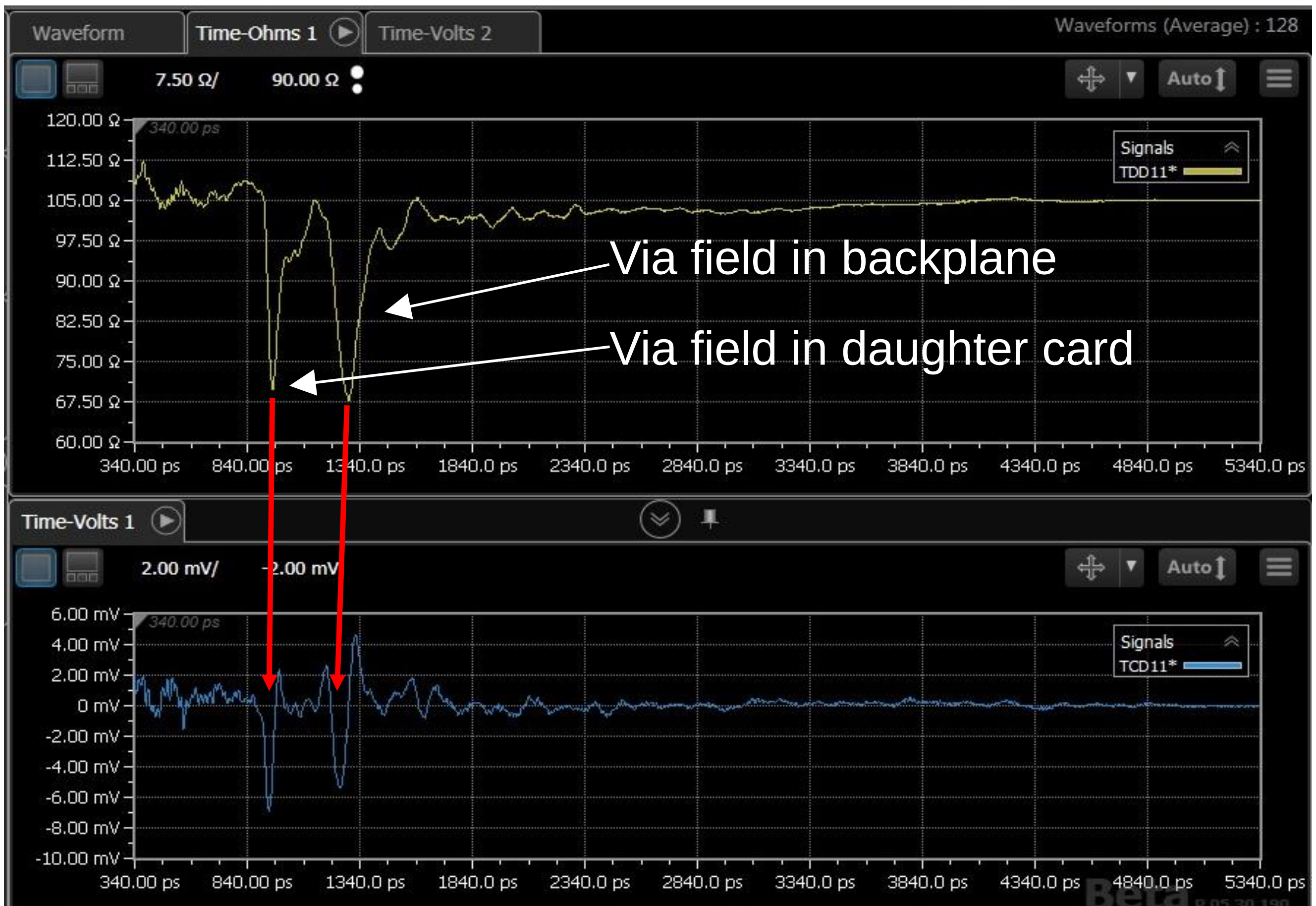
Part 2: There is mode conversion; what is causing it?

Port 1 Differential Pair Port 2

Differential Signal in

Differential Reflection T_{DD11}

Common Reflection T_{CD11}



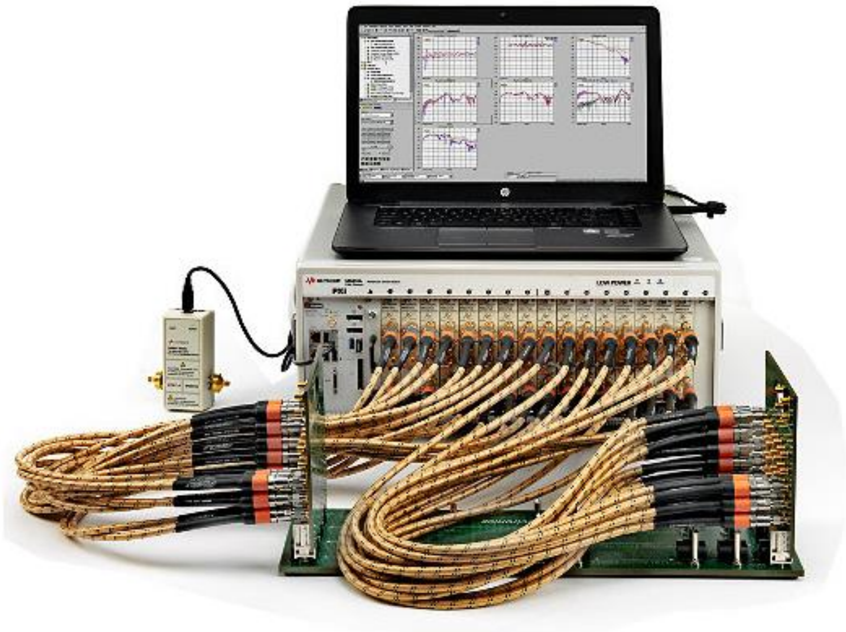
Summary

1. Even a small Common Mode signal, if it gets “out of the box”, can cause EMI and possibly an FCC certification test failure.

