Advanced TDR Measurements

“Solving Signal Integrity Problems with Advanced TDR Measurements”

Keysight Technologies	***09.09.2026***
***Thomas Giehm**, Application Engineer*	

KEYSIGHT TECHNOLOGIES

Signal Integrity in Digital Communication Channel



CPU



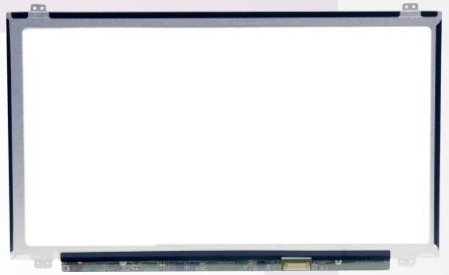
Graphic card



Cable



On board video processor



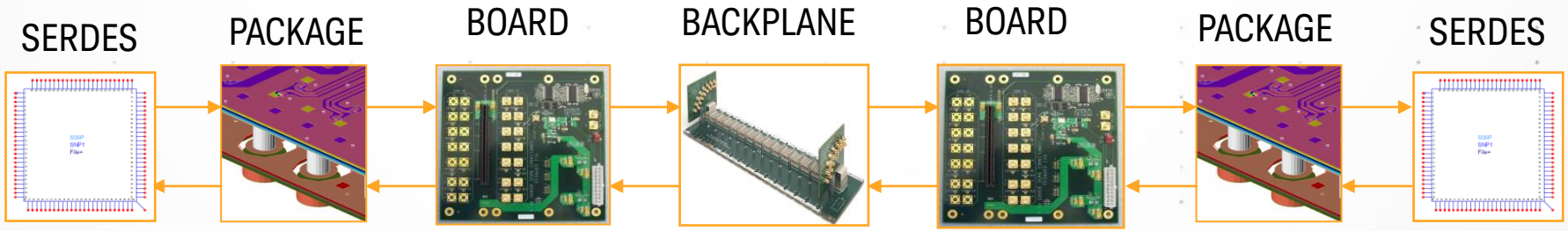
LED display

Interconnects

> Signal integrity is about the problems interconnects introduce and how to avoid them.
>
> – Dr. Eric Bogatin

Unique Challenges of Signal Integrity Design

- ✓ High-speed digital interconnects act like microwave transmission lines: reflections are everywhere!
- ✓ Multi-domain design, test and measurement is required to gain insight of optimum performance of the physical layer
- ✓ Signal integrity specialist software can simplify the complete design space from R&D throughout into production
- ✓ Powerful hardware and software tools work together

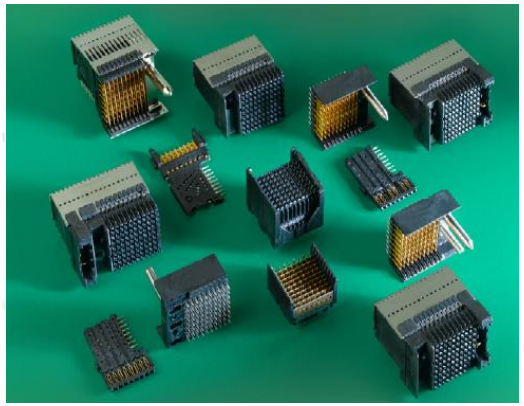


Impedance Problems are Everywhere!

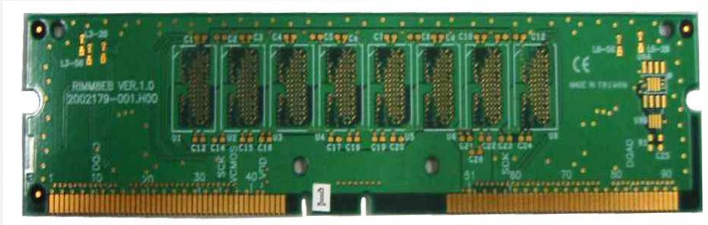
WHAT ARE DUTS FOR TDR MEASUREMENTS?



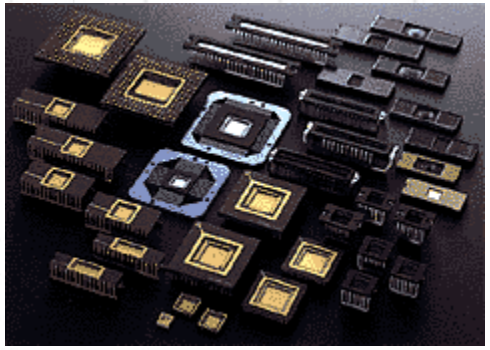
Backplanes



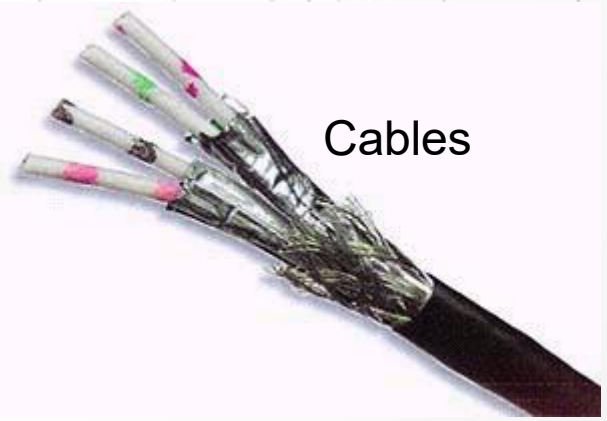
Connectors



PC Boards



IC Packages



Cables

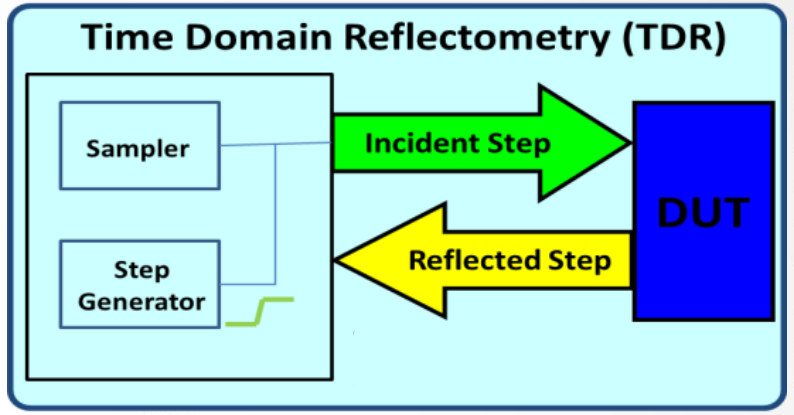
Agenda

Introduction and Quick Reviews:
- What is TDR?
- What is TDT?
- The DUT we are evaluating today

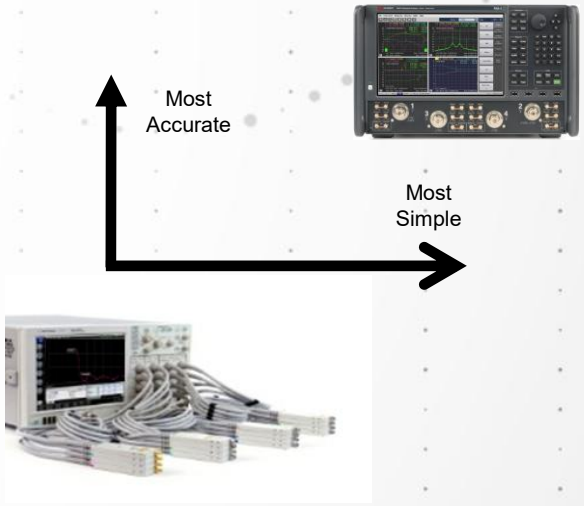
Comparing Different Signal Integrity Tools:
- Measurement Instruments
- Fixture Removal Techniques

Case Study:
- Initial TDR insights
- Measurement Results

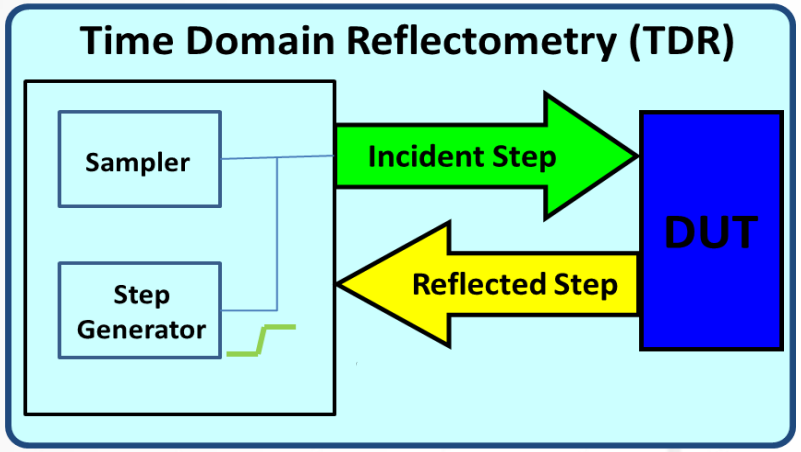
Summary/Q&A







Intro: What is TDR?

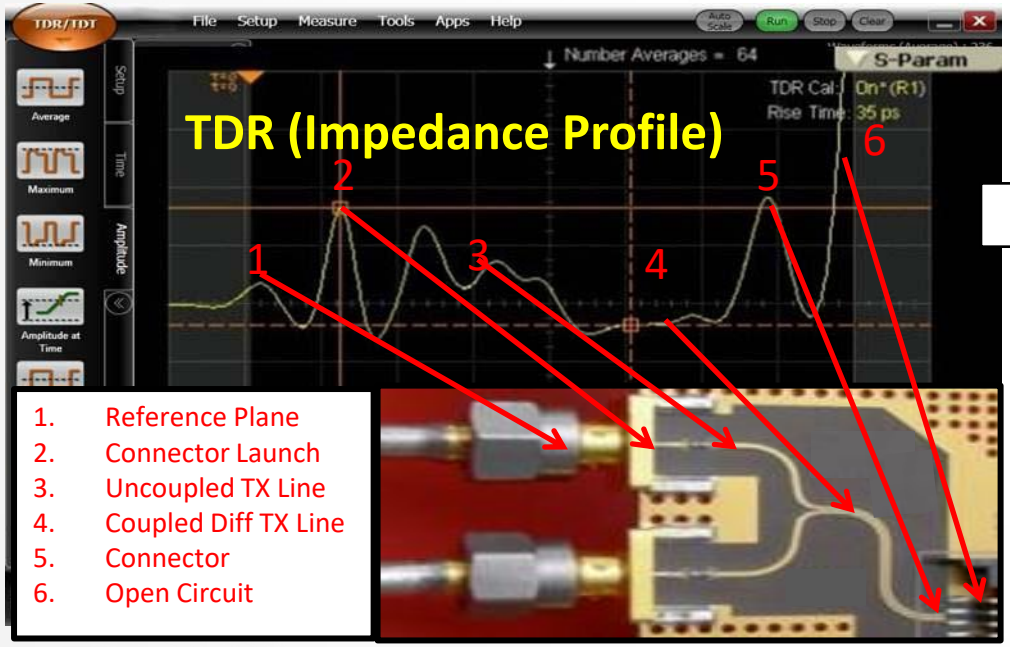


Time Domain Reflectometry (TDR)

1. Launch a fast step into the Device Under Test (DUT)
2. See what REFLECTS back from the DUT.

Example measurements:

- Impedance - locate the position and nature of each discontinuity
- Propagation/Time delay
- Excess Reactance (Capacitance or Inductance)

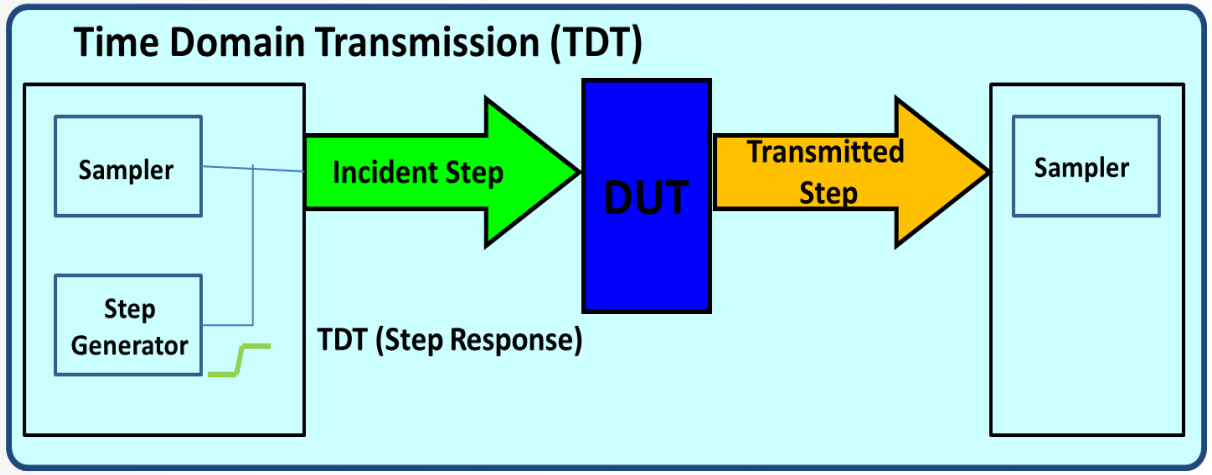


FFT



For validation & development look here for insight regarding what in the device is causing reflections

Intro: What is TDT?



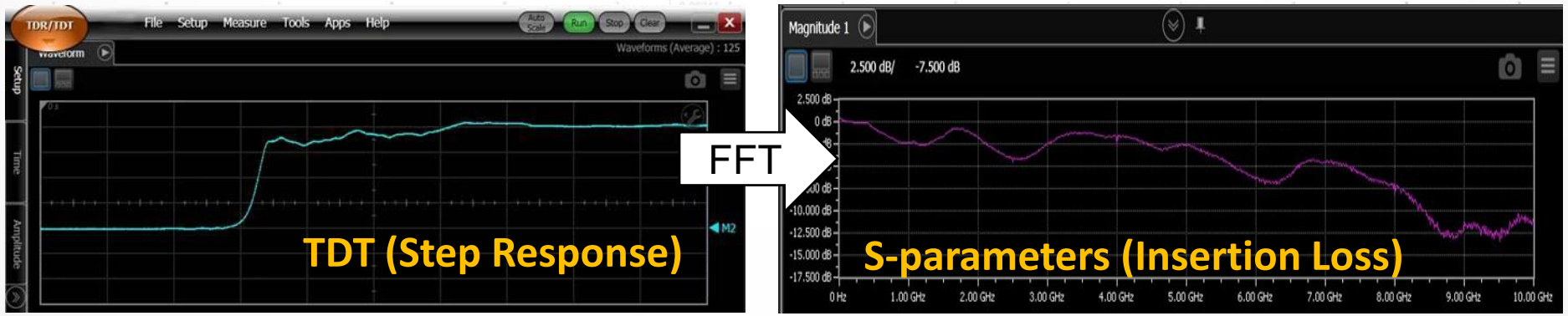
Time Domain Transmission (TDT)

1. Launch a fast step into the Device Under Test (DUT)
2. See what is transmitted THROUGH the DUT.

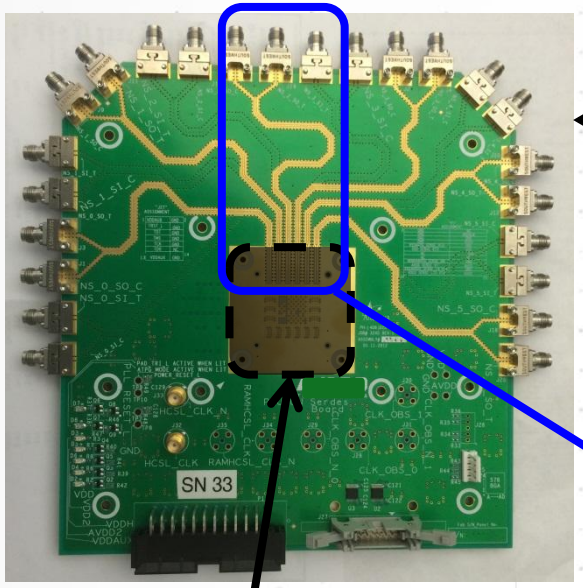
Example Measurements:

- Step Response
- Propagation/Time delay
- Rise time degradation

For development and validation, look here for loss data to support simulation or for de-embedding.

