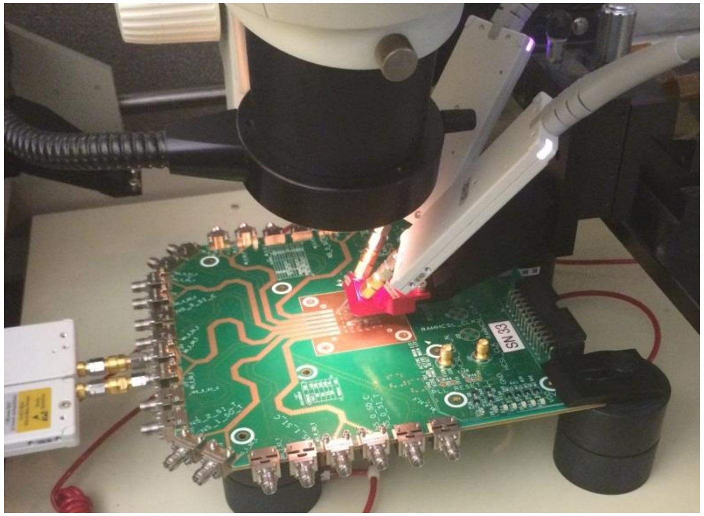
Find Signal Integrity Problems through TDR/TDT Measurements



Jon Kinney
RF/uW Application Engineer
Keysight Technologies

KEYSIGHT TECHNOLOGIES

Overview

- This presentation reviews the measurement of passive, linear networks, the structures that transport signals from point to point. These measurements characterize physical layer characteristics such as impedance, loss, discontinuities, crosstalk, emissions, susceptibility, etc. Active component characterization has different rules and considerations.
- There are two elements that will be discussed during this presentation: The instruments that are used to make these types of measurements, and the actual measurements that are made.

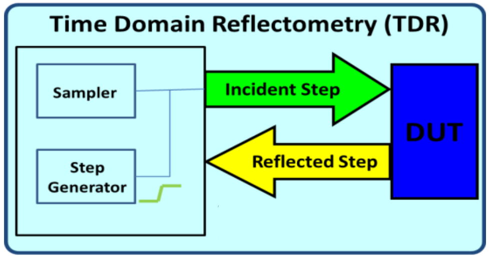
Agenda

Let’s Talk About TDR:

- What is TDR?
- What is TDT?

TDR or VNA – Which instrument to choose

- Review TDR vs VNA Differences



Comparing Different Signal Integrity Tools:

- Correction and Measurements
- Fixture Removal Techniques

Summary/Q&A

KEYSIGHT TECHNOLOGIES

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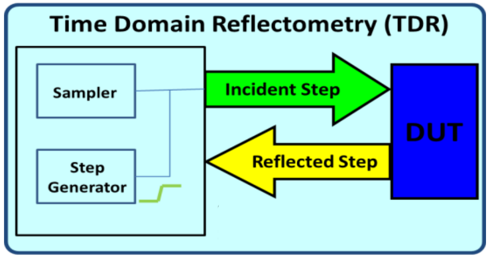

Comparing Different Signal Integrity Tools:

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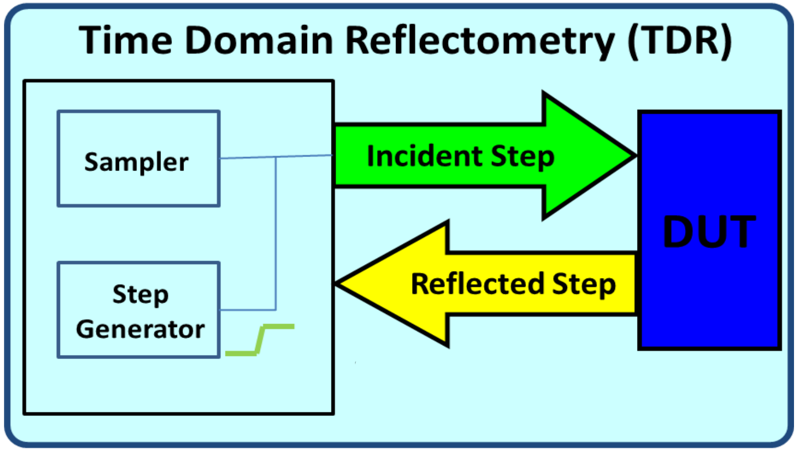
Summary/Q&A

Basic Definitions

- Definitions
  - TDR – Time Domain Reflectometer. The measurement of a calibrated incident step launch into a device and the measured reflected energy from that launch into a device.
  - TDT – Time Domain Transmittance. The measurement of a calibrated incident step launch into a device and the measured transmitted energy from that launch through a device.
  - FFT – Fast Fourier Transform. The mathematical translation of time domain response into the frequency spectrum profile and the energy observed across the spectrum.
  - IFFT – Inverse FFT. The convolution of broad spectrum frequency profile for a given period of time into the impulse response and ultimately equivalent step response profile.
  - Step response. The measured response of a calibrated incident step into a device that includes the high frequency profile and the resulting frequency settling response of the device.
  - S-parameters. Matrix profile of frequency domain measurement response of device. S-parameter measurements can be made direct from frequency domain measurement using a network analyzer or from the FFT conversion of step response profile of a time domain measurement.

Intro: What is TDR?

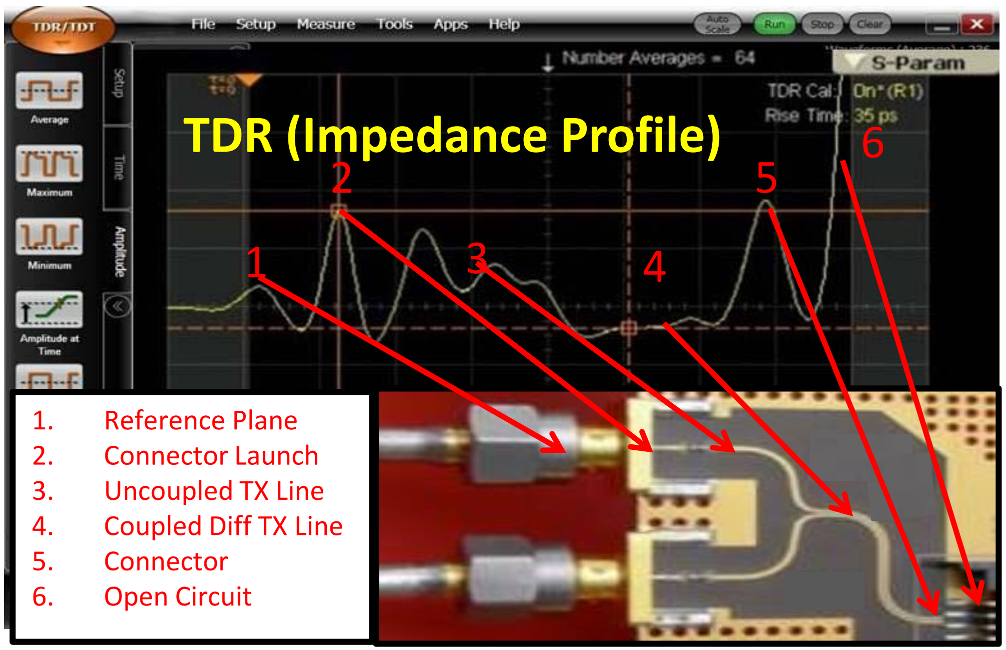


Time Domain Reflectometry (TDR)

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)



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

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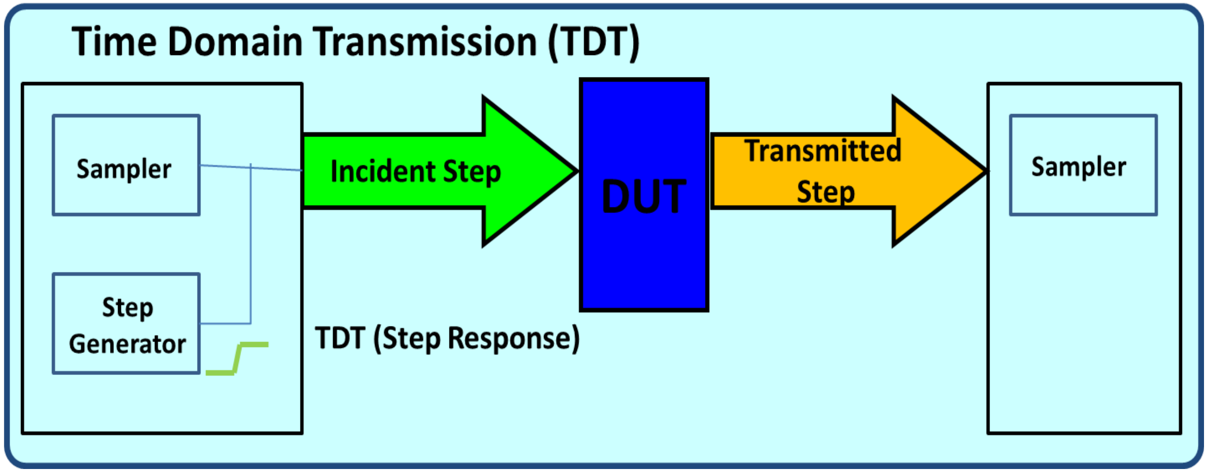
Intro: What is TDT?



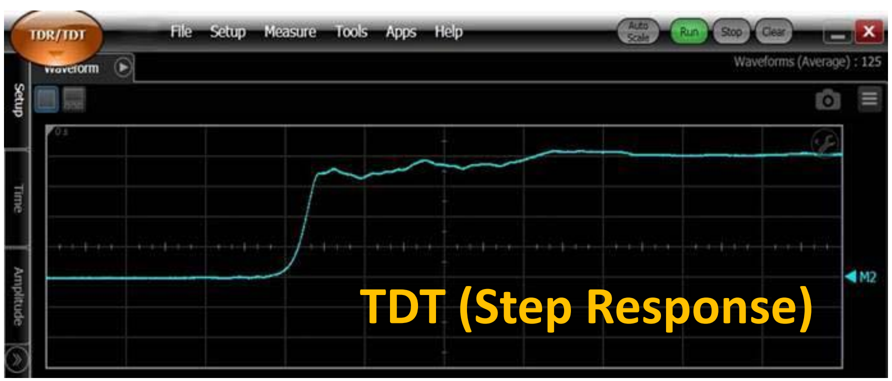
Time Domain Transmission (TDT)

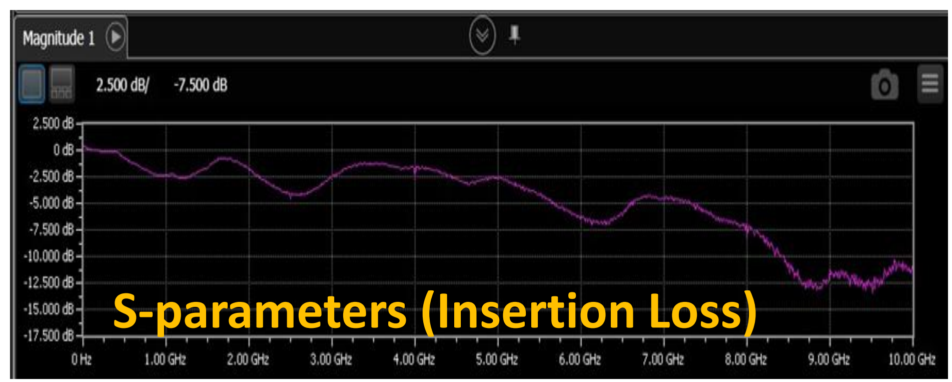
1. Launch a fast step into the Device Under Test (DUT)
2. See what is transmitted THROUGH the DUT.

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

Example Measurements:

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





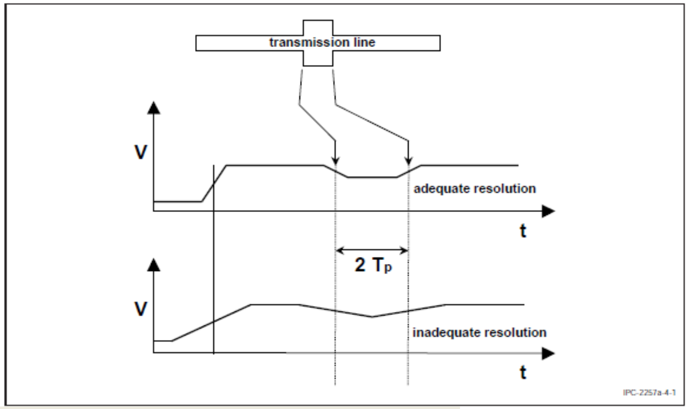
KEYSIGHT TECHNOLOGIES

TDR - Measurement System Requirements

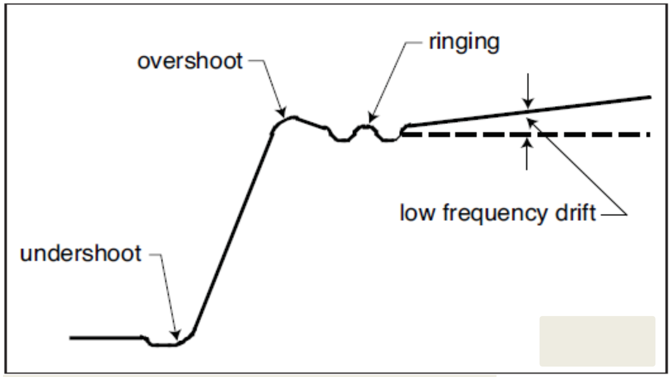
IPC-TM-650 references several key TDR system attributes that determine measurement accuracy and repeatability, including:

1. Temporal/Spatial (TDR) Resolution

- ability to resolve two closely spaced discontinuities
- determined by system bandwidth, TDR edge speed, material dielectric



IPC TM-650 2.5.5.7a Figure 4-1



IPC TM-650 2.5.5.7a Figure 4-2

2. Step Aberrations

- ringing, overshoot, undershoot, settling
- introduces measurement errors
  (Note – especially differential measurements when steps are mismatched)

3. TDR Step: Baseline, Amplitude, and Timing Drift

- TDR step generators and samplers are subject to time and temperature drifts
- constant baseline voltage, amplitude and timing of step pulse are critical to repeatability
- Example: drift can introduce measurement error due to induced skew between channels

KEYSIGHT TECHNOLOGIES

Temporal/Spatial (TDR) Resolution

TDR resolution is determined by:

1. **TDR <u>System</u> edge speed**

   Example: Trise system = 8 ps (10-90%)

Note – Tr system is <u>different</u> than Trise calculated only from scope BW

Example: BW = 50 GHz; BW = 0.35/tr
Trise Scope RX = 0.35 / 50GHz = 7 ps

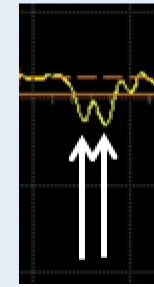
2. **Dielectric constant of transmission medium**

   Example: 4.0 (PCB)

TDR Resolution:

D min = [3E8 * 8E-12] / [2*SQRT(4)]
= 0.6 mm

$$D_{min} = \frac{c \bullet t_{rise}}{2\sqrt{\varepsilon}}$$



- $t_{r_{system}} = \sqrt{t_{r_{step}}^2 + t_{r_{scope}}^2}$
- Ɛ = dielectric constant of the transmission system
- c = speed of light in a vacuum.