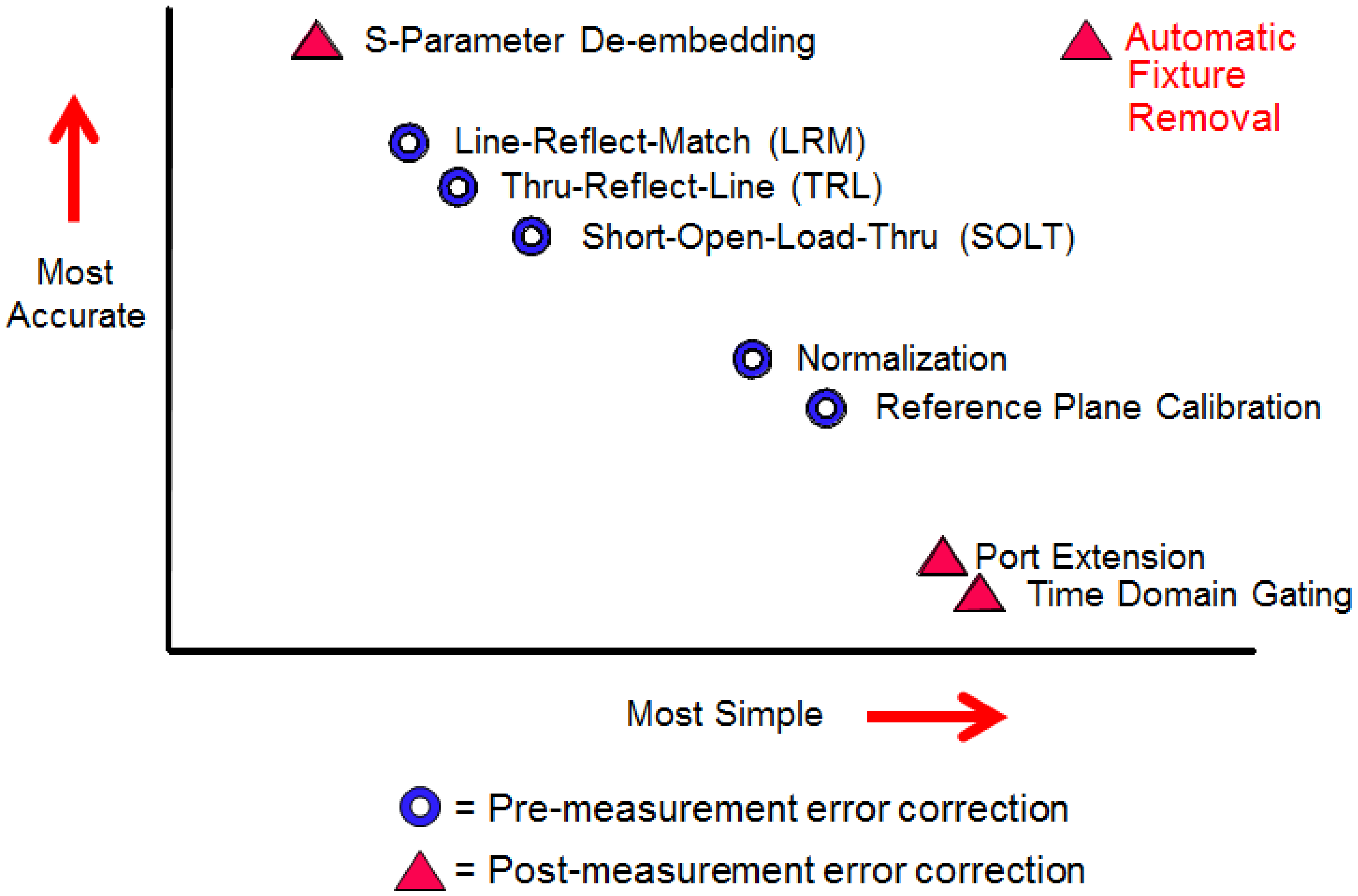
2. Any asymmetries (line width, line length, local dielectric, discontinuity in the ground plane, etc.) in a coupled differential line can cause Mode Conversion.

3. The Differential and Common signals travel at similar velocities so comparing the reflected Differential signal (T_{DD11}, impedance profile) with the reflected Common signal, T_{CD11}, will show where/what in the DUT is causing the Mode Conversion.

Error Correction



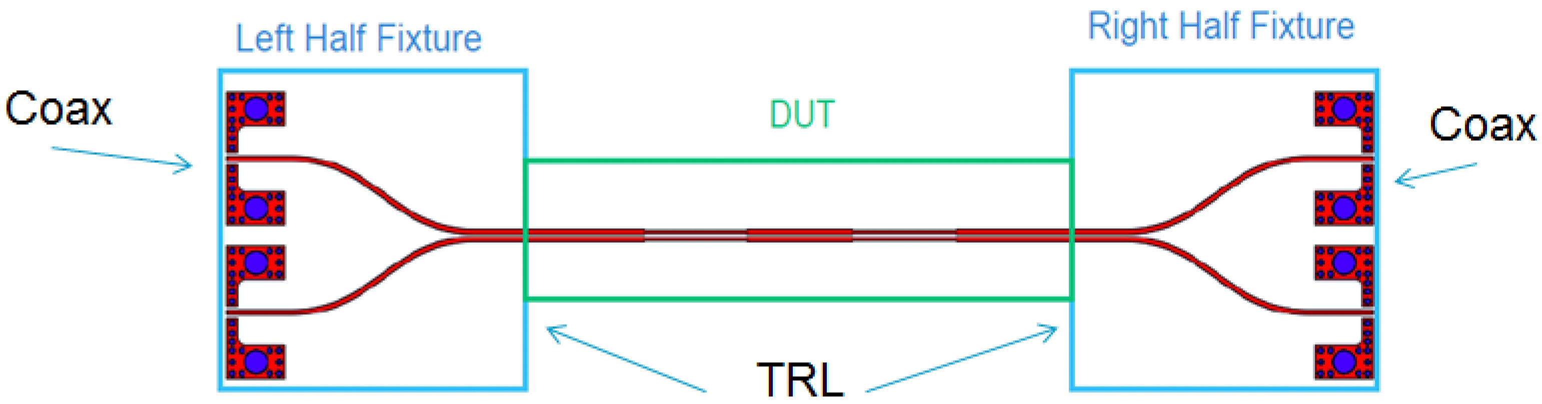
Signal Integrity Error Correction Techniques



Removing Fixtures

Historically – 2 methods:

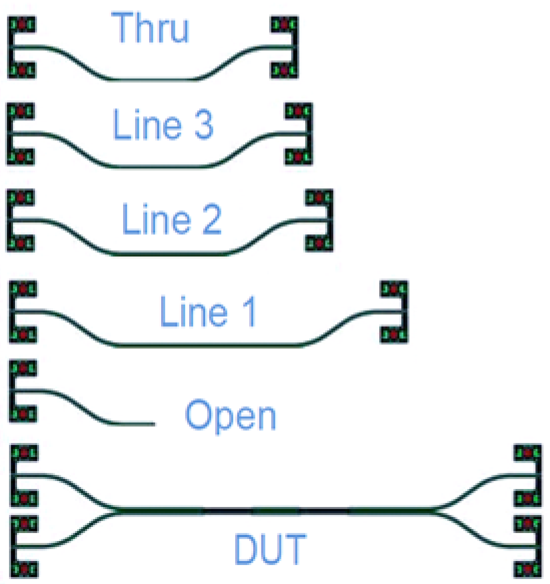
- Model the fixture using EM Simulation and then de-embed the fixtures from the measurement
- Build a calibration kit (SOLT or TRL)
  - SOLT requires characterization of standards (difficult)
  - TRL is an easier calibration technique to move measurement reference planes to the DUT. (preferred method)