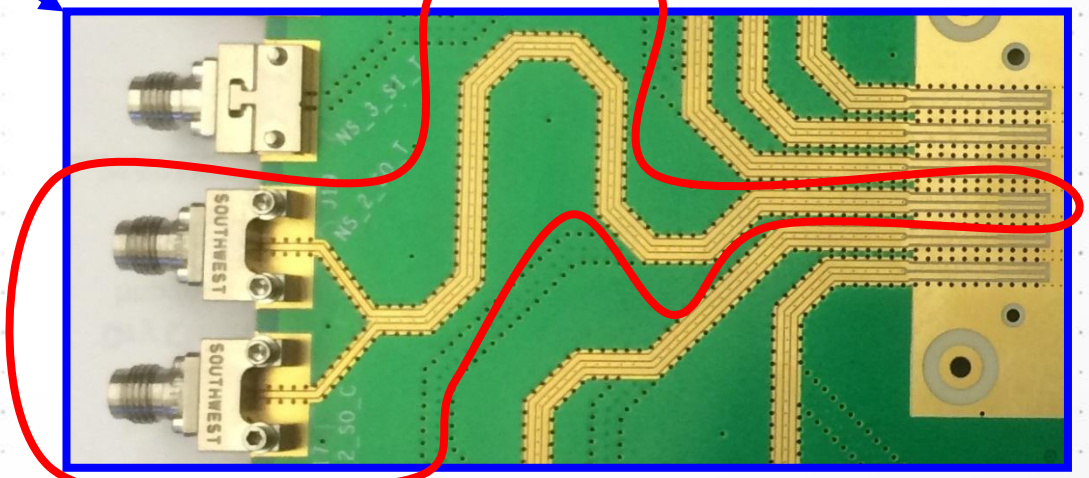


Intro: The DUT we are evaluating



The board

The channel

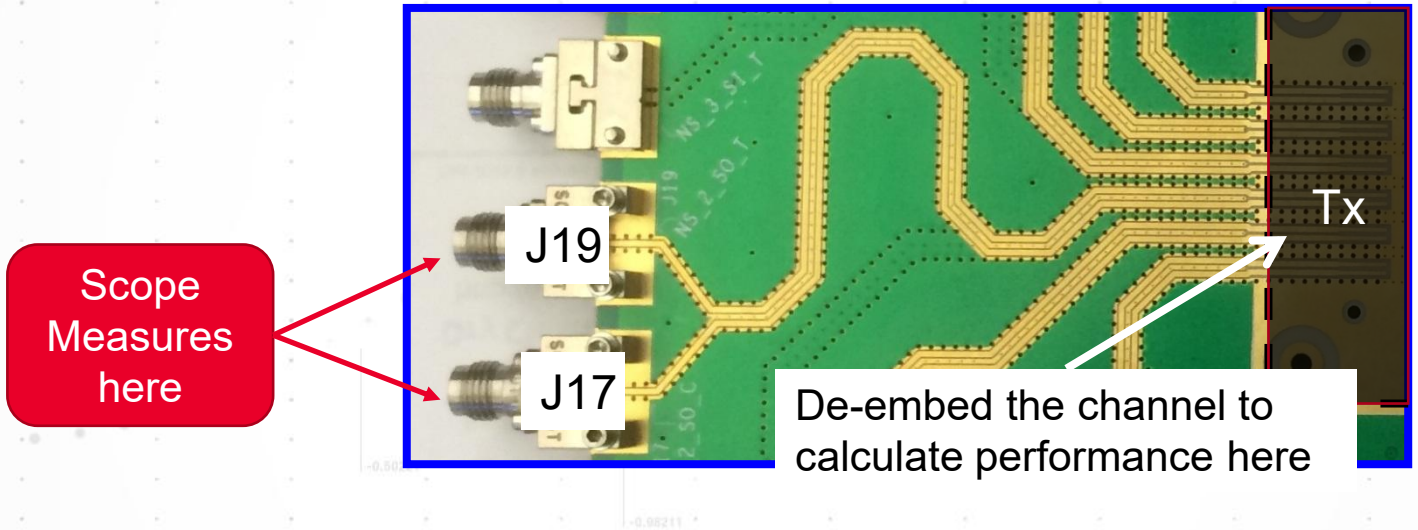


Si goes here

Intro: The DUT we are evaluating

WHAT DRIVES THE NEED FOR CHARACTERIZING THE CHANNEL?

Often the goal for Tx validation engineers: **Characterize the performance of the Tx at the ball of the BGA**



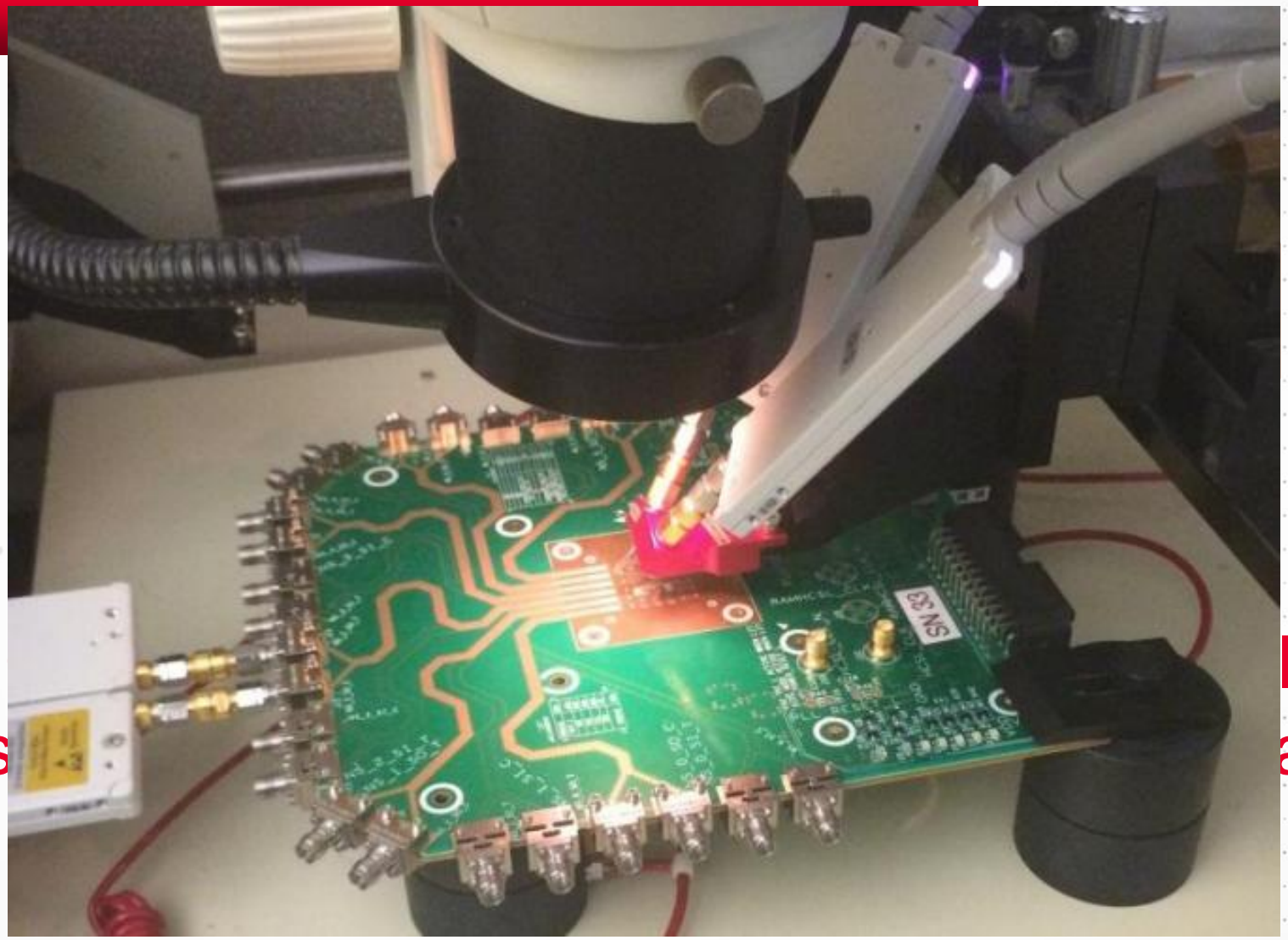
Process:

1. Measure the transmitter performance at J17 and J19 with the Oscilloscope
2. De-embed the channel from the Tx measurement at J17 and J19 using the scope de-embed function to calculate the performance at the ball of the BGA

Requires:
Channel characterization data: *channel.s4p* for a differential channel like the one above

Intro: The DUT we are evaluating

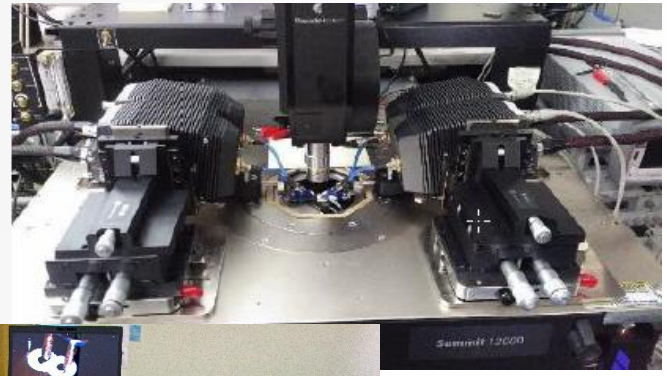
HOW DO WE C

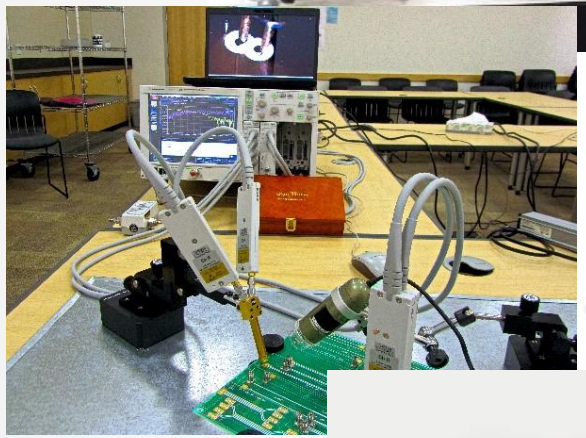


Goal:

effects luding ables

Probing or Fixturing?







Probing

Advantage

- Flexibility

Disadvantage

- Expensive
- Need ISS calibration substrate for probe tip ref plane



Fixtures

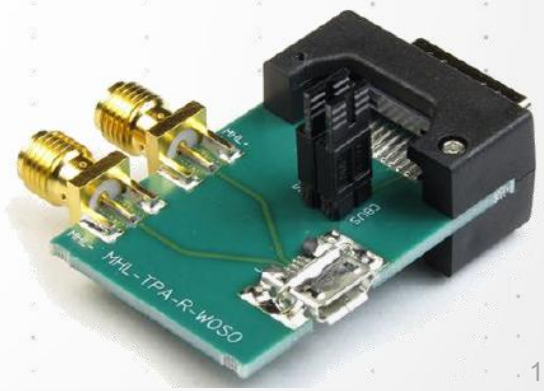
Advantage

- Easy to Use

Disadvantage

- Each application requires different fixture
- Not electrically transparent, they have mismatch, loss and delay that must be characterized and removed from the DUT measurement (de-embed)

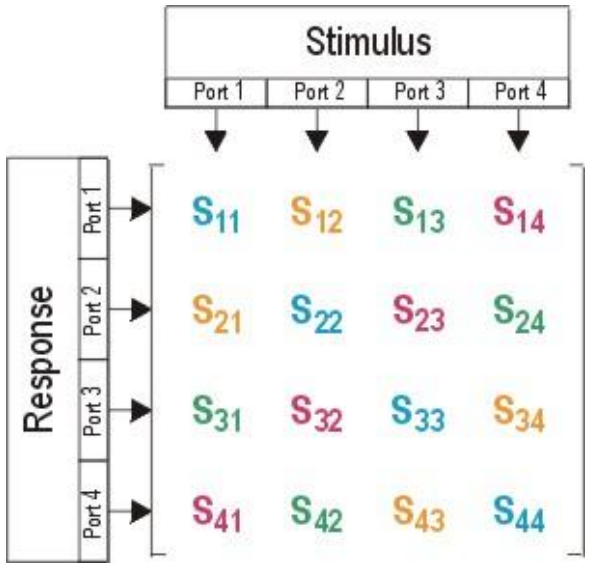




Single-ended s-Parameters



Four-port single-ended device

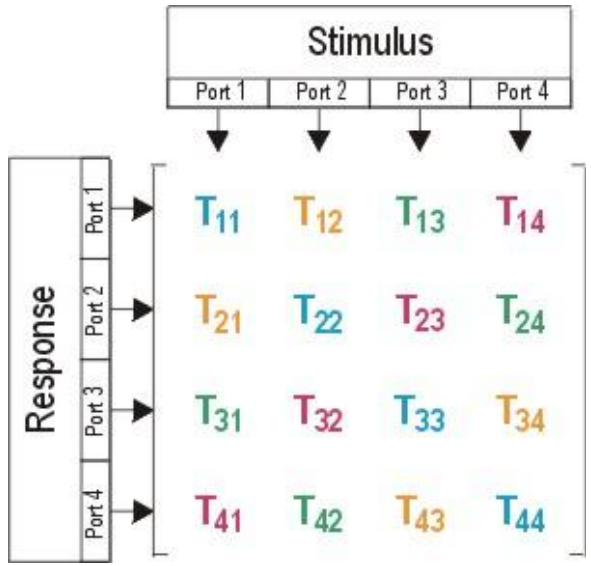


Return Loss or TDR

Insertion Loss or TDT

Near End Crosstalk (NEXT)

Far End Crosstalk (FEXT)



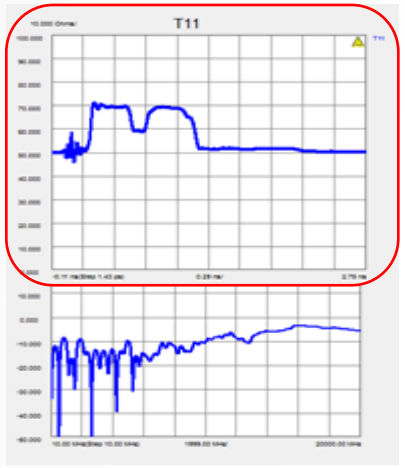
Frequency Domain Parameters

Time Domain Parameters

FFT or IFFT

Comparing SI Tools: Methods

QUICK REVIEW: S-PARAMETERS



Tremendous insight together.

Where is the most useful information?

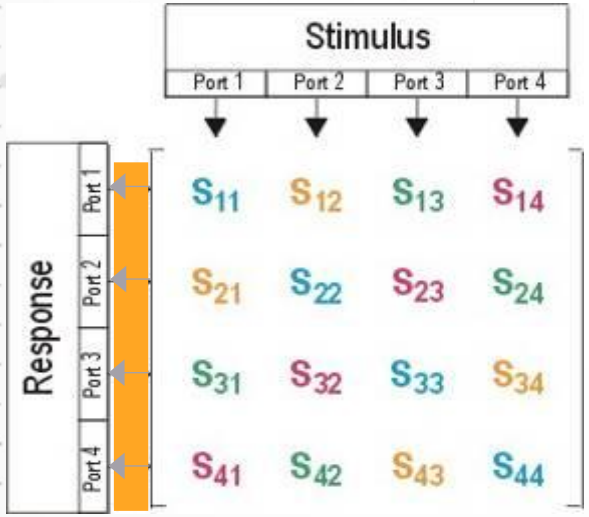
- **Time domain?**
- **Frequency domain?**

BOTH are needed!!



Four-port single-ended device





Frequency Domain Parameters

Return Loss or TDR

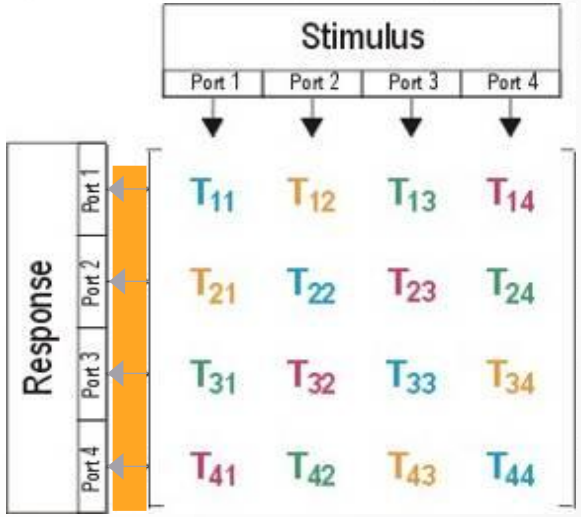
Insertion Loss or TDT

Near End Crosstalk (NEXT)

Far End Crosstalk (FEXT)

← FFT —

— IFFT →



Time Domain Parameters

Transmission Lines are Differential



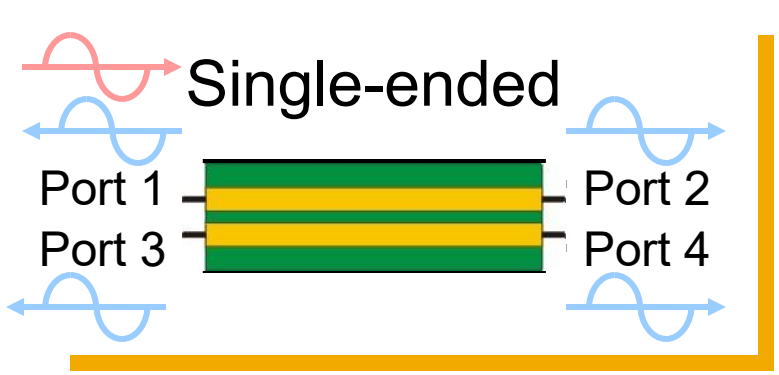
Two traces carrying complementary data, commonly used for high data rates

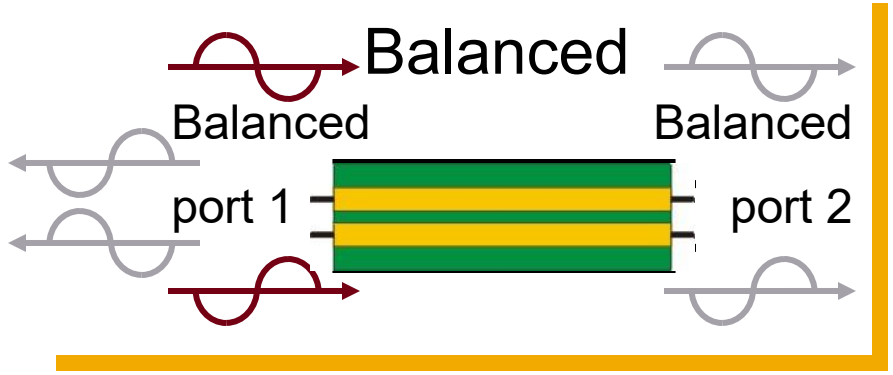
Why?

