Perform Cable Test with a Network Analyzer: From Basic Measurement to Advanced Signal Integrity Measurements for Next Generation High Speed Serial Standards
Agenda

1. Device Under Test: Cables & Connectors
2. Instrument for cables testing: Network Analyzer
3. Measurement: Frequency Domain
4. Measurement: Time Domain
5. Measurement: Enhanced Time Domain (TDR)
6. Labs
Agenda (Device Under Test)

- Specific Connectors (Fakra)
- Standard Connector (SMA, 2.4mm)
- Coaxial Cable
- No Connector
- Balanced Cable
Agenda (Measurement modes)

- Frequency Domain
- Time Domain
- Enhanced Time Domain

Common Measurement Parameters
Zc, Attenuation, Capacitance Velocity of Propagation
DC Resistance, Delay, Crosstalk, NEXT, FEXT
1. Device Under Test: Cables & Connectors
- Cable Equivalent Circuit
- Coaxial Cables and Connectors
- Balanced Cables and Connectors
- Cable Parameters
- Cable Measurement Issues
Cable is a Transmission Line

Transmission lines are needed to convey RF and microwave energy from one point to another with minimal loss.

The transmission line can be represented as an infinite series of two-port elementary components.

Resistance, Inductance, Capacitance and Admittance define Characteristic Impedance $Z_0$. 
Transmission line $Z_0$

$Z_0$ determines the relationship between voltage and current waves.

$Z_0$ is a function of physical dimensions and $\varepsilon_r$.

$Z_0$ is usually a real impedance (e.g. 50 or 75 ohms).

Characteristic impedance for coaxial airlines (ohms)

- Attenuation is lowest at 77 ohms.
- Power handling capacity peaks at 30 ohms.

Characteristic impedance for coaxial airlines (ohms)
The Type N Connector

DC to 18GHz

N type 75ohm IS NOT compatible with N Type 50ohm
The Precision 3.5 mm Connector

Air dielectric: is stable with temperature

DC to 34GHz
The SMA Connector

Usually teflon: this expands with temperature

DC to 22GHz

This pin is often the center wire of the semi-rigid cable
<table>
<thead>
<tr>
<th>Connector Type</th>
<th>Specified Upper Frequency</th>
<th>Typical Moding Accuracy</th>
<th>Connector Type</th>
<th>Mateable With</th>
<th>Dielectric</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNC</td>
<td>2 GHz</td>
<td>2.2 GHz</td>
<td>M/F</td>
<td>self</td>
<td>PTFE</td>
</tr>
<tr>
<td>SMC</td>
<td>7 GHz</td>
<td>10 GHz</td>
<td>M/F</td>
<td>self</td>
<td>PTFE</td>
</tr>
<tr>
<td>7 mm (APC-7)</td>
<td>18 GHz</td>
<td>18.5-18.6 GHz</td>
<td>SEXLESS</td>
<td>self</td>
<td>PTFE</td>
</tr>
<tr>
<td>Type N</td>
<td>18 Ghz</td>
<td>18.5-18.6 GHz</td>
<td>M/F</td>
<td>type N</td>
<td>PTFE</td>
</tr>
<tr>
<td>3.5 mm (APC-3.5)</td>
<td>26.5 GHz</td>
<td>32-33 GHz</td>
<td>M/F</td>
<td>SMA and K</td>
<td>Air</td>
</tr>
<tr>
<td>SMA (3.5 mm size)</td>
<td>26.5 GHz</td>
<td>32-33 GHz</td>
<td>M/F</td>
<td>3.5 mm and K</td>
<td>PTFE</td>
</tr>
<tr>
<td>2.92 (K) Wiltron-Anritsu</td>
<td>40 GHz</td>
<td>40-50 GHz</td>
<td>M/F</td>
<td>SMA and 3.5 mm</td>
<td>Air</td>
</tr>
<tr>
<td>2.4 mm (APC-2.4)</td>
<td>50 GHz</td>
<td>&gt;50 GHz</td>
<td>M/F</td>
<td>V connector</td>
<td>Air</td>
</tr>
<tr>
<td>1.85 mm</td>
<td>65 GHz</td>
<td>&gt;65 GHz</td>
<td>M/F</td>
<td>2.4 mm and V</td>
<td>Air</td>
</tr>
<tr>
<td>Wiltron V-connector</td>
<td>60-65 GHz</td>
<td>&gt;60 GHz</td>
<td>M/F</td>
<td>2.4 mm and 1.85mm</td>
<td>Air</td>
</tr>
<tr>
<td>1.00 mm (IEEE standard)</td>
<td>110 GHz</td>
<td>&gt;110 GHz</td>
<td>M/F</td>
<td>self</td>
<td>Air</td>
</tr>
<tr>
<td>1.10 mm (Anritsu-Wiltron)</td>
<td>110 GHz</td>
<td>&gt;110 GHz</td>
<td>M/F</td>
<td>self</td>
<td>Air</td>
</tr>
</tbody>
</table>
The ‘Automotive’ Fakra Connector

