Signal Integrity Measurements and Network Analysis
Optimizing Signal Integrity Flow Chart

Theory

Overview
- Internet infrastructure

Transmission Lines
- Differential impedance
- Multi-port S-parameters

Measurement Metrics
- Single-ended vs. differential
- Eye diagrams (NRZ, PAM4)

Practical

Typical PCB Issues
- Vias, reflections, loss
- De-embedding

Real World Measurements
- Backplane Design Case Study

Demonstration
- Physical Layer Test System (PLTS)
- USB 3.0 compliance example
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Internet Infrastructure: Terabit Network & Data Centers

Components

Modules

Line Cards

Network Elements & Systems

Copper

Router

Trunk Fiber
Keysight Now Provides Insight Across the Entire System

- **Components & Chipsets**
- **Devices**
- **Base Stations**
- **Hyperscale and Data Centers**
- **Enterprise**

**Layers 2-7**
- Mobile Device Test
- BTS Drive Test
- Drive Test
- Mobile Network Test
- Customer Experience Management
- Network Test, Visibility and Security

**Layer 1**
- Electrical, Optical and Wireless Test
- Channel Emulation

Company Profile
Keysight Now Provides Insight Across the Entire System

- Keysight Classic
- Ixia
- Anite

Our Focus Today

COMPONENTS & CHIPSETS

DEVICES

BASE STATIONS

HYPERSCALE AND DATA CENTERS

ENTERPRISE

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Drive Test

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Customer Experience Management

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Drive Test

Mobile Network Test

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Network Test, Visibility and Security

Layer 1

Electrical, Optical and Wireless Test

Layer 0

Channel Emulation

“Linear Passive Interconnect”
Signal Integrity Problems are Everywhere

Backplanes

PC Boards

IC Packages

Connectors

Cables
Backplanes are the Most Critical Link
Why are Signal Integrity Problems Getting so Bad?

Risetimes get faster

Via stub reflections get larger

Frequency domain data is now required
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Modeling Lossy Lines in the Frequency Domain

\[ V(\omega, x) = V_0 \exp(-\Gamma x) \exp(i\omega t) \]

\[ \Gamma = \alpha + i\beta = \sqrt{(R_L + i\omega L_L)(G_L + i\omega C_L)} \]

\[ Z_0 = \frac{(R_L + i\omega L_L)}{(G_L + i\omega C_L)} \]

R_L, G_L may vary with frequency

C_L, L_L are the high frequency limit values
Two traces carrying complementary data are used for higher 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.
Differential Impedance:
The Characteristic Impedance Matrix

\[ V_1 = Z_{11} I_1 + Z_{12} I_2 \]
\[ V_2 = Z_{22} I_2 + Z_{21} I_1 \]

Example of Z-parameter matrix or Characteristic Impedance Matrix [ohms]:

\[
\begin{bmatrix}
1 & 2 \\
1 & 49.6 & 6.4 \\
2 & 6.4 & 49.6
\end{bmatrix}
\]

Coupling Factor (6.4 ohms)
Self Impedance (49.6 ohms)
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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
# Single-ended to Differential S-Parameters

### Naming Convention:

S\text{mode res.}, \text{mode stim.}, \text{port res.}, \text{port stim.}

<table>
<thead>
<tr>
<th></th>
<th>Differential-Mode Stimulus</th>
<th>Common-Mode Stimulus</th>
<th>Port 1</th>
<th>Port 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S_{11}</strong></td>
<td>(S_{DD11})</td>
<td>(S_{DC11})</td>
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<tr>
<td><strong>S_{12}</strong></td>
<td>(S_{DD12})</td>
<td>(S_{DC12})</td>
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<tr>
<td><strong>S_{13}</strong></td>
<td>(S_{DD21})</td>
<td>(S_{DC21})</td>
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<tr>
<td><strong>S_{14}</strong></td>
<td>(S_{DD22})</td>
<td>(S_{DC22})</td>
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<tr>
<td><strong>S_{21}</strong></td>
<td>(S_{CD11})</td>
<td>(S_{CC11})</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>S_{22}</strong></td>
<td>(S_{CD12})</td>
<td>(S_{CC12})</td>
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<tr>
<td><strong>S_{23}</strong></td>
<td>(S_{CD21})</td>
<td>(S_{CC21})</td>
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<tr>
<td><strong>S_{24}</strong></td>
<td>(S_{CD22})</td>
<td>(S_{CC22})</td>
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<tr>
<td><strong>S_{44}</strong></td>
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</tbody>
</table>
Differential 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
Differential s-Parameter Measurements
Typical Measurement Set Ups