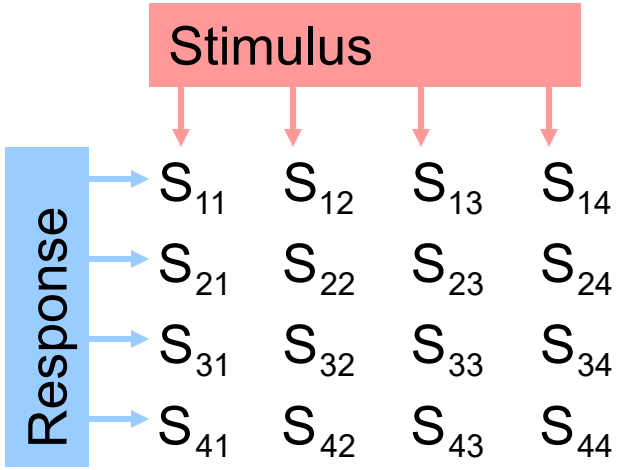
- Receiver can reject any signal that is common to both lines
- Radiation reduced (cancellation of fields)

Impedance measurements have slightly different meaning compared to single-ended measurements

Single-ended to Differential S-Parameters





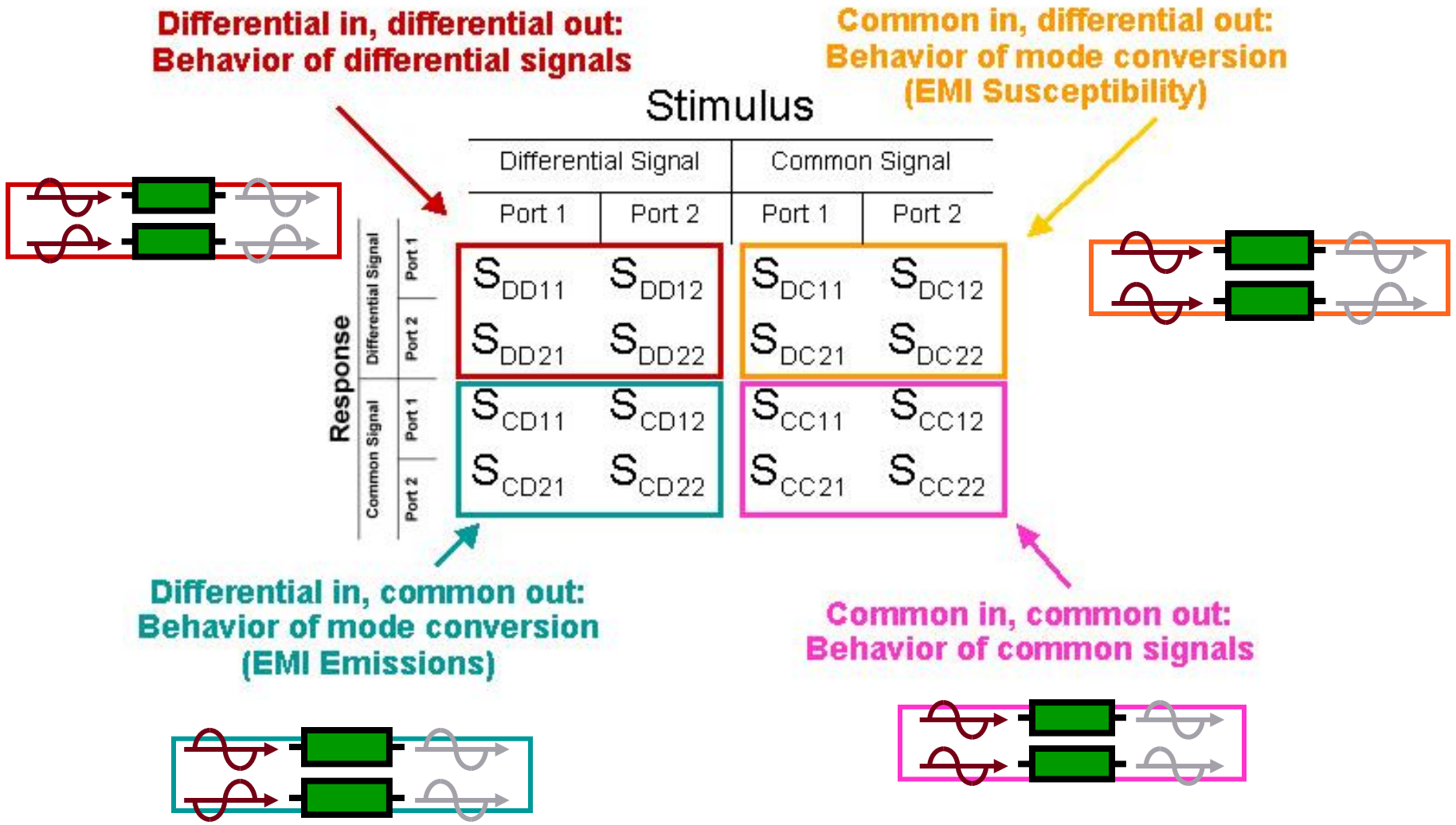


		Differential-Mode Stimulus		Common-Mode Stimulus	
		Port 1	Port 2	Port 1	Port 2
Differential-Mode Response	Port 1	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common-Mode Response	Port 1	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

Naming Convention:

$S_{\text{mode res., mode stim., port res., port stim.}}$

Differential S-parameters



Comparing SI Tools: Instruments



Keysight DCA-TDR: Time domain Instrument with time domain GUI

- ✓ **Up to 50GHz**
- ✓ **Performs oscilloscope, eye/mask, and jitter/noise measurements**
- ✓ **Useful for quick insight/troubleshooting, fault location analysis**
- ✓ Very intuitive and easy-to-use, preferred by many digital engineers
- ✓ Measures closer to DC (vs 300 kHz /10 MHz)
- ✓ Typically less expensive than a VNA with similar bandwidth



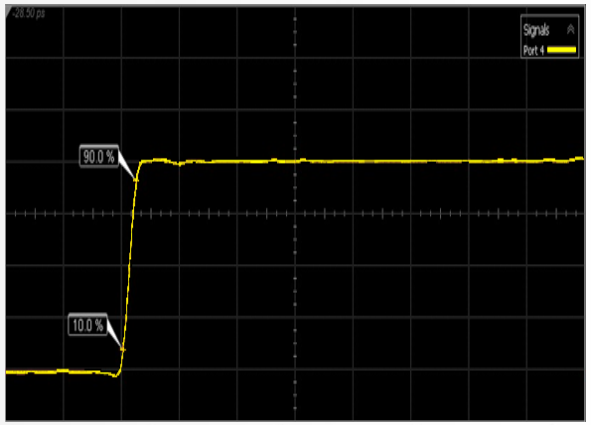
Keysight ENA/PNA: Frequency domain instrument with frequency domain GUI

- ✓ **Up to 67GHz (other versions available beyond 100GHz)**
- ✓ **"Gold Standard", the highest performance S-Parameter measurements**
- ✓ Superior dynamic range vs. any TDR
- ✓ Typically preferred by RF/Microwave engineers

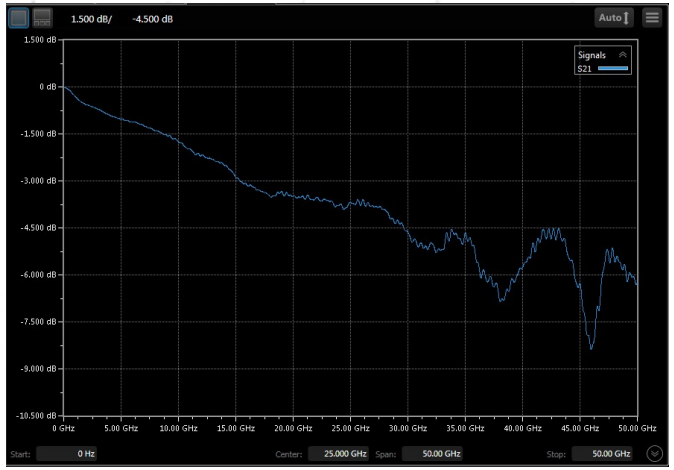
Both instruments can provide frequency domain and time domain responses

Comparing SI Tools: Instruments

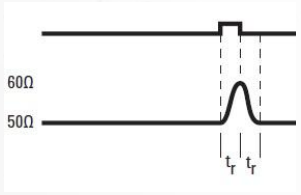
TDR: 3 IMPORTANT INSTRUMENT CONSIDERATIONS



TDR Step Edge Speed

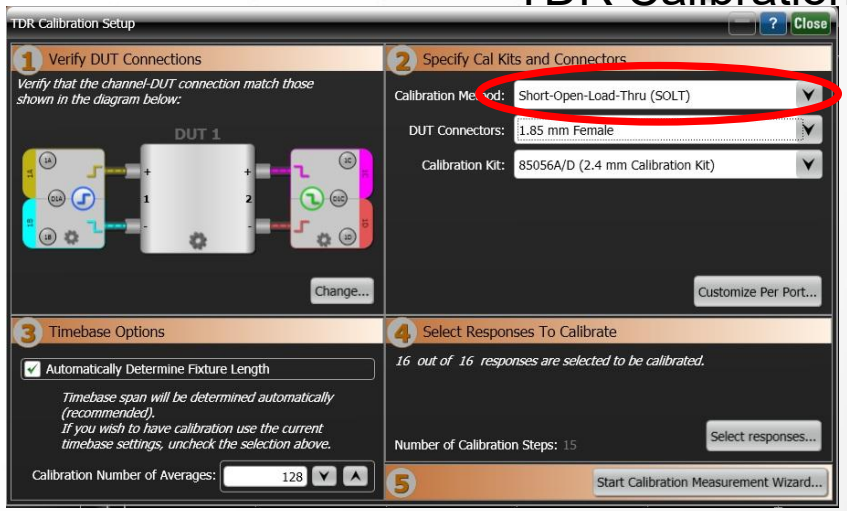


Bandwidth
Receiver?
System?
(How much do you need?)



Minimum Separation = (c * t_{rise})/2 SQRT(Ɛ)

True SOLT
TDR Calibration



Why Edge Speed is Important: Temporal/Spatial (TDR) Resolution

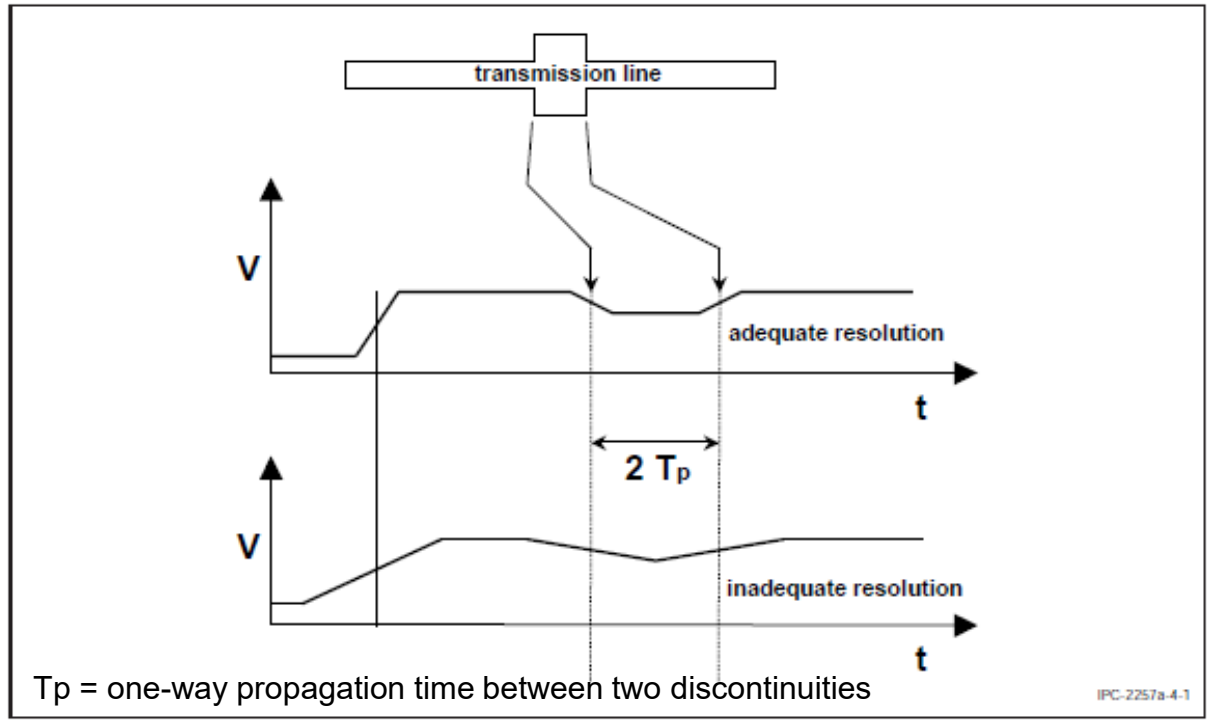


Figure 4-1 Resolution and Electrical Length of Transmission Line

Reference: Section 4-1 of IPC TM-650 2.5.5.7

"The resolution…is defined as that particular time or distance wherein two discontinuities…that would normally be individually discernable, begin to merge together because of limited TDR system bandwidth."

$$t_{r_{system}} = \sqrt{t_{r_{step}}^2 + t_{r_{scope}}^2}$$

TDR System Risetime	Resolution
10 ps	5 ps / 1 mm [0.04 in]
20 ps	10 ps / 2 mm [0.08 in]
30 ps	15 ps / 3 mm [0.12 in]
100 ps	50 ps/ 10 mm [0.39 in]
200 ps	100 ps / 20 mm [0.79 in]
500 ps	250 ps / 50 mm [1.97in]

Source: TDR resolution per IPC-TM-650 for FR4 microstrip (*vp* » $2x10^8$ m/s)

Resolution:

a. ½ * TDR System Risetime (10-90%), or

b. (*trise* x *vp*) / 2
where *vp* is propagation velocity of TX line media

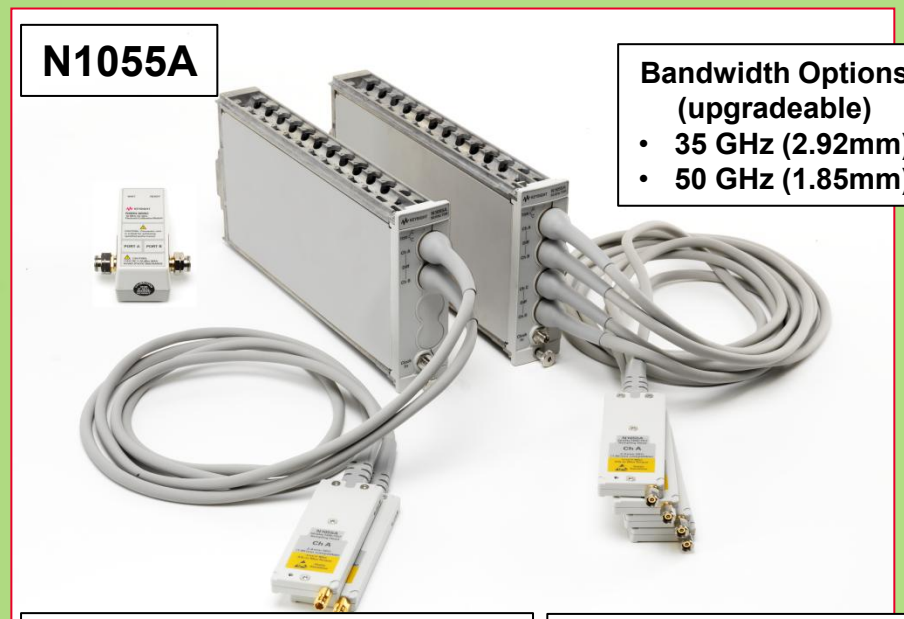
(a) and (b) complement one another.

With 8 ps TDR system risetime, TDR resolution is < 1mm.