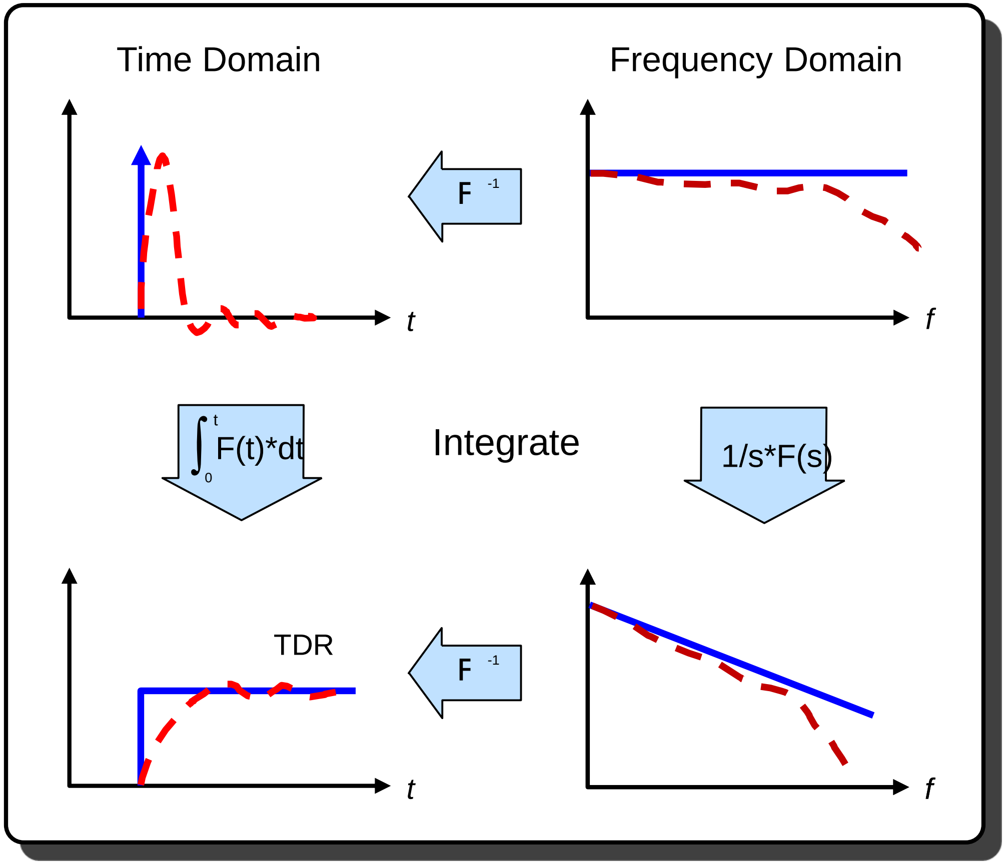
TDR System Risetime	Resolution
10 ps	5 ps / 1 mm [0.04 in]
20 ps	10 ps / 2 mm [0.08 in]
30 ps	15 ps / 3 mm [0.12 in]
100 ps	50 ps/ 10 mm [0.39 in]
200 ps	100 ps / 20 mm [0.79 in]
500 ps	250 ps / 50 mm [1.97in]

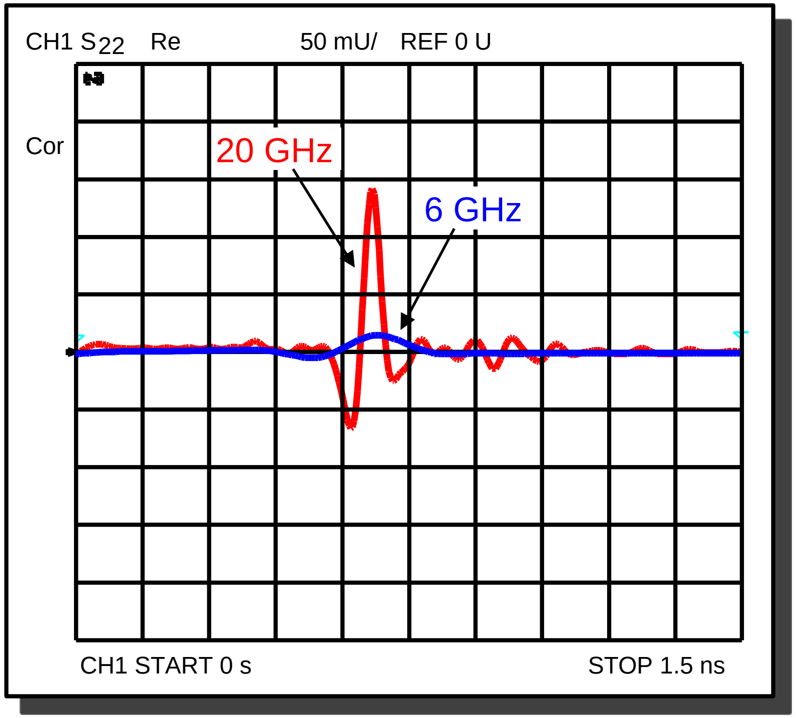
Source: TDR resolution per IPC-TM-650 for FR4 microstrip (*vp* » $2x10^8$ m/s)

KEYSIGHT TECHNOLOGIES

TDR Resolution Using a Network Analyzer

- start with broadband frequency sweep (often requires microwave VNA)
- use inverse-Fourier transform to compute time-domain
- resolution inversely proportionate to frequency span





KEYSIGHT TECHNOLOGIES

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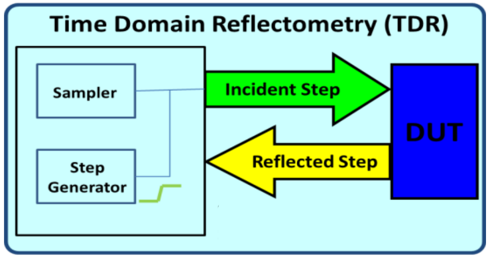

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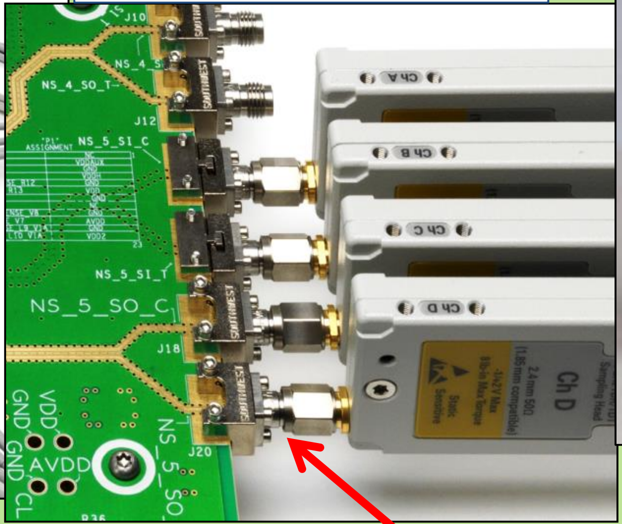
Summary/Q&A

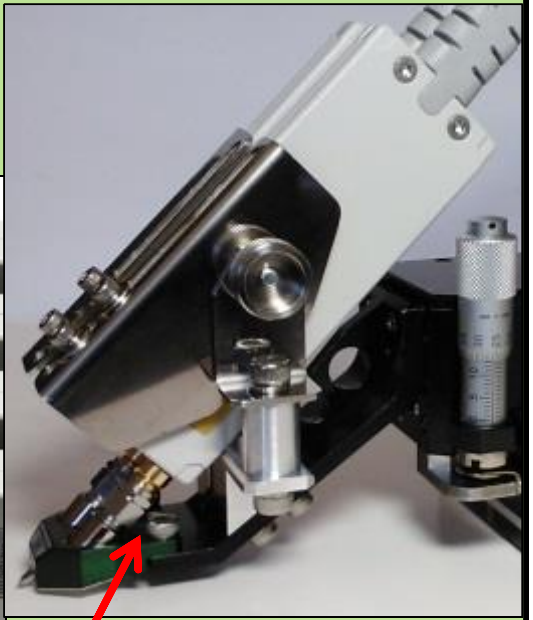
TDR/TDT Instrument

Keysight N1055A TDR/TDT 35/50 GHz Remote Head
Designed to optimize TDR resolution on up to 16 channels

Single-ended and Differential Stimulus (with True-Mode)

All RF circuitry located directly behind the connector – minimize use of cables

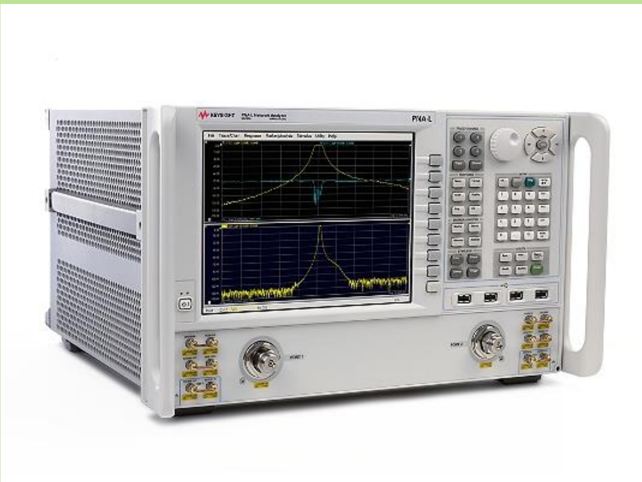


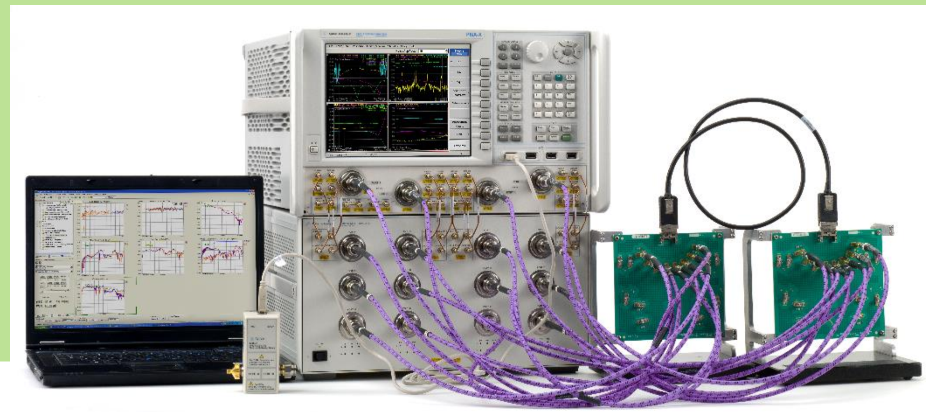


Industry's smallest remote head - direct connect to DUT or TDR probe

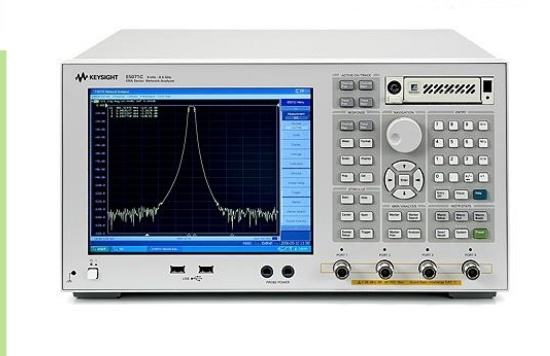
Network Analyzer Instrument

Keysight PNA/ENA series Network Analyzers
Various classes of instruments to adapt to various testing needs





PNA/ENA single source network analyzers providing broad coverage support

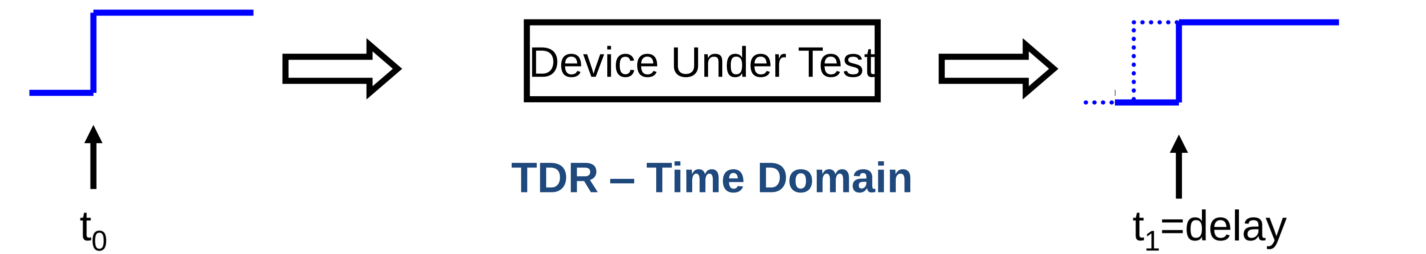


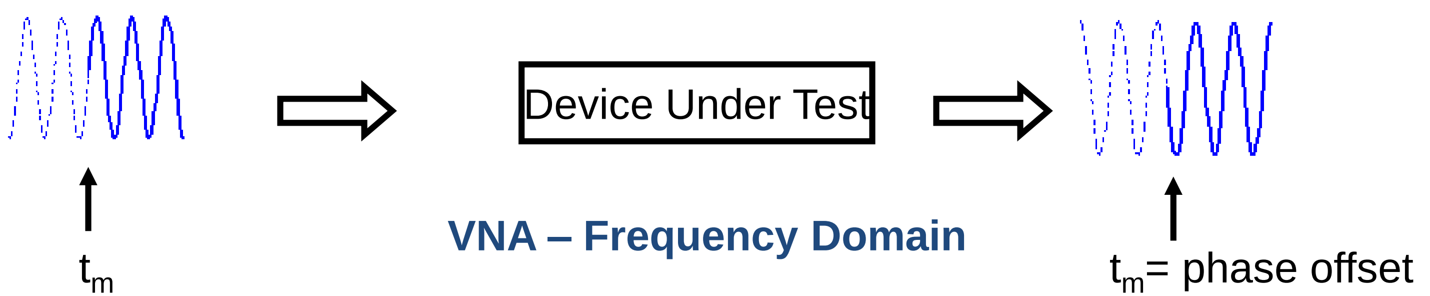
PNA-X dual source network analyzer adds non-linear characterization to toolset.