TRL (Single Ended)

Assumptions for single ended TRL

- Connectors and launches are identical
- All lines have same Transmission Line characteristics
  - Impedance, loss, propagation
  - Only differ in length
- Lines are usable 20 to 160 degrees relative to thru
- No coupling in fixture is removed
- Usually 2-4 lines depending on frequency range



Differential Cross Talk Calibration aka Diff TRL

4-port TRL Calibration Technique

Fixture may be asymmetric

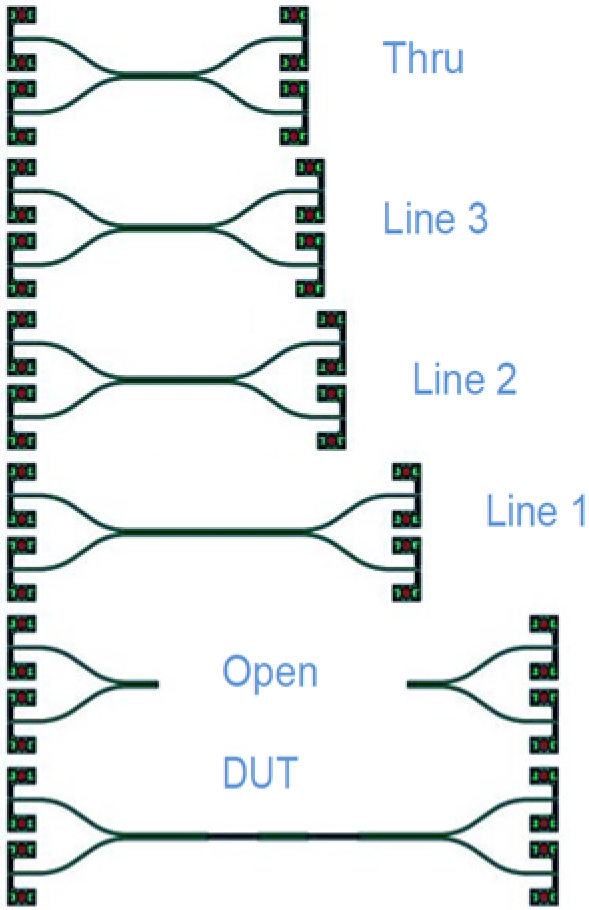
Similar assumptions to single ended TRL

- Repeatability of connector, launch, and line
- lines are usable 20 to 160 degrees relative to thru

