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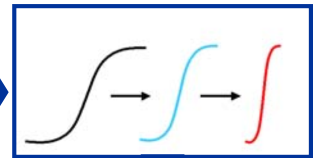
Advanced Signal Integrity Measurements of High-Speed Differential Channels

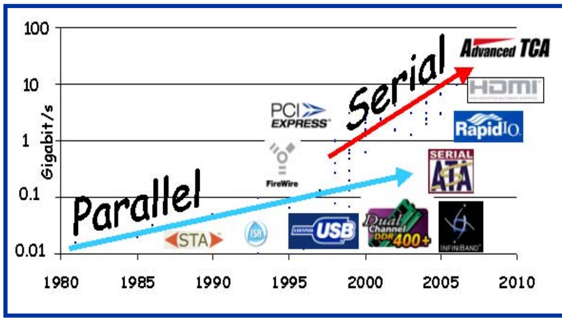
What We Will Discuss Today

- Brief review of Gb/s signal integrity issues
- Tools used for channel design and characterization
  - Time domain
  - Frequency domain
- Transmitter and receiver analysis

Signal Integrity Challenge

Risetimes become faster



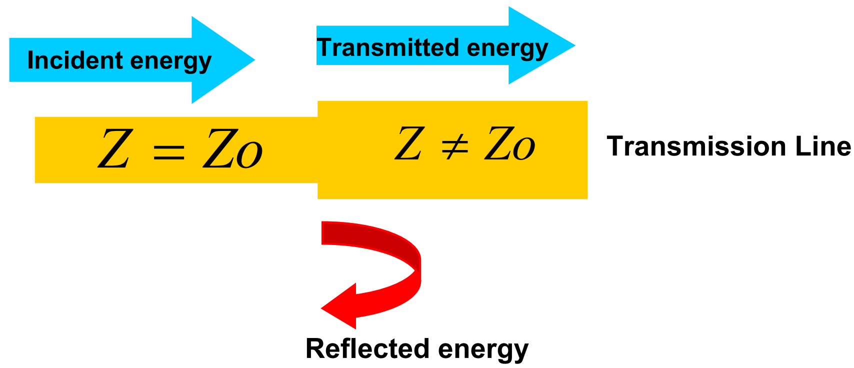


Data Rates Increase (>1Gbps)

Life gets difficult for the hardware engineers

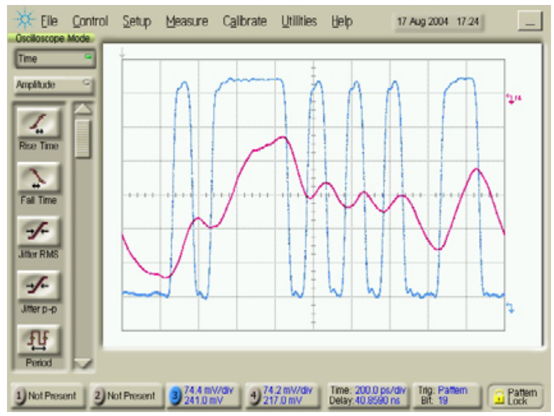
Signals Reflect

- It is not unusual to see significant portions of the signal thrown back at the transmitter



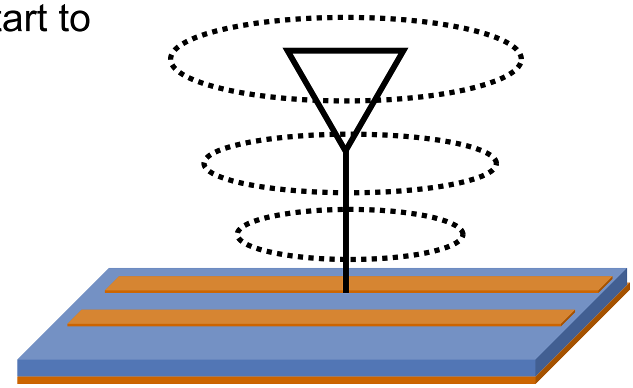
Pulses Get Distorted

- Frequency response limitations
- Reflections
- Aberrations



Electromagnetic Radiation Issues

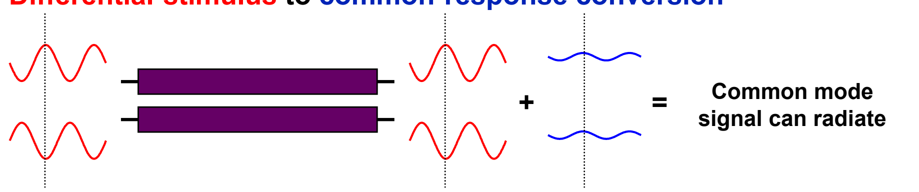
- At high frequencies, traces can start to behave like antennas



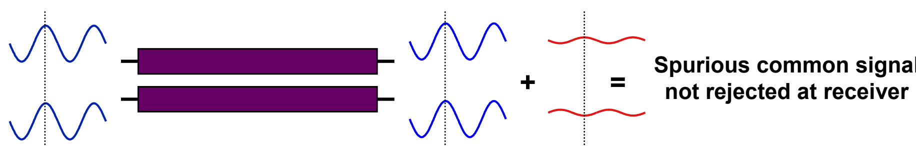
Transmission Mode Conversion

Emission or susceptibility problems

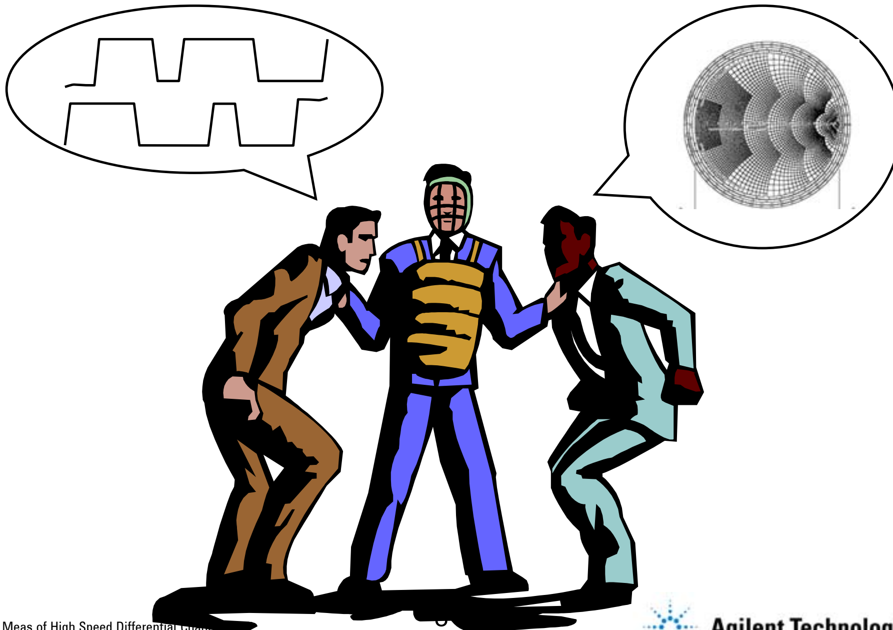
- **Differential-stimulus to common-response conversion**



- **Common-stimulus to differential-response conversion**



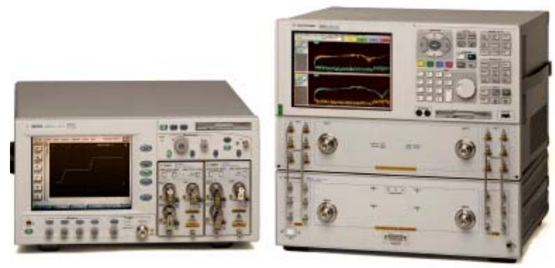
Digital Engineer or RF/uW Engineer?