KEYSIGHT TECHNOLOGIES

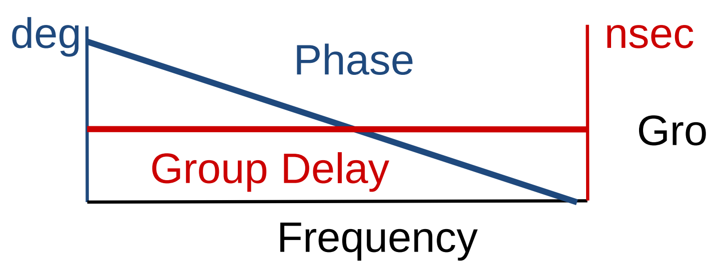
Time and Frequency Domains

With TDR, all frequencies make up each time point



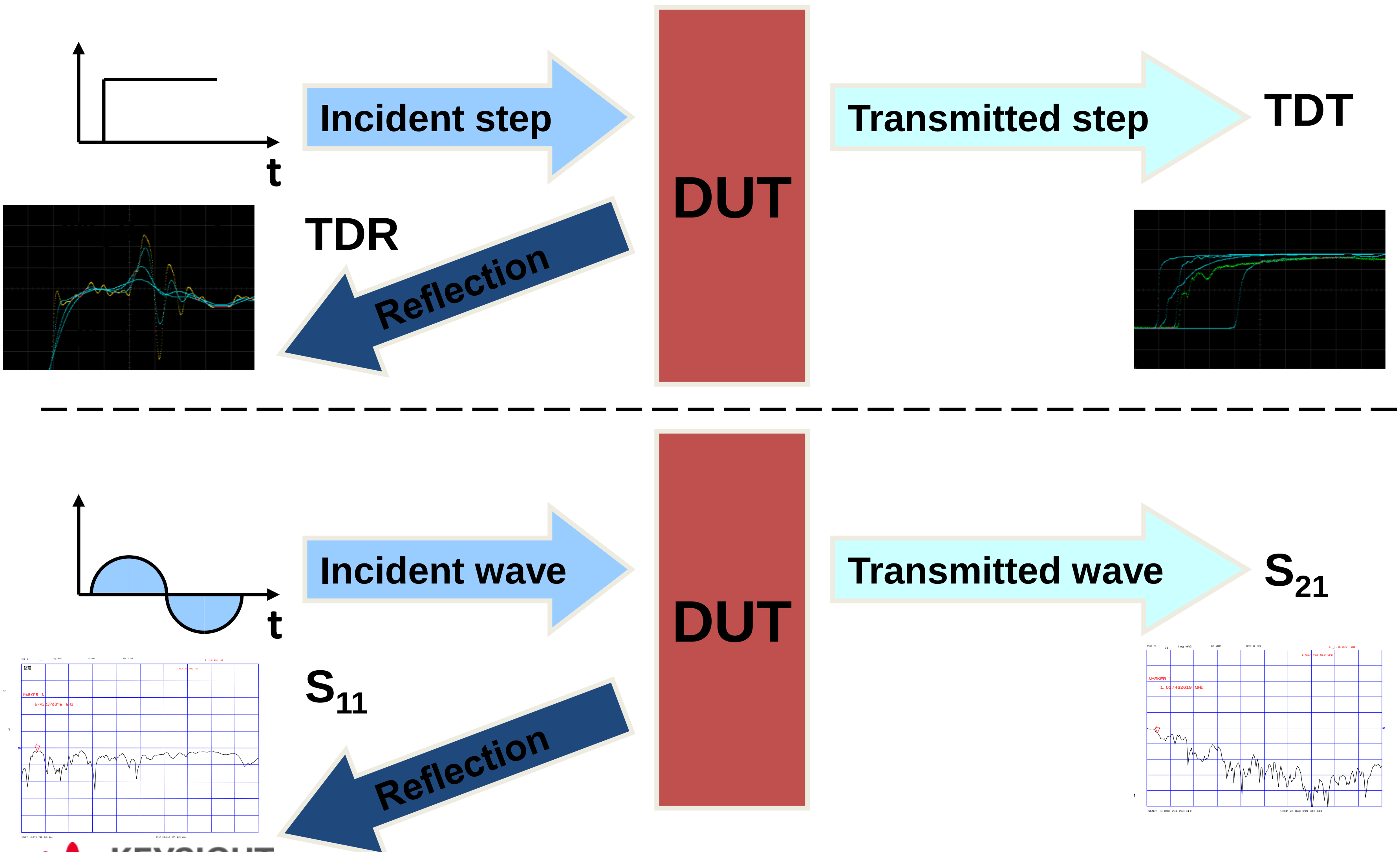


$\Delta\phi = 2\pi f$*time delay



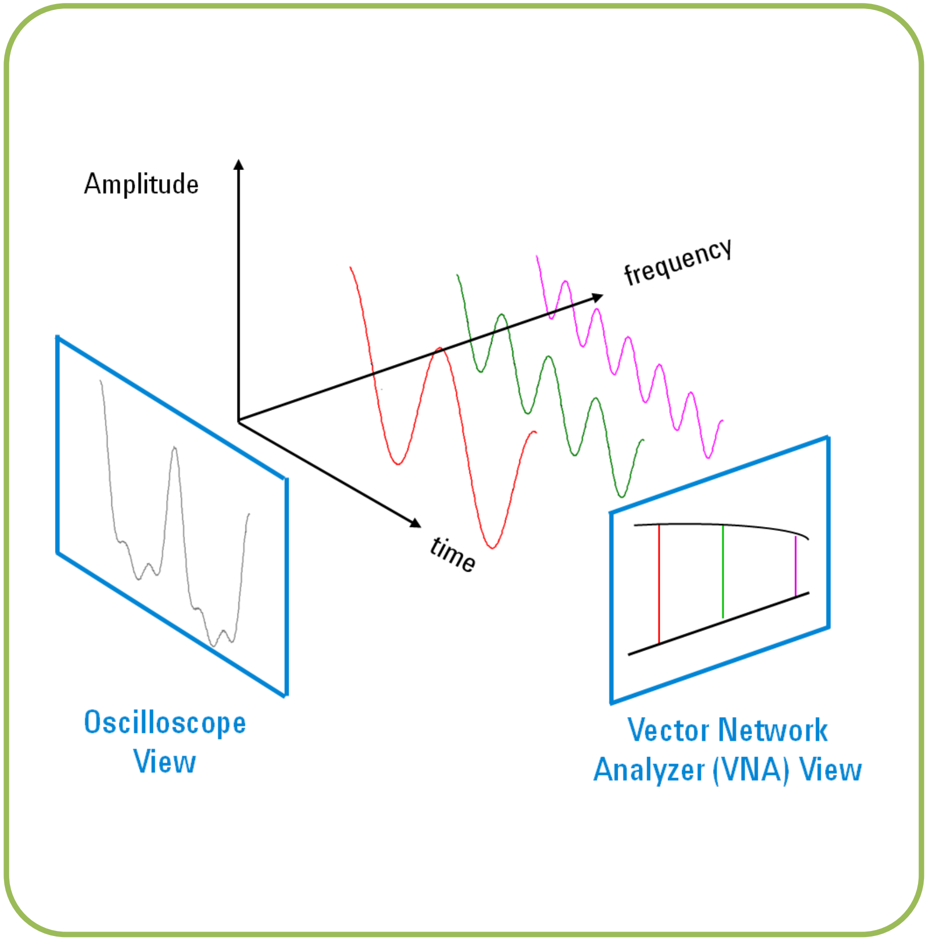
Group delay = $d\phi/df$ = time delay

TDR and VNA Measurement Techniques



KEYSIGHT TECHNOLOGIES

Time Domain and Frequency Domain Passive Measurements



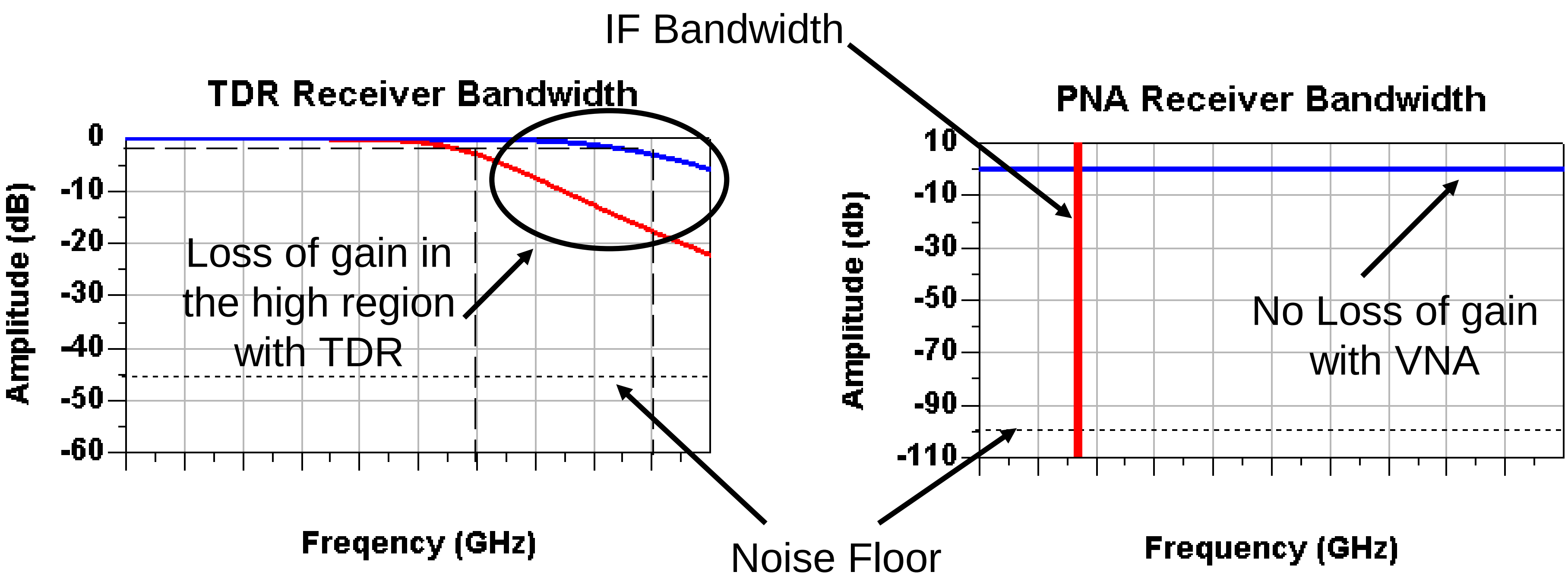
- **NO** difference in information content between the time domain view, or the frequency domain view.
- The 2 domains tell the same story, they just emphasize different parts of the story.
- Remember the digital signal profile is a function of a fundamental frequency and harmonics.

