Presentation to IEEE P802.3ap Backplane Ethernet Task Force
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Title: **PAM-4 versus NRZ Signaling: "Basic Theory"**

Source:

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Abstract: This contribution analyzes the conventional argument for PAM-4 as a solution for high loss channels, which does not correlate with observed simulation behavior. Theory is developed to explain simulation behavior.

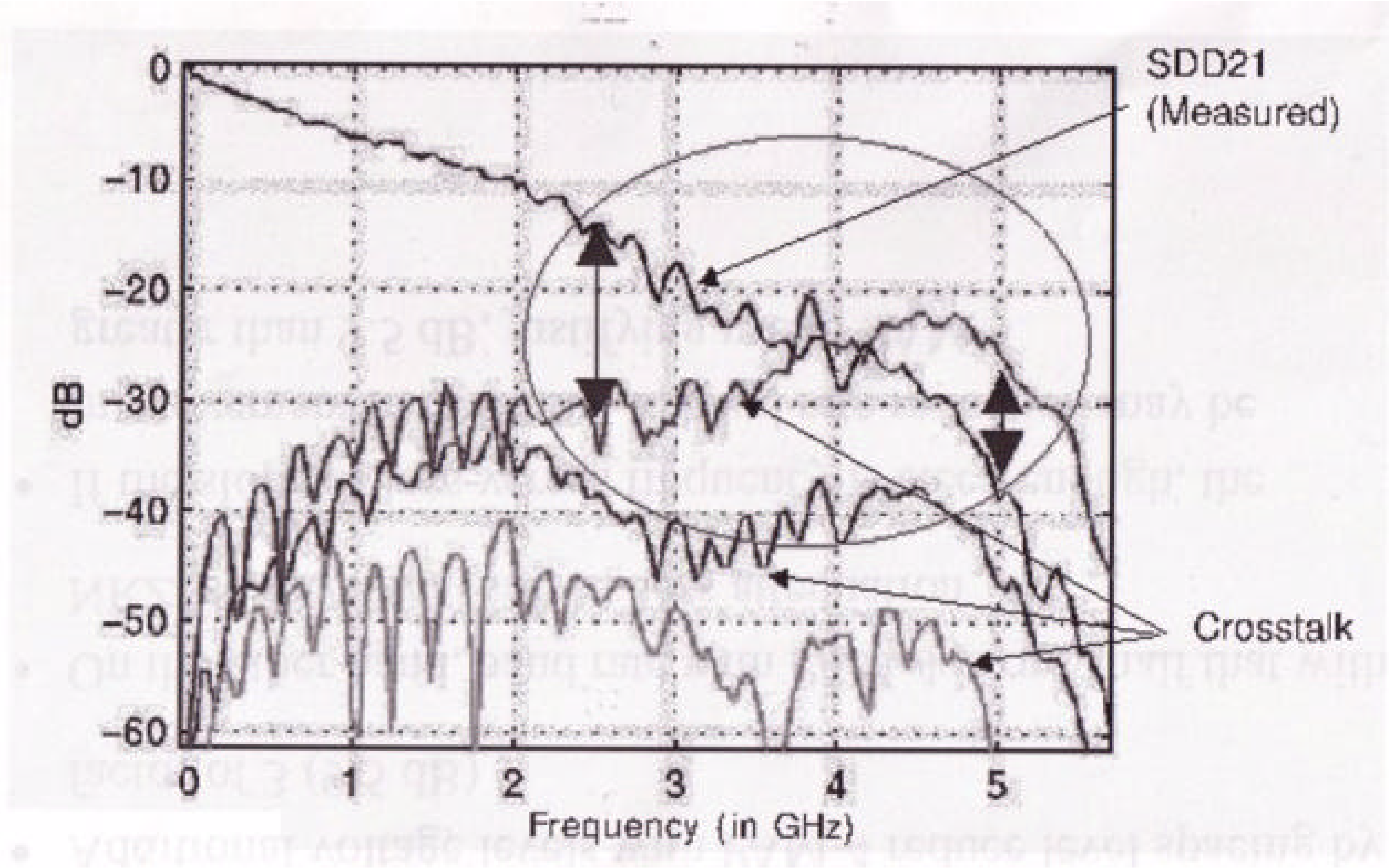
In the absence of a fundamental advantage of PAM-4 over NRZ signaling in 10 Gbps Ethernet over Backplane applications, practical considerations are provided for remaining with NRZ signaling.