DC to 6GHz

FachKRReis Automobil (Automobile Expert Group)
b. Balanced Cables and Connectors

A **balanced line** or **balanced signal pair** is a **transmission line** consisting of two conductors of the same type, each of which have equal **impedances** along their lengths and equal impedances to **ground** and to other circuits.

The main advantage of the balanced line format is good rejection of external noise.

Main disadvantage is the limited frequency coverage.
Balanced Cables and Connectors: LAN

<table>
<thead>
<tr>
<th>Class</th>
<th>Category</th>
<th>Max Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>D:1995</td>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>D:2002</td>
<td>5E</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>250</td>
</tr>
<tr>
<td>EA</td>
<td>6A</td>
<td>500</td>
</tr>
<tr>
<td>F</td>
<td>7</td>
<td>600</td>
</tr>
<tr>
<td>FA</td>
<td>7A</td>
<td>1000</td>
</tr>
</tbody>
</table>

S/UTP

S/STP

Screened / Unshielded Twisted Pair

Screened / Shielded Twisted Pair

Local Area Network
Balanced Cables and Connectors: USB

From USB 2.0 to USB 3.0: more complex connector, cable and test (e.g. Cross Talk)
Cable Parameters

The two principle factors which cause **Attenuation** are:
- Loss of conductors (caused by high frequency film effect),
- Dielectric loss.

The **Capacitance** (pF/m at 1kHz) of a cable is indicated by the properties of the dielectric (the amount of electric charge when a potential difference exists between the two. Is directly proportional to the regularity of the dielectric's properties (typical values is 67 pF/m for PE).

In the case of coaxial cables it is:

\[
C = \frac{\varepsilon}{18.\log\left(\frac{D}{d}\right)}
\]

**Propagation speed** is the speed of which an electrical signal travels along a line of Transmission. Is the ratio between speed of propagation within the cable and the speed in open space (66% for PE, Solid PolyEthylene dielectric).

**Characteristic Impedance**

Zo has to be as uniform as possible. The quality of the conductor and the geometry of the cable are not constant, causing signal distortion and loss.

**Screening attenuation** depends on the external conductor's characteristics, which prevents the exchange of electromagnetic waves between the cable and the external environment.

The **Return Loss** or **Structural Return Loss** (SRL is a specialized measurement of return loss referenced to the cable impedance) parameter is the measurement of the cable's production accuracy (mainly: constant dielectric extrusion pressure and cooling control).

The impedance of the cable

\[
Z_{in}(\omega) = Z_0 \times \frac{(1 + \rho(\omega))}{(1 - \rho(\omega))}
\]

\[Z_0 = \text{system impedance, 50 or 75 } \Omega\]

\[Z_{average} \text{ impedance}\]

\[
Z_{cable} = \frac{1}{N} \sum_{n=1}^{N} |Z_{in}(\omega_n)|
\]

**structural return loss for the cable**

\[
\rho_{SRL}(\omega) = \frac{Z_{in}(\omega) - Z_{cable}}{Z_{in}(\omega) + Z_{cable}}
\]
Cable Parameters using VNA

- Attenuation is $S_{21}^{FreqD}$
- Return Loss is $S_{11}^{FreqD}$
  - SRL
  - Characteristic Impedance Zo
- Screening attenuation (coaxial) is $S_{21}^{FreqD}$
- Cross Talk (balanced) is $S_{21}^{FreqD}$
- Length, Propagation speed is $S_{11}^{TimeD}$
- [Capacitance @ 1kHz requires LCR Meter]
Cable Measurement Issues

- Frequency Broadband
- Long electrical length (from swept to stepped sweep)
- Reflection path loss (reflection dynamic range)
- Non-Insertable (requires adapters)
- Non-standard impedances (requires conversion)
- Balanced (requires phy/sim BalUn transformer)
2. Instrument for cables testing: Network Analyzer

- Block Diagram (sources, signal separation devices, receivers, analysis)
- S parameters
- Magnitude and Phase
- Calibration (insertable, not-insertable, ...)
- Fixture Simulator function
- Differential and Common Parameters (dd, dc, cc)
Network Analyzer Block Diagram

SOURCE

Incident

DUT

Transmitted

Reflected

INCIDENT (R)