KEYSIGHT TECHNOLOGIES

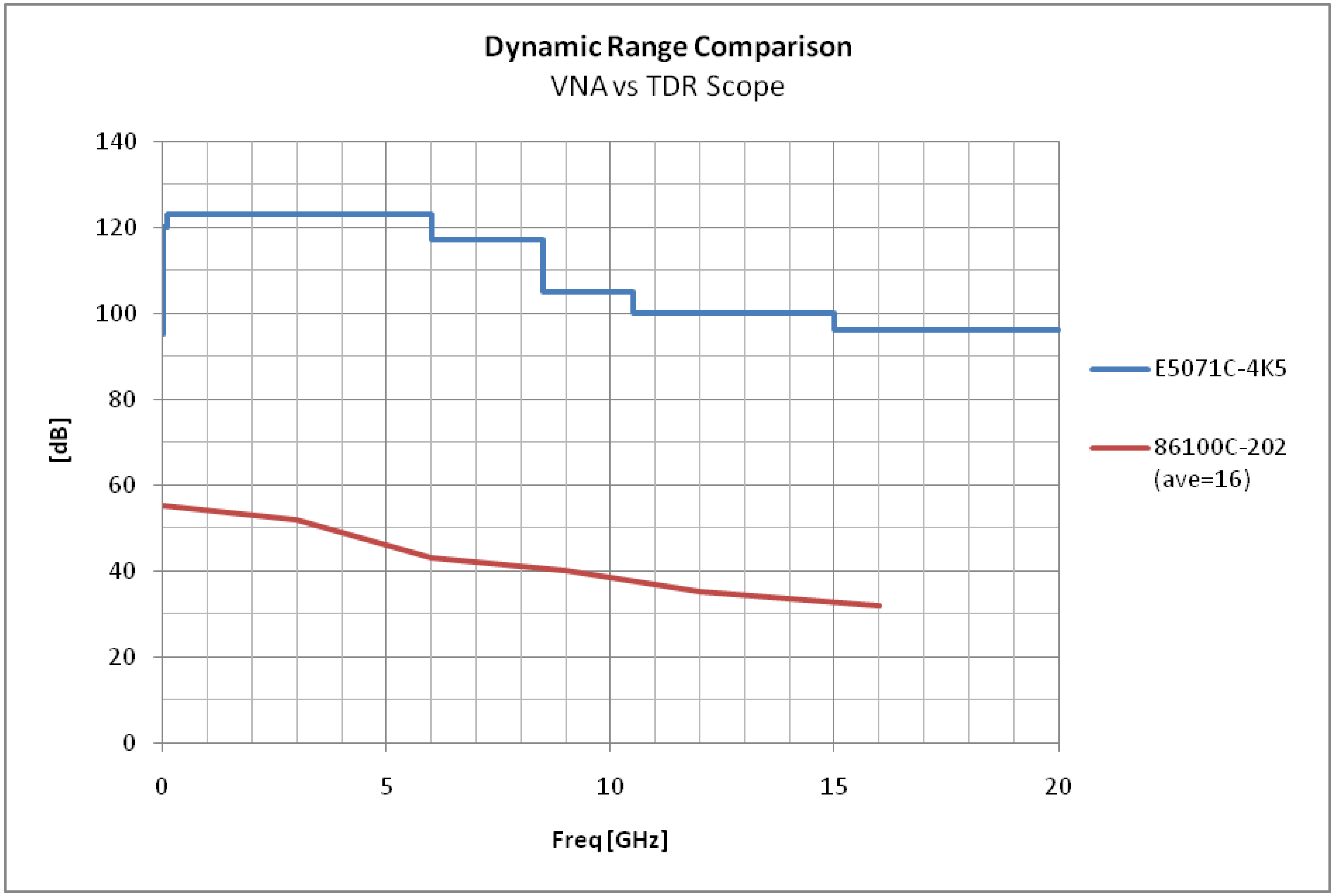
TDR and VNA Receiver Bandwidths

TDR Uses
Wide-Band Receivers,
Hardware Defined Bandwidth

VNA Uses
Narrow Band Receivers
(definable by setting IF BW),
User selected Frequency Range

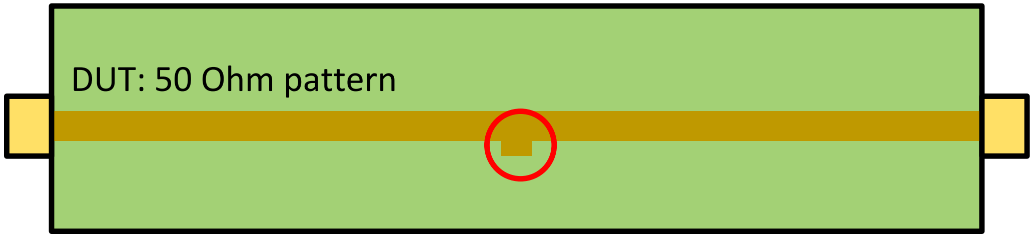


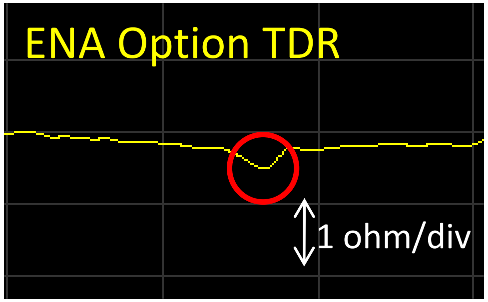
TDR and VNA Receiver Bandwidths

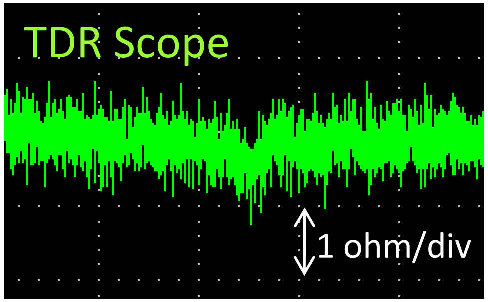


Measurement Response Time

for Signal Integrity Design and Verification





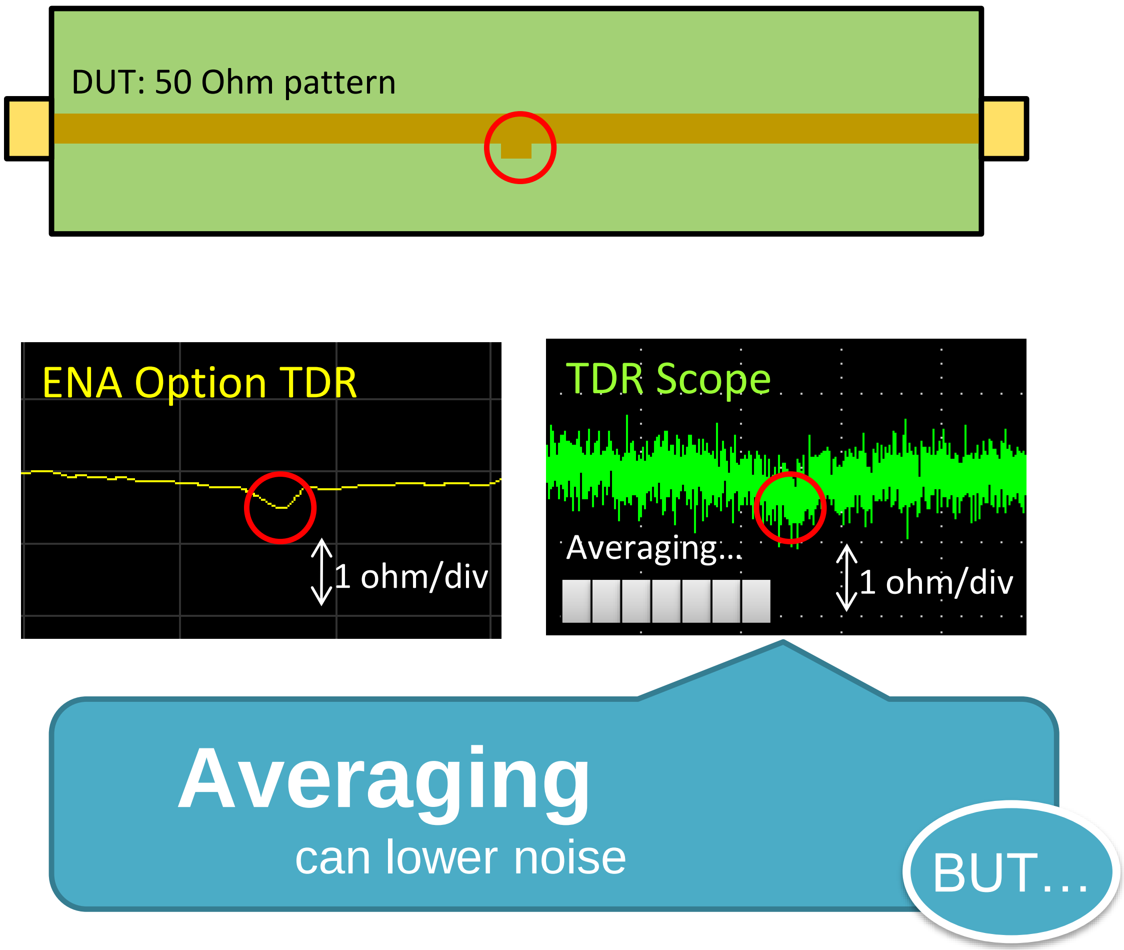


VNA Based TDR measurements

= Low Noise

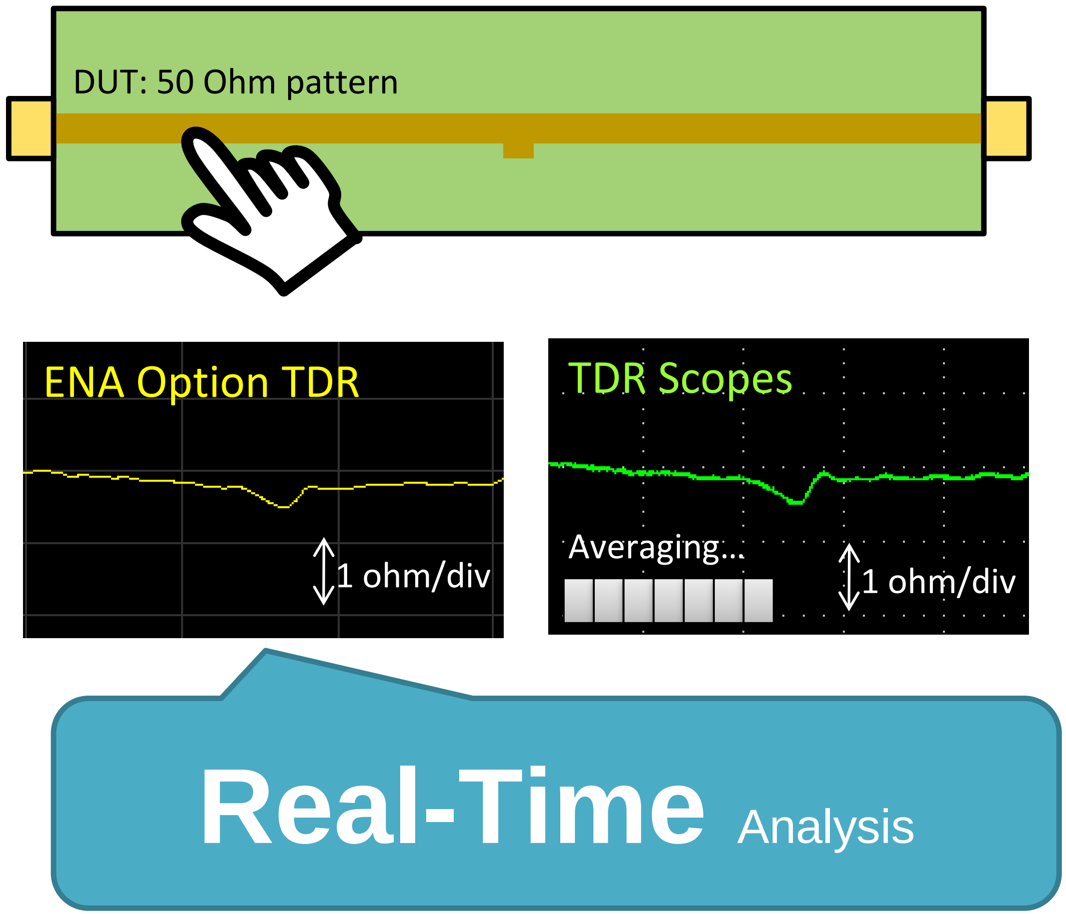
Measurement Response Time

for Signal Integrity Design and Verification



Measurement Response Time

for Signal Integrity Design and Verification

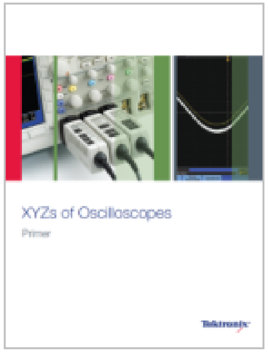


ESD Robustness

for Signal Integrity Design and Verification

TDR Scope

Difficult to implement protection circuits inside the instrument without sacrificing performance.



"In addition, **protection diodes cannot be placed in front of the sampling bridge as this would limit the bandwidth.** This reduces the safe input voltage for a sampling oscilloscope to about 3 V, as compared to 500 V available on other oscilloscopes."

Tektronix ApNote "XYZ of Oscilloscopes", p17 (02/09, 03W-8605-3)

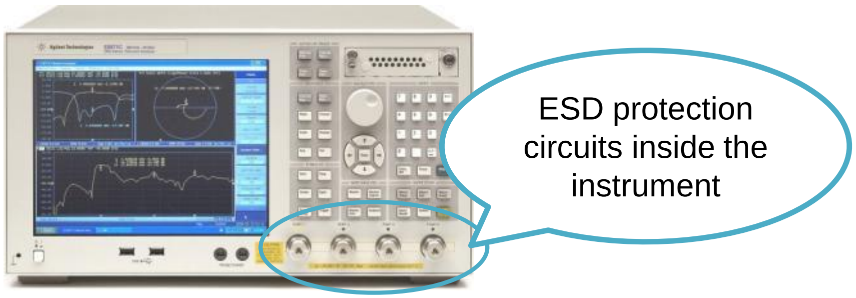
External ESD protection module (80A02) available, but rise time is degraded.

- Single-channel protection and plugs into sampling mainframe
- $4K USD / module
- Reflected rise time when used with 80E04: **28ps -> 37ps**

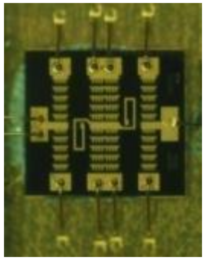
ESD Robustness

for Signal Integrity Design and Verification

ENA Option 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 significantly increase ESD robustness, while at the same time maintaining excellent RF performance (22ps rise time for 20GHz models).

To ensure high robustness against ESD, ENA Option TDR is tested for ESD survival according to IEC801-2 Human Body Model.