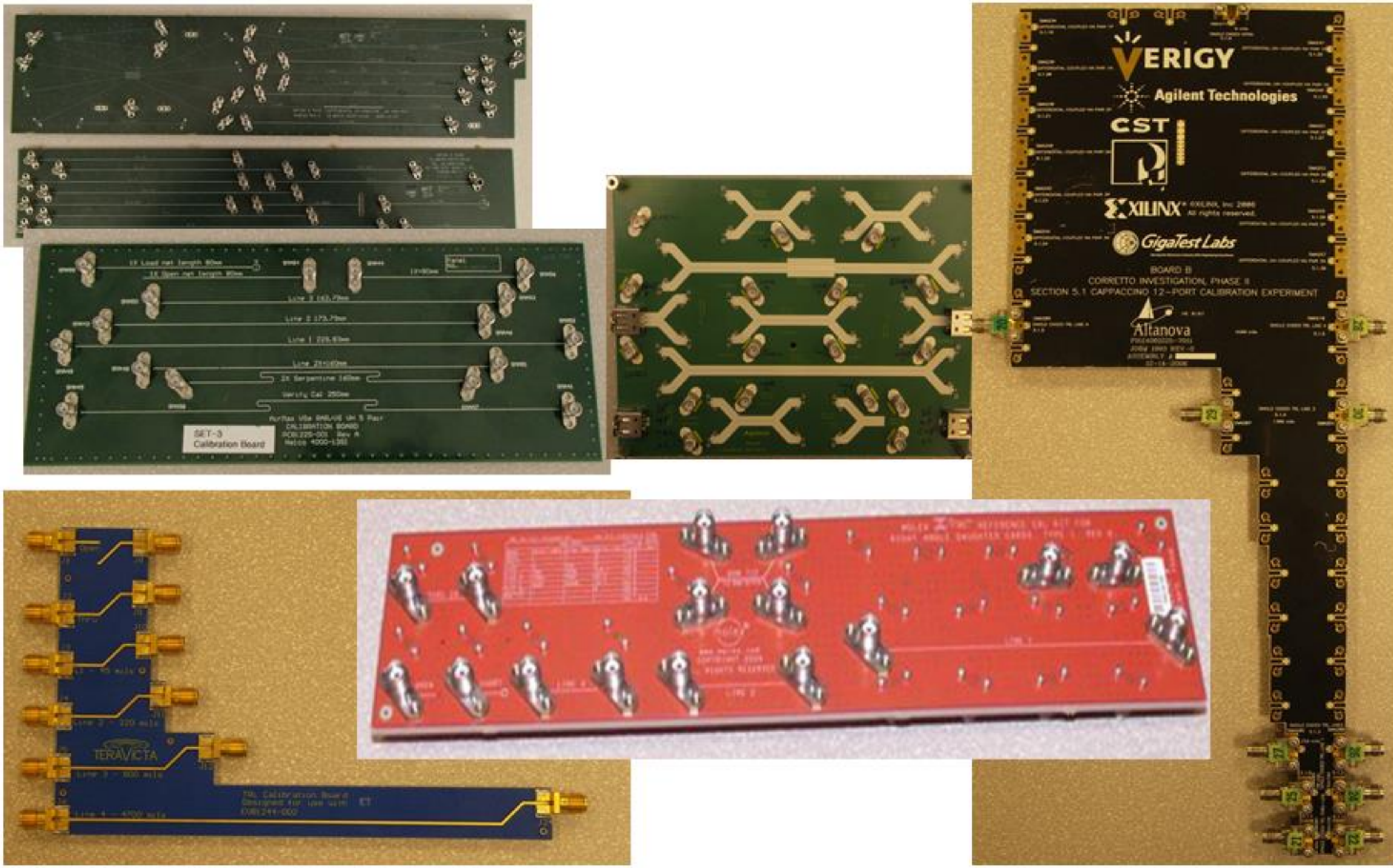
Additional differential constraints

- SDCnm and SCDnm < -30 dB
- Skew between lines < 10 degrees

Coupling in fixture is removed

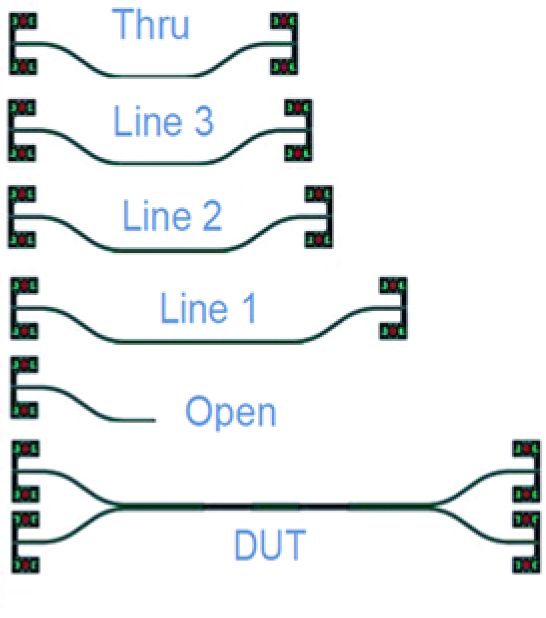


Example of Typical TRL Calibration Kits

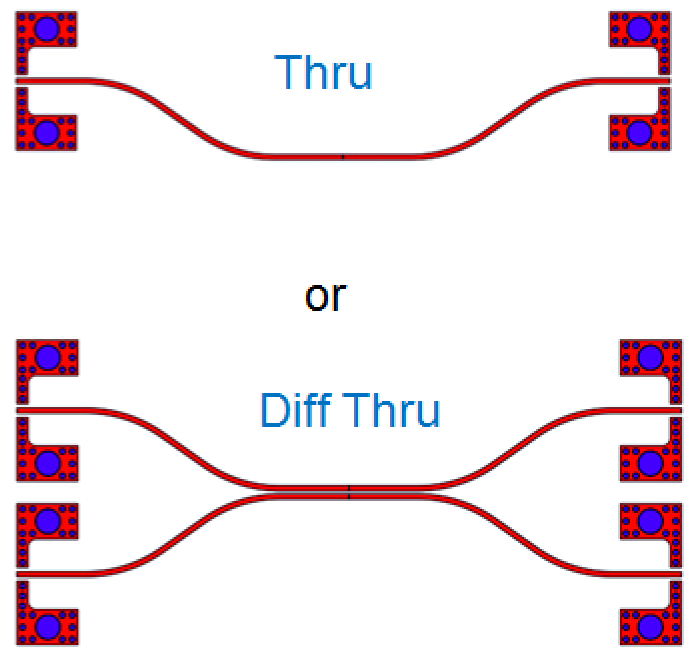


Automatic Fixture Removal (2X THRU)

Yesterday TRL



Today AFR

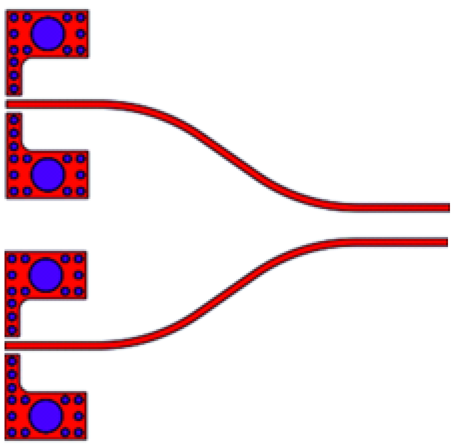


Note: Customers are now migrating from TRL to AFR after comparing results.

Automatic Fixture Removal (1-Port)

New:

- Open or Short
- Best when 2X THRU is hard to fab



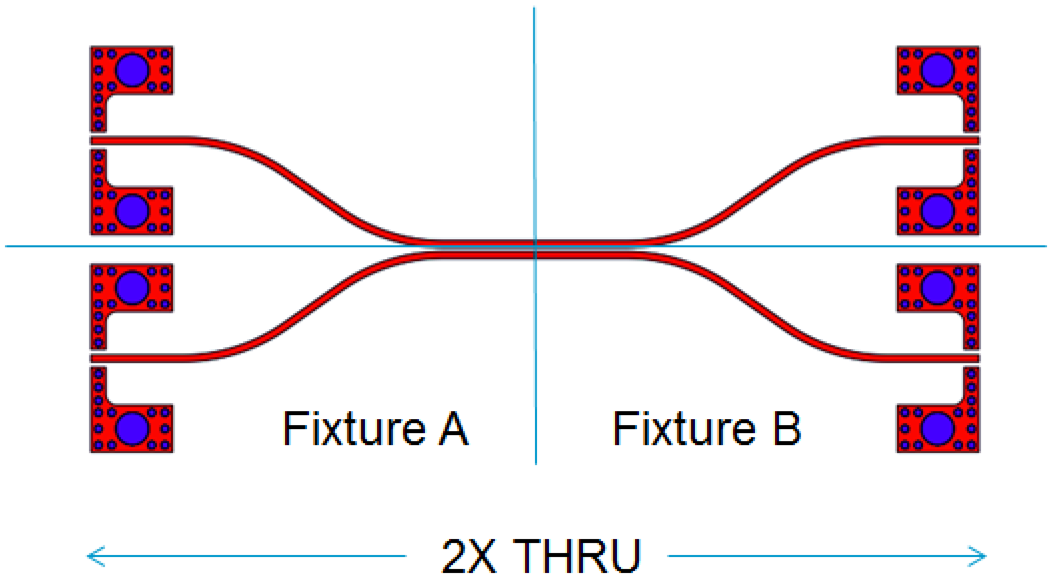
Applications:

- Fast, easy and inexpensive to fabricate
- Smallest footprint
- PC board
  - measure unloaded board
  - load part and measure
- Probes
  - measure open and shorted
- Socketed packages
  - measure open fixture
  - measure loaded part

Differential Automatic Fixture Removal

Assumptions:

- 2X THRU can be Asymmetric in length and match
- Still needs to be Symmetric top to bottom with minimal mode conversion
- The return loss and insertion loss of the 2xThru cannot cross each other in the measurement frequency range, often at least 5 dB separation is required
- Impedance of fixture and 2X THRU calibration standard must be identical!