Comparing SI Tools: Instruments

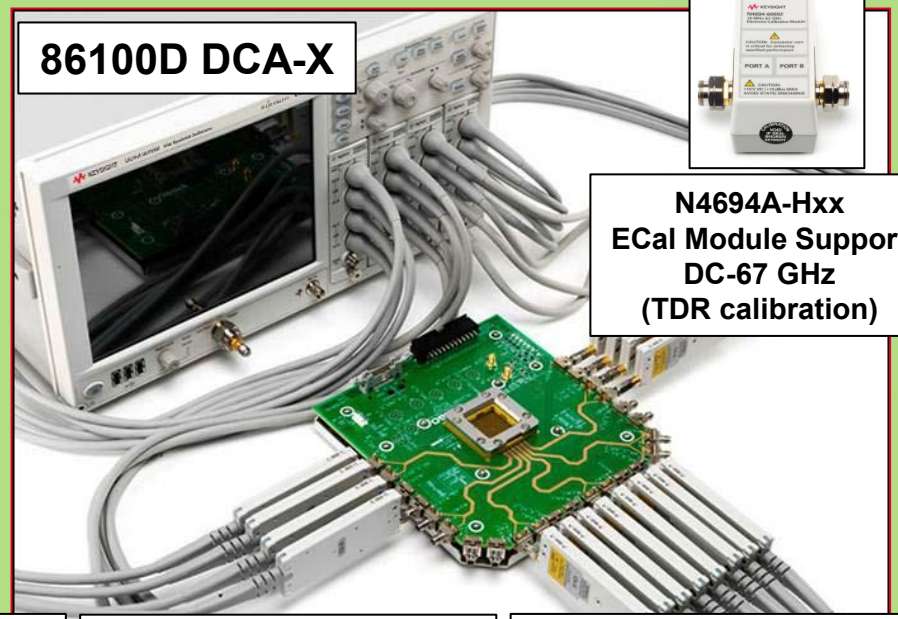
TDR: KEYSIGHT'S NEWEST TDR/TDT MODULE

N1055A



Bandwidth Options (upgradeable)
- 35 GHz (2.92mm)
- 50 GHz (1.85mm)

86100D DCA-X



N4694A-Hxx ECal Module Support DC-67 GHz (TDR calibration)

TDR Edge Speed (10-90%)
- Calibrated ~ 6 ps typ (50 GHz BW)
- Raw HW ~ 9 ps typ (50 GHz BW)

TDR Stimulus
- Single-ended and Differential
- Mixed or True-Mode stimulus

Channel Count Per module
- 2 channel (upgradeable)
- 4 channel
- M or F connector option

Mainframe Channel Count
- Up to 16 channels
- TDR/TDT or Receiver only
- Simultaneous acquisition

- Highest resolution TDR/TDT measurements
- Fast and accurate multiport S-parameters, live right on the box
- World's easiest-to-use solution

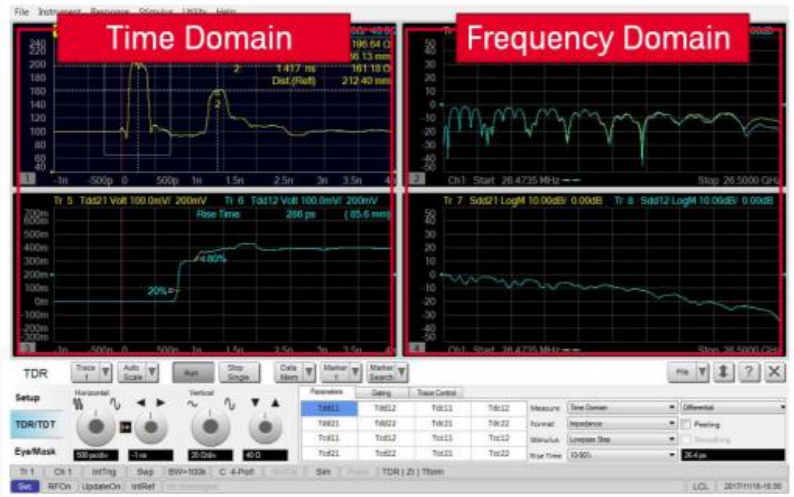
Comparing SI Tools: Instruments

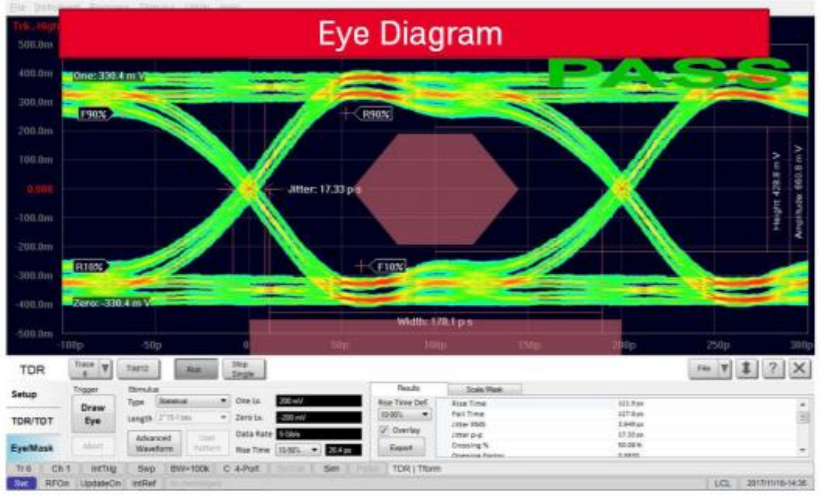
S93011A ENHANCED TIME DOMAIN ANALYSIS WITH TDR FOR PNA SERIES VNA

- **Up to 67 GHz of bandwidth with 6.66 ps rise time enables measurement to the latest high-speed serial standards**
- **Unmatched performance**
  - Low noise floor for accurate and repeatable measurements: 20 µV rms
  - Wide dynamic range to observe the true performance
  - of your device: > 110 dB
  - Fast measurement speed for real-time analysis: 251 msec (1601 points, 2-port cal)
- **State-of-the art calibration techniques reduce measurement errors**
  - Automatic deskew ensures easy removal of fixture and
  - probe effects
  - Full calibration available for the utmost in measurement accuracy



www.keysight.com/find/pna-tdr





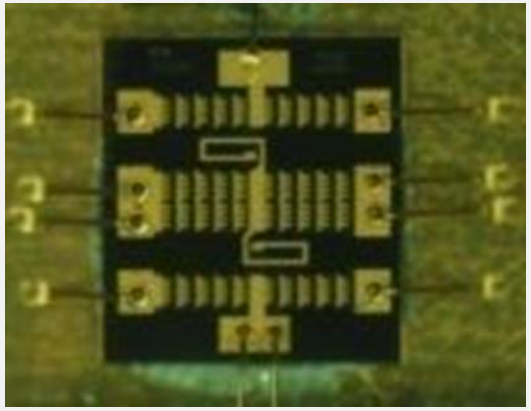
Higher ESD Robustness

ENA-TDR

Higher robustness against ESD, because protection circuits are implemented inside the instrument for all ports, while maintaining excellent RF performance.



Proprietary ESD protection chip



Reduce instrument repair fees and downtime

ENA Option TDR Certified MOIs

Available for free download at www.keysight.com/find/ena-tdr_compliance

Cable / Connector

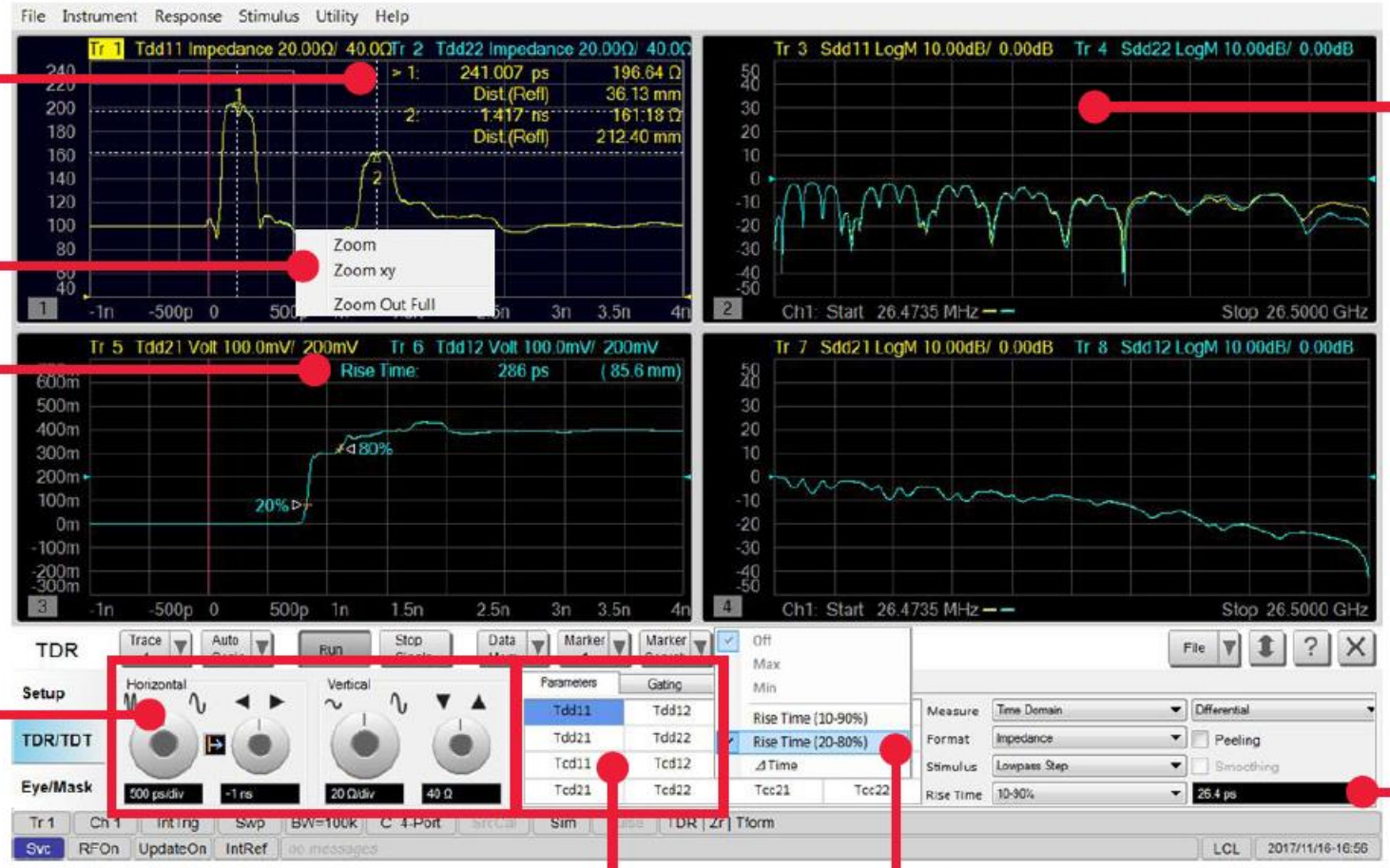
- USB
- HDMI
- SATA
- DisplayPort
- 100BASE-TX
- 10GBASE-T
- 10GBASE-KR/40GBASE-KR
- MHL
- PCIe
- BroadR-Reach

Tx/Rx Impedance (Hot TDR)

- HDMI
- SATA
- MIPI
- 10GBASE-KR/40GBASE-KR
- MHL
- Thunderbolt
- SD Card (UHS-II)
- Cfast

Designed for Multi-Domain Challenges

TDR/TDT MODE



Up to 9 markers

Zooming

Rise time measurement

Dedicated controls for common adjustments

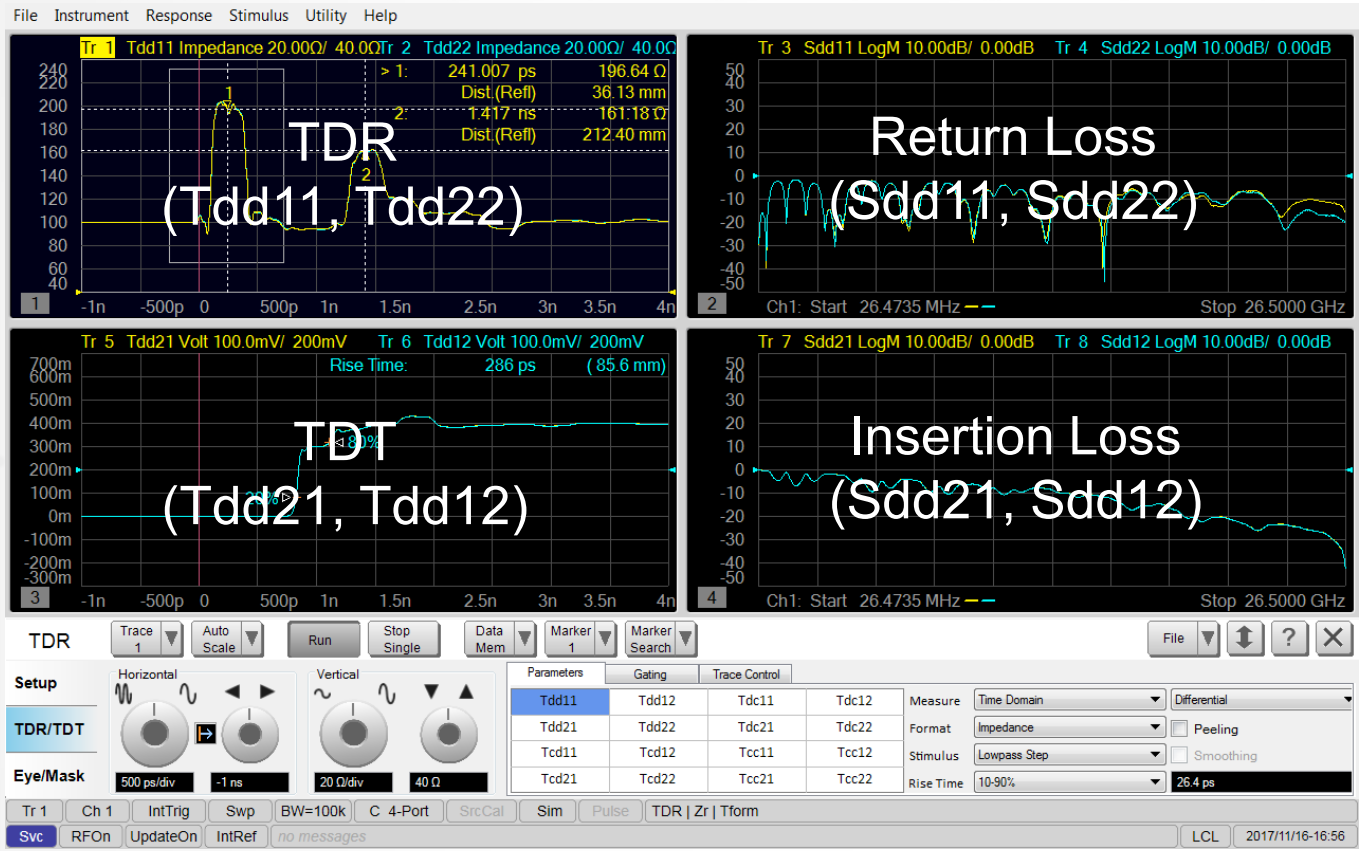
Automatic display allocation for most common measurement parameters depending on selected device topology

Set rise time to characterize expected performance at different edge speeds

Flexibility to set measurement parameter for each individual trace

ΔTime (skew) measurements

Simple and Intuitive Operation



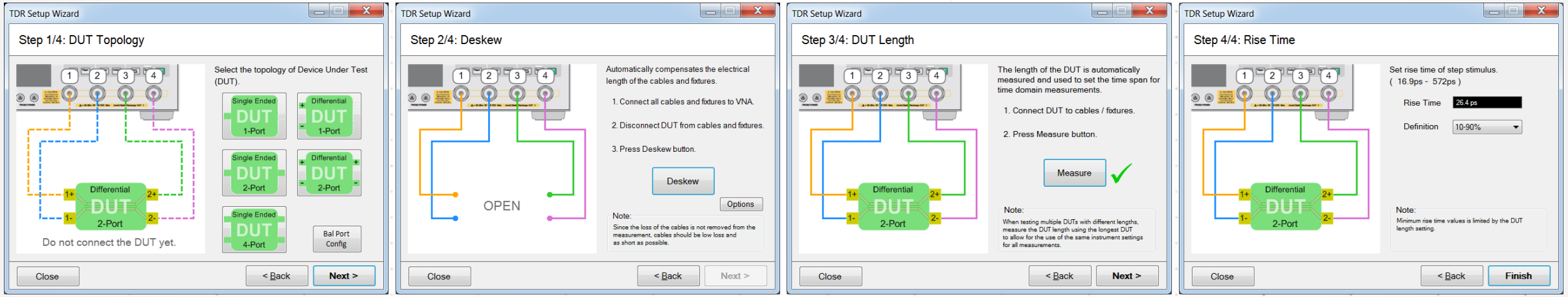
- Dedicated GUI for TDR analysis provides intuitive operation for users not familiar to VNAs and S-parameter measurements
- Easily locate source of loss, reflections and crosstalk by simultaneous analysis of both time and frequency domains

Similar look-and-feel to TDR scopes

Simple and Intuitive Operation

SETUP WIZARD

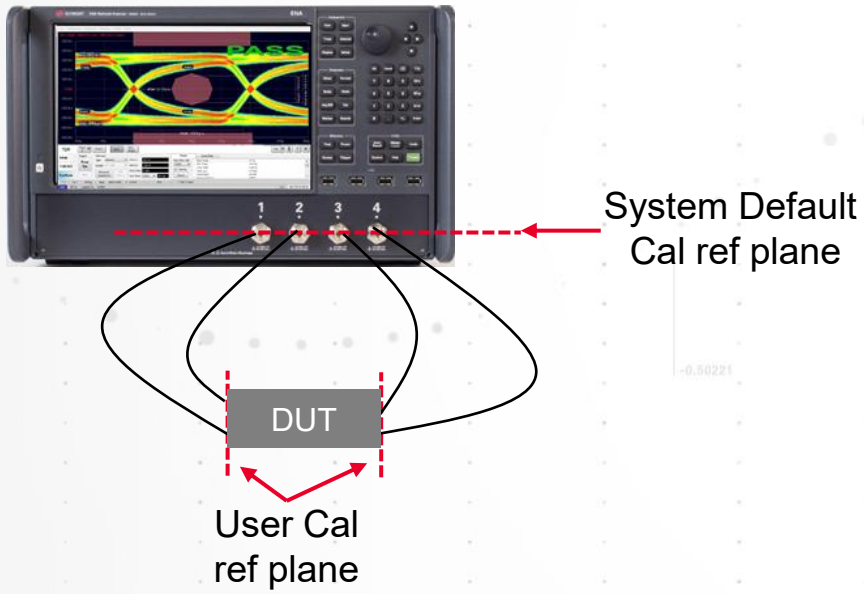
- The Setup Wizard guides you through all of the steps, making setup intuitive and error-free
- Automatically sets the optimum parameters (range, resolution, windowing, etc.) for your DUT