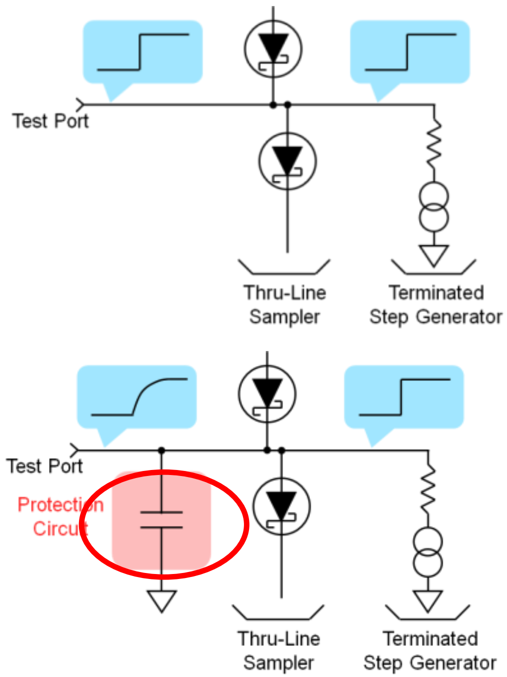
ESD Survival	IEC 801-2 Human Body Model. (150 pF, 330 Ω) RF Output Center pins tested to 3 kV, 10 cycles

KEYSIGHT TECHNOLOGIES

ESD Robustness

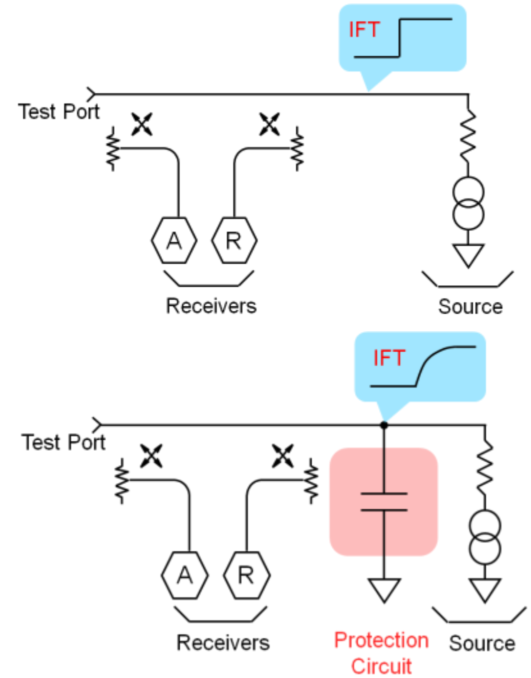
for Signal Integrity Design and Verification

TDR Scope



Implementing a protection circuit is difficult, because it will slow down the rise time of the step stimulus.

ENA Option TDR



ENA Option TDR measures the vector ratios of the transmitted and received signals. Therefore, the effects of the protection circuit will be canceled out.

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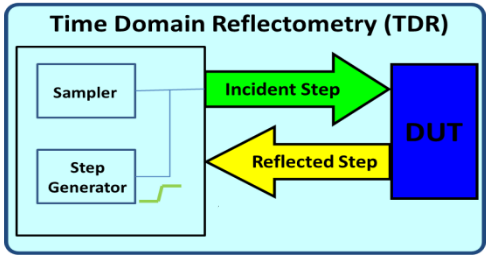

Comparing Different Signal Integrity Tools:

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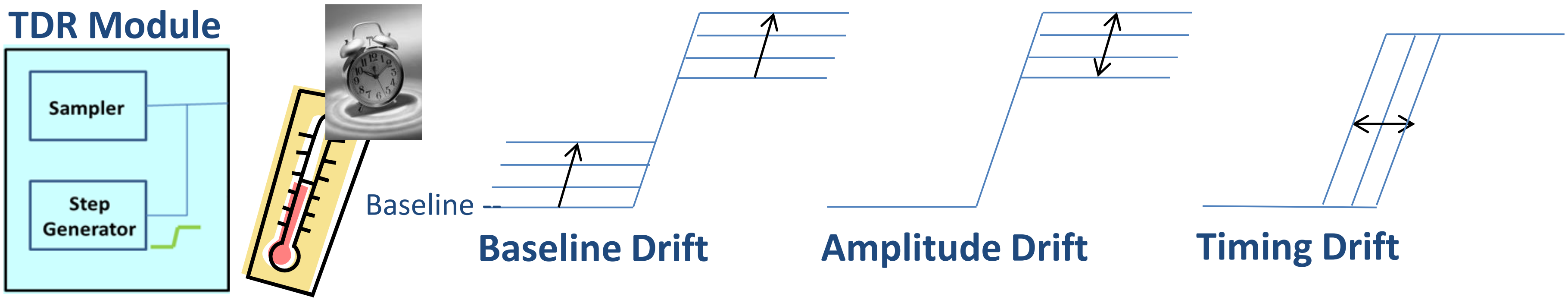
Summary/Q&A

KEYSIGHT TECHNOLOGIES

TDR Baseline, Amplitude and Timing Drift

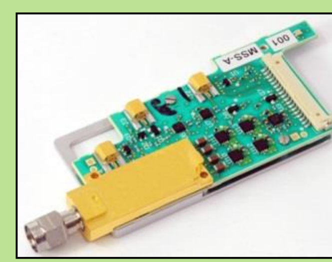
- TDR step generators and samplers are subject to time and temperature drifts
- Drift causes accuracy and repeatability issues
- Example: since all channels do not move together, differential skew is introduced



(Avoid locating TDR systems under air conditioning vents!)

N1055A employs advanced temperature compensation HW and SW:

1. Calibrate, measure and store baseline TDR step performance during TDR calibration
2. In real-time: measure each incident step, determine change since calibration, and apply corrections to measured results



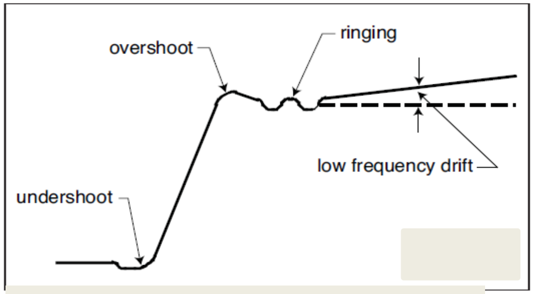
Results in extremely stable step amplitude and timing

➢ **greater TDR/TDT accuracy over time and temperature**

TDR Step Aberrations – attempt to minimize

1. Start with high performance TDR hardware (raw performance)

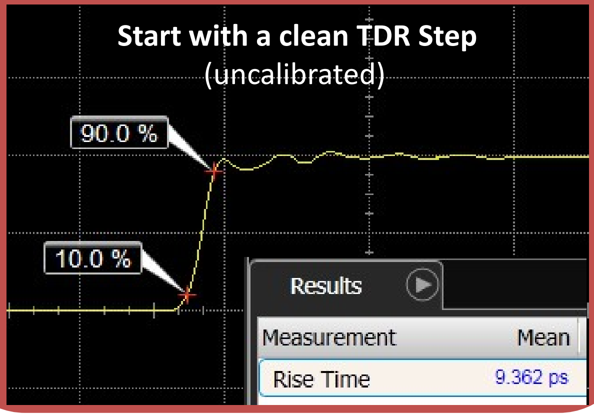
- Minimize ringing, overshoot, undershoot, settling
- Fast TDR edge speeds have inherently more aberrations and can benefit from TDR calibration



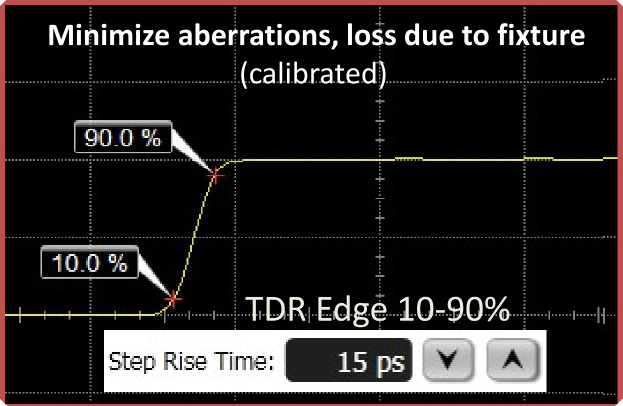
IPC TM-650 2.5.5.7a Figure 4-2

2. Perform TDR Calibration* (optional; capabilities are vendor specific)

- Removes systematic TDR step imperfections and impact of adapters, cables, and fixtures
- Optimizes match of differential TDR steps to minimize measurement error
- Enables control of TDR edge speeds for Standards compliant measurements
- Automatically de-skews channels



→ TDR Calibration →



* Note – a TDR Calibration is not simply a basic module/vertical calibration or temperature compensation.

KEYSIGHT TECHNOLOGIES

TDR Calibration Methods (vendor specific)

a. Mechanical Calibration Kits (traceable to National Standards)

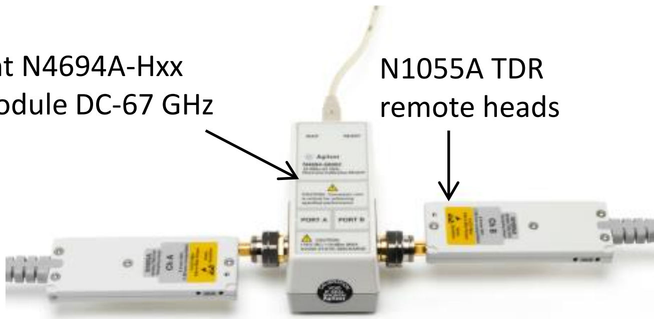
- Connect SLT or SOLT (Short, Open, Load, Thru) to reference plane
- Each standard used improves calibration (some vendors only use <u>one</u> Std)

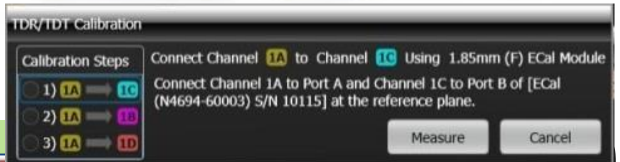
b. Electronic Calibration (ECal) for TDR – Keysight TDR only

- Contains up to 7 electronic states (traceable to National Standards)
- Calibrated from DC – 67 GHz
- Minimizes # of connections & torque errors

Keysight N4694A-Hxx ECal module DC-67 GHz

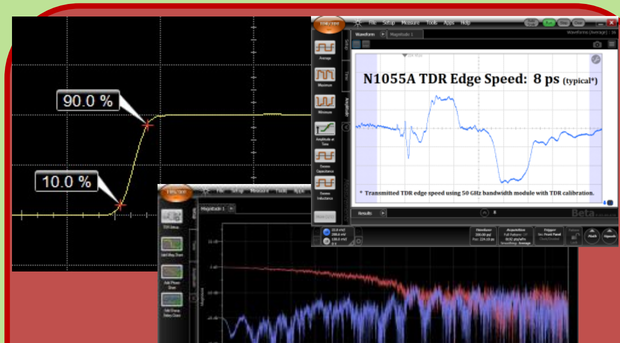
N1055A TDR remote heads





TDR calibration wizard using mechanical standards or ECal

N1055A - Benefits of TDR Calibration



Calibrated Step – all results displayed in real-time

Adjustable rise time

Auto de-skew TDR Channels

KEYSIGHT TECHNOLOGIES

VNA Measurement Error Modeling

Systematic errors

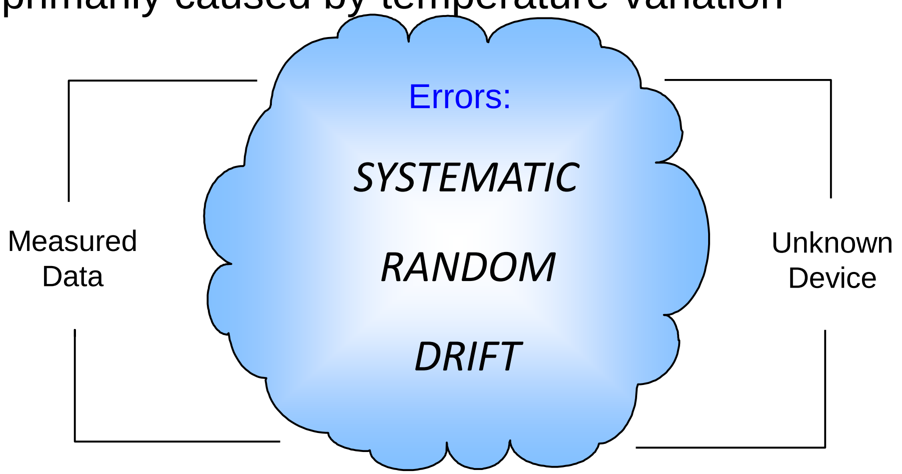
- due to imperfections in the analyzer and test setup
- assumed to be time invariant (predictable)

Random errors

- vary with time in random fashion (unpredictable)
- main contributors: instrument noise, switch and connector repeatability