Differential Automatic Fixture Removal

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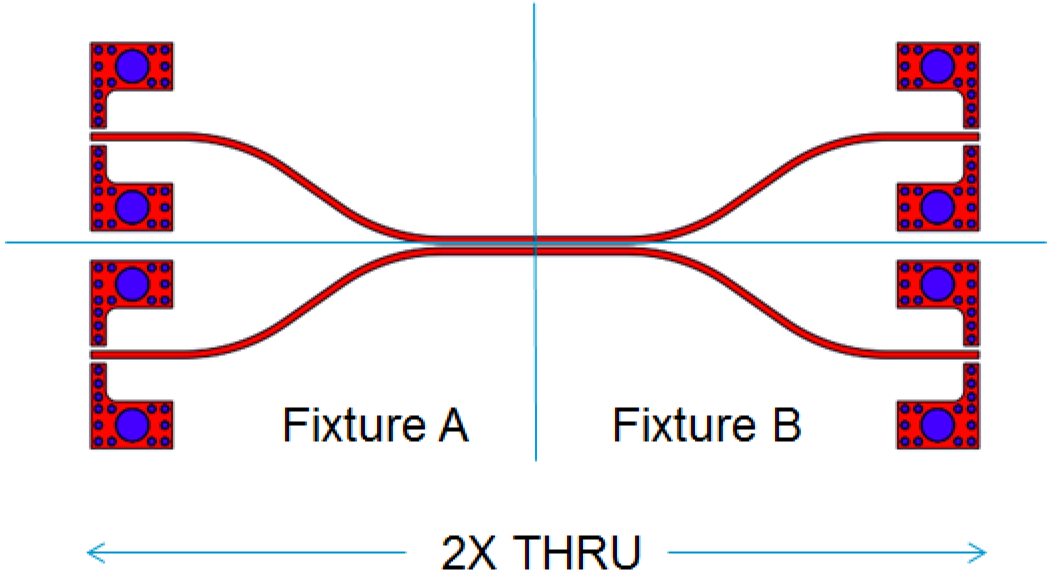
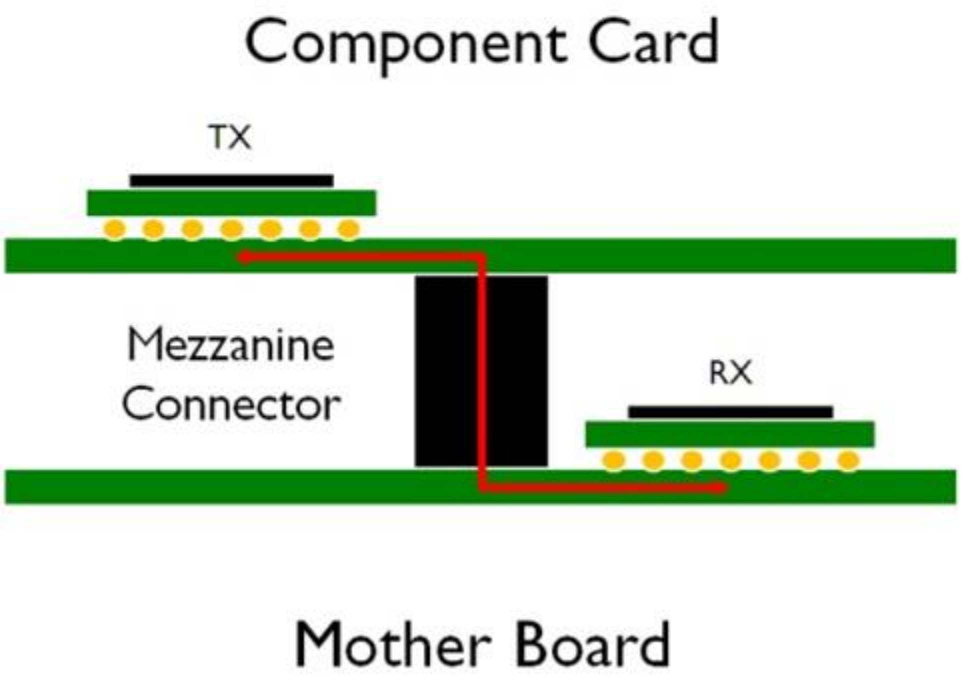
- Still needs to be Symmetric top to bottom with minimal mode conversion
- The return loss and insertion loss of the 2xThru cannot cross each other in the measurement frequency range, often at least 5 dB separation is required
- ~~Impedance of fixture and 2X THRU calibration standard must be identical!~~

No longer a restriction in PLTS 2016!



Design Case Study- Mezzanine Connector



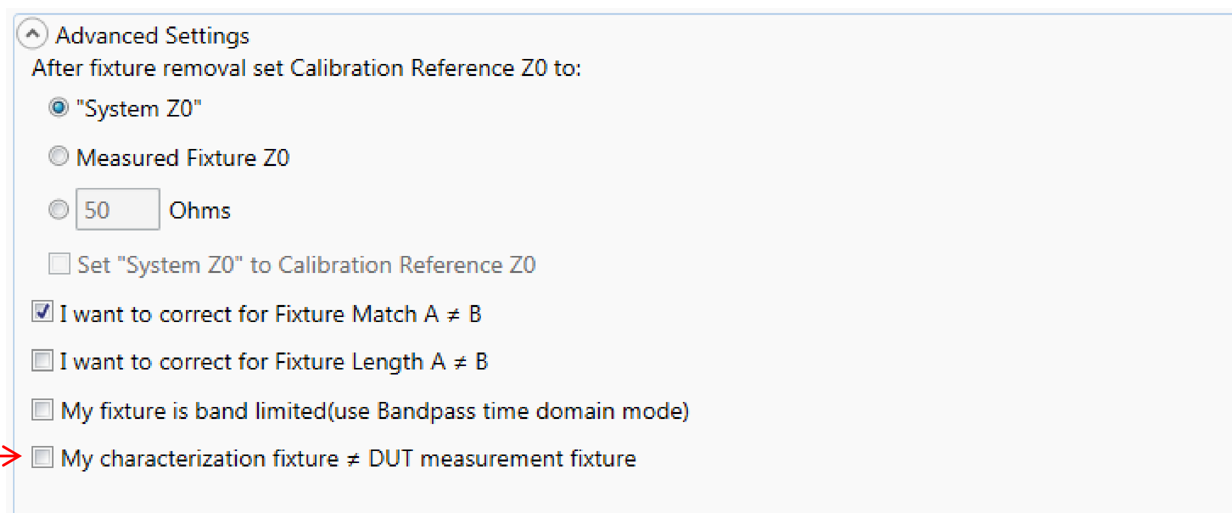
Design Case Study Objective

– A test-fixture is required to characterize connectors

– Standard test-fixture removal methods (TRL, AFR) have some issues

  • Do not take into account the impedance variations between the calibration structure and test-fixture