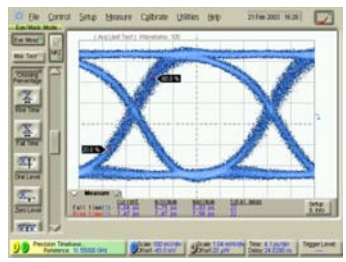


Two headed bits or smith chart

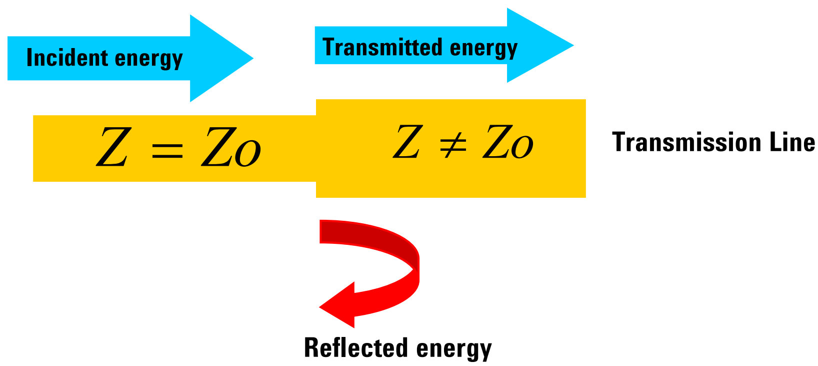
Time or Frequency Domain?

- Digital engineer toolbox
  - Time domain
  - Oscilloscopes/TDR
- RF/uW engineer toolbox
  - Frequency domain
  - Network Analyzers



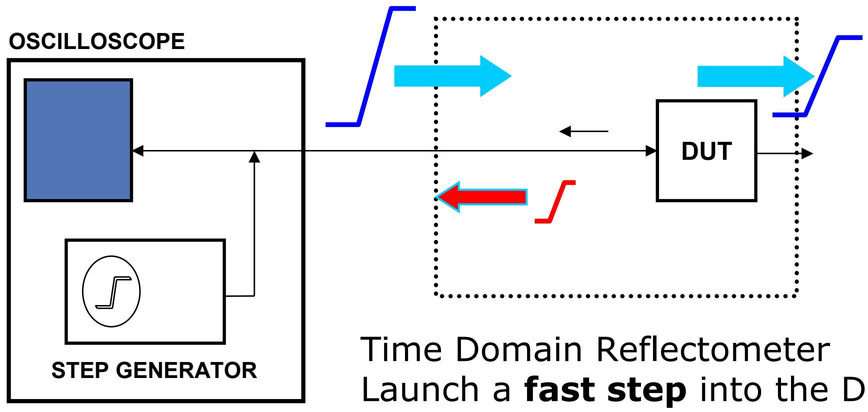


Characterizing Media Performance



Need easier to follow graphics, but the concept is right

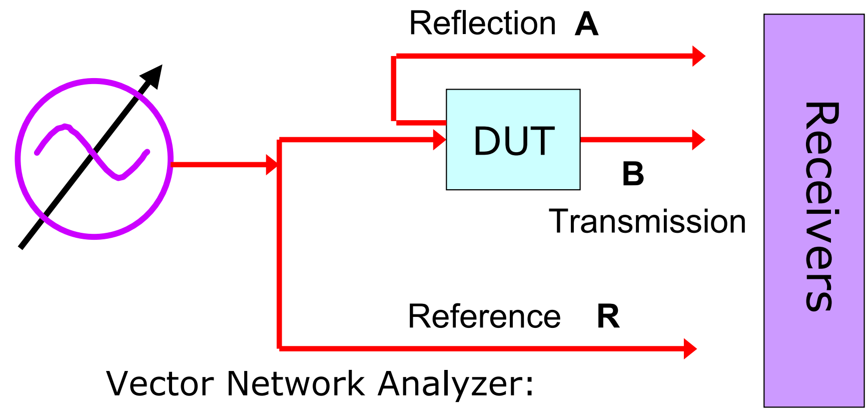
Characterizing Media Performance: TDR



Time Domain Reflectometer
Launch a **fast step** into the DUT
What reflected back?
What transmitted through?
Observe with a wide BW scope

Need easier to follow graphics, but the concept is right

Characterizing Media Performance: VNA

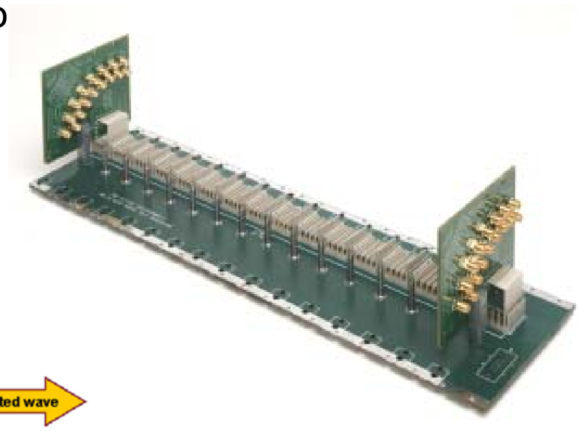


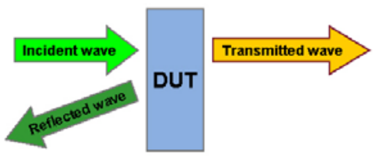
Vector Network Analyzer:

Launch a **swept sinusoid** into the DUT
What reflected back?
What transmitted through?
Observe with narrowband receivers
tuned to the input frequency

Characterizing Board Impedance

- Will the signals get reflected due to imperfect impedance?