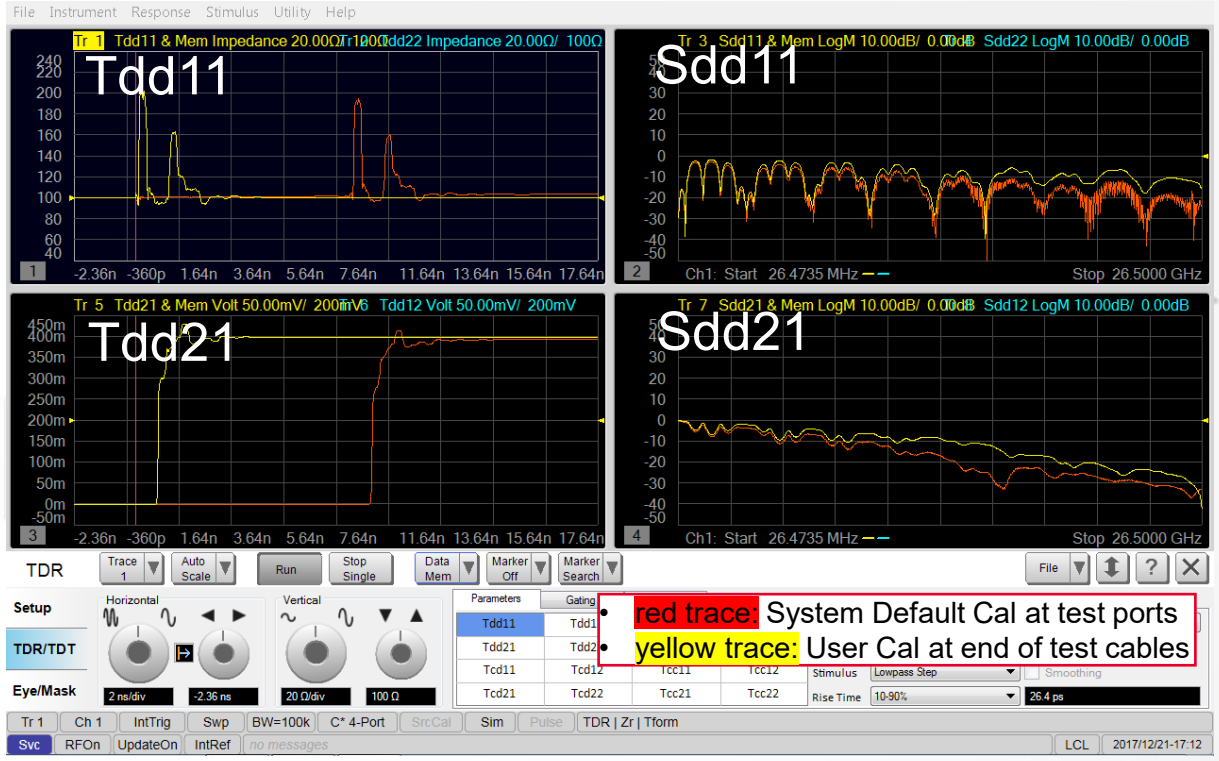


Simple 4-step operation

Fast and Accurate Measurements

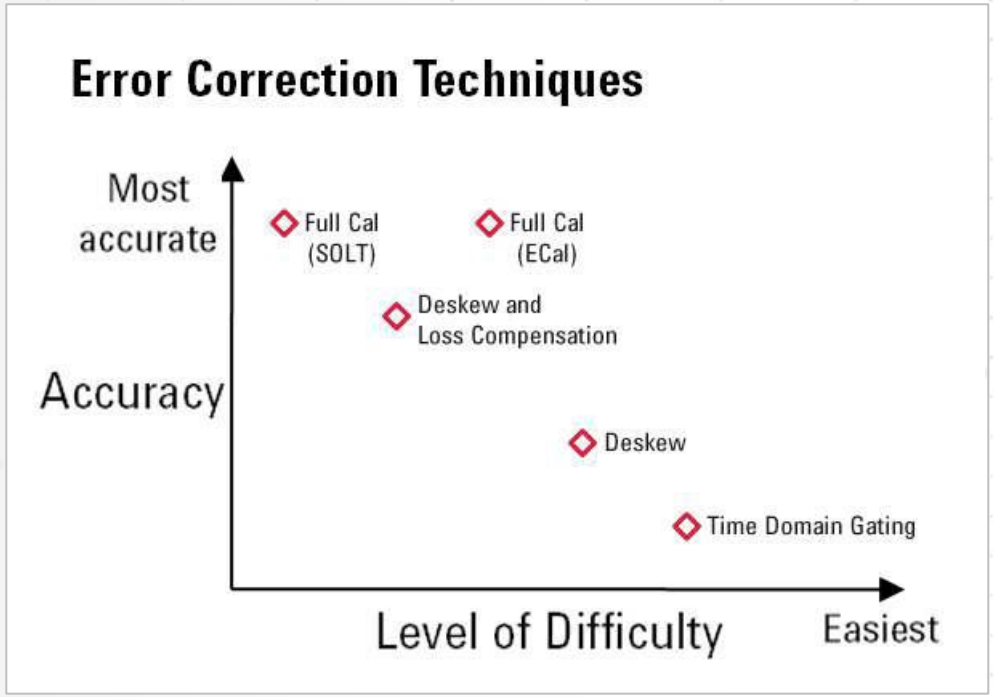
To achieve reasonable accuracy without user calibration, calibration at the test ports is performed at the factory ("System Default" calset) and applied in the TDR Measurement Class.





User calibration is recommended for higher accuracy

Fast and Accurate Measurements



Deskew

- Commonly used in time domain instruments
- Simple to perform
- Only corrects for delay



Full calibration (ECal)

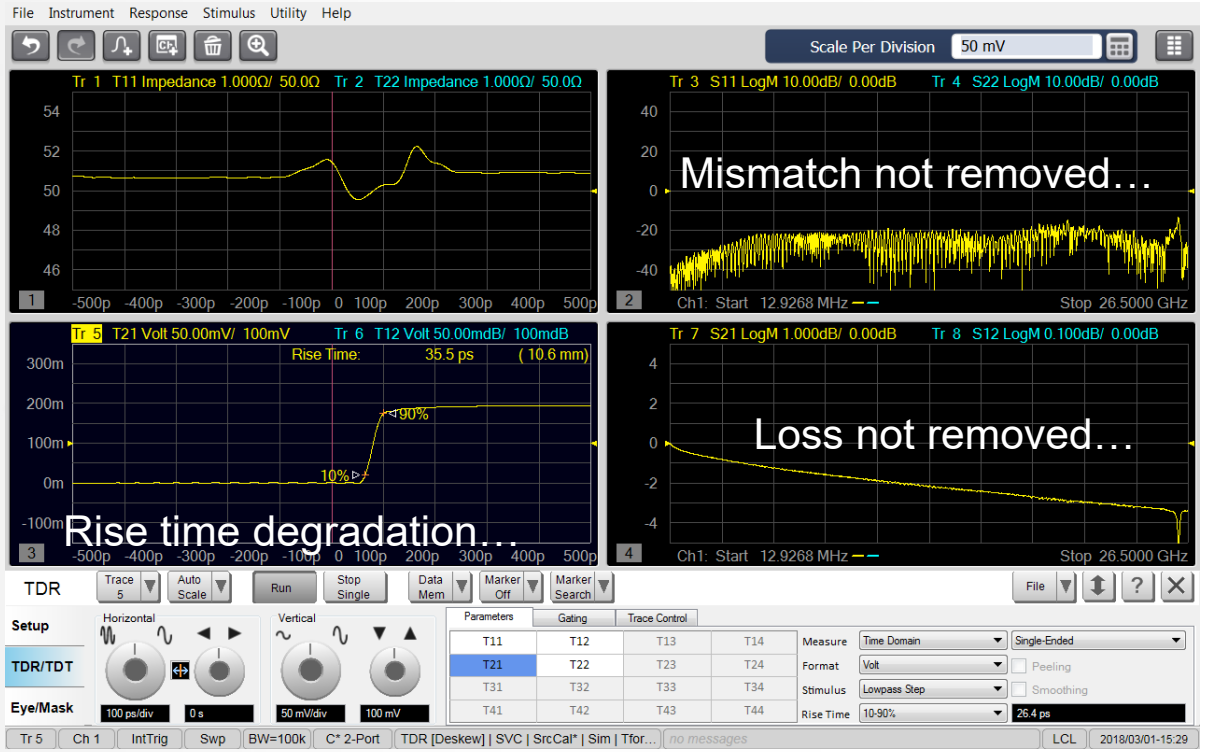
- Commonly used in frequency domain instruments
- Requires more standards
- Accounts for all major sources of error



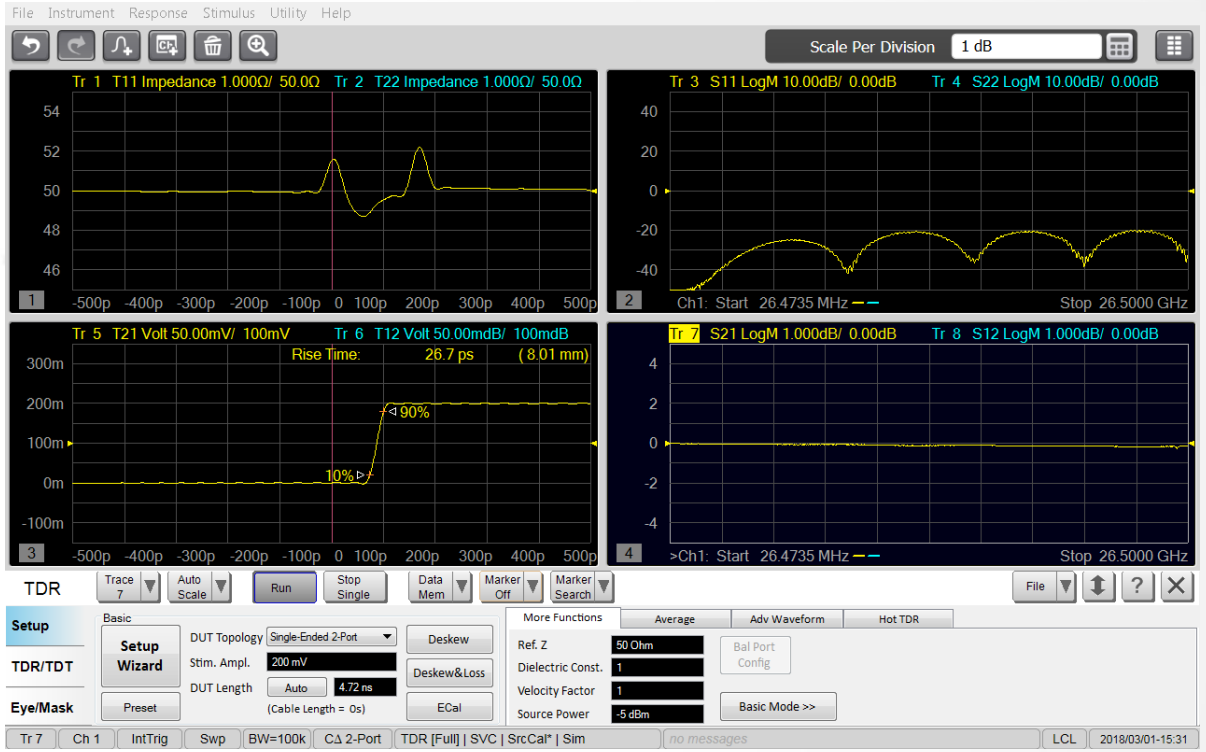
Measure the true performance of your device

Fast and Accurate Measurements

Deskew

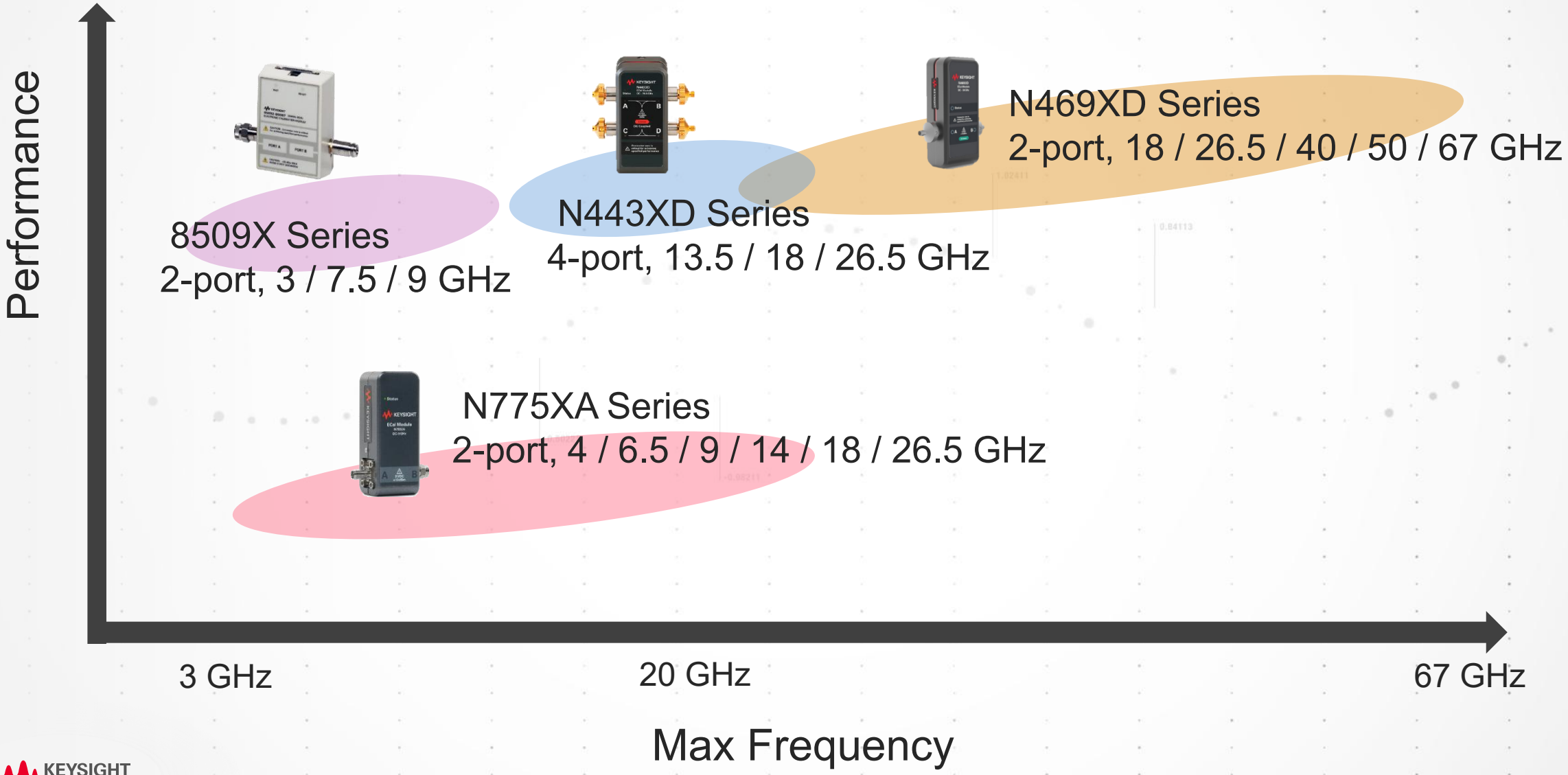


Full calibration (ECal)



Full calibration (ECal) recommended for higher accuracy

Keysight ECal Module Landscape



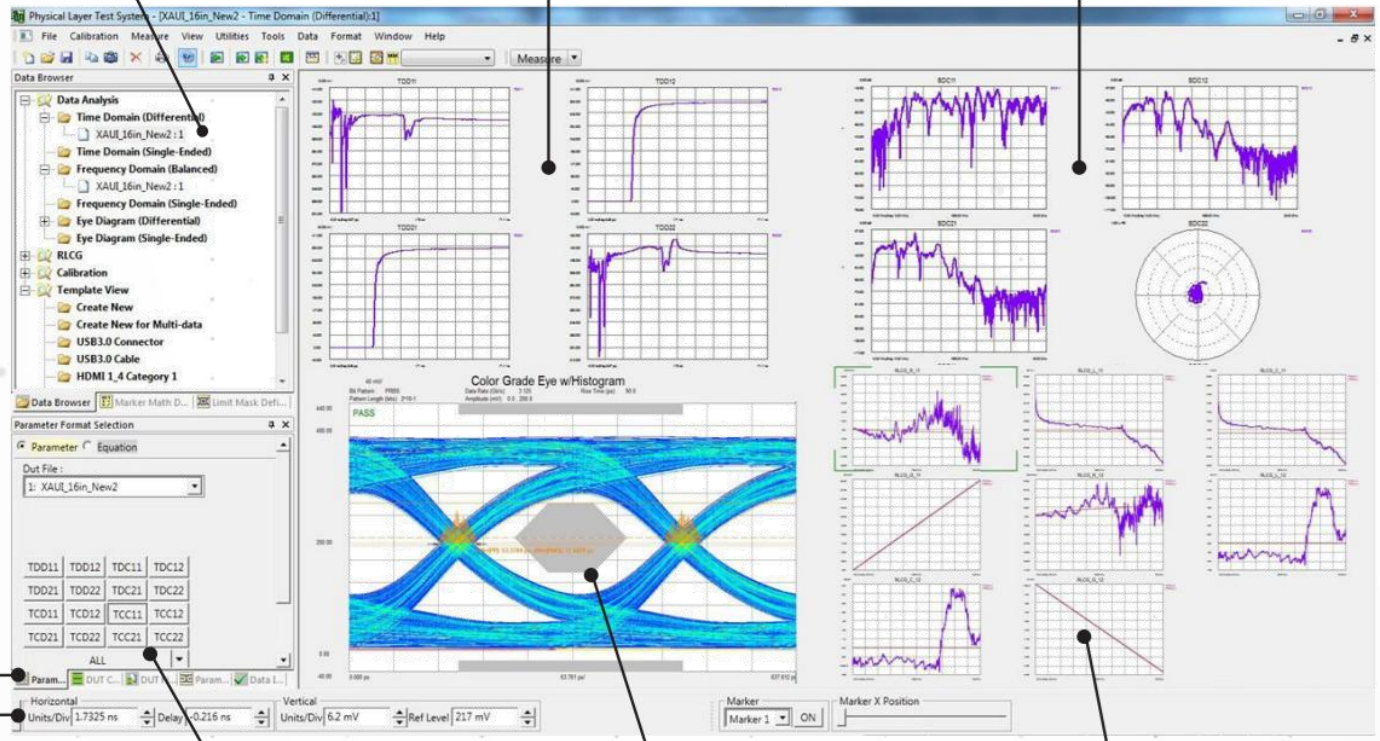
Comparing SI Tools: Physical Layer Test System (PLTS)