Time Domain Reflectometer (TDR)

Vector Network Analyzer (VNA)
High Spatial Resolution Measurement Set Up

- Millimeter Wave Vector Network Analyzer (VNA)
- 900Hz → 120GHz frequency sweep
- 6-picosecond effective TDR risetime
- less than 400 microns to be resolved in high-performance BGA (ball grid array) ceramic IC packages
Vector Network Analyzer

The VNA is known to have the most accurate calibration standards of any test and measurement instrumentation. Agilent VNA’s enable PLTS to acquire data with unparalleled precision.

Software

You don’t need to know how to operate a VNA - the PLTS software controls all instrument hardware via GPIB or LAN. The measurement algorithms, user interface and data manipulation code is resident on the external computer.

Data

The power of PLTS is in the completeness and accuracy of the data. Both time and frequency domain information allows unique insight into device performance. With just one measurement, the design engineer can view any combination of single-ended, differential, Time Domain Reflection (TDR), Time Domain Transmission (TDT), return loss, and insertion loss data in a variety of graphical formats. Perhaps the most groundbreaking capability is mixed mode analysis where mode conversion can highlight hardware that is susceptible to EMI or radiating radio frequency.

Electronic Calibration Module

Calibrating a multiport VNA can be a daunting experience with traditional mechanical calibration kits. This is why Keysight developed the Ecal to make calibration and accurate s-parameter measurements a quick and easy process.

New MATLAB / Python compatibility

Vector Network Analyzer

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Differential Eye Diagram Analysis

NRZ @ 3.125 Gbps

PAM4 @ 3.125 Gbps

NRZ @ 6.25 Gbps

PAM4 @ 6.25 Gbps
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Typical PCB Manufacturing Issues

1. Excess capacitance in through hole
2. Localized crosstalk
3. Localized changes in conductor width
4. Localized changes in conductor spacing
5. Reflections due to via stub
6. Nonuniform dielectric
7. Surface treatment thickness nonuniformity
8. Localized changes in foil thickness
9. Anodic conductive filament (ACF) shorting
Via Stubs Create Capacitive Loads
Backplane Connectors Are Advanced

- High Precision Molded Components
- Differential Signal Traces
- Surface Mount Terminals
- Double sided shield
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High Speed Backplane Design Case Study

XAUI – eXtended Attachment Unit Interface
High Speed Backplane Impedance Profile: “Walking the Channel” aka “Be The Signal”
High Speed Backplane Impedance Profile
High Speed Backplane Impedance Profile
High Speed Backplane Impedance Profile
High Speed Backplane Impedance Profile
Complete Channel Analysis with PLTS: USB 3.0 Connector
Error Correction Techniques

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

Most Accurate vs. Most Simple

○ = Pre-measurement error correction
△ = Post-measurement error correction
Engineering Tool Overload

How many tools do we need?
When do we hit saturation?
How can we simplify?

One possible solution…

*tool integration*
Technical Resources

• Free 400G Poster www.keysight.com search “400G poster”

• PLTS Website: www.keysight.com/find/plts
  - Configuration Guide
  - Application Notes Library
  - Video Tutorials
  - Quick Quote
  - DesignCon Papers and Technical Forum Video

• Free Signal Integrity Book: www.keysight.com/find/RessoBook

• Check out the Keysight YouTube channel
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