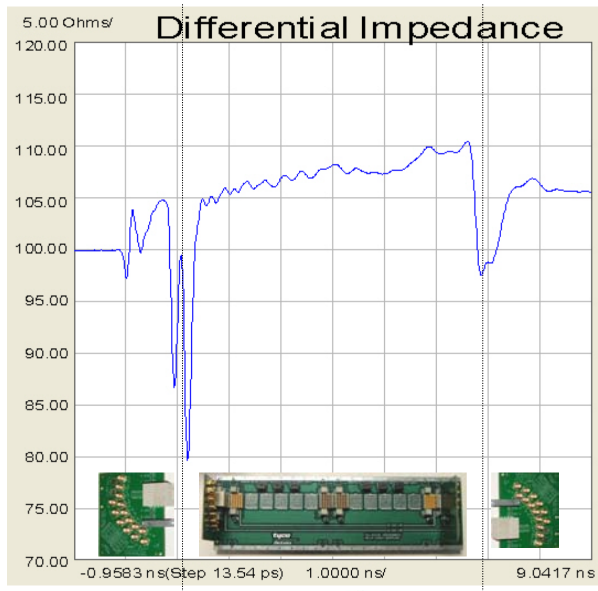




Many applications, not just backplanes.

Characterizing Board Impedance: TDR

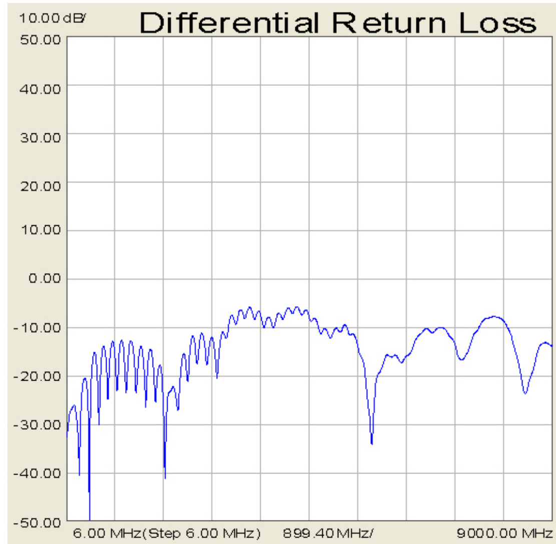
- TDR displays signal reflection versus *time/position*
- Impedance profile derived directly from reflected signal

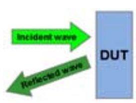


Add picture of daughter card and backplane and superimpose

Characterizing Board Reflections: VNA

- VNA displays signal reflection versus *frequency*
- Reflections generally get worse as frequency increases (harder to control the impedance)





SI Meas of High Speed Differential Channel

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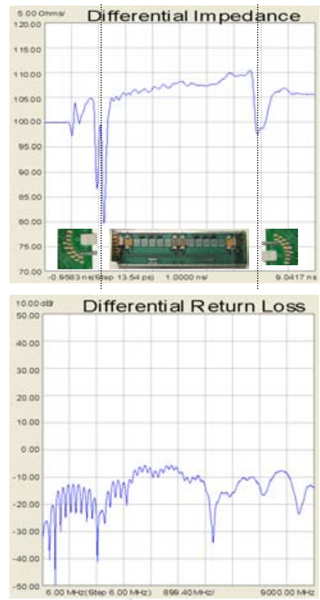
Differential return loss is the frequency response of the DUT that is seen by the differential signal as it propagates through the DUT. You want to optimize design for low levels….10-12dB is typical for digital devices, although microwave device require 20-40dB.

Time or Frequency Domain?

- Which measurement set is better?
- Time: Easy setup, easy to understand. Easy to pinpoint big problems quickly.
- Frequency: Precision, high dynamic range, insight into subtle issues like resonances



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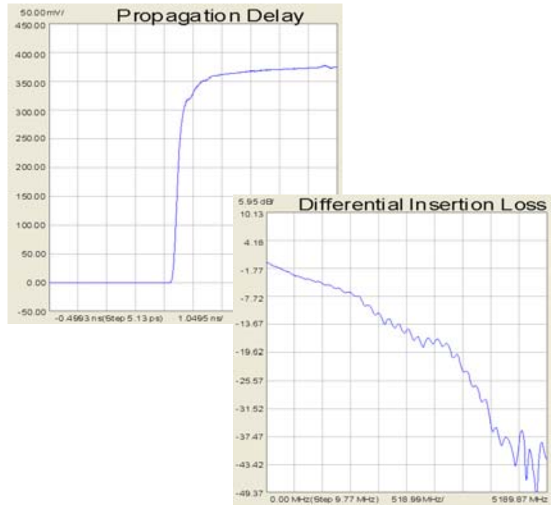
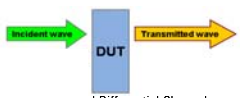
This is the closing slide of that section. State the comparison and complementary nature of these two…periodicity of freq nulls and the actual reflective discontinuties in the time. When you have two reflection sites within a device, the two signals beat against one another. They will sometimes beat in-phase and sometimes out-of phase. When they beat out of phase with each other, this is where we get a null in the frequency domain. And the distance between the reflective sites change the frequency spacing of the nulls. The larger the distance in reflective sites are in the time domain, the smaller the spacing of the nulls in the freq domain.

Board Transmission **Performance**

- Send test signal in and observe what comes out the far end

- TDT: Fast step
- VNA: Swept frequency sinusoid



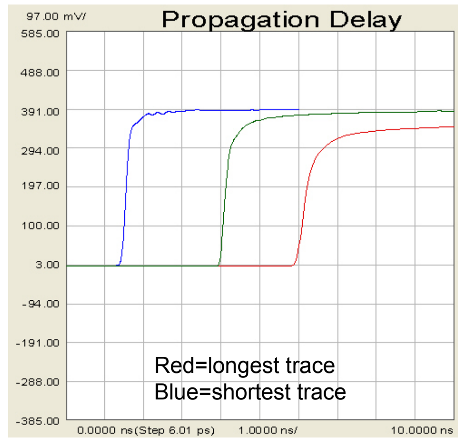


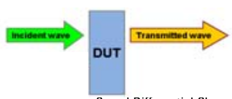
d Differential Channels

Need measurement results…throw in TDT graphic. Beginning of segment…make only one dut per slide…

Time Domain Transmission (TDT)

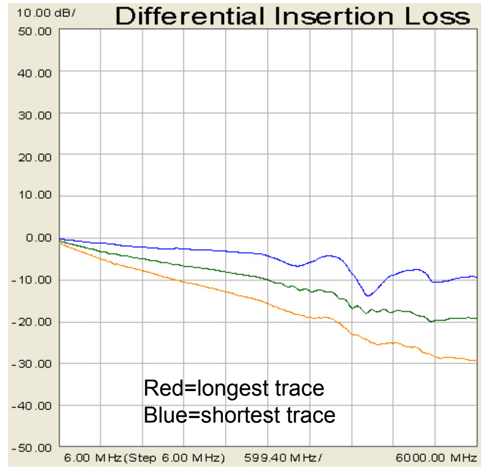
- TDT: Simple concept and result: When did the pulse arrive and how did it change?

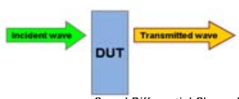




VNA Insertion Loss Result

- VNA: Easy to observe how well different frequency ranges propagate: What is the frequency response that the differential signal sees?