DATA ANALYSIS WITH N-PORT PLTS

File and view management with the data browser

Time domain analysis:
- 2 n^2 parameters
- 7 formats
- time or distance

Frequency domain analysis:
- 2 n^2 parameters
- 8 formats



Format, scaling, and marker control with easy access toolbars

Plot and trace management with context-sensitive parameter buttons

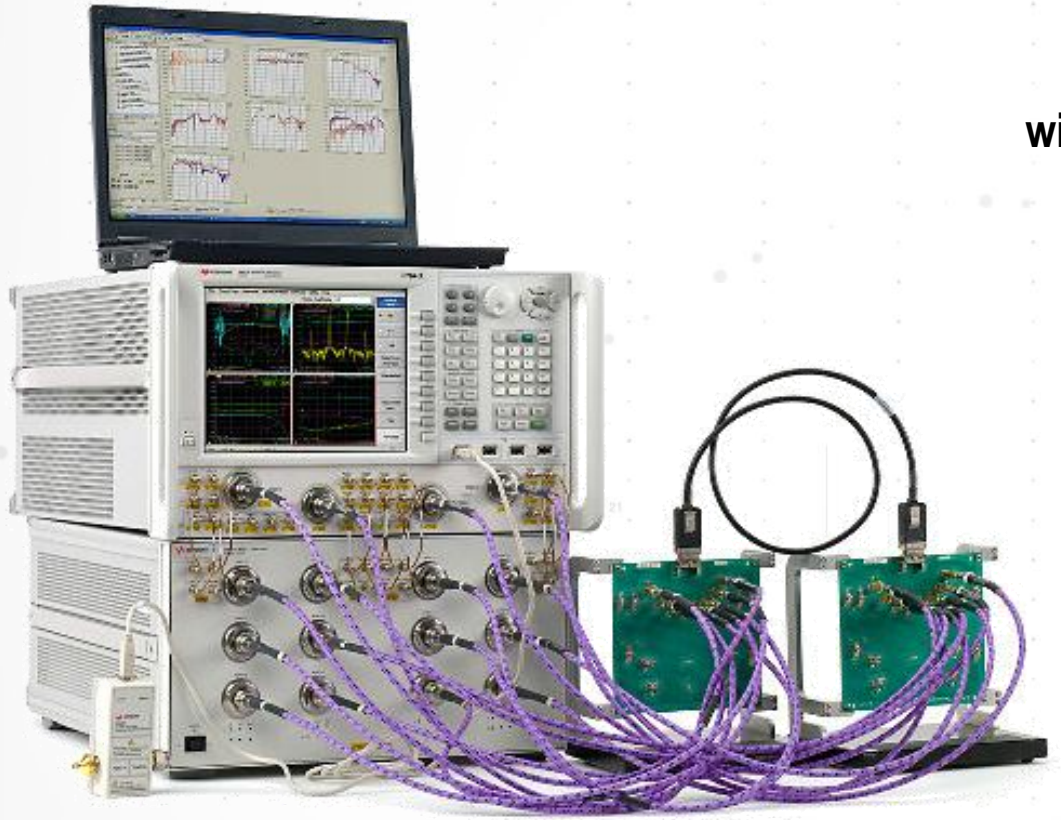
Eye diagram analysis:
- n^2 parameters
- 8 formats

RLCG model extraction
- 2 n^2 parameters

www.keysight.com/find/plts

Comparing SI Tools: Physical Layer Test System (PLTS)

CROSS-HARDWARE MEASUREMENT SYSTEM

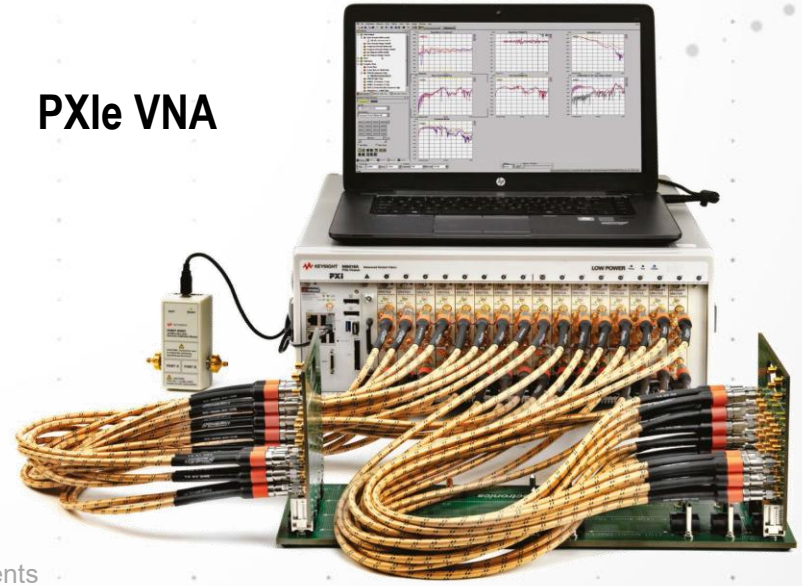


ENA/PNA/PNA-X

DCA-X 86100D
with TDR modules



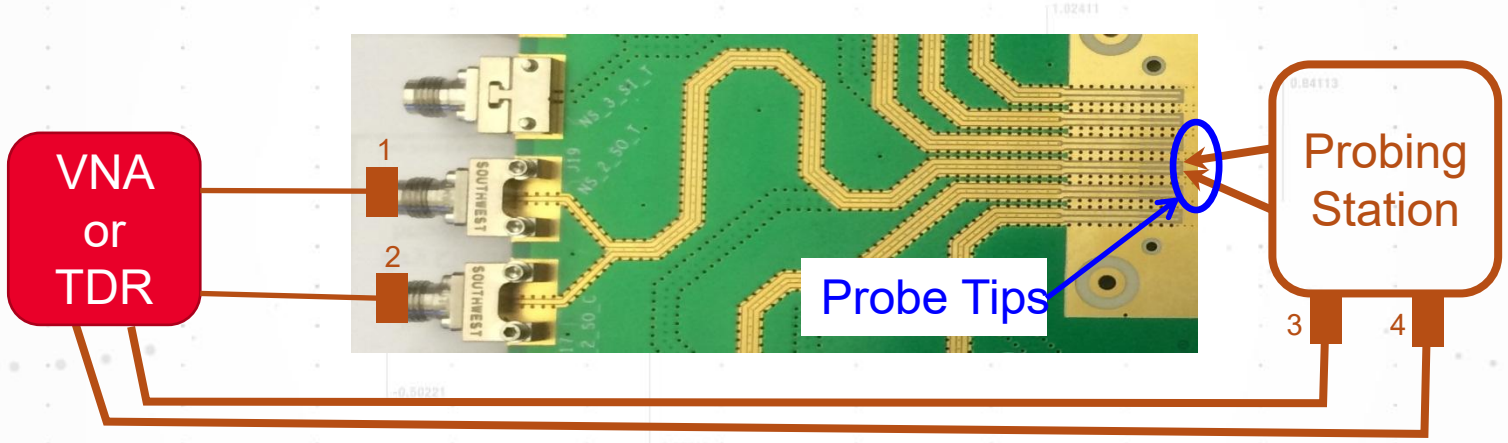
PXIe VNA



Comparing SI Tools: Fixture Removal Techniques

OUR GOAL

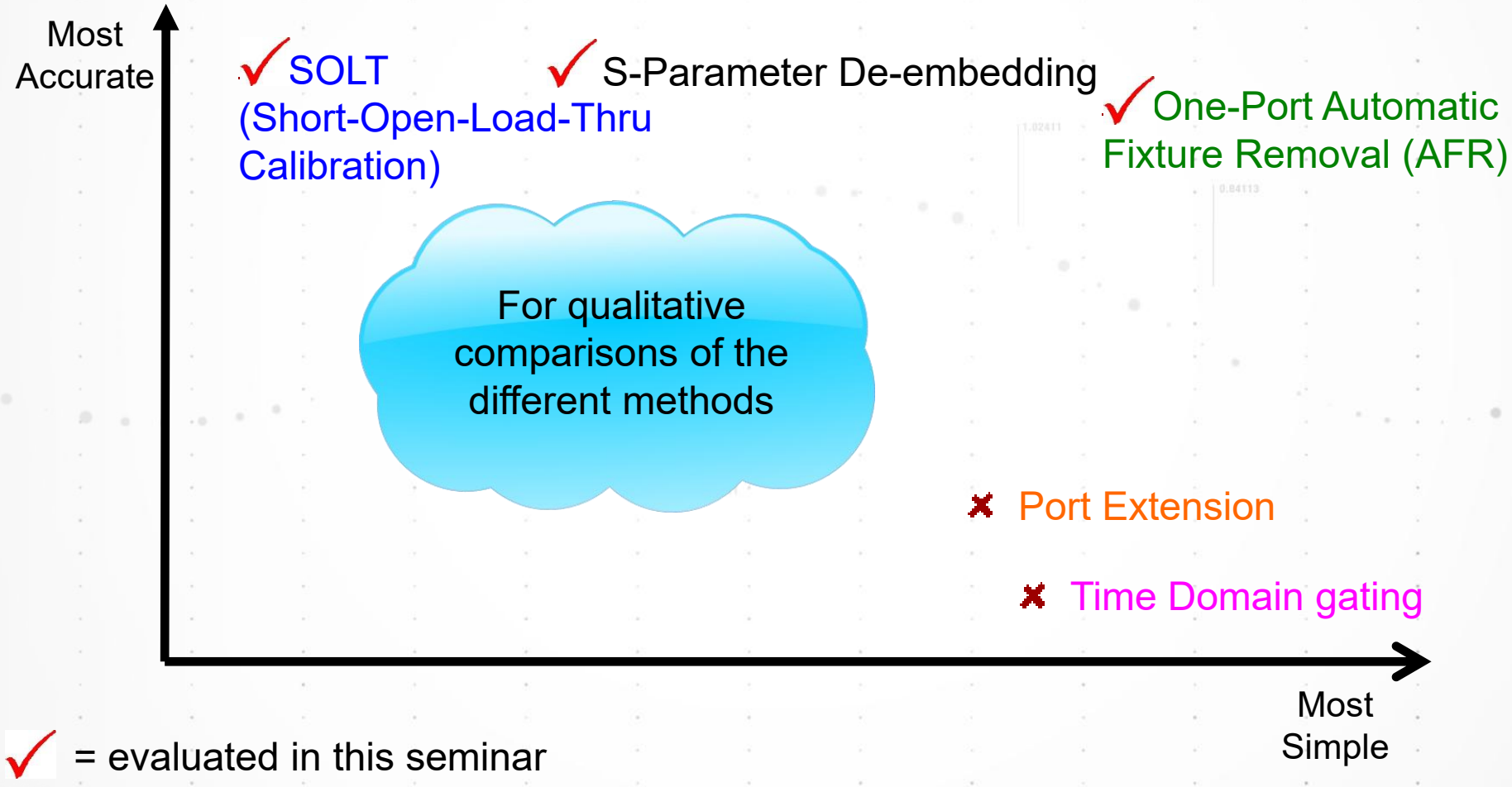
What are we trying to accomplish?



Goal: Characterize the channel WITHOUT including effects of non-ideal instrument performance, cables and probes!

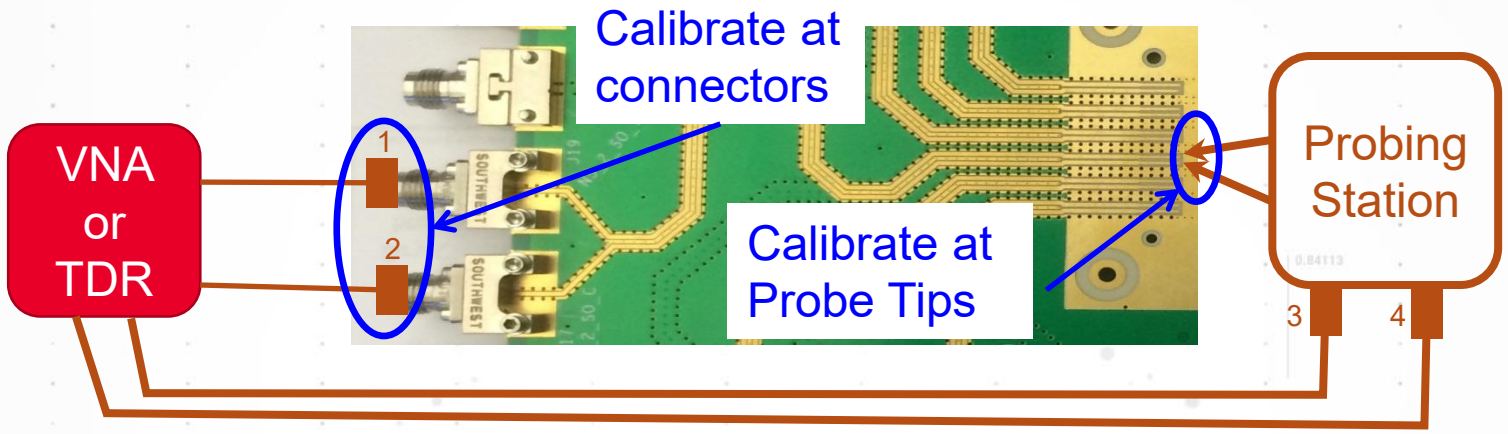
Comparing SI Tools: Fixture Removal Techniques

OVERVIEW OF FIXTURE REMOVAL TECHNIQUES



Comparing SI Tools: Fixture Removal Techniques

SOLT CALIBRATION



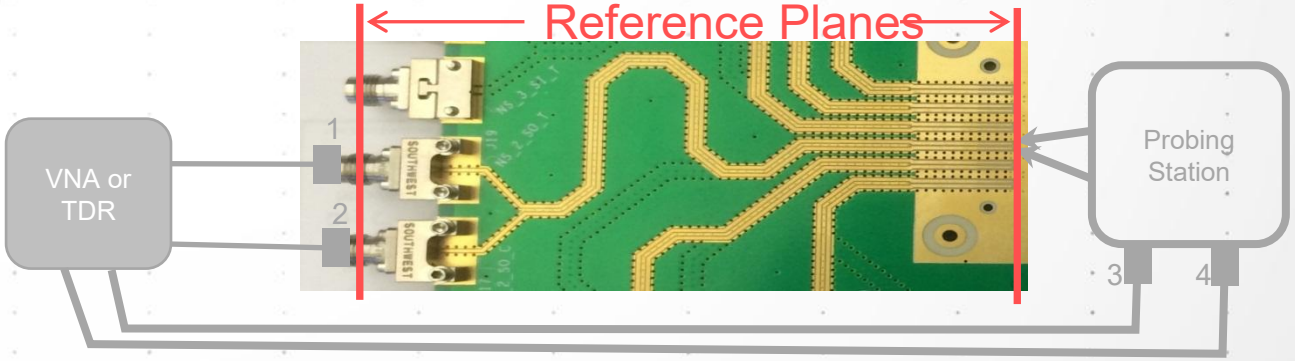
Goal: Characterize the channel WITHOUT including effects of non-ideal instrument performance, cables and probes

Process with SOLT Calibration:

1. SOLT calibration at VNA/TDR connectors 1&2
2. SOLT calibration at the probe tips using a calibration substrate

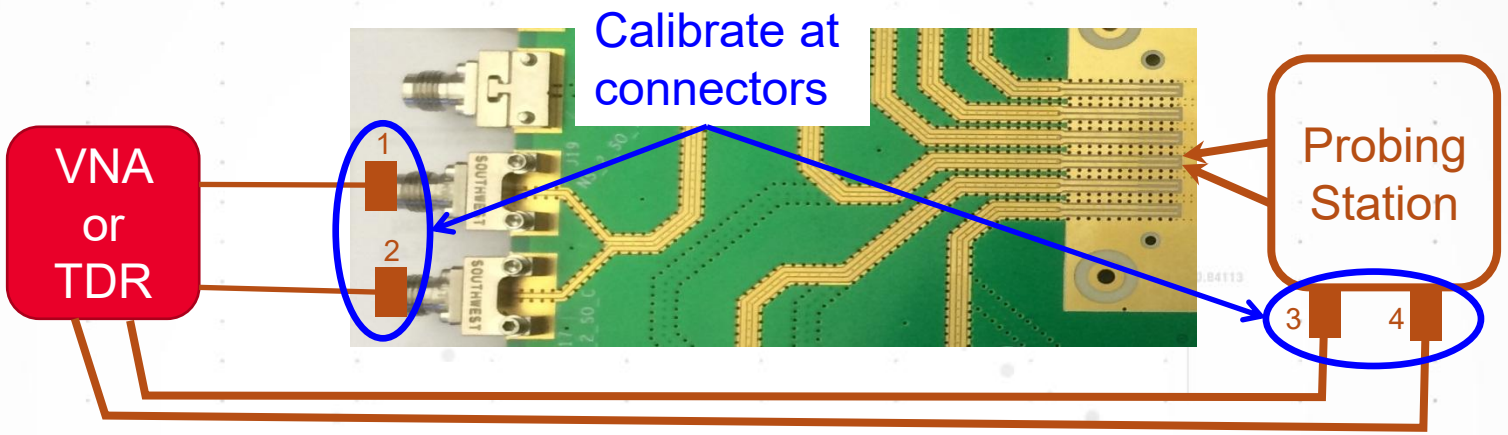
The above can be done directly on the VNA and TDR with no other external tools

