Find Signal Integrity Problems through TDR/TDT Measurements

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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.
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
Agenda

Let’s Talk About TDR:
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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
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

TDT (Step Response)

S-parameters (Insertion Loss)
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

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
Temporal/Spatial (TDR) Resolution

TDR resolution is determined by:

1. **TDR System edge speed**
   
   Example: Trise system = 8 ps (10-90%)

   **Note** – Tr system is different 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:**
   
   \[ D_{\text{min}} = \frac{3 \times 10^8 \times 8 \times 10^{-12}}{2 \times \sqrt{4}} = 0.6 \text{ mm} \]

   \[ t_{\text{rise}} = \sqrt{\frac{t_{\text{step}}^2 + t_{\text{scope}}^2}{2}} \]

   \[ c \]

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

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

   **Dielectric constant of the transmission system**

   **c** = speed of light in a vacuum.

   **Source:** TDR resolution per IPC-TM-650 for FR4 microstrip (\(v_p \gg 2 \times 10^8 \text{ m/s}\))
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
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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.
Time and Frequency Domains

With TDR, all frequencies make up each time point

\[ t_m = \text{phase offset} \]

\[ t_0 = \text{delay} \]

\[ t_1 = \text{delay} \]

\[ t_m = \text{phase offset} \]

\[ \Delta \phi = 2\pi f \times \text{time delay} \]

\[ \text{Group delay} = \frac{\Delta \phi}{df} = \text{time delay} \]
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.
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

IF Bandwidth

Loss of gain in the high region with TDR

No Loss of gain with VNA

Noise Floor
TDR and VNA Receiver Bandwidths

Dynamic Range Comparison
VNA vs TDR Scope

Freq [GHz]

[dB]

E5071C-4K5

86100C-202 (ave=16)
Measurement Response Time
for Signal Integrity Design and Verification

DUT: 50 Ohm pattern

ENA Option TDR

TDR Scope

VNA Based TDR measurements
= Low Noise
Measurement Response Time for Signal Integrity Design and Verification

DUT: 50 Ohm pattern

ENA Option TDR

TDR Scope

Averaging... 1 ohm/div

Averaging can lower noise

BUT…
Measurement Response Time
for Signal Integrity Design and Verification

DUT: 50 Ohm pattern

ENA Option TDR

TDR Scopes

Real-Time Analysis

ENA Option TDR
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

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.

<table>
<thead>
<tr>
<th>ESD Survival</th>
<th>IEC 801-2 Human Body Model. (150 pF, 330 Ω) RF Output Center pins tested to 3 kV, 10 cycles</th>
</tr>
</thead>
</table>
ENA Option TDR measures the vector ratios of the transmitted and received signals. Therefore, the effects of the protection circuit will be canceled out.

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

TDR or VNA – Which instrument to choose
  ➢ Review TDR vs VNA Differences

Let’s Talk About TDR:
  ➢ What is TDR?
  ➢ What is TDT?

Comparing Different Signal Integrity Tools:
  ➢ Correction and Measurements
  ➢ Fixture Removal Techniques

Summary/Q&A
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

**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

(Avoid locating TDR systems under air conditioning vents!)
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

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

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

N1055A - Benefits of TDR Calibration

Calibrated Step – all results displayed in real-time

Adjustable rise time

Auto de-skew TDR Channels

Keysight N4694A-Hxx ECal module DC-67 GHz
N1055A TDR remote heads

TDR calibration wizard using mechanical standards or ECal
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
VNA Systematic Measurement Errors

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

- Convenient
- Generally not accurate
- No errors removed

**1-PORT**

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

- 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
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
Using Reciprocity to Assure Good Calibration

- Reciprocity is the constraint that for passive devices $S_{12}=S_{21}$.
- In VNA measurements $S_{12}$ virtually overlays $S_{21}$ 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**

$$S_{13}(\text{Mag}) = S_{31}(\text{Mag}); \quad S_{13}(\text{Phase}) = S_{31}(\text{Phase})$$

$$S_{24}(\text{Mag}) = S_{42}(\text{Mag}); \quad S_{24}(\text{Phase}) = S_{42}(\text{Phase})$$
Correction Techniques

- S-Parameter De-embedding
- Line-Reflect-Match (LRM)
- Thru-Reflect-Line (TRL)
- Short-Open-Load-Thru (SOLT)
- Normalization
- Reference Plane Calibration
- Port Extension
- Time Domain Gating