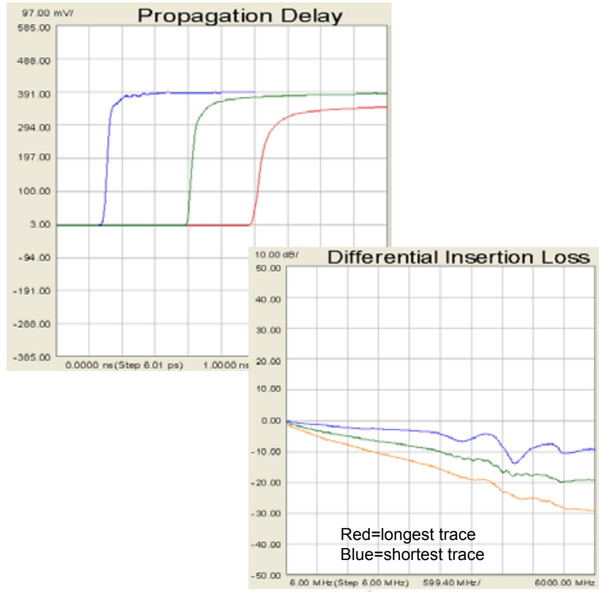


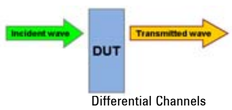


Speed Differential Channels

Time or Frequency Domain?

- Time: Easy to see how data signals might be affected through the board (pulse distortion and propagation)
- Frequency: Easy to observe the board performance and relate to physical quantities (loss versus frequency)





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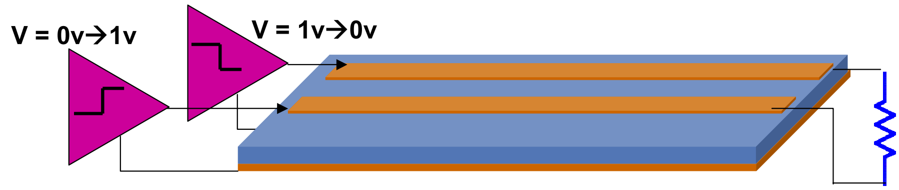
Summary and conclusion of comparing synergy 1

Differential Transmission Lines



- Two traces carrying complementary data, commonly used for high data rates
- Why?
  - Receiver can reject any signal that is common to both lines
  - Radiation reduced (cancellation of fields)
- Impedance measurements have slightly different meaning compared to single-ended measurements

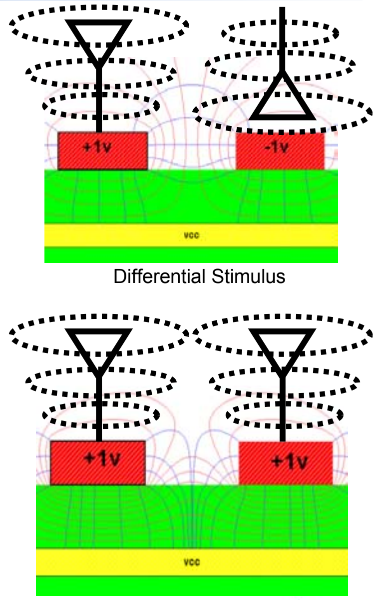
No brain dump too early…"the differential structure behaves differently and we need to study this phenomena with new tools…This experiment leads to the simplest possible description of differential impedance. When the two coplanar lines were driven as a single ended transmission line, the signal was the voltage difference between the two lines. The impedance the signal saw was 150 Ohms where there was no plane and 100 Ohms where there was a plane. In the region where there is a plane below, the transmission line look like two coupled microstrip lines as part of a differential pair.

When the two transmission lines are driven by single ended signals that are exactly out of phase, we call this differential driving. As the signals propagates down the differential pair, there is a voltage pattern between each signal line and the reference plane below. In addition, there is a signal between the two signal lines. This is called the difference signal or differential signal. If the differential pair is driven symmetrically, the differential signal is twice the single ended signal.

The difference signal is the same signal as when the two coplanar traces are driven as a single ended line, in the previous example. In this case, the impedance the signal saw was 100 Ohms in the region where there was a plane. If the two microstrips were driven differentially, the difference signal would see an impedance of 100 Ohms as well. We call the impedance the difference signal sees, the difference impedance or differential impedance.

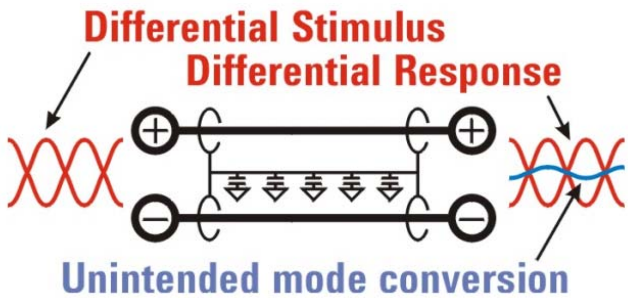
Digging Deeper: Radiation

- As data rates go up, frequencies increase. Lines become antennas (both send and receive) and corrupt the communication (BER)
- One solution is the use of differential transmission lines



One problem with these diagrams…the fields actually look stronger for the differential signal. I think it's because we observe the field between the conductors, whereas the radiation issue is one far away to either side. Also, you might want to mention there is a reciprocity in antennas as far as if it's a good transmitter it will also be a good receiver.

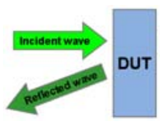
Mode Conversion

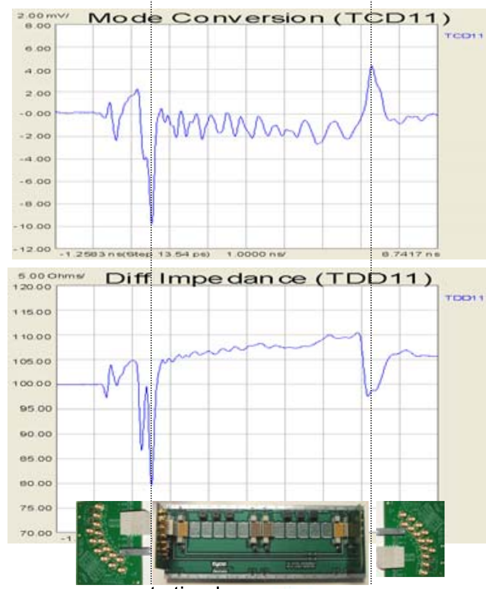


- Mode conversion caused by asymmetries in differential transmission line
- Can cause the differential signal to be converted to a common mode signal
  - Possible radiation problems
- Can cause a common mode signal to be converted to a differential signal
  - Possibly susceptible to radiation

Mode Conversion: Time Domain

- Measure impedance profile
- Stimulate with a differential signal (two steps) and measure the reflected common mode response
- Overlay both and identify structure that creates mode conversion (via field)