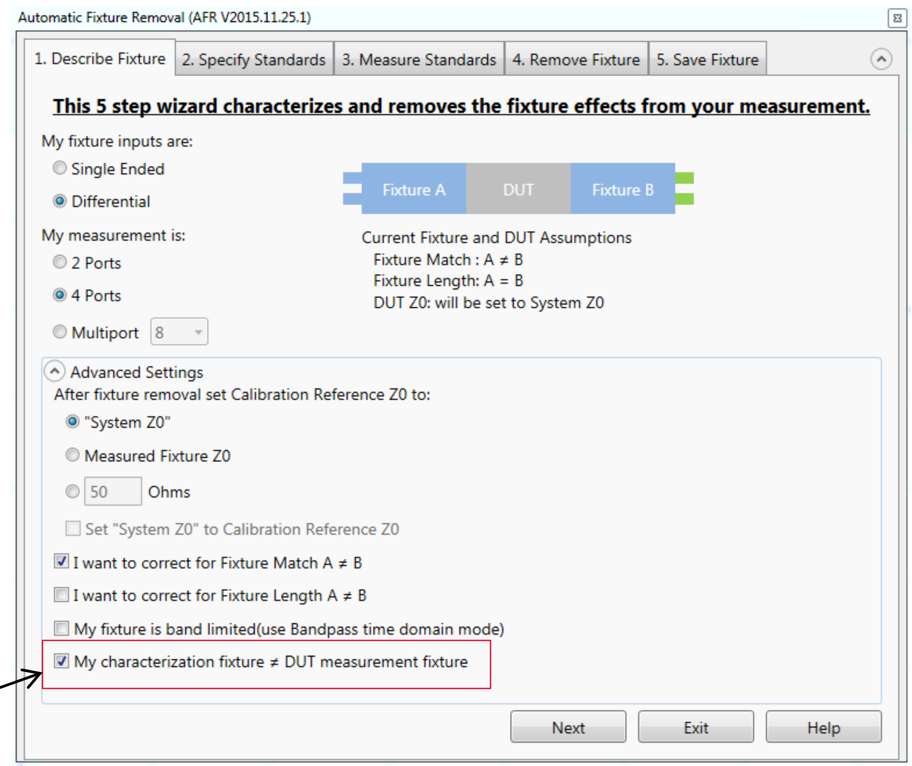
– In this design case study a new test-fixture removal method is introduced that overcomes (some of) the issues with standard test-fixture removal methods.



Design Case Study- Mezzanine Connector

Step 1

- Describe the test fixture



☑ My characterization fixture ≠ DUT measurement fixture

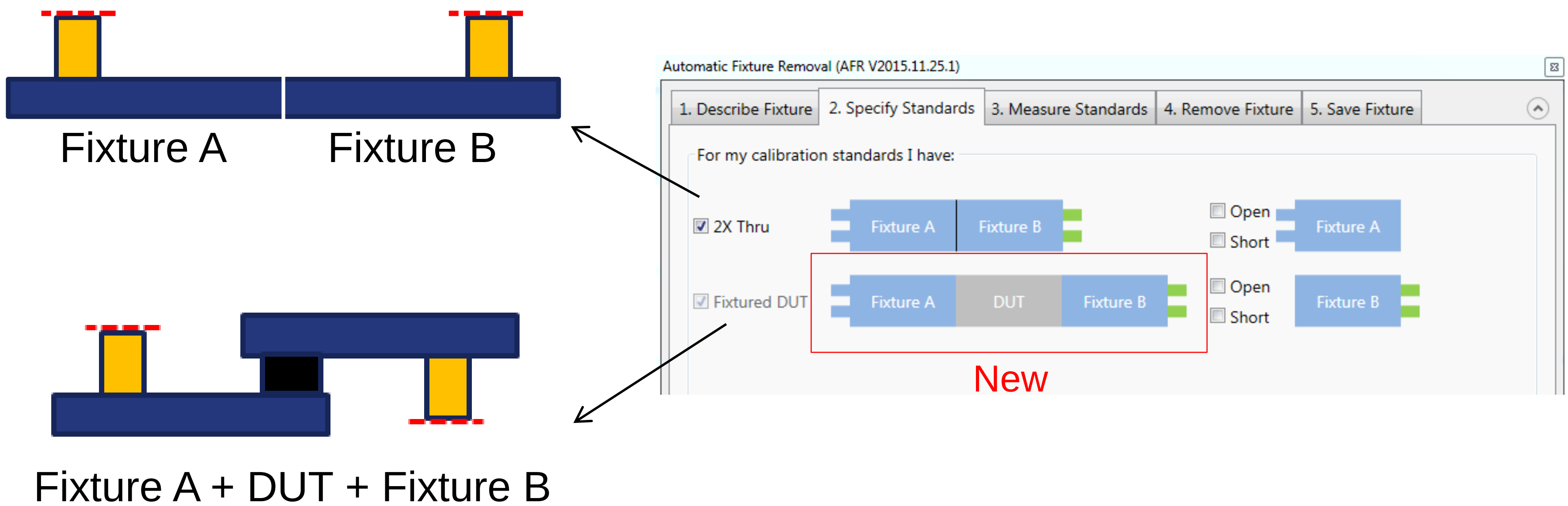
New enhancement when fixture impedance is different from 2X THRU

