Agenda

• Full-Link KR Example
• What is a “Pathological Channel”
• Measuring Pathological Channels
• Band Limited S-Parameters
• Using the Pulse Response to Gain Insight

BREAK

• Serial Link Equalization Techniques
• Simulating with IBIS-AMI Models
• Test Strategies for Pathological Channels
• Test Cases Simulated
• Test Cases Measured Internal Eye
• Summary
Using Single Pulse Response to Gain Insight of the Channel

- Tim Wang Lee, Wild River Technologies

Frequency Domain

Single Pulse Response of a Channel

Time Domain

dB(S21)

Lossless

Lossy

DesignCon 2017

JAN 31-FEB 2, 2017
The Impulse Response Characterizes a Channel

In an LTI system, the impulse response characterizes the system completely.

\[ y(t) = x(t) * h(t) \]

*: Convolution operator

The Single Pulse Response of a Channel

Single pulse function

\[ p(t) \]

**width**$_{pulse}$ = \( \frac{1}{\text{data rate}} \)

Pulse height: depends (NRZ/PAM4)

When using NRZ, the response is the single **Bit** response.

Single pulse response properties:
- Is a deconstructed eye.
- Shows effect of equalization.
- Gives insights to reflection and crosstalk.
- Helps characterize frequency-dependent loss.

\[ q(t) = p(t) * h(t) \]
Frequency Spectrum of the Single Pulse

Single pulse function

Linear Time-Invariant

Channel: \( h(t) \)

Investigate on different loss mechanisms:
- Conductor loss
- Dielectric

Fourier Transform

Single pulse Response

Fourier Transform

freq, Hz

1E9 1E10 1E11

1E9 1E10 1E11

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Single Pulse Response Conductor Loss Signature

TX: 32 Gbps ($f_0=16$ GHz), Rise Time: 15 psec
T-Line: 5 inch, microstrip FR4 50 Ohm ($w = 20$ mil)

\[
Loss_{\text{cond}} \approx \frac{\text{len (inch)}}{w \text{ (mil)}} \sqrt{f} = 1 \text{ dB} |_{16 \text{ GHz}}
\]

Pulse Response vs. Cond. Loss

Single Pulse Response Dielectric Loss Signature

TX: 32 Gbps ($f_0=16$ GHz), Rise Time: 15 psec
T-Line: 5 inch, microstrip FR4 50 Ohm (Dk = 4)
Df = 0~0.02, 0.05 step.

$$\text{Loss}_{\text{diele}} \approx \text{len} \cdot f \cdot (\text{GHz}) \cdot 2.3 \cdot Df \cdot \sqrt{Dk}$$

Loss in a channel -- Rule of Thumb -- 9

Single Pulse Response Example with WRT ISI-32

ISI 13-inch channel

Rule of thumb:
loss ~ 0.1 dB/inch/GHz
Expect: ~16 dB at 16 GHz

-15 dB at 16 GHz
Single Pulse Response Mismatch Signatures

TX: 32 Gbps, Rise Time: 15 psec
T-Line: 1 inch, microstrip FR4
50 Ohm, lossless
UI: 31.25 psec

One way delay = ~ 0.167 nsec
Round Trip delay = ~ 0.33 nsec

“Ghosts (bits) from the past.”

R_Source | R Mstrip | R_Term
20 Ohms | 50 Ohms | 10~70 Ohm
Examine Single-ended Crosstalk With Step Response

T-Line: 1 inch, microstrip FR4, 50 Ohm, lossless

One way delay \(~0.167\) nsec

Lenz’s Law: induced current opposes the change of current

S = 1W
Two Steps Make a Single Pulse Crosstalk Signature

At Tx

T-Line: 1 inch, microstrip FR4
50 Ohm, lossless
Single-ended channel

Tx Rx

S = 1W

At Rx

Not a trivial signature.
Imagine with loss.
Single Pulse Response Example: WRT XTALK-32

The general shape is identical to what we expected, but not the sign. Why?

Differential signaling!

We learn a lot more by exercising engineering knowledge and safe simulation.
Summary on Single Pulse Response

Single Pulse Response
(NRZ: Single Bit)

- Gives quick insight to the resulting eye.
- Identifies loss, mismatch and mismatch.
- Understand the effect of different equalization.
Resources

- Wild River Technologies
  - Booth #850

- Impulse response and signal integrity

- Impulse response and linear system
  - Dennis Freeman. 6.003 Signals and Systems. Fall 2011. Massachusetts Institute of Technology: MIT OpenCourseWare, https://ocw.mit.edu. License: Creative Commons BY-NC-SA.
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• Full-Link KR Example
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• S-Parameter Data Mining
• Measuring Band Limited S-Parameters
• Using the Single Pulse Response to Gain Insight

■ BREAK

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• Strategies for managing Pathological Channels
• Test Cases Simulated
• Test Cases Measured Internal Eye
• Conclusion
Single Pulse Response and Equalization

Tim Wang Lee, Wild River Technologies

**Linear Time-Invariant Channel**

![Diagram of Linear Time-Invariant Channel](image)

**CTLE**

![Graph of CTLE with voltage vs. time](image)

**FFE**

![Graph of FFE with voltage vs. time](image)

**DFE**

![Graph of DFE with voltage vs. time](image)
Looking at a Real Channel, ISI and the Root Cause

What's the root cause of ISI?