(VNA Only)

- Pre-measurement error correction
- Post-measurement error correction

Most Accurate
Most Simple
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 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

- $\text{SDC}_{nm}$ and $\text{SCD}_{nm} < -30 \text{ dB}$
- Skew between lines < 10 degrees

Coupling in fixture is removed
Automatic Fixture Removal (2X THRU)

Yesterday TRL

Today AFR

Thru

Line 3

Line 2

Line 1

Open

DUT

Thru

or

Diff Thru

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
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

\[
b_1 = S_{11} a_1 + S_{12} a_2
\]

\[
b_2 = S_{21} a_1 + S_{22} a_2
\]
Single-Ended S-Parameters and TDR/TDT

Port 1 — Port 2
Port 3 — Port 4
Four-port single-ended device

Frequency Domain Parameters

<table>
<thead>
<tr>
<th>Port 1</th>
<th>Port 2</th>
<th>Port 3</th>
<th>Port 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_{11}</td>
<td>S_{12}</td>
<td>S_{13}</td>
<td>S_{14}</td>
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<tr>
<td>S_{21}</td>
<td>S_{22}</td>
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<td>S_{31}</td>
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<td>S_{34}</td>
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<td>S_{41}</td>
<td>S_{42}</td>
<td>S_{43}</td>
<td>S_{44}</td>
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</tbody>
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Time Domain Parameters

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</table>

Return Loss or TDR
Insertion Loss or TDT
Near End Crosstalk (NEXT)
Far End Crosstalk (FEXT)

FFT or IFFT
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 $\rightarrow$ Common
    - Common $\rightarrow$ Differential
- Differential signal integrity design tools are needed
Single-Ended to Differential S-Parameters

**Stimulus**

Port 1: $S_{11}$, $S_{12}$, $S_{13}$, $S_{14}$

Port 2: $S_{21}$, $S_{22}$, $S_{23}$, $S_{24}$

Port 3: $S_{31}$, $S_{32}$, $S_{33}$, $S_{34}$

Port 4: $S_{41}$, $S_{42}$, $S_{43}$, $S_{44}$

**Response**

**Naming Convention:** $S_{\text{mode res.}, \text{mode stim.}, \text{port res.}, \text{port stim.}}$

**Differential-Mode Stimulus**

Port 1: $S_{DD_{11}}$, $S_{DD_{12}}$

Port 2: $S_{DD_{21}}$, $S_{DD_{22}}$

**Common-Mode Stimulus**

Port 1: $S_{DC_{11}}$, $S_{DC_{12}}$, $S_{CC_{11}}$, $S_{CC_{12}}$

Port 2: $S_{DC_{21}}$, $S_{DC_{22}}$, $S_{CC_{21}}$, $S_{CC_{22}}$

**Balanced**

Port 1: Balanced

Port 2: Balanced

**Balanced**

Port 1: Balanced

Port 2: Balanced
Mixed-Mode S-Parameters

Differential in, differential out: Behavior of differential signals

Common in, differential out: Behavior of mode conversion (EMI Susceptibility)

Differential in, common out: Behavior of mode conversion (EMI Emissions)

Common in, common out: Behavior of common signals
Signal Integrity as Function of S-Parameters

**GOOD Signal Integrity**

- \( R_1 = R_2 = Z_0 \)
- Well Controlled Impedance Environment
- \( S_{11} \rightarrow \text{low reflections} \)
- \( S_{21} \rightarrow \text{high transmission} \)

**POOR Signal Integrity**

- \( R_1, R_2 \neq Z_0 \)
- Impedance Discontinuities Present
- \( S_{11} \rightarrow \text{high reflections} \)
- \( S_{21} \rightarrow \text{low transmission} \)
The Complexity of it all

- Frequency Range
- Accuracy
- Voltage & Temp Drift
- Reciprocity
- Calibration
- SOLT
- Risetime
- Device Length
- Device Complexity
- Repeatability
- Normalization
- Source Error
- Rcvr BW
- Source Drift
- Source Stability
- Averaging
- Number of Points
- IF BW
- Time Base
- Instrument Architectures
- Noise Floor
- Dynamic Range
- Signal-to-Noise Ratio
- Filter Roll-off

- Time Step
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:
  – https://www.youtube.com/watch?v=cXF6mJaHfyc
QUESTIONS??