REFLECTED (A)

TRANSMITTED (B)

RECEIVER / DETECTOR

PROCESSOR / DISPLAY

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S parameters

Completely characterize a two port device with four S-parameters

\[ S_{11} = \text{forward reflection coefficient (input match)} \]
\[ S_{22} = \text{reverse reflection coefficient (output match)} \]
\[ S_{21} = \text{forward transmission coefficient (gain or loss)} \]
\[ S_{12} = \text{reverse transmission coefficient (isolation)} \]

Remember, S-parameters are inherently complex, linear quantities. However, we often express them in a log-magnitude format.
S parameters

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

\[ b_2 = S_{21}a_1 + S_{22}a_2 \]
The Need For Calibration

Why do we have to calibrate?
- It is impossible to make perfect hardware
- It would be extremely difficult and expensive to make hardware good enough to entirely eliminate the need for error correction

How do we get accuracy?
- With vector-error-corrected calibration
- Not the same as the yearly instrument calibration

What does calibration do for us?
- Removes the largest contributor to measurement uncertainty: systematic errors
- Provides best picture of true performance of DUT
Measurement Error Modeling

**Systematic errors**
- Due to imperfections in the analyzer and test setup
- Assumed to be time invariant (predictable)
- Generally, are largest sources of error

**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
Systematic Measurement Errors

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

- Reflection tracking (A/R)
- Transmission tracking (B/R)

Frequency response

Directivity

Crosstalk

Source Mismatch

Load Mismatch

DUT
What is Vector-Error Correction?

**Vector-error correction**…
- Is a process for characterizing systematic error terms
- Measures known electrical standards
- Removes effects of error terms from subsequent measurements

**Electrical standards**…
- Can be mechanical or electronic
- Are often an open, short, load, and thru, but can be arbitrary impedances as well
Using Known Standards to Correct for Systematic Errors

- **1-port calibration** *(reflection measurements)*
  - Only three systematic error terms measured
  - Directivity, source match, and reflection tracking

- **Full two-port calibration** *(reflection and transmission measurements)*
  - Twelve systematic error terms measured
  - Usually requires 12 measurements on four known standards (SOLT)

- Standards defined in *cal kit definition* file
  - Network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit
Before and After A One-Port Calibration
Two-Port Error Correction

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward and reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to use a network analyzers!!!
Response versus Two-Port Calibration

Measuring filter insertion loss

After two-port calibration

After response calibration

Uncorrected
ECal: Electronic Calibration

• Variety of two- and four-port modules cover 300 kHz to 67 GHz
• Nine connector types available, 50 and 75 ohms
• Single-connection calibration
  ▪ dramatically reduces calibration time
  ▪ makes calibrations easy to perform
  ▪ minimizes wear on cables and standards
  ▪ eliminates operator errors
• Highly repeatable temperature-compensated characterized terminations provide excellent accuracy
Calibration Kit Solutions

Coaxial (*):
- APC7 Agilent [www.agilent.com]
- N (50/75ohm) Agilent [www.agilent.com]
- 3.5mm (SMA) Agilent [www.agilent.com]
- 2.4mm Agilent [www.agilent.com]
- 1mm Agilent [www.agilent.com]
- BNC Maury Microwave [www.maurymw.com]
- Automotive Fakra Rosenberger [www.rosenberger.com]

Balanced (*):  
- USB3.0 BitifEye [www.bitifeye.com]
- LAN
- Automotive LVDS (adapters: Rosenberger [www.rosenberger.com])

(*)
Full-2-Port (complete ad accurate) calibration procedure at Cal Plane 2 (DUT Plane) is possible only with a Calibration Kit with same mechanical configuration of the Device Under Test (eg. Fakra CalKit if DUT has Fakra connectors).
Otherwise use Calibration Kit suitable for Cal Plane 1 and try to compensate the Adapters contribution between Cal Plane 1 and Cal Plane 2:
- using De-Embedding,
- using Port Extension.
Fixture Simulator function

* Calculated in Fixture Simulator if it is turned on.
De-Embedding

Exclude undesired 2-port network from measured S-parameter

- De-embedding ON/OFF is applied to all ports.
- Each port can be chosen as “None” or “User”.
- Undesired network is specified by Touchstone file (.s2p).
Embedding (Port Matching)

Include matching network of each port into measured S-parameter

- Port matching ON/OFF is applied to all ports.
- Matching network is defined by each port independently.
- Matching network is specified by pre-defined circuit models or Touchstone file (.s2p).
• “0” for Series C means "no capacitor".
• Touchstone file (.s2p) can be defined for "User".
Matching Circuit: Differential