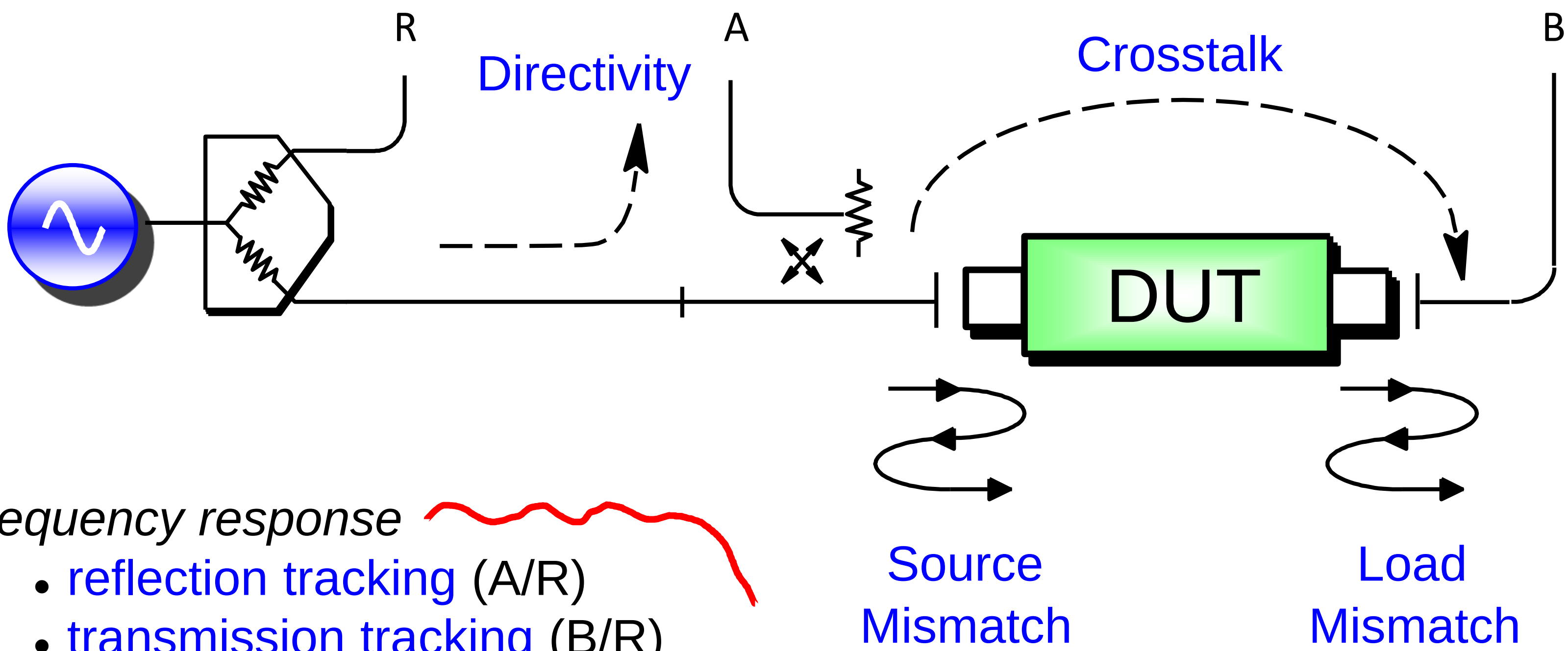
Drift errors

- due to system performance changing *after* a calibration has been done
- primarily caused by temperature variation



KEYSIGHT TECHNOLOGIES

VNA Systematic Measurement Errors



Frequency response

- reflection tracking (A/R)
- transmission tracking (B/R)

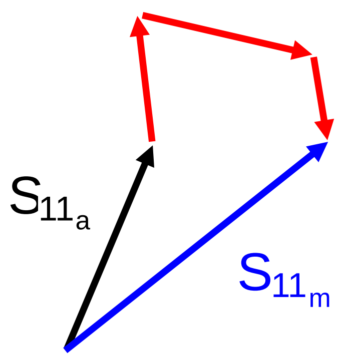
Six forward and six reverse error terms yields 12 error terms for two-port devices

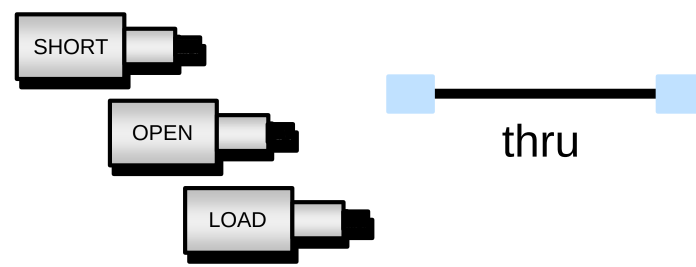
KEYSIGHT TECHNOLOGIES

VNA Types of Error Correction

- response (normalization)
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

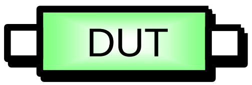
- vector
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error





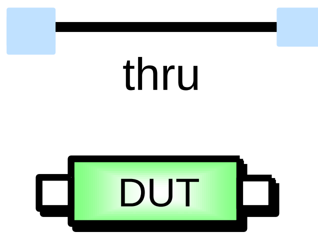
VNA Errors and Calibration Standards

UNCORRECTED



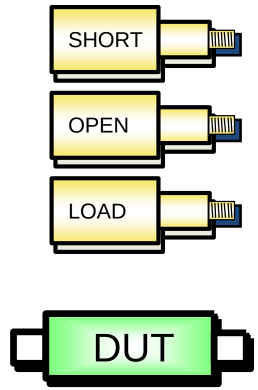
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



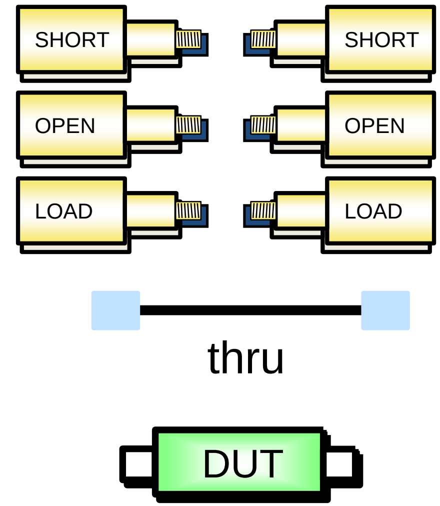
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

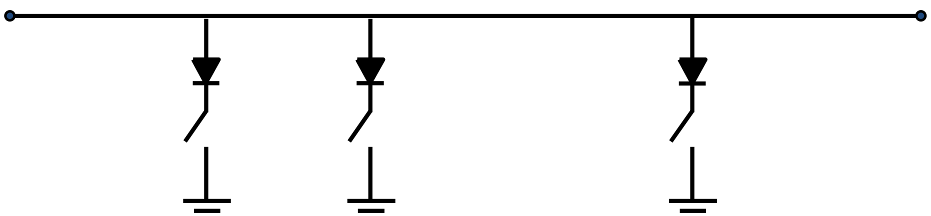
ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

KEYSIGHT TECHNOLOGIES

VNA ECal: Electronic Calibration

- Variety of modules cover 300 kHz to 67 GHz
- 2 and 4-port versions available
- Choose from six connector types (50 Ω and 75 Ω)
- Mix and match connectors (1.85mm, 2.4mm, 2.92mm, 3.5mm, Type-N, 7/16)
- Single-connection
  - reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated terminations provide excellent accuracy

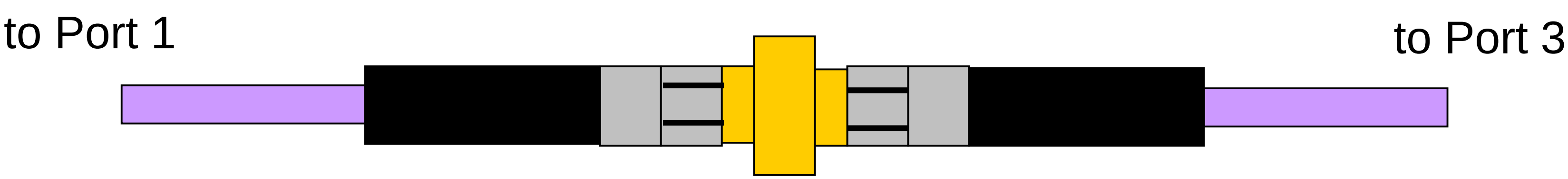


KEYSIGHT TECHNOLOGIES

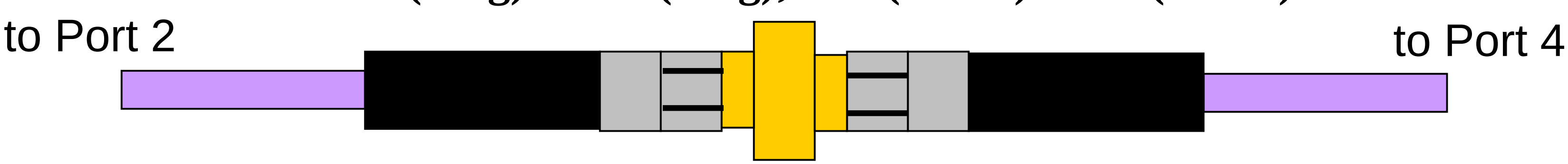
Using Reciprocity to Assure Good Calibration

- Reciprocity is the constraint that for passive devices S12=S21.
- In VNA measurements S12 virtually overlays S21 when a Thru path is measured. For TDR measurements the alignment may have more variability.
- Be aware when exporting data that some tools may require a certain level of reciprocity (eg. HSPICE).

Reciprocity on a Thru Adapter SE Measurement

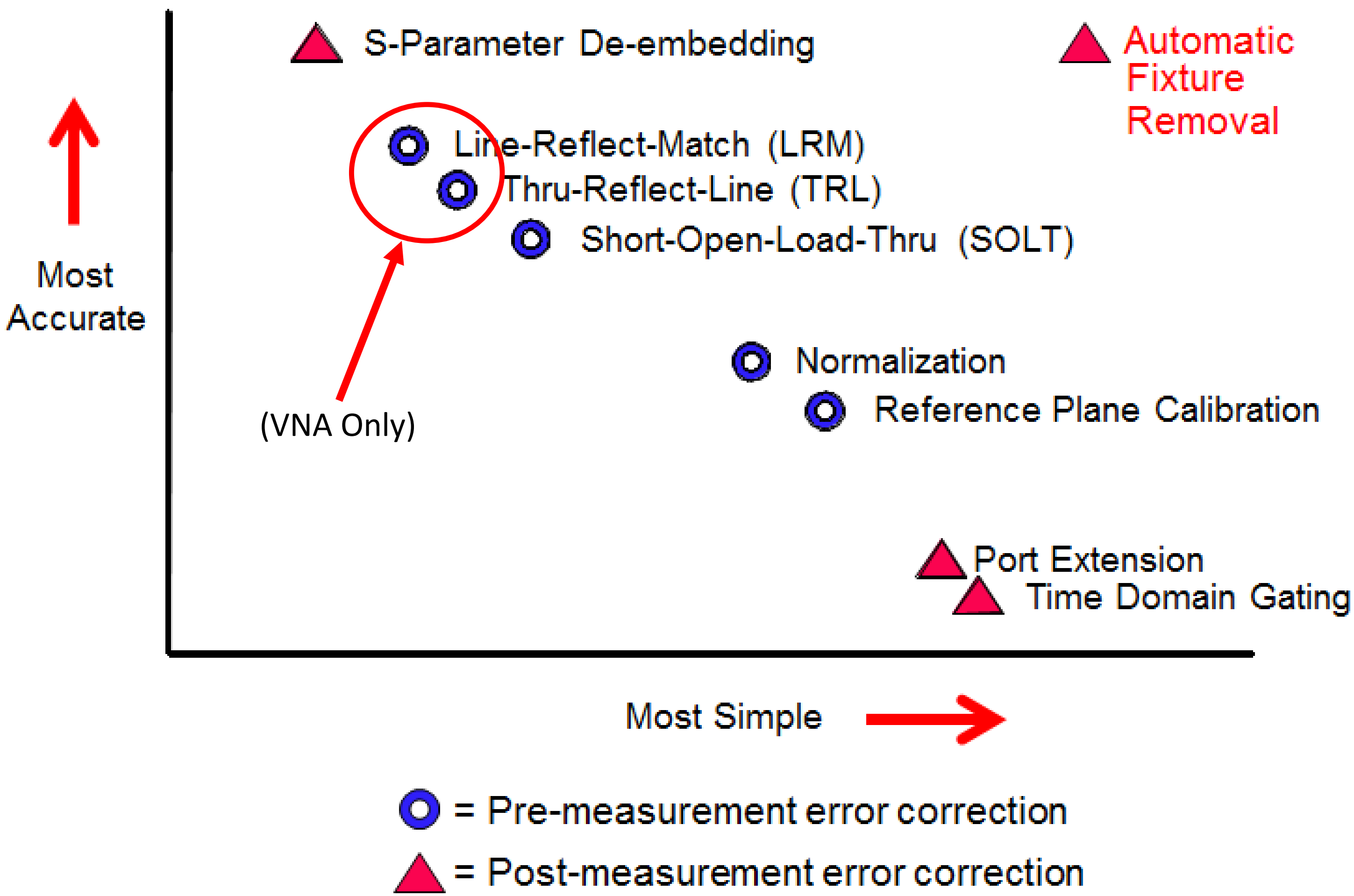


S13(Mag) = S31(Mag); S13(Phase) = S31(Phase)



S24(Mag) = S42(Mag); S24(Phase) = S42(Phase)

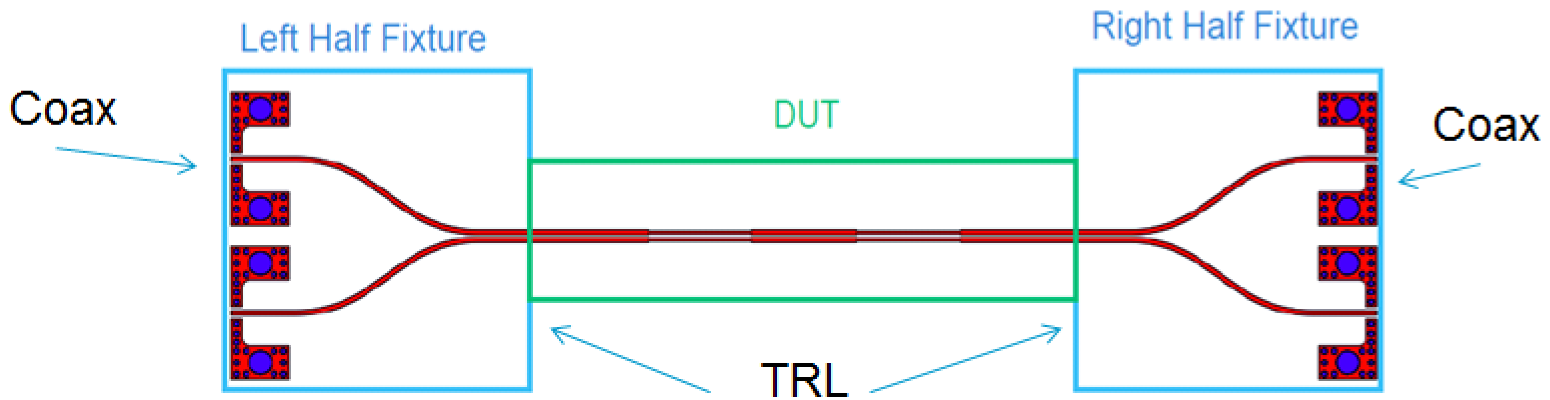
Correction Techniques



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)