3. Measure the DUT:



Comparing SI Tools: Fixture Removal Techniques

DE-EMBEDDING THE PROBE

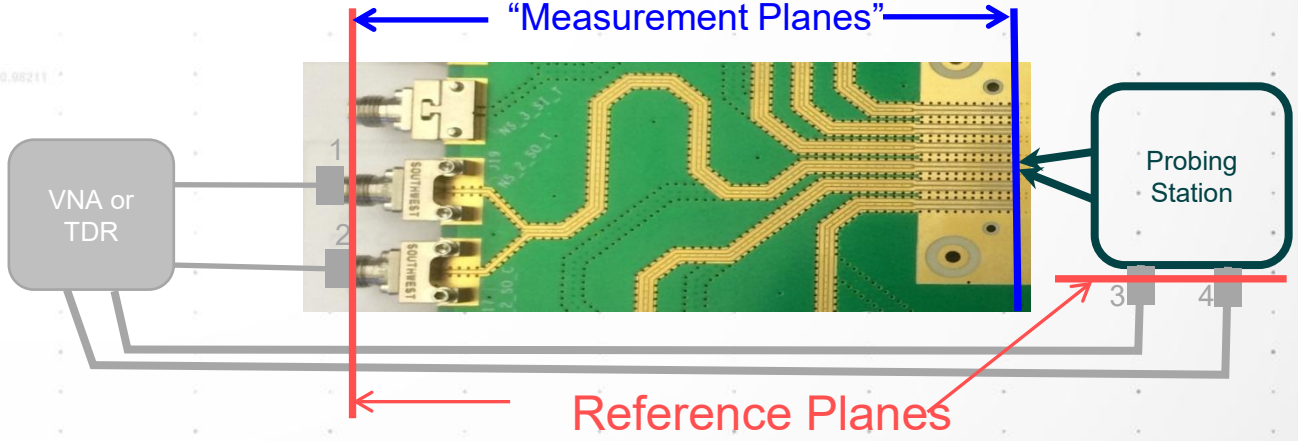


Goal: Characterize the channel WITHOUT including effects of non-ideal instrument performance, cables and probes

Process with Probe De-embedding:

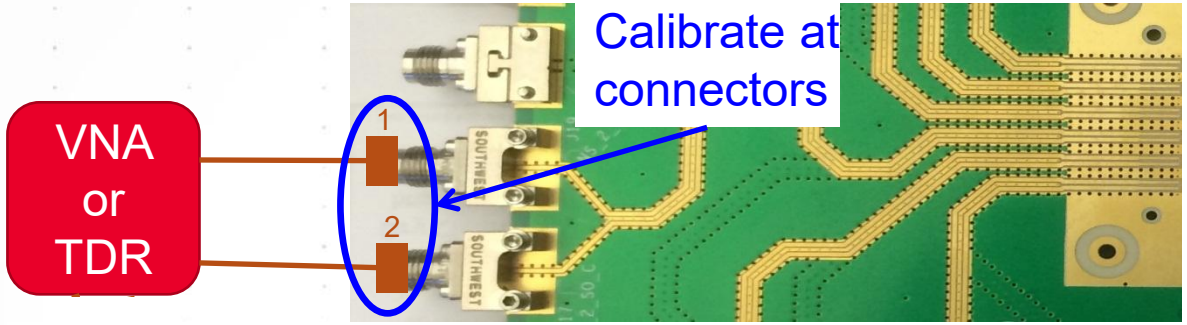
1. SOLT calibration at VNA/TDR connectors 1&2
2. SOLT calibration at VNA/TDR connectors 3&4
3. Measure the DUT + Probes
4. De-embed the probes

This will be done using Keysight Physical Layer Test System software (PLTS), N1930B.
This can also be done directly on the Keysight TDR or PNA



Comparing SI Tools: Fixture Removal Techniques

ONE-PORT AFR (AUTOMATIC FIXTURE REMOVAL)

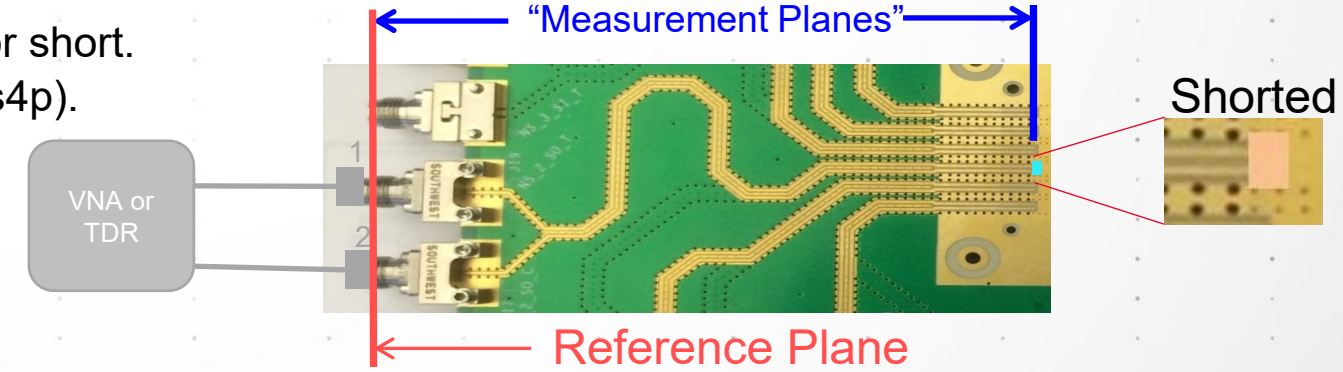


Goal: Characterize the channel WITHOUT including effects of non-ideal instrument performance, cables and probes

Process with One-Port AFR:

1. SOLT calibration at VNA/TDR connectors 1&2
2. Do not use VNA/TDR channels 3&4
3. Measure SDD11 of the channel into an open and/or short.
4. Use one-port AFR to determine SDD21 (channel .s4p).

This will be done using Keysight Physical Layer Test System software (PLTS) P/N N1930B. This can be done directly on the Keysight PNA today.

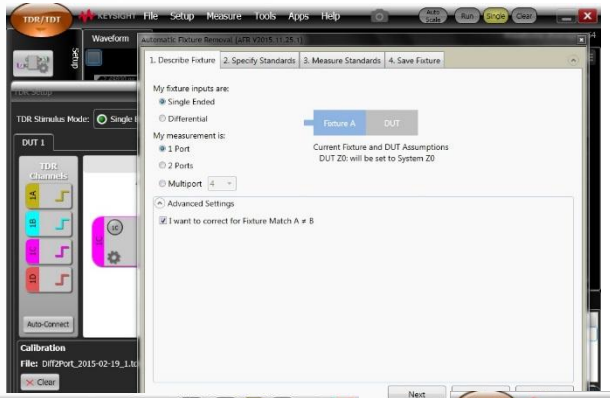


AFR (Automatic Fixture Removal)

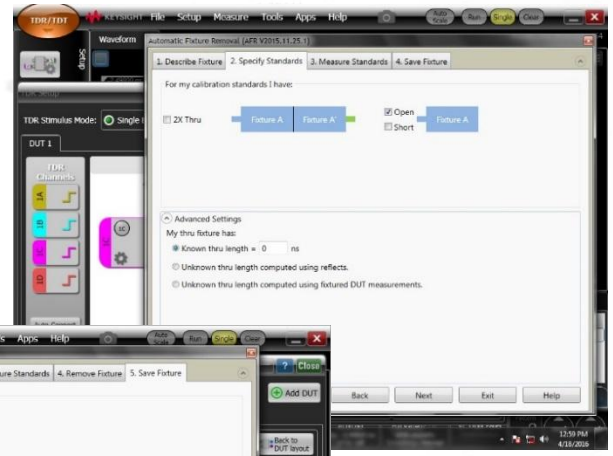
Keysight N1930B Physical Layer Test System (PLTS) AFR is now available in the TDR. Need to characterize a fixture with only one connectorized port (such as a probe)? AFR makes it easy!

1. Launch the AFR wizard and describe your fixture.

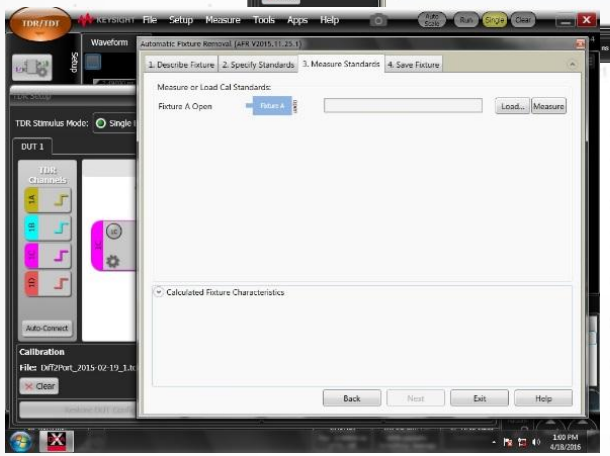


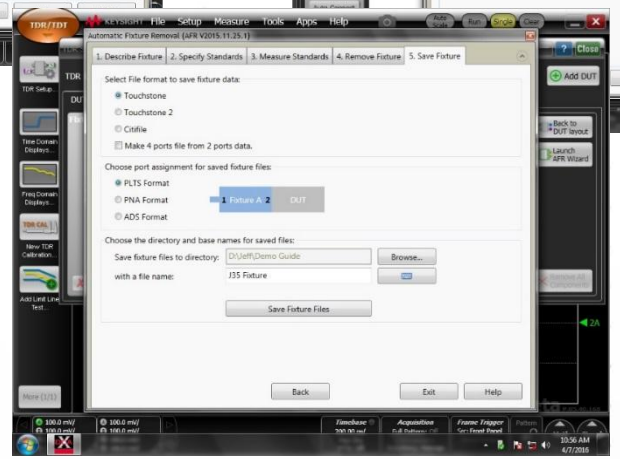


2. Choose how the non-connectorized fixture port will be terminated (open, shorted or both)



3. Measure the fixture + termination(s)



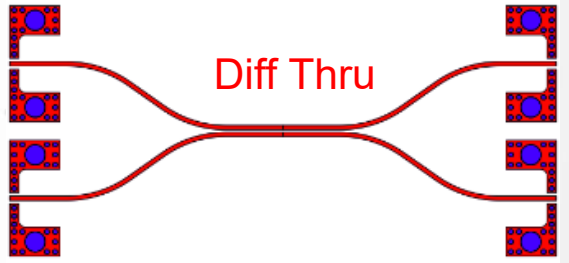


4. Save the Touchstone file

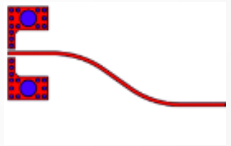
Today is **AFR**



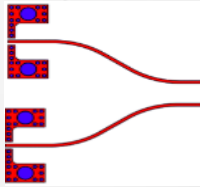
O



Or

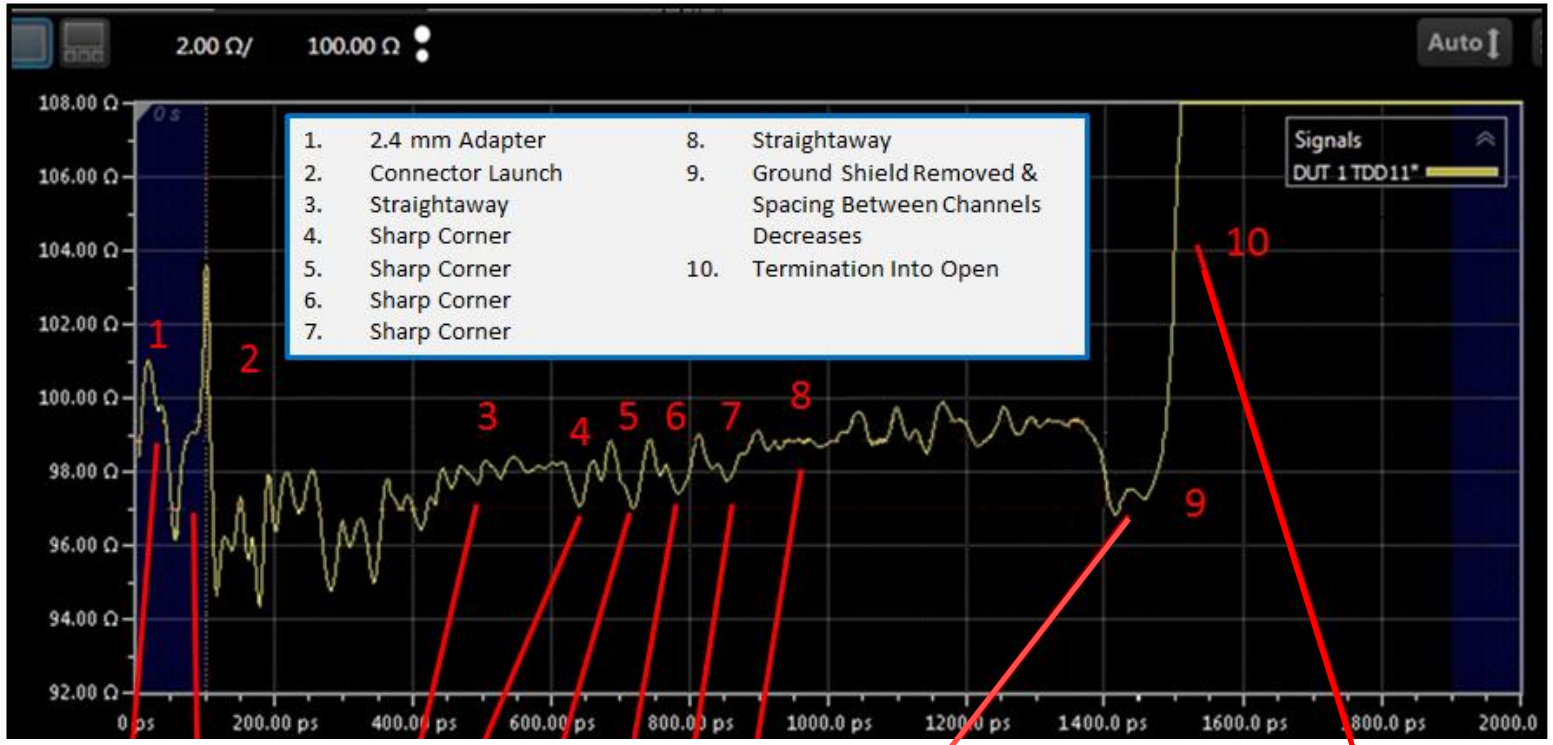


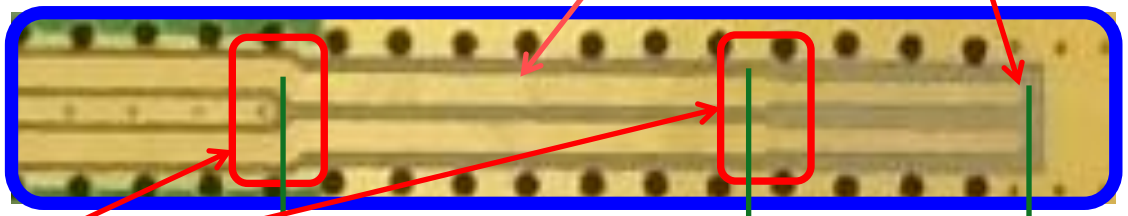
Open



You are now ready to de-embed your fixture!