Port 1

DUT

Port 2

Port 3

Measured S-parameter

Embedded Response

Select Circuit

None

Shunt L-Shunt C (FLPC)

User (Touchstone File)
> Characteristic Impedance Conversion

Convert S-parameter measured with 50 ohms to arbitrary port characteristic impedance

- Impedance Conversion ON/OFF is applied to all ports.
- Port impedance can be specified at each port.
- Example: SAW filter
  - Port 1 50Ω --> 100Ω
  - Port 2 50Ω

Port 1: 50Ω  Port 2: 50Ω
Port 1: 100Ω  Port 2: 50Ω

S11 on Log Mag & Smith

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Single-ended to Mixed-mode conversion

Measure
Single-ended S-parameters

Simulate Hybrid Balun to extract differential and common

Obtain
Mixed-mode S-parameters

\[
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\]

\[
\begin{bmatrix}
V_{\text{diff}} \\
V_{\text{comm}}
\end{bmatrix}
= \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}
\]

\[
\begin{bmatrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{bmatrix}
\]
**Mixed-Mode S-Parameters**

- **Sdd11** is the differential Attenuation

- **Sdc11** is the LCL (Longitudinal Conversion Loss)

![Diagram showing S-parameters](image)

The S-parameters are organized as a matrix with the following structure:

$$
\begin{bmatrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{bmatrix}
$$
3. Measurement: Frequency Domain
- Measurement Technique
- Insertion Loss, Attenuation and Phase matching
- Return Loss and Impedance
- Cross Talk, FEXT, NEXT
- Screening Attenuation
Measurement Technique: Frequency Sweep

Source -> Incident Wave -> DUT (Device Under Test) -> Reflected Wave

1st point (f = Fstart)

2nd point (f = Fstart + ΔF)

Nth point (f = Fstop)

Reference signal

DUT

Band pass filter

Frequency sweep

Agilent Technologies
Coaxial Cable Measurement:
- Return Loss, Zin
- Insertion Loss, Attenuation and Phase Matching
Coaxial Cable Measurement:
> Return Loss → Failure in manufacturing process
To maximize Dynamic Range:
- Decrease IFBW
- Increase Source Power [external Amplifier]
- If possible use Receiver’s direct inputs

Ref. “Standards, Design & Installation of CATV-Cables”, Bernhard Mund, bedea
Balanced Cable Measurement:
- Insertion Loss, LCL
- Return Loss, Zin

The characteristic impedance ($Z_c$) is given as the following equation:

$$Z_c = Z_0 \times \sqrt{\frac{(1 + S_{dd11})(1 + S_{dd22}) - S_{dd12}S_{dd21}}{(1 - S_{dd11})(1 - S_{dd22}) - S_{dd12}S_{dd21}}} \times \sqrt{\frac{(1 + S_{dd11})(1 - S_{dd22}) + S_{dd12}S_{dd21}}{(1 - S_{dd11})(1 + S_{dd22}) + S_{dd12}S_{dd21}}}$$
Balanced Cable Measurement:
- CrossTalk, FEXT, NEXT
4. Measurement: Time Domain
- Measurement Technique
- Resolution and Range
- Delay, Length and Velocity Factor
- Gating
What is time domain?

- useful for measuring impedance values along a transmission line and for evaluating a device problem (discontinuity) in time or distance.
- Time domain display provides a more intuitive and direct look at the device under test (DUT) characteristics and gives more meaningful information concerning the broadband response of a transmission system than other measuring techniques by showing the effect of each discontinuity as a function of time or distance.
TDR Time Domain Reflectometry Technology

STEP / SNAP GENERATOR
DIRECTIONAL COUPLER
UNKNOWN

OSCILLOSCOPE
Chan 1

Trigger

2t

t
TDR Basics 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

![Diagram showing TDR Basics Using a Network Analyzer](image)

Time Domain
- TDR
- \( \int_{0}^{\infty} F(t) \, dt \)

Frequency Domain
- \( F^{-1} \)
- \( 1/s \cdot F(s) \)

Example Graph:
- CH1 START 0 s
- STOP 1.5 ns
- 20 GHz
- 6 GHz
Frequency Domain $S_{11}$ Response of Semi-rigid Coax Cable
Time Domain $S_{11}$ Response of Semi-rigid Coax Cable
(1) Frequency Data: Resolution and Range
(1) Effect of Frequency Span on Resolution

For Example (Return Loss meas, so /2):
- Frequency Span = 1GHz
- \( k = 0.45 \) (TD mode and Window)
- Velocity Factor = 0.66 (PE)

\[
\text{Resolution (s)} = \frac{k}{\text{Frequency Span}}
\]

\[
\text{Resolution (m)} = \frac{k}{\text{Frequency Span}} \cdot c \cdot \text{Velocity Factor}
\]

Resolution (s) = 0.5ns
Resolution (m) = 0.05m
Resolution as a Function of Frequency Span (2)
(1) What is the **Maximum Range** that can be measured?