Input pulse waveform

BR: 32 Gbps
f₀ = 16 GHz
RT: 15 psec

A 13 inch stripline channel

Single pulse response

What's the root cause of ISI?
Frequency-dependent Loss Causes ISI

- ISI After measured channel
- No ISI After simulated channel

Equalization

Need to equalize the frequency dependent loss.
### Different Equalization Approaches

<table>
<thead>
<tr>
<th>Continuous Time Linear Eq.</th>
<th>Feed Forward Eq.</th>
<th>Decision Feedback Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear</td>
<td>Linear</td>
<td>Non-Linear</td>
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<tr>
<td>Analog</td>
<td>Digital</td>
<td>Digital</td>
</tr>
<tr>
<td>Only post cursor</td>
<td>Pre and post cursor</td>
<td>Only post cursor</td>
</tr>
<tr>
<td>Tx* or Rx</td>
<td>Tx* or Rx</td>
<td>Rx</td>
</tr>
</tbody>
</table>

*Need a back channel*
Linear Equalization at Rx and its Influence on Crosstalk

Assume channels are symmetric, and equalization is linear.

How about EQ at Tx?

x1, x2, y1, y2 are signals, and the blocks represent the transfer functions of each structure respectively.
Linear Equalization at Tx and its Influence on Crosstalk

Assume channels are symmetric, and equalization is linear.

Equalization at Tx can affect system crosstalk level.

Given the same channel, crosstalk is sensitive to EQ location if two adjacent channels require different EQ.
Summary of Equalizers and Priorities

Which tool do you grab first, and when?

**Tx Equalization**
- Power limitation
- Adaptation to channel
- System crosstalk level

**Rx Equalization**
- Noise amplification
- Implementation complexity
- Signal to noise ratio

Channel

+ Noise
+ Crosstalk voltage

Start here!
The goal of CTLE is to create a high-pass filter that complements the loss-pass nature of the channel.
Flattened Channel Response after CTLE

Construct transfer function from high pass filter $1/S_{21}$:

$$H(s) = \frac{A(s)}{B(s)} = K \frac{(s + z_1)}{(s + p_1)(s + p_2)}$$

- $z_1 = 2\pi \cdot (3.8 \text{ GHz})$
- $p_1 = 2\pi \cdot (50 \text{ GHz})$
- $p_2 = 2\pi \cdot (51 \text{ GHz})$

Can use transfer function to construct passive or active analog CTLE filter.

Result CTLE Filter

Response after CTLE filter
Eye closes if there is 2-3 UI leakage in single pulse response.

Normalized Single Pulse Spectrum

After Lossy Channel
With CTLE
Lossless
Feed Forward Equalizer at TX

Lossy Channel Single Pulse Resp.

Pre-cursor  Post-cursor

Pre-distorted pulse at Tx

Power Spectrum (dB)

De-emphasis
Pre-emphasis

Channel Frequency Resp.

Need a back channel!

Feed Forward Equalizer Algorithm

Caution!

Delay

C1  C2  C3

Taps

Delay

Delay

Channel Frequency Resp.

S21 (dB)
Single Pulse Response and FFE

After Lossy Channel
With CTLE
Lossless
Decision Feedback Equalizer

Lossy Channel Single Pulse Resp.

Received Waveform

Voltage (V)

34.0 34.1 34.2 34.3 34.4

Non-linearity

Voltage (V)

34.0 34.1 34.2 34.3 34.4

Power Spectrum (dB)

1E9 1E10 1E11

freq, Hz

Lossless channel

Symbol Detector

With DFE

After Lossy Channel

Feedback Decision Algorithm

Received Waveform

Voltage (V)

34.0 34.1 34.2 34.3 34.4

Non-linearity

Voltage (V)

34.0 34.1 34.2 34.3 34.4

Power Spectrum (dB)

1E9 1E10 1E11

freq, Hz

Lossless channel
Summary of Equalization

• EQ equalizes the frequency-dependent spectrum.
• Equalization at Tx can affect system crosstalk level.
• Use analysis and simulation with Tx/Rx IBIS-AMI models to determine what EQ to use and where.

When it comes to EQ, one size does not fit all.
Resources

- Wild River Technologies
  - Booth #850

- Equalization Techniques