Note: Acknowledgements to Samtec for use of graphics

Design Case Study- Mezzanine Connector

Step 2

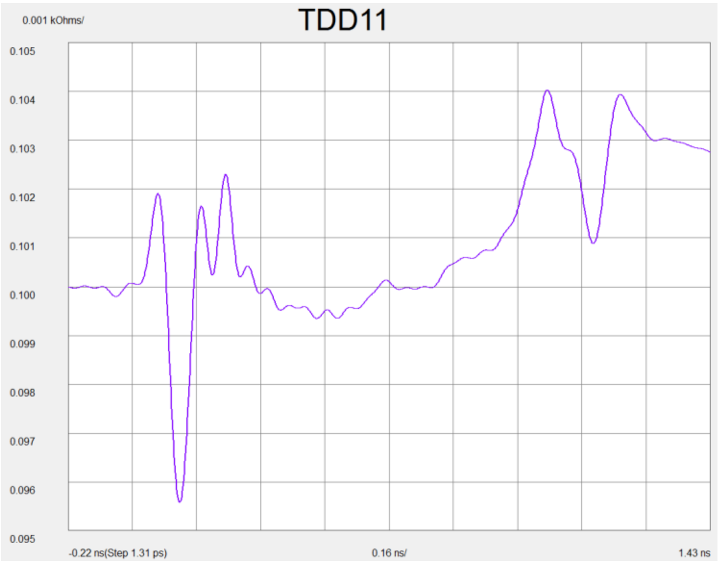
- Specify standards

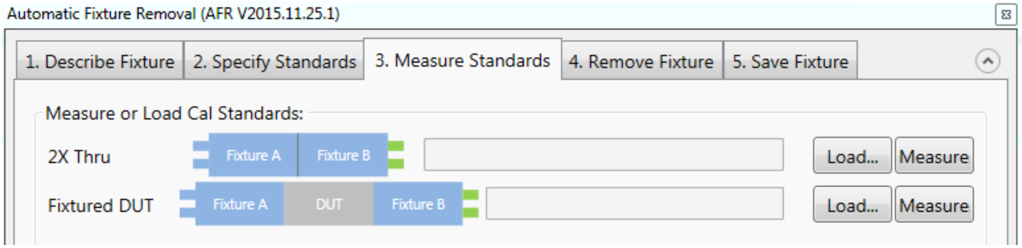


Design Case Study- Mezzanine Connector

Step 3

- Measure the standards



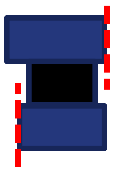


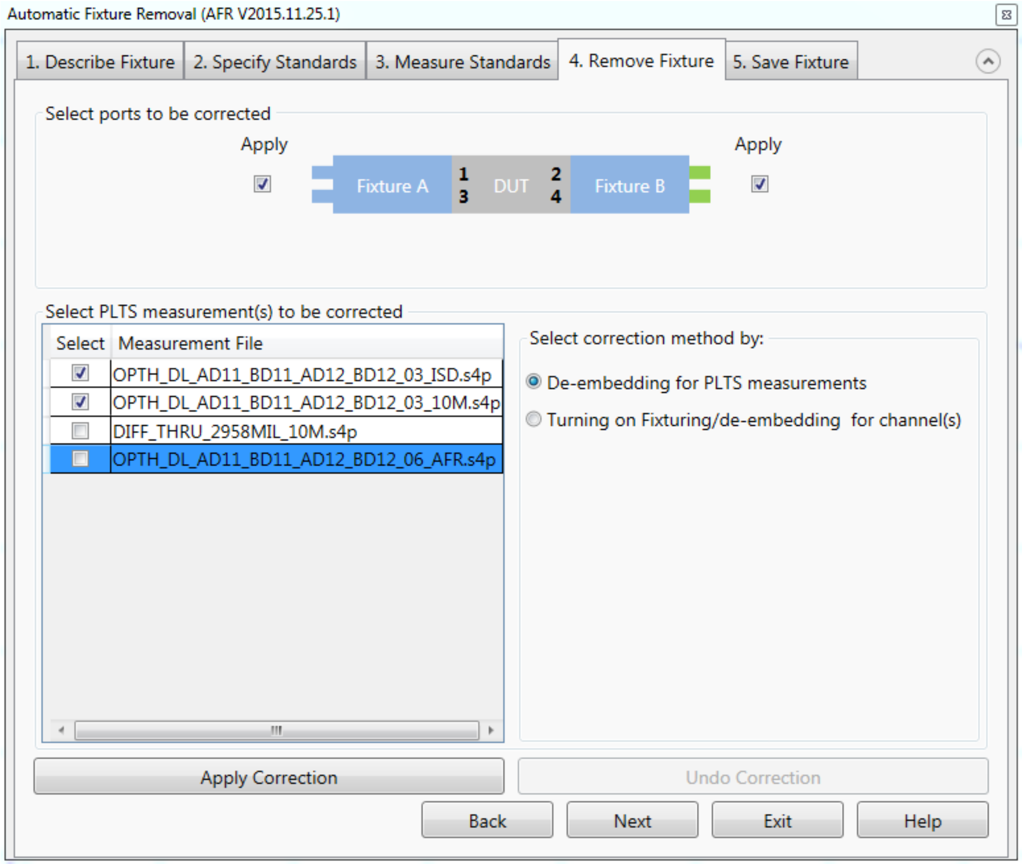
Note: Use previously measured "Fixtured DUT" as calibration standard