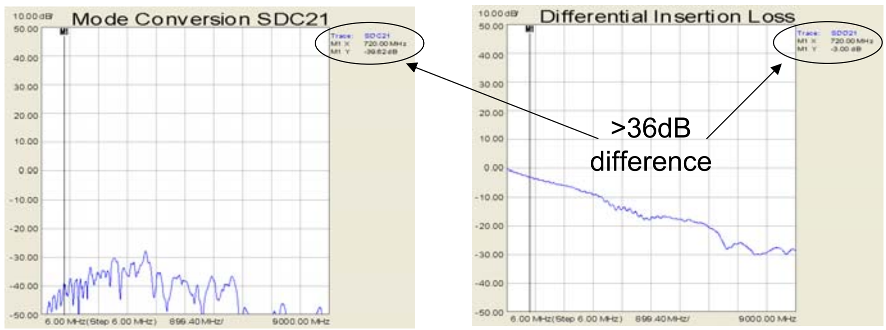




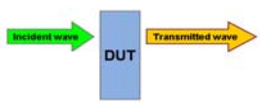
Parameter Naming Convention:

$S/T_{\text{mode response., mode stimulus., port response., port stimulus.}}$

Mode conversion: Frequency Domain



- Stimulate each channel, measure each receive port, combine the results
- Look for largest delta dB between insertion loss and mode conversion
- Larger delta dB indicates larger signal to noise ratio at receiver



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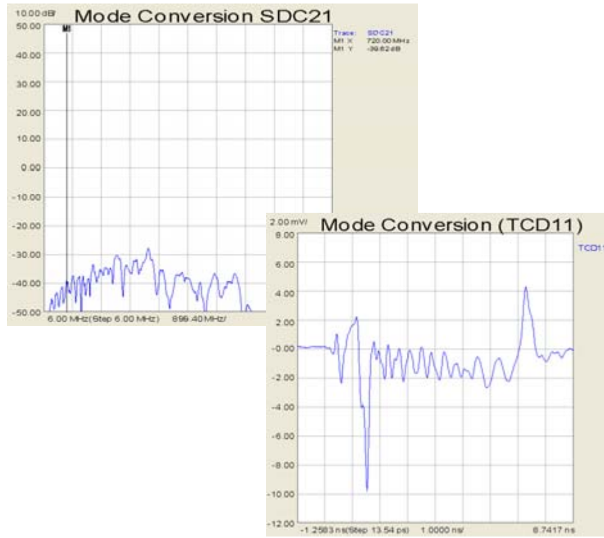
Change “return loss” to “insertion loss”. Basically, the comparison of mode comnversion in the freq domain here shows the signal to noise ratio at the receiver. The bigger the difference in these two parameters (Scd21 and Sdd21) shows a better S/N ratio.

Mode Conversion: Time or Frequency?

- Time: Easy to observe where the mode conversion is occurring
- Frequency: High dynamic range to observe even very small levels of mode conversion

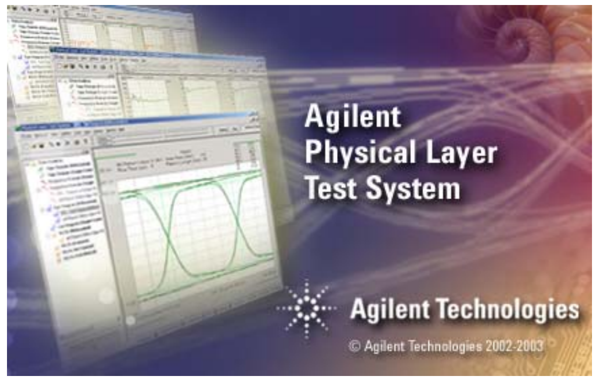


Time domain mode conversion is more intuitive (locating discon), but if the dut is extremely well designed, then the very low levels of mode conversion with not be seen with the tdr. Important lead up slide…"so far, we have compared time and freq domain data analysis in many different ways…reflection, transmission and mode conversion…so what is the bottom line…which do I choose?"

The answer is…→ you don't have a choice…you need to use both…

"Okay…now which domain do I choose?"

- Answer is…both!
- With the right test system, both time domain and frequency domain data is available for comprehensive analysis



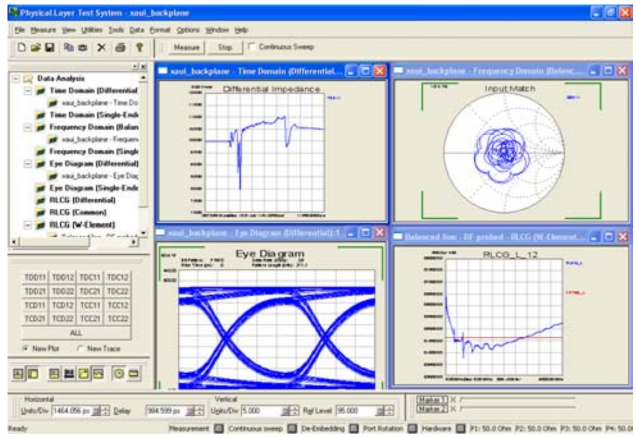
You don't have a choice, you need to work in BOTH domains. If you have the right design tool, this is easy. The PLTS is a software application that runs on an external laptop that can work just as easily in the time domain as the freq domain. It'll perform the Fast Fourier Transform and Inverse Fast Fourier Transform to move smoothly and effortlessly between the two domains. With the click of a button, impedance becomes return loss, or TDT becomes insertion loss. Every mode of analysis is based on mathematics performed on the basic data file of 4-port s-parameters, also called Touchstone files.

Also, PLTS will calibrate and directly control the instrument measurements. Which brings us to an area that you DO have a choice…You DO have a choice of which measurement engine you choose. Keep this choice in mind as we go through the next few slides…

Best of Both Worlds…

•Both TDR and VNA test equipment acquire sufficient information to provide complete time and frequency domain analysis

TDR S-Parameters



Eye Diagrams RLCG

•Forward and Reverse Directions

•Transmission and Reflection Terms

•Single-ended, Differential-Mode, Common-Mode and Mode Conversion

•Eye Diagrams with “Virtual Pulse Generator”

•RLCG Transmission Line Model Extraction

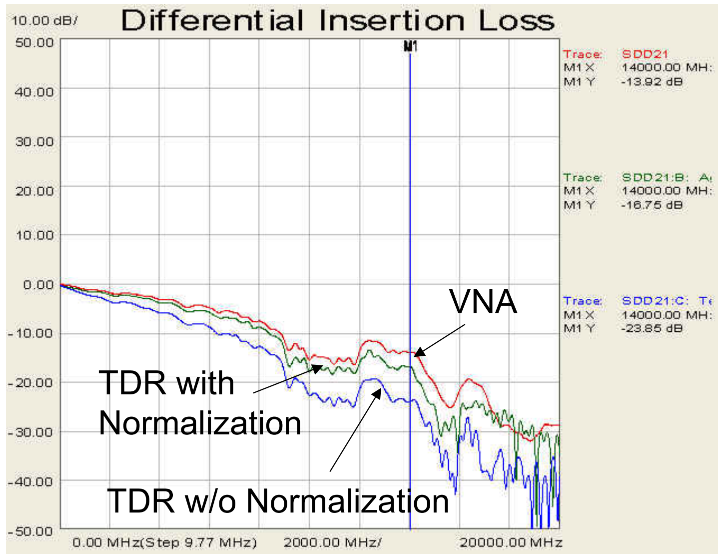
Comparing the Results

- How good are the frequency domain results from the TDR compared to the VNA?
- Comparison with and without TDR calibration
- What do you give up versus what you get?