![Diagram of a measurement setup with a cable and measurement points.](image)

---

**Range (s)**

\[
\text{Range (s)} = \frac{\# \text{ of points} - 1}{\text{Frequency Span}}
\]

**Range (m)**

\[
\text{Range (m)} = \frac{\# \text{ of points} - 1}{\text{Frequency Span}} \cdot c \cdot \text{Velocity Factor}
\]

---

**For Example (Return Loss meas, so \(\times 2\)):**
- **Frequency Span** = 1GHz
- **# of points** = 201
- **Velocity Factor** = 0.66 (PE)

\[
\text{Range (s)} = 100\text{ns} \\
\text{Range (m)} = 19.8\text{m}
\]
Time domain Modes
## (2) Summary on modes

<table>
<thead>
<tr>
<th>Modes</th>
<th>Low-pass</th>
<th>Bandpass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓ Simulates traditional TDR</td>
<td>✓ Same as narrow-band time domain</td>
</tr>
<tr>
<td></td>
<td>✓ DC value extrapolated</td>
<td>✓ Most general purpose mode</td>
</tr>
<tr>
<td></td>
<td>✓ Start frequency harmonically</td>
<td>✓ Any arbitrary frequency range</td>
</tr>
<tr>
<td></td>
<td>related throughout span</td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Higher (twice) resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>than bandpass</td>
<td></td>
</tr>
<tr>
<td>Step excitation</td>
<td>Ideal for identifying</td>
<td></td>
</tr>
<tr>
<td></td>
<td>discontinuities (location &amp;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>type) in devices that pass</td>
<td></td>
</tr>
<tr>
<td></td>
<td>low frequencies.</td>
<td></td>
</tr>
<tr>
<td>Impulse</td>
<td>Ideal for seeing small responses</td>
<td>Ideal for measuring band-limited</td>
</tr>
<tr>
<td>excitation</td>
<td>in devices that pass low</td>
<td>devices such as filters. Also useful</td>
</tr>
<tr>
<td></td>
<td>frequencies, such as cables.</td>
<td>for fault location (but not type)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>especially when system cannot pass low</td>
</tr>
<tr>
<td></td>
<td></td>
<td>frequencies.</td>
</tr>
<tr>
<td>Reflection</td>
<td>Horizontal axis shows 2-way</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>travel time.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal axis shows 1-way (actual)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>travel time.</td>
<td></td>
</tr>
</tbody>
</table>
(4) Gating Operation

1. Original Frequency Response
2. Time Domain w/ Gate
3. Frequency Response w/ Gate
4. Time Domain w/ Gate

Filter Out this Response

IFFT

FFT
(4) Gating Example: Time Domain response

Remove the effects of the Input Connector

Gate On
(5) Frequency Domain response with Gate On

Use Gating to show the frequency response of the output connector & termination only
Coaxial cables with adapter and N connector
Coaxial cable with adapter and Fakra connector
Balanced cable with adapter and LVDS connector
5. Measurement: Enhanced Time Domain (TDR)
- Measurement Technique
- Eye Diagram and Mask
- Jitter, Emphasis, Equalization
What is ENA Option TDR?

The ENA Option TDR is an application software embedded on the ENA, which provides an **one-box solution** for high speed serial interconnect analysis.

**3 Breakthroughs**

*for Signal Integrity Design and Verification*

- Simple and Intuitive Operation
- Fast and Accurate Measurements
- ESD Robustness
One-box Solution
for High Speed Serial Interconnect Analysis

Time domain

Frequency domain

Eye diagram
One-box Solution
for High Speed Serial Interconnect Analysis

- Time domain
- Frequency domain
- Eye diagram

- Automatic display allocation for most common measurement parameters depending on selected device topology
- Up to 9 markers
- Zoom
- Rise time
- Flexibility to set measurement parameter for each individual trace
- Time (skew) measurements

Dedicated controls for common adjustments

Set rise time to characterize expected performance at slower edge speeds

Frequency domain

Time domain

Eye diagram
One-box Solution
for High Speed Serial Interconnect Analysis

Eye Diagram

Time domain

Frequency domain

Eye diagram
One-box Solution for High Speed Serial Interconnect Analysis

Time domain

Frequency domain

Eye diagram

Eye mask editor

Eye mask test

Virtual bit pattern generator

Automated eye diagram measurement results

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Three Breakthroughs for Signal Integrity Design and Verification

**Simple and Intuitive**

**Similar look-and-feel to TDR scopes**
Intuitive operation even for users unfamiliar to vector network analyzers and S-parameter measurements.
Three Breakthroughs for Signal Integrity Design and Verification

Simple and Intuitive

**Setup Wizard**
Guides the user through all of the required steps, making setup, error correction, and measurement intuitive and error-free.