Case Study, Quick TDR Insights: Impedance Profile



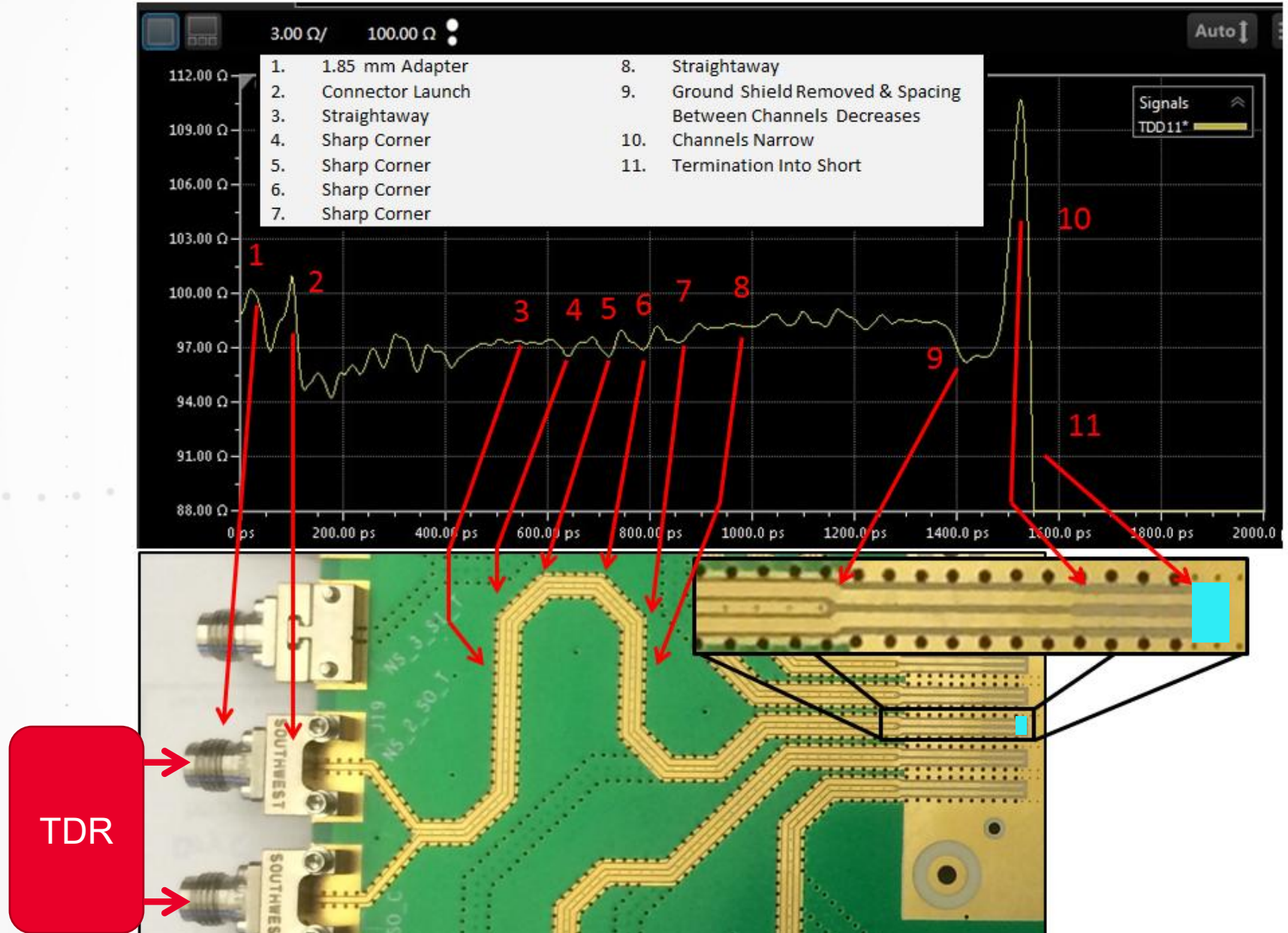


Impedance Transitions

Should be capacitive (lower impedance)

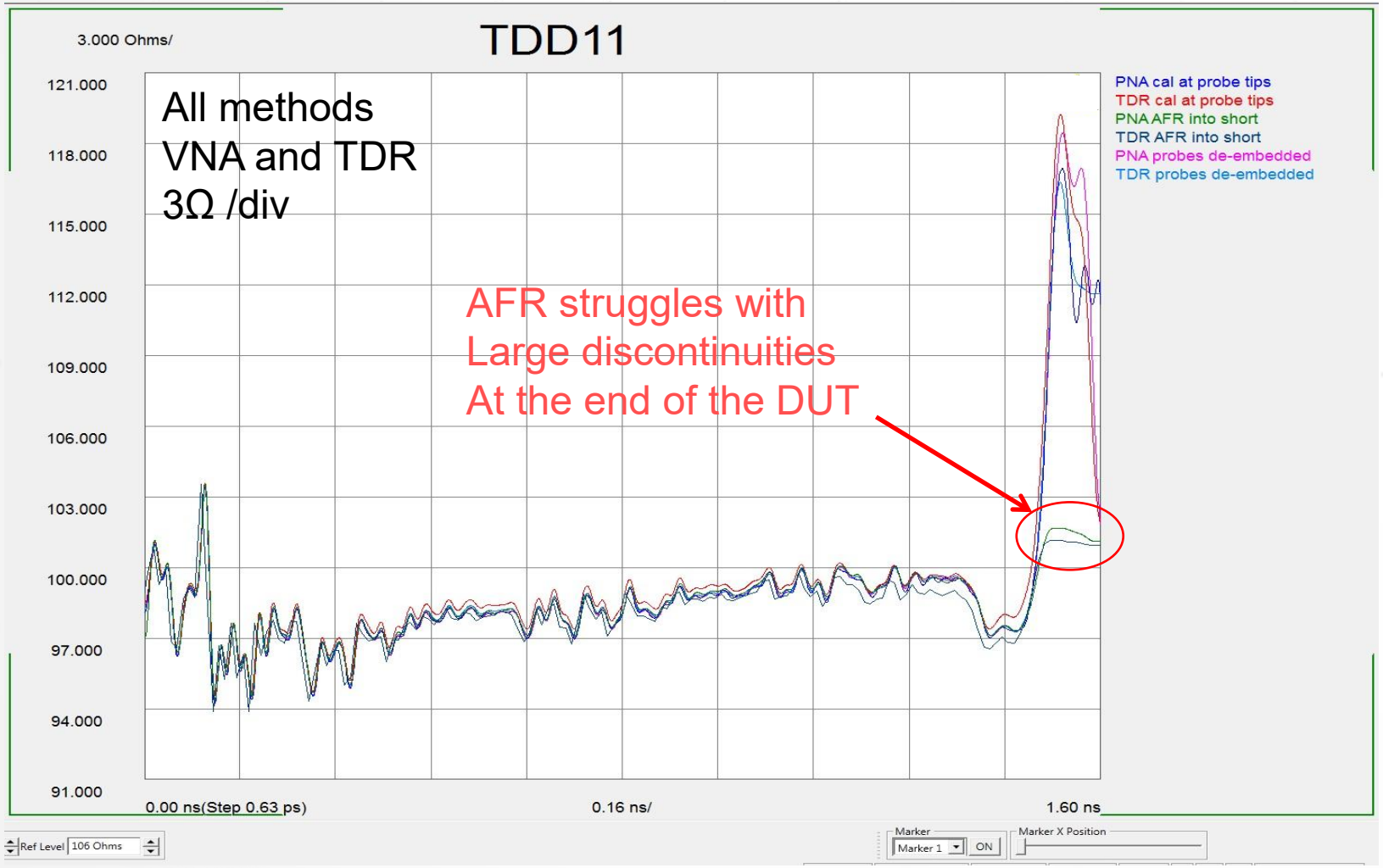
Should be inductive (higher impedance)

Case Study, TDR insights: Impedance Profile Into Short



Channel Characterization, Impedance Profile

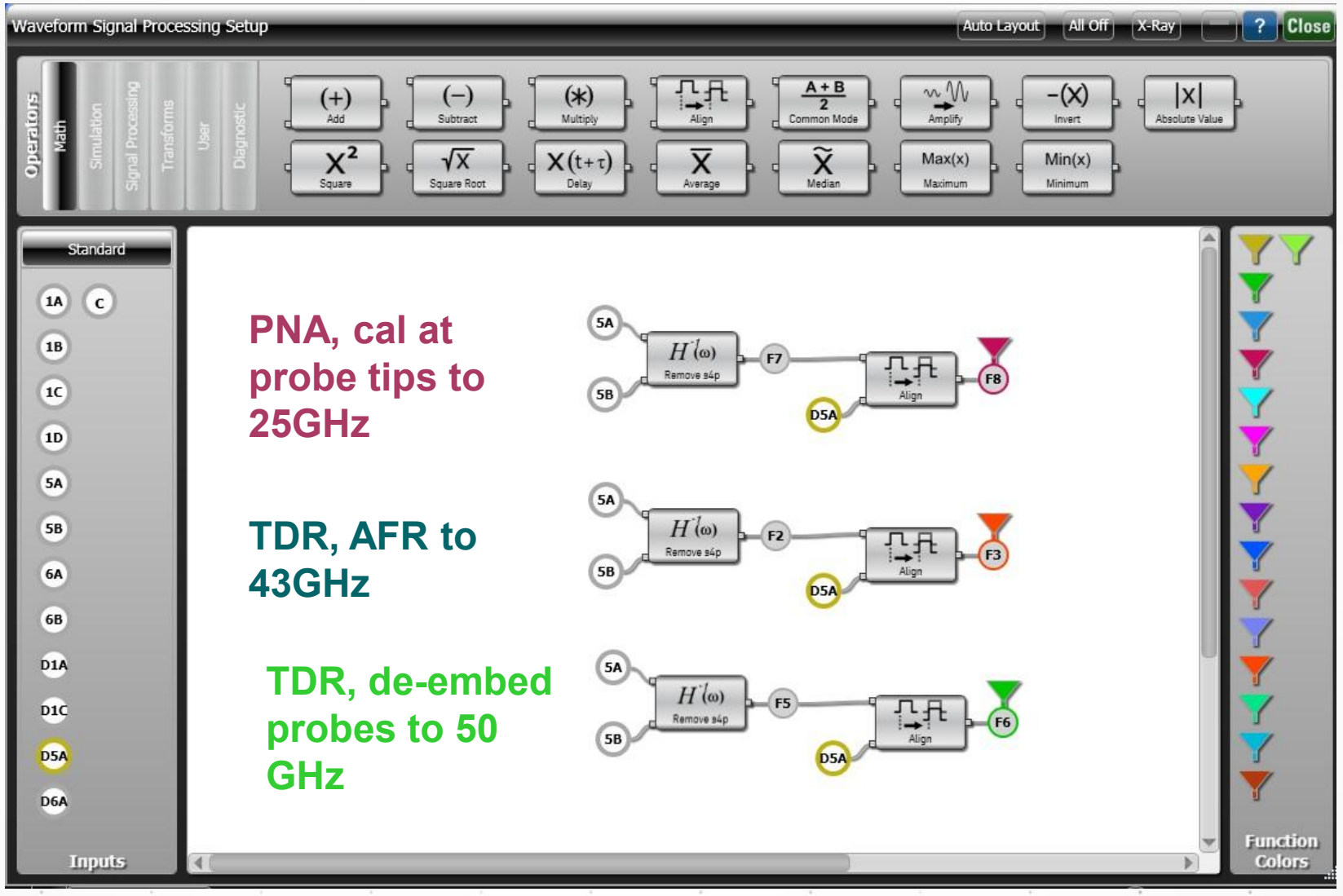
ALL METHODS, 14 PS 10-90 EDGE SPEED



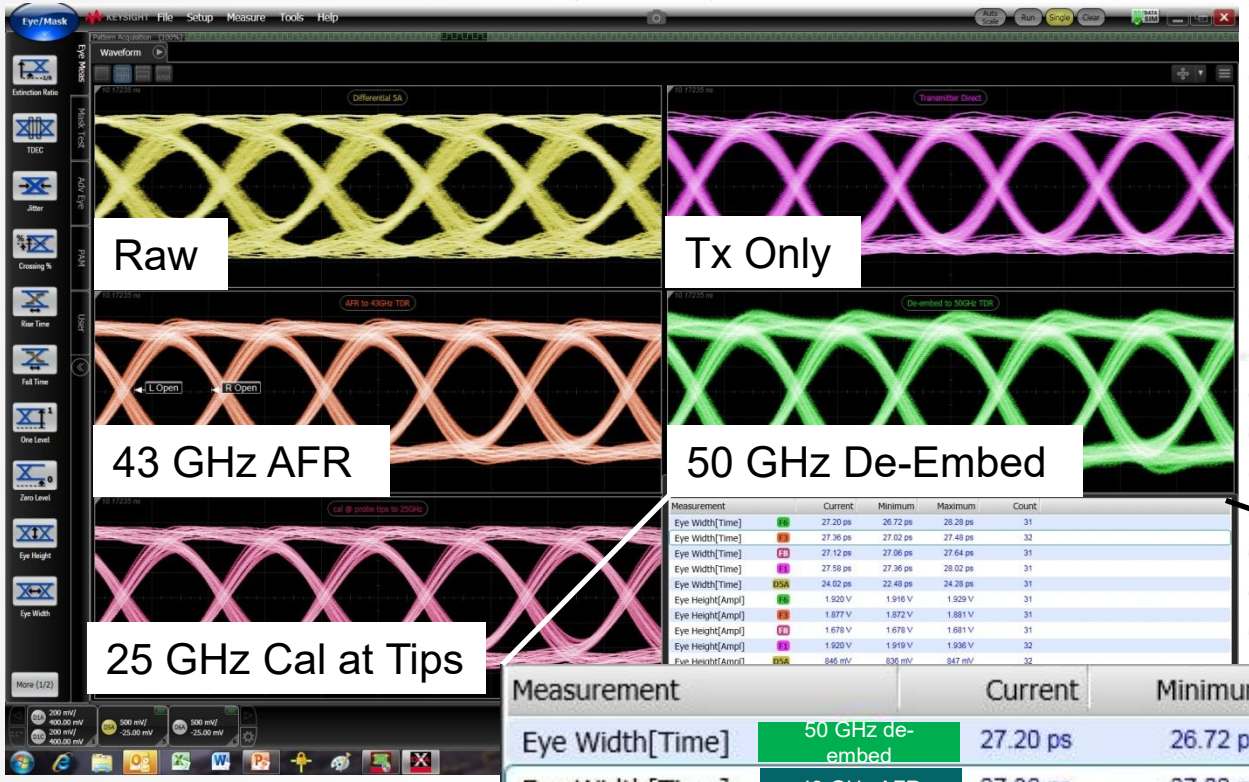
Summary:

- Good correlation for both instruments and ALL methods

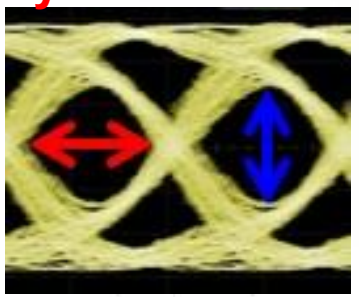
De-embedding the channel using the TDR/Scope



De-embedding the channel using the TDR/Scope



Eye Width



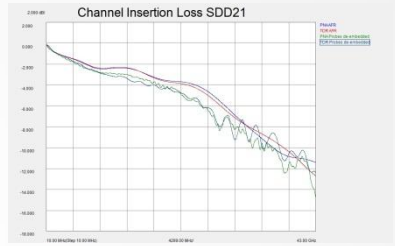
Eye Height

Measurement		Current	Minimum	Maximum	Count
Eye Width[Time]	50 GHz de-embed	27.20 ps	26.72 ps	28.28 ps	31
Eye Width[Time]	43 GHz AFR	27.36 ps	27.02 ps	27.48 ps	32
Eye Width[Time]	25 GHz cal at tips	27.12 ps	27.06 ps	27.64 ps	31
Eye Width[Time]	Tx ONLY	27.58 ps	27.36 ps	28.02 ps	31
Eye Width[Time]	Raw at channel end	24.02 ps	22.48 ps	24.28 ps	31
Eye Height[Ampl]	50 GHz de-embed	1.920 V	1.916 V	1.929 V	31
Eye Height[Ampl]	43 GHz AFR	1.877 V	1.872 V	1.881 V	31
Eye Height[Ampl]	25 GHz cal at tips	1.678 V	1.678 V	1.681 V	31
Eye Height[Ampl]	Tx ONLY	1.920 V	1.919 V	1.936 V	32
Eye Height[Ampl]	Raw at channel end	846 mV	836 mV	847 mV	32

Summary:

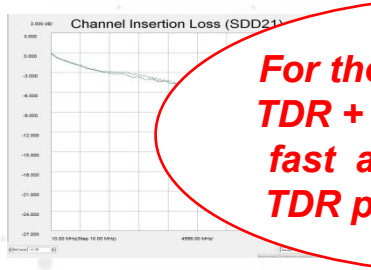
- Significant improvement in EYE opening with de-embedding, as expected (10% width, >100% height).
- Eye Width correlation across instruments and methods within 2.5% of Tx only.
- Eye Height for probe at cal tips method low.
- Eye Height for AFR and Probe De-embed within 2.5% of Tx only.

Summary



- One-port AFR is the fastest and easiest measurement technique requiring no special hardware and had very good correlation with the other methods.

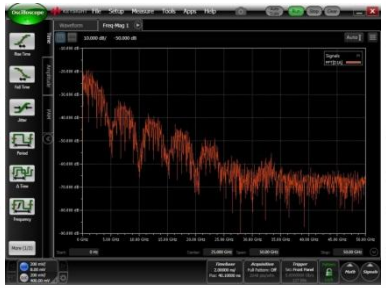
- TDR measurement results correlated well with the VNA measurement results for all three fixture removal approaches:
  - SOLT at the probe tips
  - De-embedding the probe
  - One-Port AFR

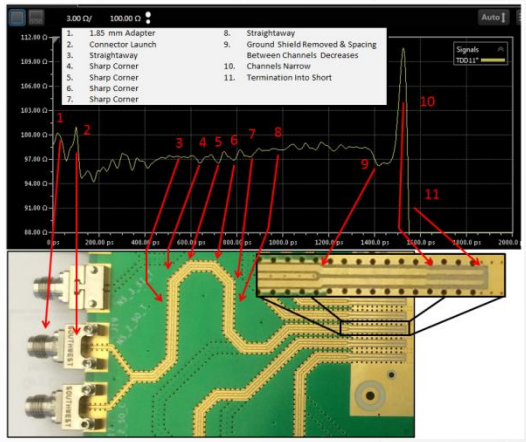


For these measurements TDR + AFR was accurate, fast and easy PLUS the TDR provided additional insights !!

- The flexibility and fast live updates of the TDR offered additional and valuable insights:
  - Fast and easy identification of the causes of discontinuities in the impedance profile
  - Measured the spectral content of the Tx signal to determine frequency test limits
  - Provided simulation/de-embedding of the channel and scope/eye measurements







Acronyms and Names

- DUT: Device Under Test
- SOLT: In this paper refers to a TDR/VNA calibration technique using Short, Open, Load and Thru mechanical standards.
- ECal: In this paper refers to a TDR/VNA calibrating technique based on an electronic Calibration module characterized over a wide frequency range
- AFR: In this paper refers to Automatic Fixture Removal.