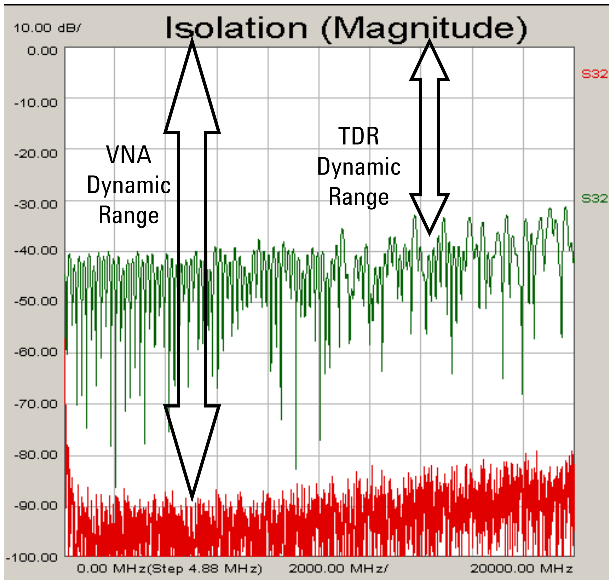
Native VNA means VNA in the frequency domain directly (sdd21 of VNA, RPC and Normalization)

Comparison of VNA & TDR with Normalization

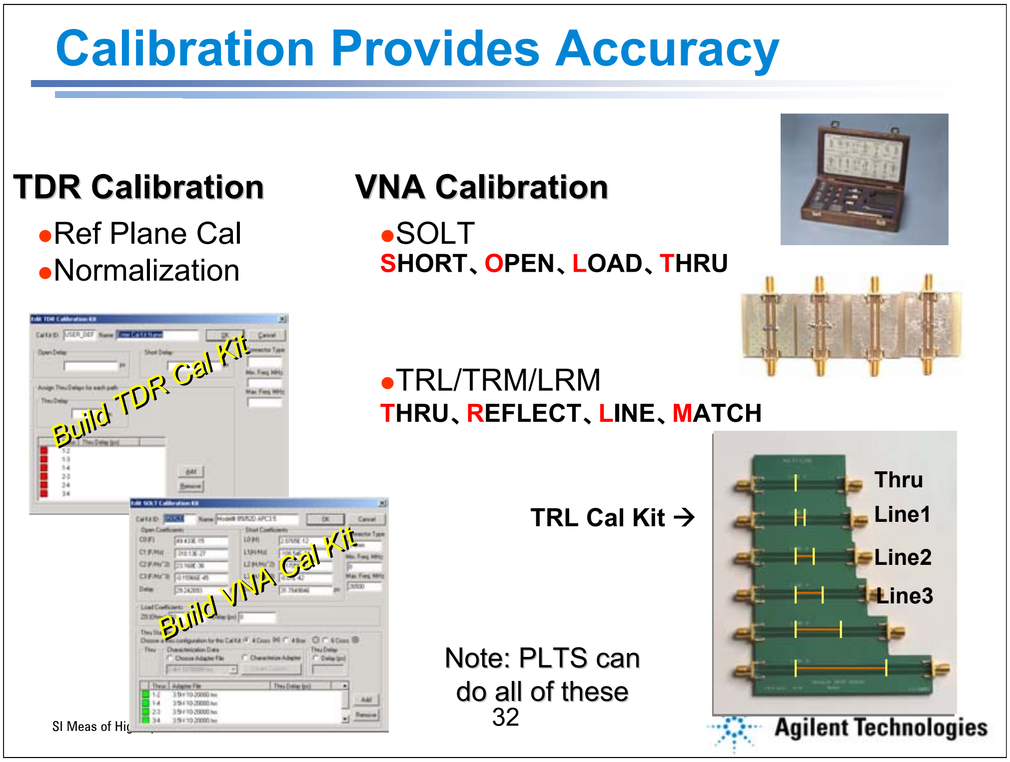
- •Data from VNA and Normalized TDR closely track
- •Normalization corrects TDR frequency response



VNA has More Dynamic Range



- What is the smallest signal measurable?
- VNA allows signal measurements down to -80dB due to narrow band tuned receiver



Calibration…why do we need it?

Types of Error Correction

There are two basic types of error correction —response (normalization) corrections,and vector corrections.

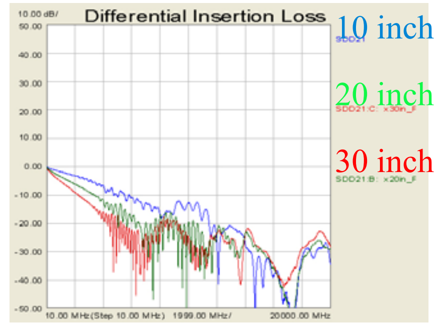
Response calibration **is simple to perform,but corrects for only a few of the 12 possible systematic error terms (namely,reflection and transmission tracking). Response calibration is a normalized measurement in which a reference trace is stored in the network analyzer 's memory,and the stored trace is divided into measurement data for normalization.A more advanced form of response calibration for reflection measurements,called open/short averaging,is commonly found on scalar analyzers and averages two traces to derive a reference trace.**

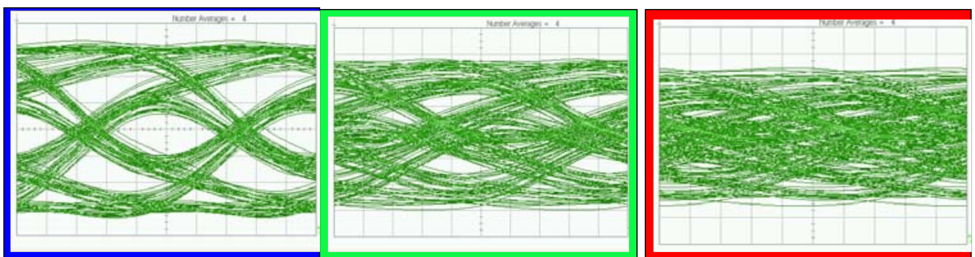
Vector error correction **is a more thorough method of removing systematic errors.This type of error correction requires a network analyzer capable of measuring (but not necessarily displaying)phase as well as magnitude,and a set of calibration standards with known,precise electrical characteristics.**

Bottom line…VNA's have a much broader range of calibrations and therefore provide superior accuracy.e

Limited BW Degrades the Data Stream

- As boards get larger and rates get faster, the bandwidth limitations (SDD21) become significant problems
- What will happen as we transmit 10 Gb/s through various lengths?