Fast and Accurate

ESD Robustness

ESD protection inside

4 steps!!
Three Breakthroughs for Signal Integrity Design and Verification

No time-domain instrument can surpass the accuracy, sensitivity, noise floor, and autocalibration routines inherent to a network analyzer.
Three Breakthroughs
for Signal Integrity Design and Verification

Simple and Intuitive

Fast and Accurate

ESD Robustness

ENA Option TDR

TDR Scope

DUT: 50 Ohm pattern

1 ohm/div

VNA Based TDR measurements

= Low Noise
Three Breakthroughs for Signal Integrity Design and Verification

Simple and Intuitive

Fast and Accurate

ESD Robustness

ENA Option TDR

DUT: 50 Ohm pattern

TDR Scope

Averaging... 1 ohm/div

Averaging can lower noise

BUT...
Three Breakthroughs for Signal Integrity Design and Verification

DUT: 50 Ohm pattern

ENAOption TDR

TDR Scopes

Real-Time Analysis
Three Breakthroughs for Signal Integrity Design and Verification

Dynamic range is generally defined as the maximum power the receiver can accurately measure minus the receiver noise floor.

Dynamic Range Comparison
VNA vs TDR Scope

ESD Robustness
ESD protection inside

Fast and Accurate

Simple and Intuitive

E5071C Datasheet (5989-5479EN) July 10, 2009 … System Dynamic Range 10Hz IFBW
86100C Technical Specifications (5989-0278EN) October 1, 2009 … Attenuation Dynamic Range Internal
Three Breakthroughs for Signal Integrity Design and Verification

TDR Scopes

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
Three Breakthroughs 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.

<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>
Measurement Correlation
TDR/TDT

- DUT: USB3.0 Cable
- 50 ps rise time (20-80%)
Measurement Correlation

Eye Diagram

• DUT: USB3.0 Cable
• PRBS \(2^{7}-1\) @ 5 Gbps

Refer to Appendix for DisplayPort and SATA correlation data.
Summary

The Agilent ENA Option TDR application...

• Provides **one-box solution** for high speed serial interconnect analysis

  - Time domain
  - Frequency domain
  - Eye diagram

• Brings **three breakthroughs** for signal integrity design and verification

  - Simple & Intuitive Operation
  - Fast & Accurate Measurements
  - ESD Robustness
USB 3.0 Cable/Connector Compliance Test Solution

New features added to the cable assembly for SuperSpeed operation.
Agilent Digital Standards Program

Our solutions are driven and supported by Agilent experts involved in international standards committees:

- Joint Electronic Devices Engineering Council (JEDEC)
- PCI Special Interest Group (PCI-SIG®)
- Video Electronics Standards Association (VESA)
- Serial ATA International Organization (SATA-IO)
- USB-Implementers Forum (USB-IF)
- Mobile Industry Processor Interface (MIPI) Alliance
- Optical Internetworking Forum (OIF)

We’re active in standards meetings, workshops, plugfests, and seminars

Our customers test with highest confidence and achieve compliance faster
USB 3.0 Cable/Connector Compliance Test Solution
Cable Assembly

New features added to the cable assembly for SuperSpeed operation.


Agilent Technologies
USB 3.0 Cable/Connector Compliance Test Solution

Measurement Parameters

USB 3.0 Cable Assembly

Time Domain Measurements
- Mated Connector Impedance
- Cable Electrical Performance
  - Characteristic Impedance
  - Intra-pair Skew
- Near-end Crosstalk between SuperSpeed Pairs
- Differential Near-end Crosstalk between SuperSpeed Pairs
- Differential Crosstalk between D=~/D- and SuperSpeed Pairs

Frequency Domain Measurements
- Differential Insertion Loss (Sdd21)
- Differential–to-Common-Mode Conversion (Scd21)

USB 3.0 specs make sure cable assemblies support 5 Gb/s transfer rate.
USB 3.0 Cable/Connector Compliance Test Solution
Solution Overview

• USB 3.0 cable/connector compliance testing requires parametric measurements in both time and frequency domains