Design Case Study- Mezzanine Connector

Step 4

- Remove the fixtures

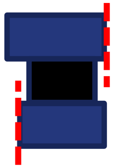


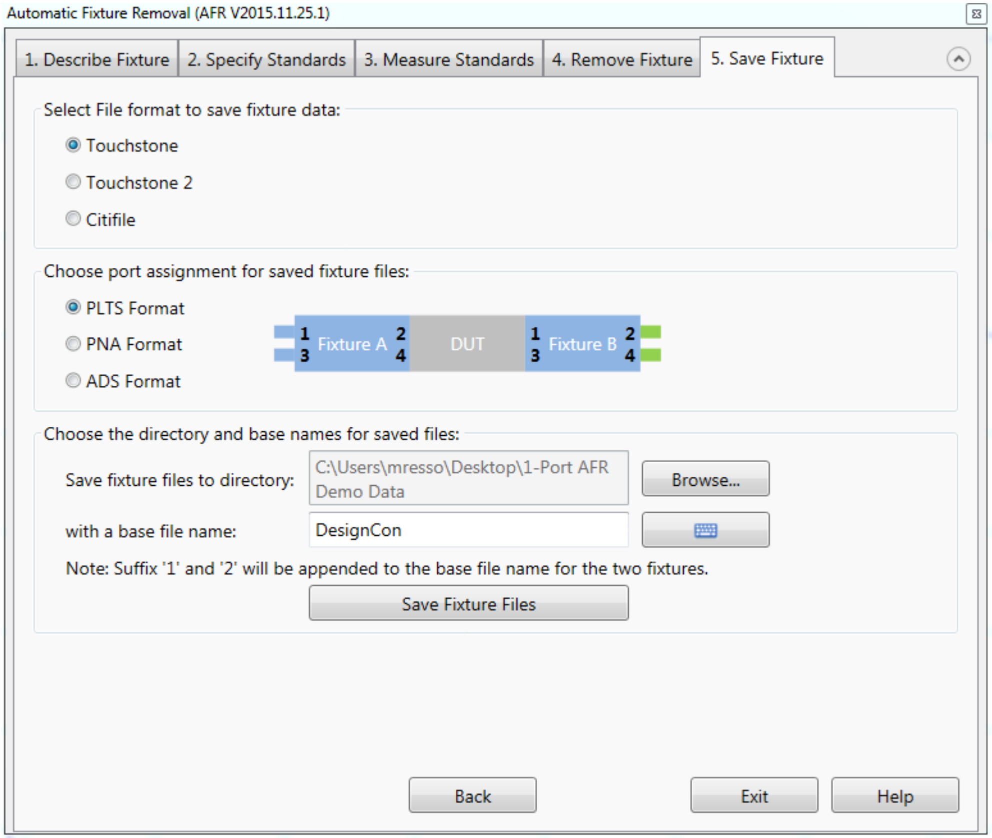


Design Case Study- Mezzanine Connector

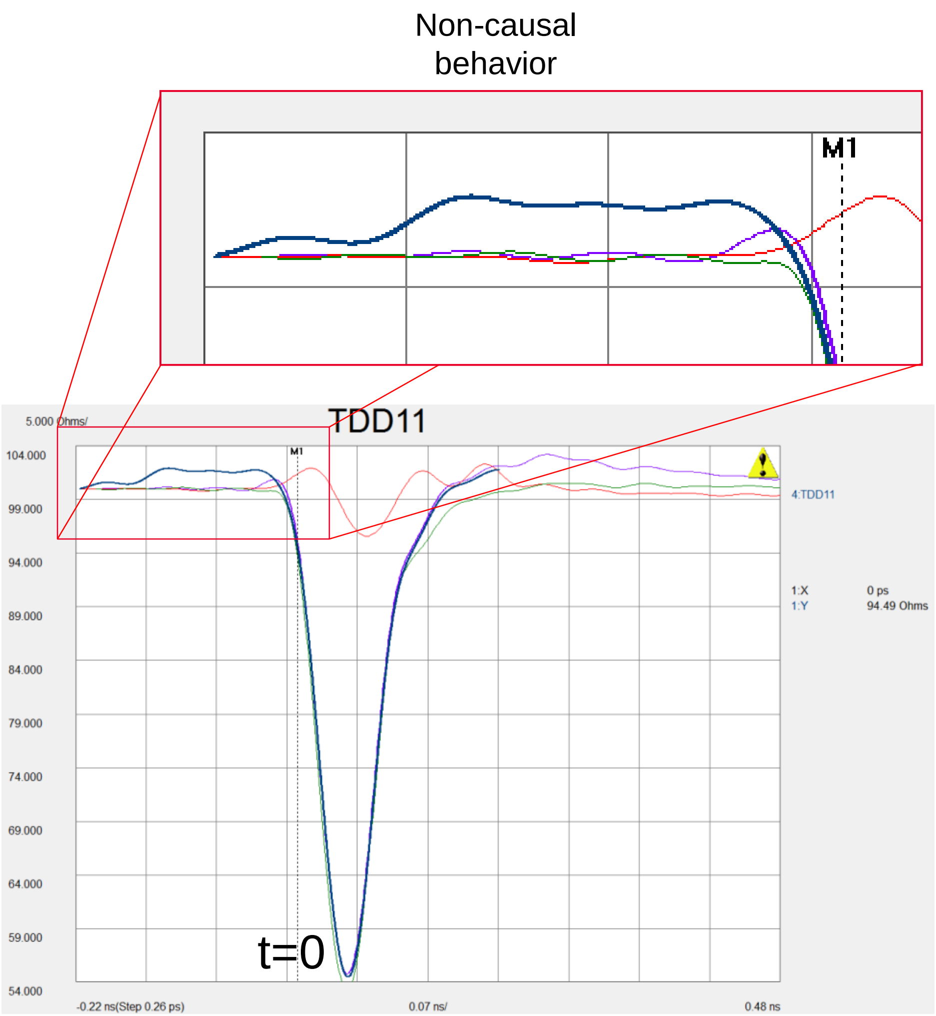
Step 5

- Save all files (de-embedded DUT and test fixtures models)

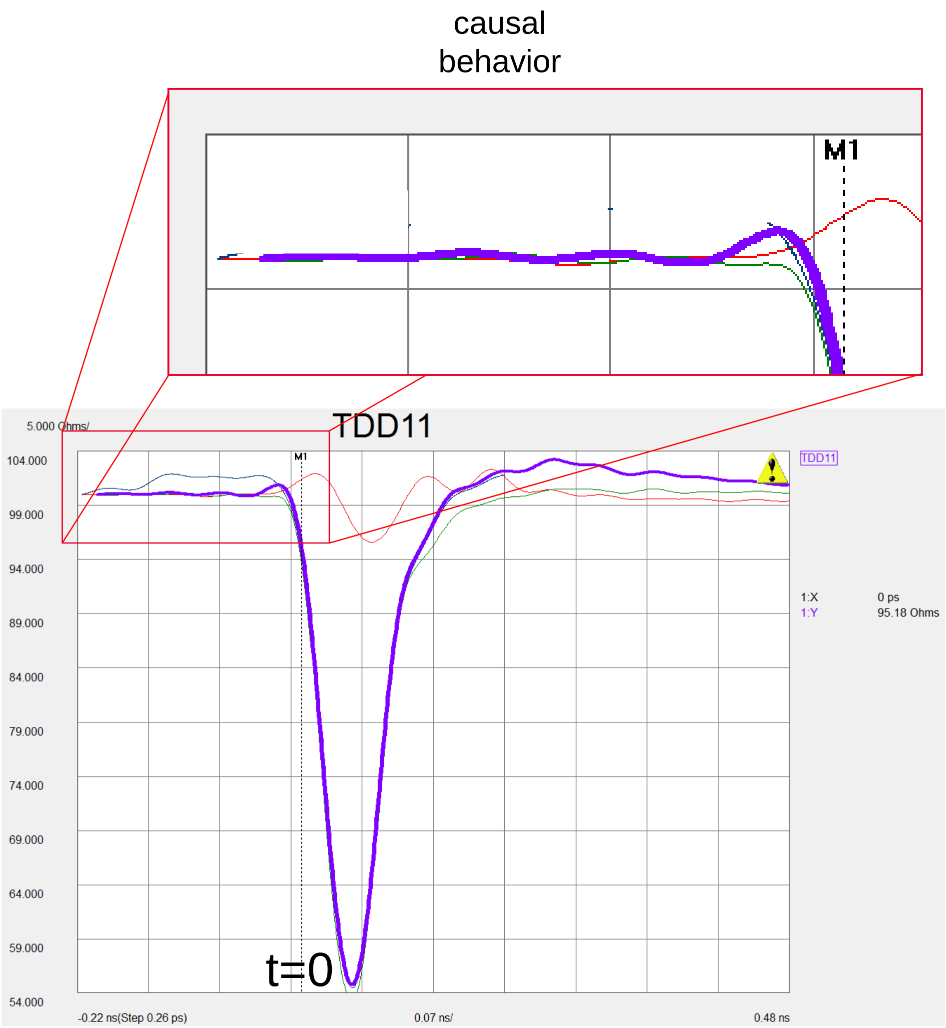




Comparison of Before and After AFR Enhancement in PLTS 2016



Before



After

Conclusions

- Simulation, TDR, VNA with Error correction are all critically important
- New applications push state of the art test and measurement
- Simulation + Measurement = Insight only if the calibration is good

Thank You!

Acknowledgements: Special thanks to Stefaan Sercu and Jim Nadolny of Samtec