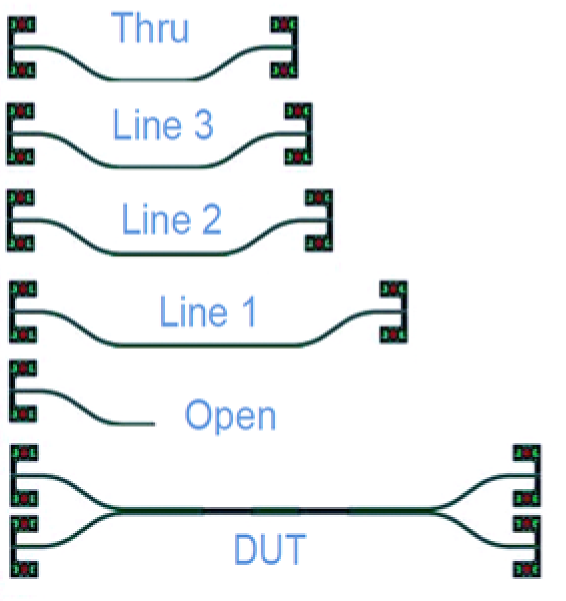


KEYSIGHT TECHNOLOGIES

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



KEYSIGHT TECHNOLOGIES

Differential Crosstalk Calibration aka Diff TRL

4-port TRL Calibration Technique

Fixture may be asymmetric

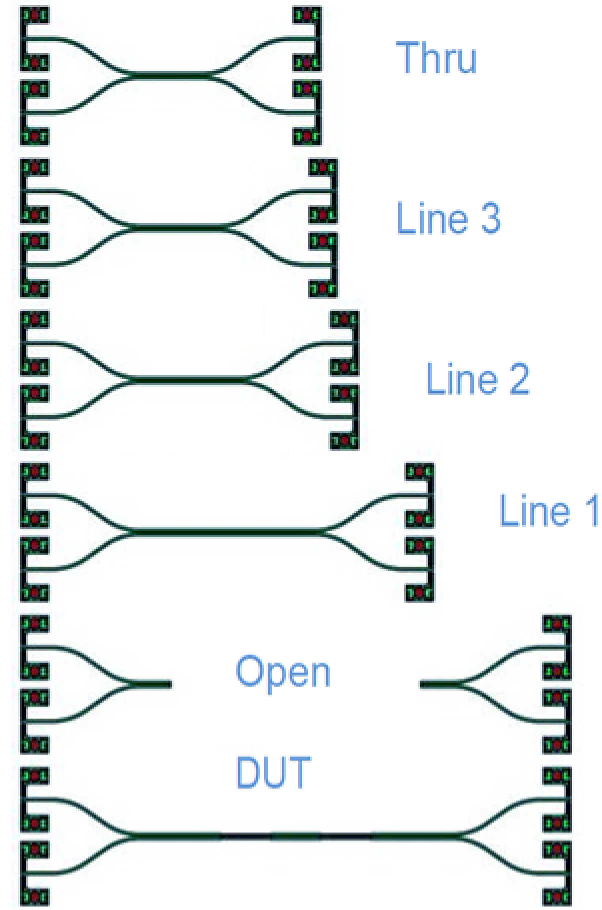
Similar assumptions to single ended TRL

- 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

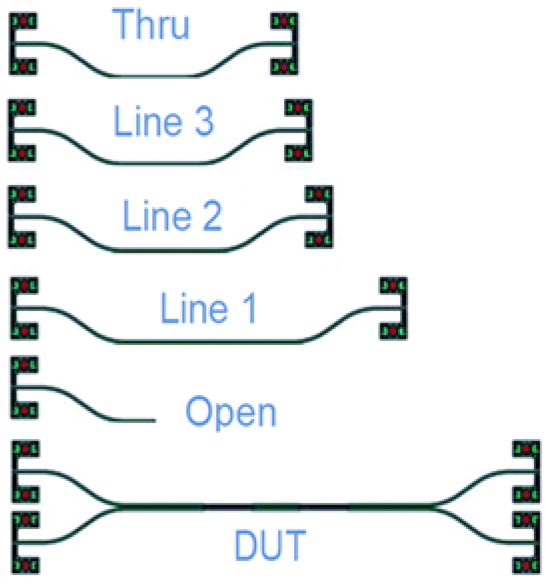
Coupling in fixture is removed



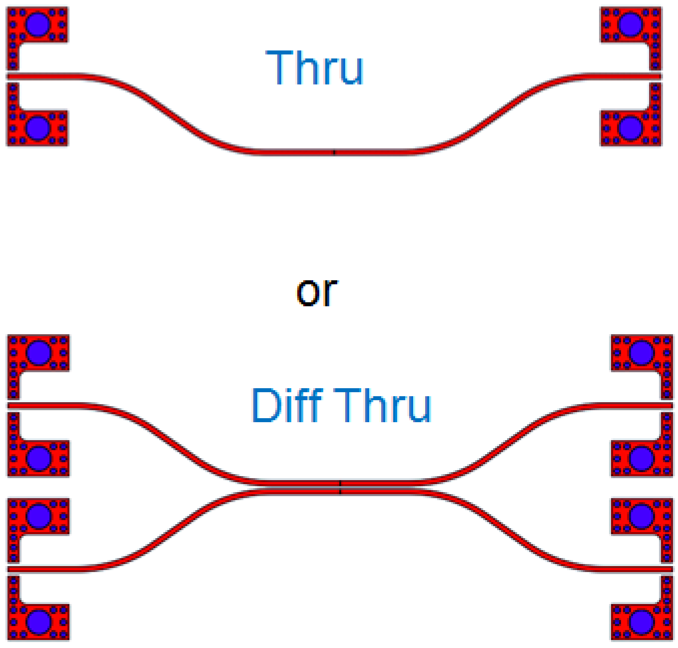
KEYSIGHT TECHNOLOGIES

Automatic Fixture Removal (2X THRU)

Yesterday TRL



Today AFR



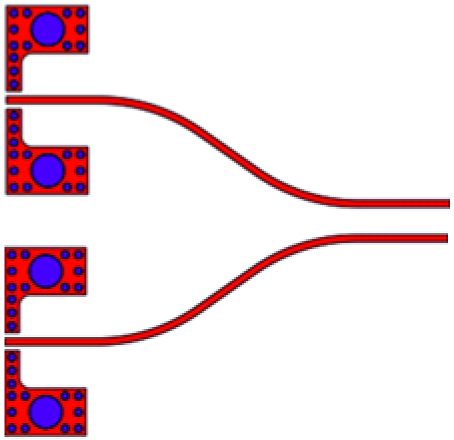
Note: Customers are now migrating from TRL to AFR after comparing results.

KEYSIGHT TECHNOLOGIES

Automatic Fixture Removal (1-Port)

New:

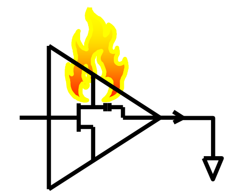
- Open or Short
- Best when 2X THRU is hard to fab



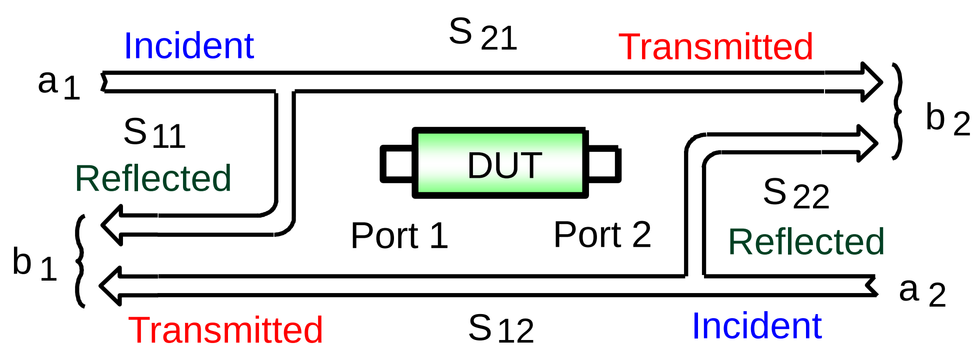
Applications:

- 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

Why Use S-Parameters?



- relatively easy to obtain at high frequencies
  - measure voltage traveling waves with a vector network analyzer
- relate to familiar measurements (gain, loss, reflection coefficient ...)
- can cascade S-parameters of multiple devices to predict system performance
- can compute H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files electronic-simulation tools



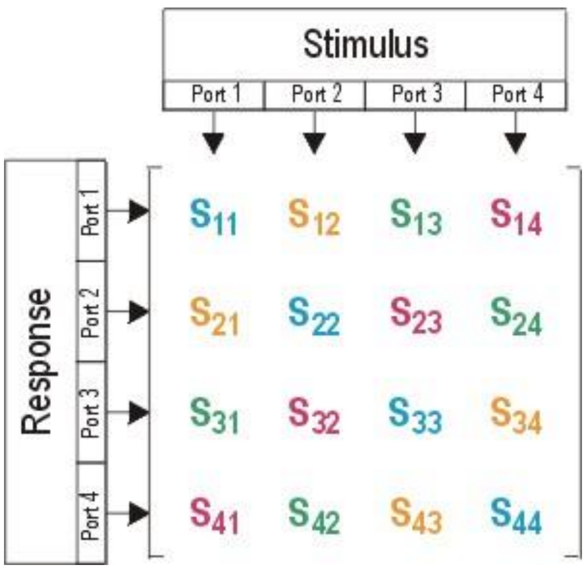
$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

KEYSIGHT TECHNOLOGIES

Single-Ended S-Parameters and TDR/TDT

Four-port single-ended device

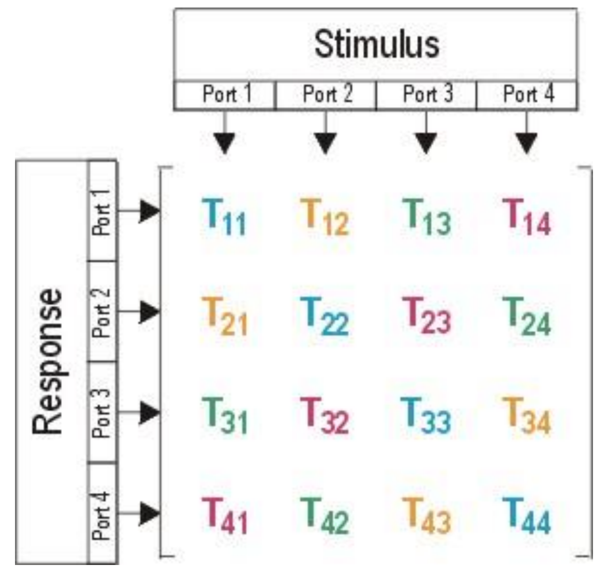


Return Loss or TDR

Insertion Loss or TDT

Near End Crosstalk (NEXT)

Far End Crosstalk (FEXT)



Frequency Domain Parameters

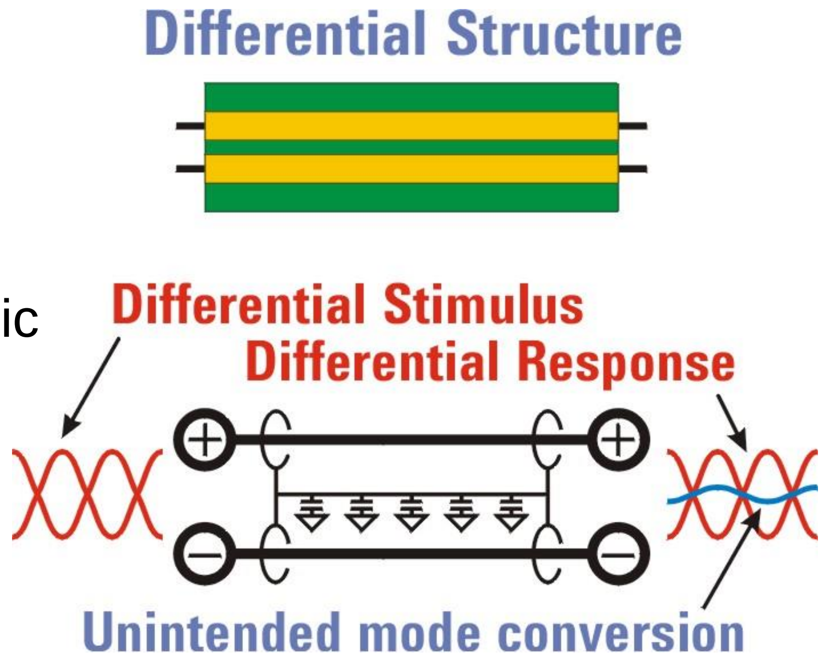
Time Domain Parameters

FFT or IFFT

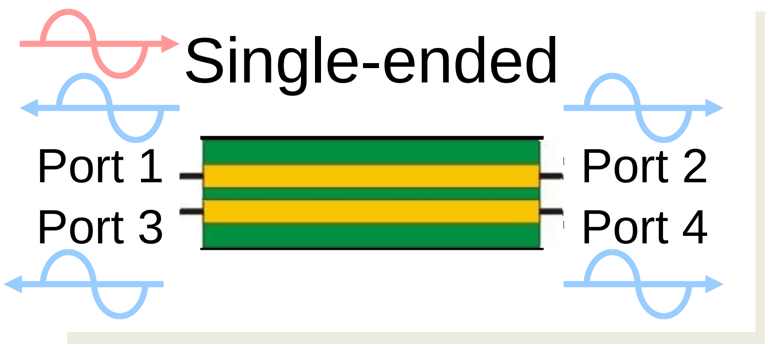
KEYSIGHT TECHNOLOGIES

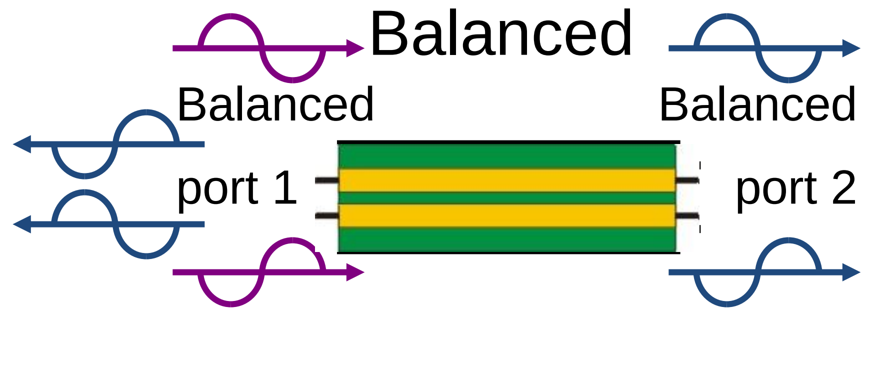
Trend Towards Differential Topologies

- Ideal differential devices
  - Low voltage requirements
  - Noise and EMI immunity
  - Virtual grounding
- Non-ideal devices are not symmetric
  - Can be identified by mode-conversions
    - Differential → Common
    - Common → Differential
- Differential signal integrity design tools are needed