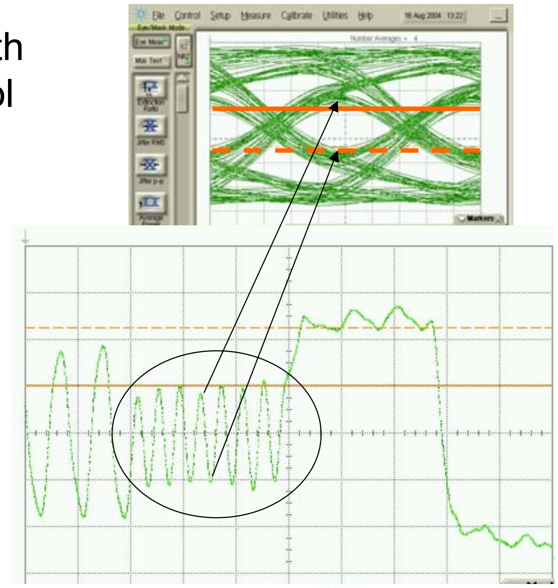
This is a place where we should push the beauty of working in both domains….I'd like to consider some native scope eyes here

Also, is there a modeling aspect to cover here?

How Does the Board Degrade the Signal?

- Reduced bandwidth leads to Intersymbol Interference problems

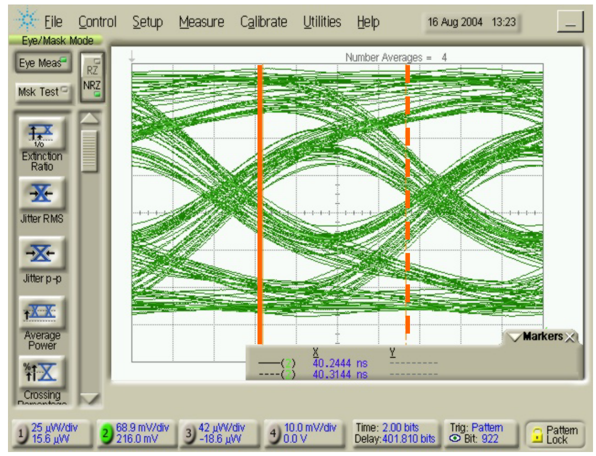
  - Signals too slow to reach 'final' amplitude (vertical eye closure)



Note:10 inch trace length

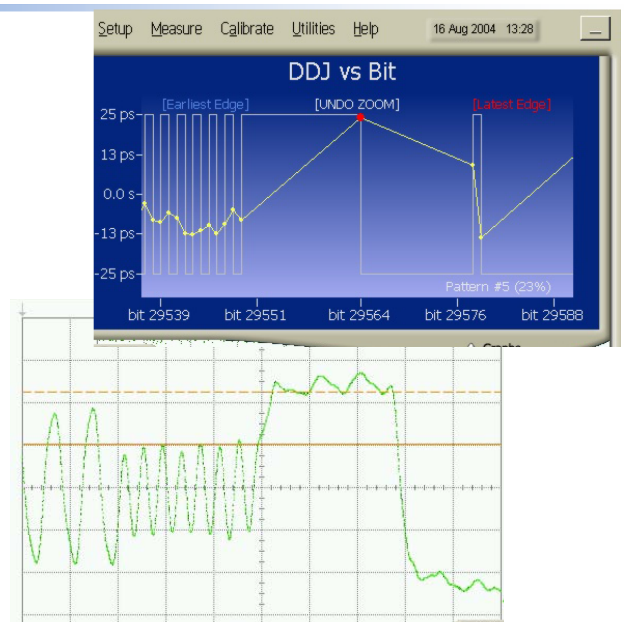
Intersymbol Interference: Jitter

- Bandwidth also has an impact on horizontal eye closure (jitter)



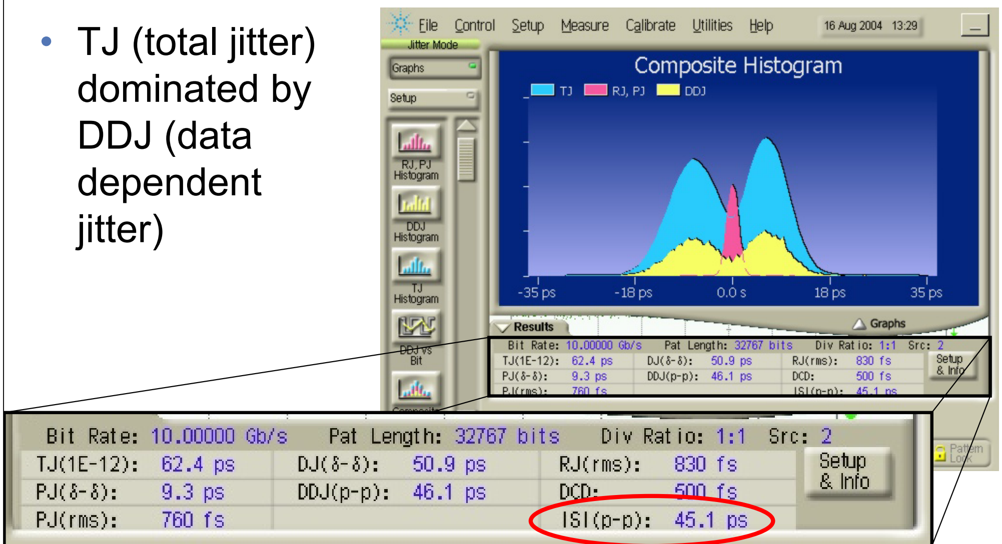
Analyzing the Jitter

- Signals begin transitions (1 to 0, or 0 to 1) from different amplitudes.
- Edges advanced or delayed (horizontal closure or jitter)



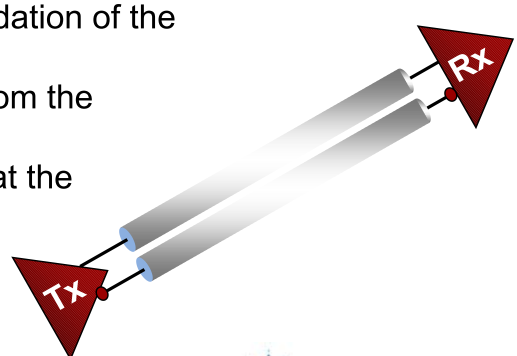
Analyzing the jitter

- TJ (total jitter) dominated by DDJ (data dependent jitter)