Conventional Argument for PAM-4

- **Additional voltage levels with PAM-4 reduce level spacing by a factor of 3 (9.5 dB).**
- **Baud rate with PAM-4 is half that of NRZ, so the signal suffers less attenuation.**
- **If the slope of loss versus frequency is steep enough, the improvement in SNR due to baud rate reduction may be greater than 9.5 dB, justifying use of PAM-4.**

Example Channel at 10 Gb/s

Following figure from hoppin_01_0104 presented in January, 2004 Interim Study Group illustrates the conventional wisdom:



Loss at 5 GHz is 24 dB higher than at 2.5 GHz => use PAM-4.

Important Questions

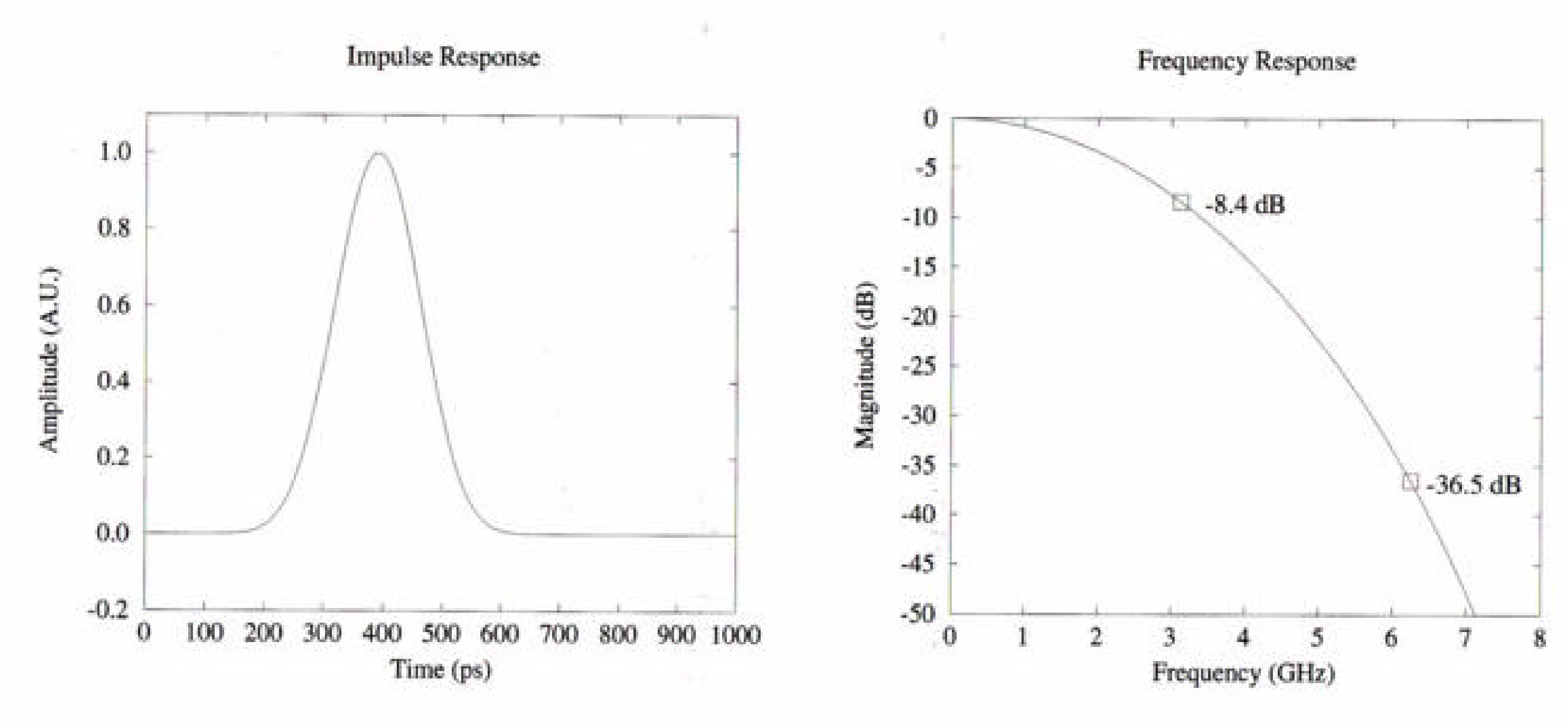
- Simulations performed by IBM Research do not correlate with this conventional wisdom.
  - Simulations performed on customer backplanes.
  - Backplanes designed for 5 Gb/s (i.e. legacy at 10 Gb/s).
  - Slope of loss such that SDD21 difference >> 9.5 dB.
  - None of the cases simulated to date have shown any significant advantage for PAM-4 signaling over NRZ signaling.
- WHY?