Single-Ended to Differential S-Parameters





Response \ Stimulus				
	S_{11}	S_{12}	S_{13}	S_{14}
	S_{21}	S_{22}	S_{23}	S_{24}
	S_{31}	S_{32}	S_{33}	S_{34}
	S_{41}	S_{42}	S_{43}	S_{44}

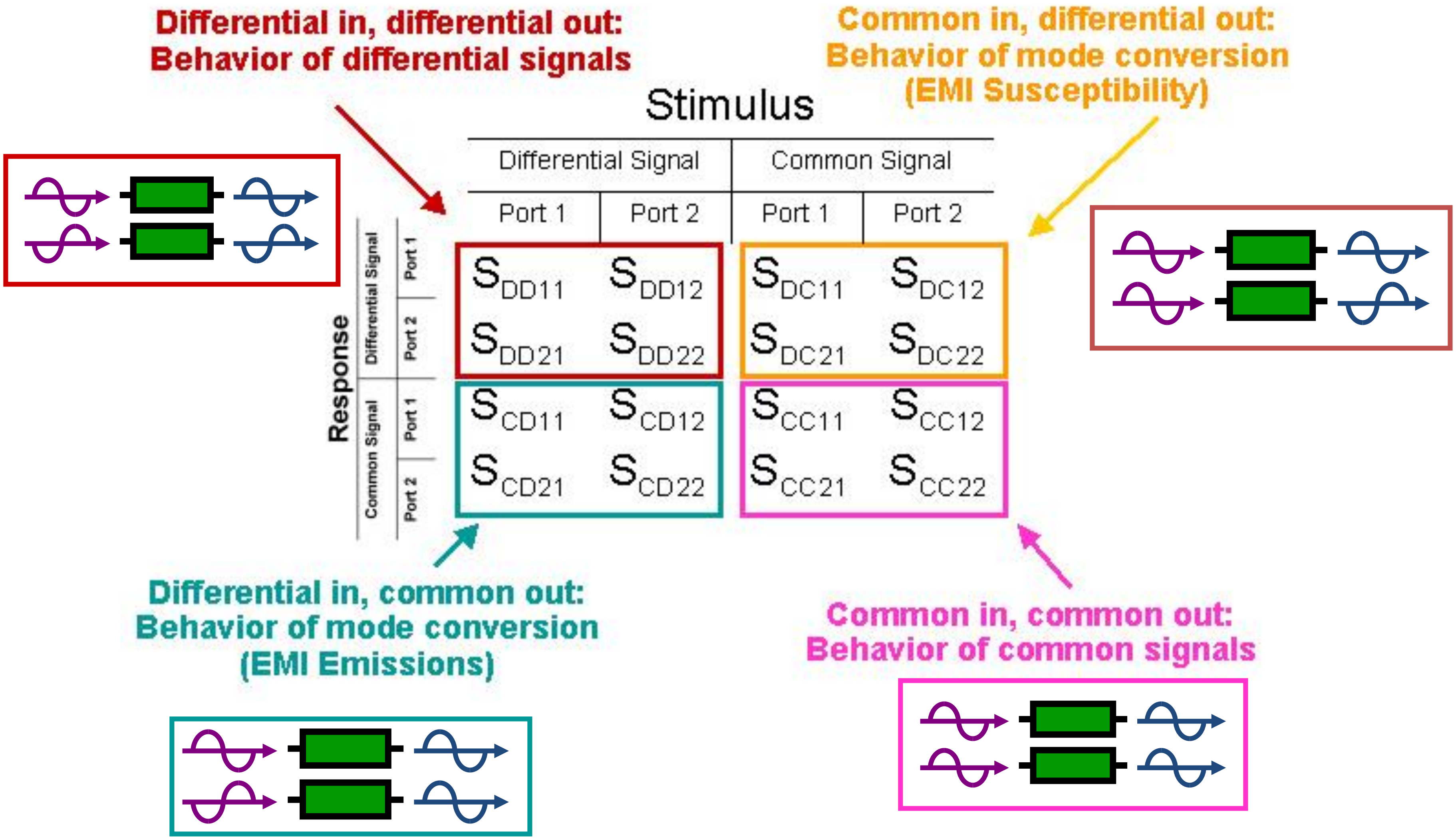
		Differential-Mode Stimulus		Common-Mode Stimulus	
		Port 1	Port 2	Port 1	Port 2
Differential-Mode Response	Port 1	S_{DD11}	S_{DD12}	S_{DC11}	S_{DC12}
	Port 2	S_{DD21}	S_{DD22}	S_{DC21}	S_{DC22}
Common-Mode Response	Port 1	S_{CD11}	S_{CD12}	S_{CC11}	S_{CC12}
	Port 2	S_{CD21}	S_{CD22}	S_{CC21}	S_{CC22}

Naming Convention:

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

KEYSIGHT TECHNOLOGIES

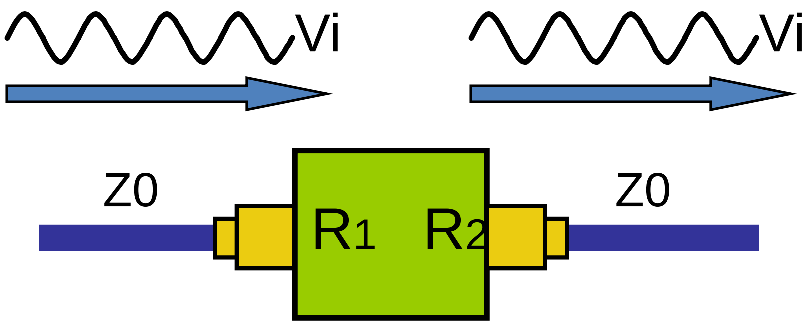
Mixed-Mode S-Parameters



KEYSIGHT
TECHNOLOGIES

Signal Integrity as Function of S-Parameters

GOOD Signal Integrity

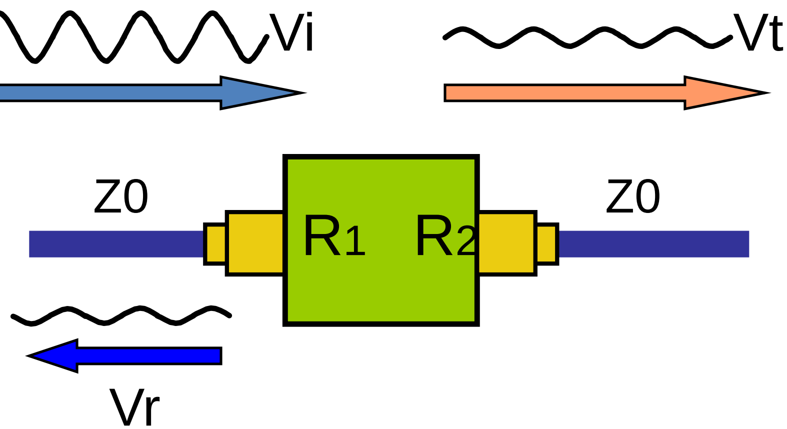


R1=R2=Z0

Well Controlled Impedance Environment

S11→low reflections
S21→high transmission

POOR Signal Integrity



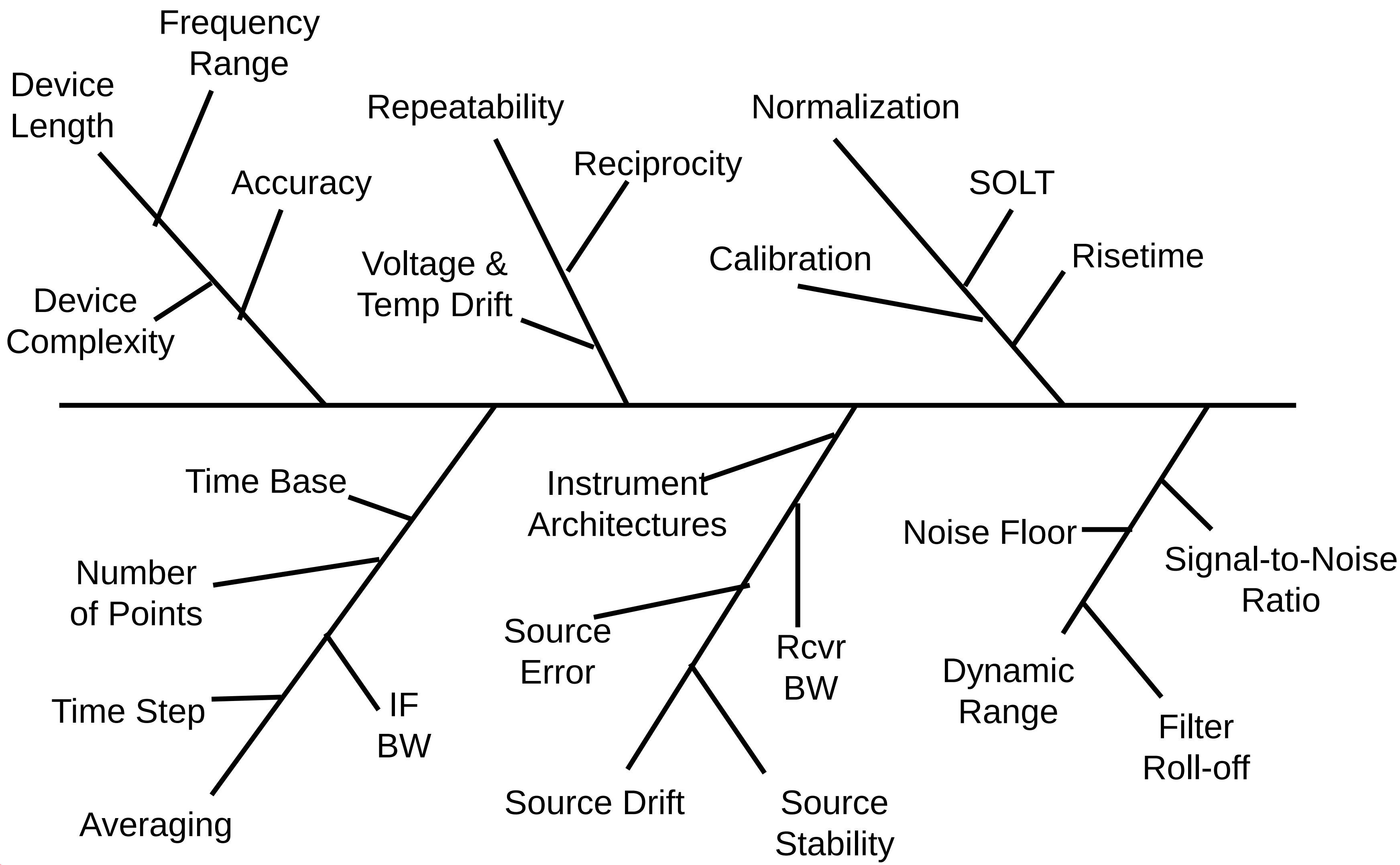
$R_1, R_2 \neq Z0$

Impedance Discontinuities Present

S11→high reflections
S21→low transmission

KEYSIGHT TECHNOLOGIES

The Complexity of it all



Solutions Discussed Today

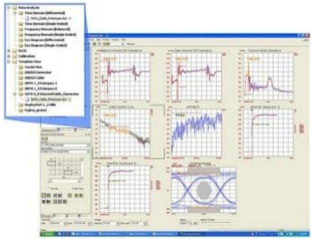
- VNA: N5245A, 50 GHz PNA-X with option:
  – 400, Four Ports, dual source

  www.keysight.com/find/PNA

- Equivalent Time Sampling Oscilloscope: 86100D DCA-X options
  – ETR, Enhanced Trigger
  – 202, Enhanced Impedance and S-parameter Software
  – SIM, InfiniiSim-DCA Waveform Transformation Toolset

  TDR Module: N1055A with option:
  – 54F, four channel, 50GHz remote heads with female 1.85mm connectors

  www.keysight.com/find/tdr



- PLTS: N1930B with options:
  – 1FP, Base Analysis fixed license
  – 3FP, Measurement and Calibration, Fixed License
  – 5FP, Advanced Calibration, Fixed License

  www.keysight.com/find/PLTS

- Papers and Video on One-Port AFR:
  – http://literature.cdn.keysight.com/litweb/pdf/5990-8443EN.pdf?id=2061639
  – http://literature.cdn.keysight.com/litweb/pdf/5992-0656EN.pdf?id=2589631
  – https://www.youtube.com/watch?v=cXF6mJaHfyc

QUESTIONS??

KEYSIGHT TECHNOLOGIES