Possible Solutions

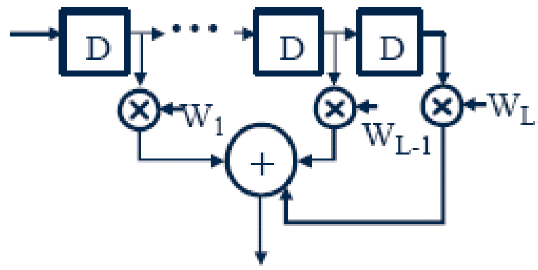
- Better board material?
  - FR4 type material still used (cost, rugged)
- Active Signal Integrity: What can be done at the transmitter or receiver to compensate for the degradation of the channel?
  - Pre-distort the signal from the transmitter
  - Reverse the distortion at the receiver(equalization)



Getek, rogers, duriod,

Receiver Equalization

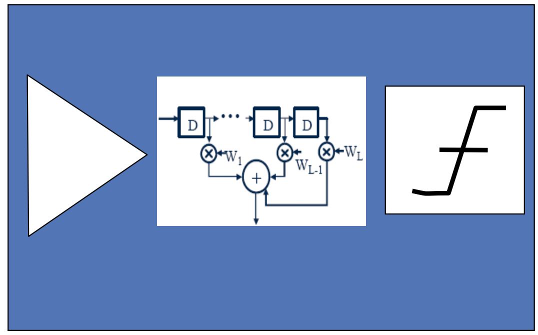
- Invert the channel frequency response and combine
  - Example: Tap off signal and feedback with various delays and weights
- Design process
  - Need to know the channel response (SDD21)



Jared Zerbe, RAMBUS

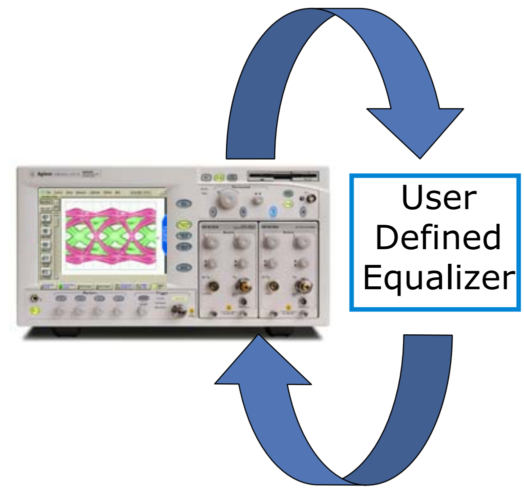
Receiver Equalizer Verification

- Hard to see how the waveform is changed (the equalizer is internal to the receiver)
- Hard to model:
  - Requires the equalizer circuit and the complete data waveform at the receiver input



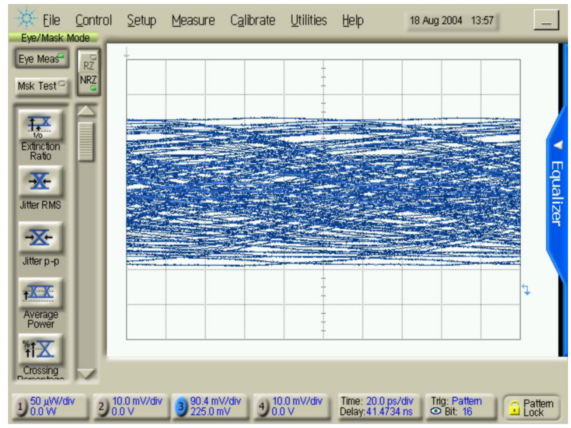
Build the Equalizer into the Scope

- Rather than port scope waveform data to a PC, put the model into the scope
- View the 'processed' waveform in real time on the scope



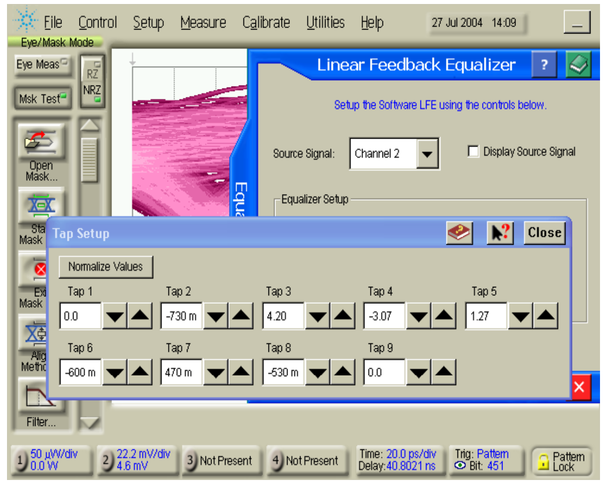
10 Gb/s Through 30 inches FR4

- Case study:
  - Opening up a completely closed eye with a linear equalizer



Verifying the Receiver Design

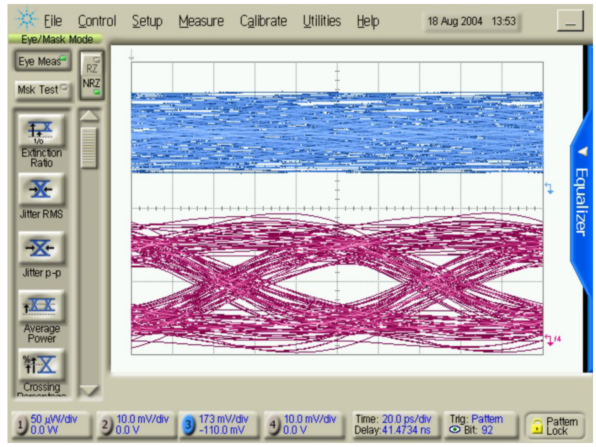
- S-parameter data defines the channel, used for equalizer design
- User implements the equalizer design in the scope
  - Number of taps, weights, and delays



May not be directly observable (at internal node)

Real Time Equalizer Analysis

- Live waveform passes through the virtual equalizer and is displayed in real time
  - Also can work for most Matlab functions



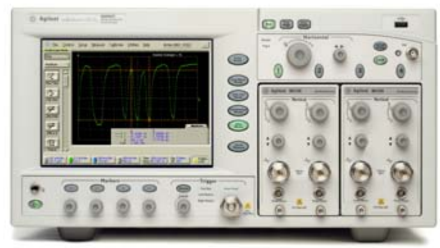
Summary

- High speed communications = hard work
- Design engineers must be comfortable in both the time and frequency domains
- Make sure you have the right tools in your toolbox

Summarize all that we talked about…

Resources

- Agilent instruments discussed today:
  - 86100C DCA-J
    - TDR with N1930A
    - Jitter Analysis
    - Equalizer Analysis
  - Physical Layer Test System



PLTS Configuration Details

Software Only
- N1930A-010 node-locked license
- N1930A-020 floating license

PNA Bundles
(PNA+ Test Set+Software)
- N1953B (10MHz to 20GHz)
- N1955B (10MHz to 40GHz)
- N1957B (10MHz to 50GHz)

Test Set Only
- N4419B (10MHz to 20GHz)
- N4420B (10MHz to 40GHz)
- N4421B (10MHz to 50GHz)

TDR
- 86100C w/54754A TDR module(s)
- CSA8000 w/80E04 TDR module(s)
- TDS8000 w/80E04 TDR module(s)