Analysis Approach

- **Approach used to answer these questions:**
  - **Study simplified channel models.**
  - **Turn off jitter and voltage noise sources in simulations.**
  - **Use large numbers of taps (e.g., up to 20) in DFE so that performance is best possible (not limited by implementation).**
  - **Fixed receiver gain at unity.**
- **Analysis goal is to focus on a basic comparison of signaling methods in relation to the SDD21 loss curve.**

Counter Example to PAM-4 Argument

Consider channel with 25th-order Bessel filter response



Loss in this example is 28dB greater at 6.25 GHz than at 3.125 GHz.

Bessel Filter Simulation Results

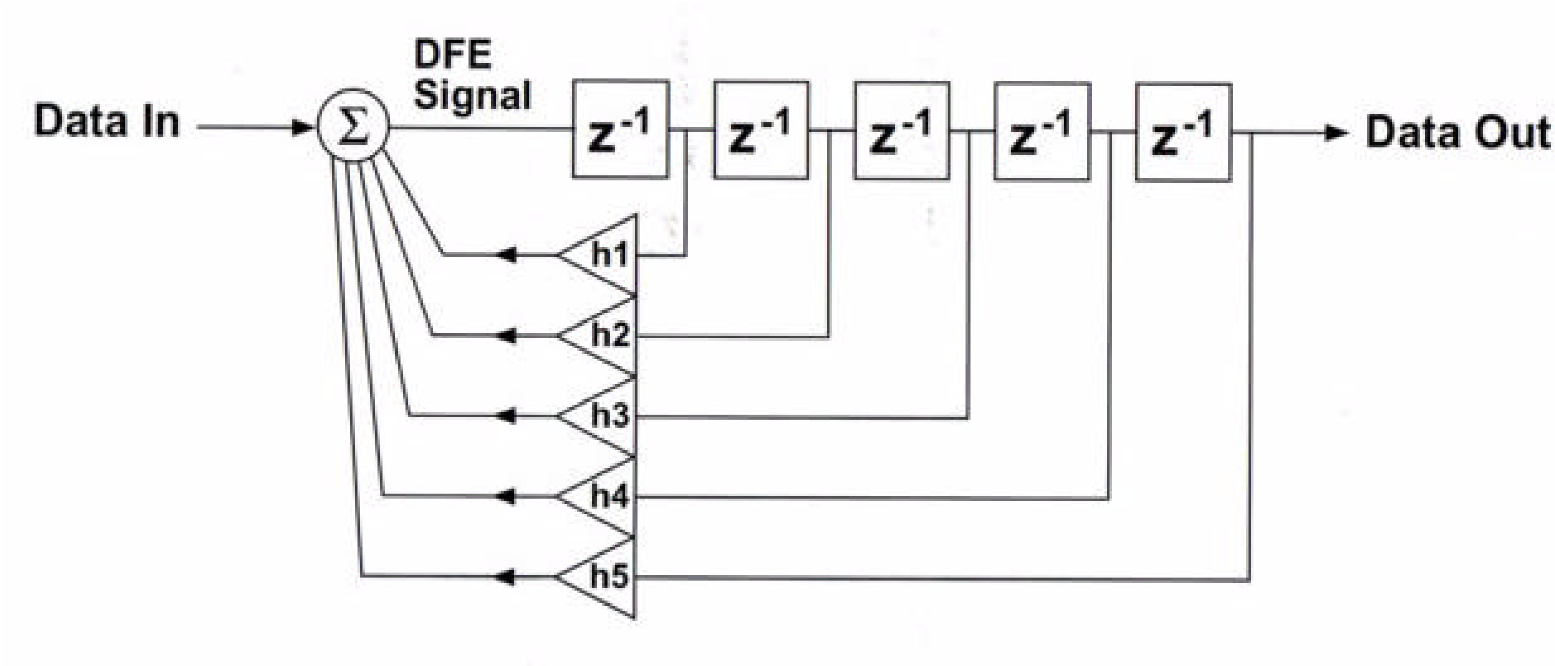
- Bessel Filter has low loss at frequency of interest for PAM-4, but loss gets dramatically larger within band of interest for NRZ. Should be a prime candidate for PAM-4 given the loss characteristics of the channel.