**Frequency Domain**
• Insertion Loss (Sdd21)
• Mode Conversion (Scd21)

**Time Domain**
• Mated Connector Impedance Profile (TDR)
• Crosstalk (NEXT, FEXT) (TDT)

**Traditional Solution**
- Vector Network Analyzer (VNA)
- TDR Scope

**New Solution**
- **ALL** parameters can be measured with ENA Option TDR
- One-box Solution !!
USB 3.0 Cable/Connector Compliance Test Solution
Developers Conference (Taiwan, April 2010)

“SuperSpeed USB Compliance: Overview”, Rahman Ismail, Intel Corporation

ENA Option TDR introduced as recommended solution for CabCon compliance test.

http://www.usb.org/developers/ssusb
USB 3.0 Cable/Connector Compliance Test Solution
ENA Option TDR Solution

• ENA Mainframe
  • E5071C-480: 4-port, 9kHz to 8.5GHz
  • E5071C-485: 4-port, 100kHz to 8.5GHz
  • E5071C-4D5: 4-port, 300kHz to 14GHz
  • E5071C-4K5: 4-port, 300kHz 20GHz

• Enhanced Time Domain Analysis Option (E5071C-TDR)

• ECAL Module
  • N4431B for E5071C-480/485
  • N4433A for E5071C-4D5/4K5

• Method of Implementation (MOI) document available for download on Agilent.com
• State files (480, 485, 4D5, 4K5) and cal kit definition file for official cal fixtures are also available

SuperSpeed Cable Test Fixtures
Fixtures for testing SuperSpeed cable assemblies and USB 3.0 connectors are available for purchase through Allion and BitifEye.
http://www.usb.org/developers/ssusb/ssusbtools/

www.agilent.com/find/ena-tdr_usb3-cabcon
USB 3.0 Cable/Connector Compliance Test Solution

Measurement Parameters

**Frequency Domain**

1. Insertion Loss (Sdd21)
2. Mode Conversion (Scd21)
3. D+/D- Pair Attenuation (Sdd21)

**Time Domain**

1. Connector Z (Tdd11, Tdd22)
2. Cable Z (Tdd11, Tdd22)
3. Intra-Pair Skew (T31, T42)
4. D+/D- Intra-Pair Skew & Propagation Delay (T31, T42)
5. Near End Xtalk D+/D- SS Xtalk (Tdd21)

**Other Parameters**

- Active Ch/Trace
- Response
- Stimulus
- Mfr/Analysis
- Instr State

Agilent Technologies
USB 3.0 Cable/Connector Compliance Test Solution

Summary

ENA Option TDR Cable/Connector Compliance Testing Solution is ….

• **One-box solution** which provides complete characterization of high speed digital interconnects (time domain, frequency domain, eye diagram)
• Similar look-and-feel to traditional TDR scopes, providing *simple and intuitive operation*
even for users unfamiliar to VNAs and S-parameters
• Adopted by test labs worldwide
High-Speed Digital Bus Compliance Test and Characterization

Industry-leading Instruments + BitifEye Software

Taking Test Automation to the Next Level

Automated HDMI Cable Testing
HDMI Cable Test Station
Agilent ENA-TDR and ECal, BitifEye Switch, Software
HDMI Cable Test Station
Agilent ENA-TDR and ECaL, BitifEye Switch, Software
• Test Equipment (see Agilent HDMI Cable Test MOI):

4. Resource Requirements
1. E5071C ENA Series Network Analyzer with Enhanced Time Domain Analysis Option
   Note: Ensure that
   - Test set option is any one of 480/485/4D5/4K5
   - E5071C firmware revision A.10.05 or above is installed.
   - E5071C-TDR application software revision A.01.50 or above is installed.
2. Electronic Calibration Module N4431B (for 480/485) or N4433A (for 4D5/4K5)
3. 3.5 mm cables 8 GHz bandwidth or equivalent x4
4. Certified HDMI receptacle fixtures (ex. Agilent 1080B-H02) x2
5. Certified HDMI plug fixtures (ex. Agilent 1080B-H01) x1
   Note: The plug fixture is used for the jitter adjustment in the eye diagram test. It should
   have similar characteristics to the receptacle fixtures.
6. 50 Ohm terminators to terminate unused fixture connectors x12
7. Female to female adaptors to connect fixture and test cables (if necessary)

- Included in BitifEye switch bundle
- not needed with switch bundle
- not needed with switch bundle
- optional BitifEye switch bundle
- BitifEye test automation software
  # Bundle software BIT-2011-9450 (new customers), upgrade product BIT-2011-0450 (installed customer base)
N5990A Test Automation Software
HDMI Compliance Test and Product Characterization

Services

ValiFrame Test Automation Software Platform
(Base Product, BIT-2001-0009-0)

User Programming (MS .NET dlls)

LabView, VEE, C#, VB, C++

New

Cable Test
BIT-***-0450

User Programming

Legacy Code

Low Speed Test

Instrument Software

Standard Instruments

Source Test Software

Sink Test Software

Cable Test Software

Test Sequencer

Custom Solution

Test integration

HDMI-Sink
VF Opt. 150
Prot., HDCP
VF Opt. 350
HEC, ARC
VF Opt. 351

HDMI Source
N5399B

Real-time
Oscilloscope

TMDS Sig.
Generator

Protocol
Gen./Analyzer

Pulse Arb Fct.
Generator

TDR,
ENA

Multi-f, Volt-f,
LCR-meter

Low Speed
VF Opt. 470

Investigation

Agilent Technologies
N5990A Test Automation Software Overview
Digital Bus Compliance Test and Characterization

Customizations
BitifEye and Partner Services; Support

Test Sequencer
N5990A Test Automation Software Platform

Legacy Code, User Progr.
... C, C++, C#, Visual Basic, VEE, LabView, Python

Cable Test Software
... TBT, BIT..., USB, BIT..., DP, BIT..., HDMI, BIT...

Protocol/Ctrl/ HDCP Test
... MIPI, MHL, HDMI N5990A-350

Rx Test Software
... Rx, PCIe, N5990A-101, HDMI N5990A-150

Tx Test Software
USB U7243A N5990A-202, HDMI N5990B N5990A-250

Standard Instruments
Pulse Data Generators, AWGs, BERTs, Real-time Oscilloscopes, Protocol Testers, ENA-TDR

Opt. 500
BIT-...

Opt. 3xx
Interface Opt. 2xx

Opt. 1xx

Test Automation, System Integration
Automated HDMI Cable Test Details
Station Configuration Examples
Automated HDMI Cable Test Details
DUT Configuration

![Configure Product Window]

- **Product Number:** HDMI Cable Test
- **Serial Number:**
- **Description:**
- **User Name:** Unknown User
- **Comment:**
- **Initial Start Date:** 3/15/2012 9:20:20 AM
- **Compliance Mode:**
- **Last Test Date:** 3/19/2012 9:20:20 AM
- **Expert Mode:**
- **Cable Test Configuration**
  - **Category Type:**
    - **Category 1**
    - **Category 2**
  - **Configuration:**
    - Home
    - Automotive_EE
    - Automotive_AA
  - **Cable Type:**
    - Passive
- **DUT Length:**
  - **Auto measure DUT length (Recommended):**
  - **Set DUT length manually (meters):**

[Image of Configure Product window with configured options]
Automated HDMI Cable Test Details
Calibration and Test Procedures

- **Test 5-4**: Intra-Pair Skew
- **Test 5-5**: Inter-Pair Skew
- **Test 5-6**: Far End Crosstalk
- **Test 5-7**: Attenuation and Phase
- **Test 5-8**: Differential Impedance

User-selectable test parameters in **Expert Mode**!
Automated HDMI Cable Test Details

Connection Diagram Examples
Automated HDMI Cable Test Details

De-Embedding

De-embedding files:
Module 1 / Port 1
Module 2 / Port 1

Connect the ENA to Switch Box as shown above.
Automated HDMI Cable Test Details

De-Embedding

- De-embedding moves the measurement plane from the instrument connectors to the switch connectors; it compensates the impact caused by the switch.
- Consists of two steps:
  1. Calibrate the ENA-TDR for a single ended setup by using the ECal module.
  2. Measure the four paths of the module and save the de-embedding files.
- Once the files are saved, they are valid until the switch wears out or is replaced.
Automated HDMI Cable Test Coverage

CTS Test Result Example
Automated HDMI Cable Test Coverage
More CTS Test Result Examples
Questions?
References/backup slides
Agilent E5071C ENA Network Analyzer Portfolio

- Flexible Lineup for a Variety of Applications
  
  *Select the number of ports, frequency, and bias tee to fit your application*

<table>
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<th>Number of ports</th>
<th>Frequency range</th>
<th>Option numbers</th>
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</table>
The E5071C is a safe investment because of its flexibility. You can easily upgrade any feature of the E5071C whenever you need the feature! This includes not only software options like enhanced time domain mode, frequency offset mode, and MWA, but also hardware options such as frequency and number of test-ports.

**Buy the bandwidth you need today, upgrade to higher bandwidth in the future!!**