- PAM-4 Simulation Conditions: no FFE, 2-tap of DFE
  - Vertical Eye = 137 mV
  - Horizontal Eye = 50 ps

- NRZ Simulation Conditions: no FFE, 2-tap of DFE
  - Vertical Eye = 265 mV
  - Horizontal Eye = 60 ps

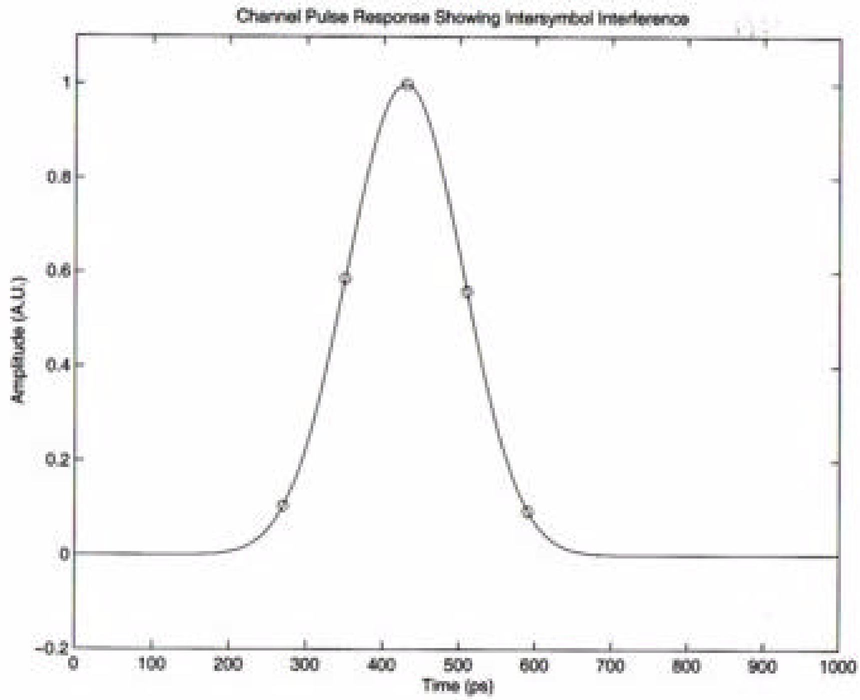
- NRZ Eye is larger despite conventional wisdom.....

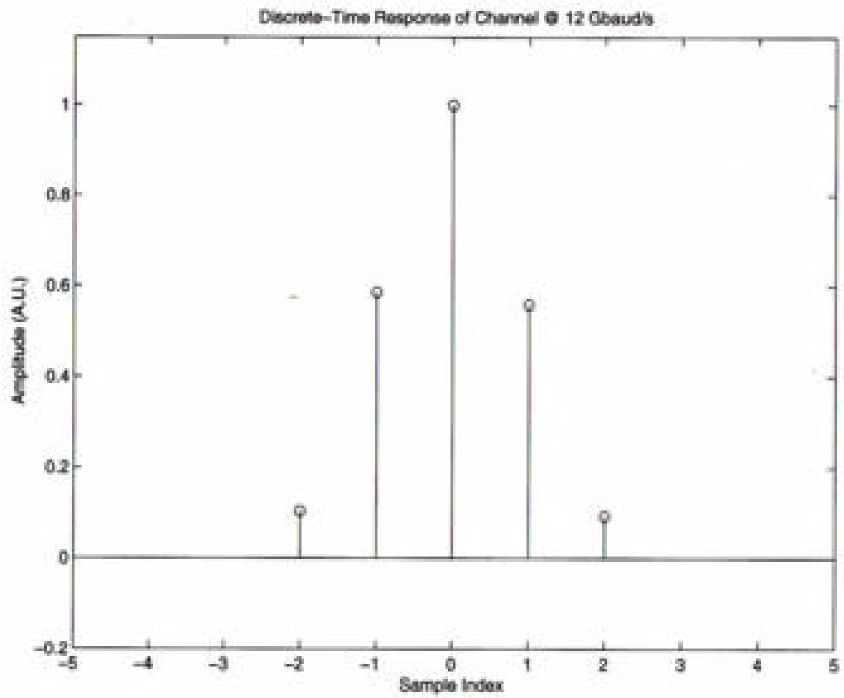
Conventional Argument Breaks Down with DFE



- DFE feedback used to cancel intersymbol interference due to "post-cursors" in channel impulse response.
- Elimination of these post-cursors modifies (i.e. equalizes) frequency response without amplifying noise or crosstalk.

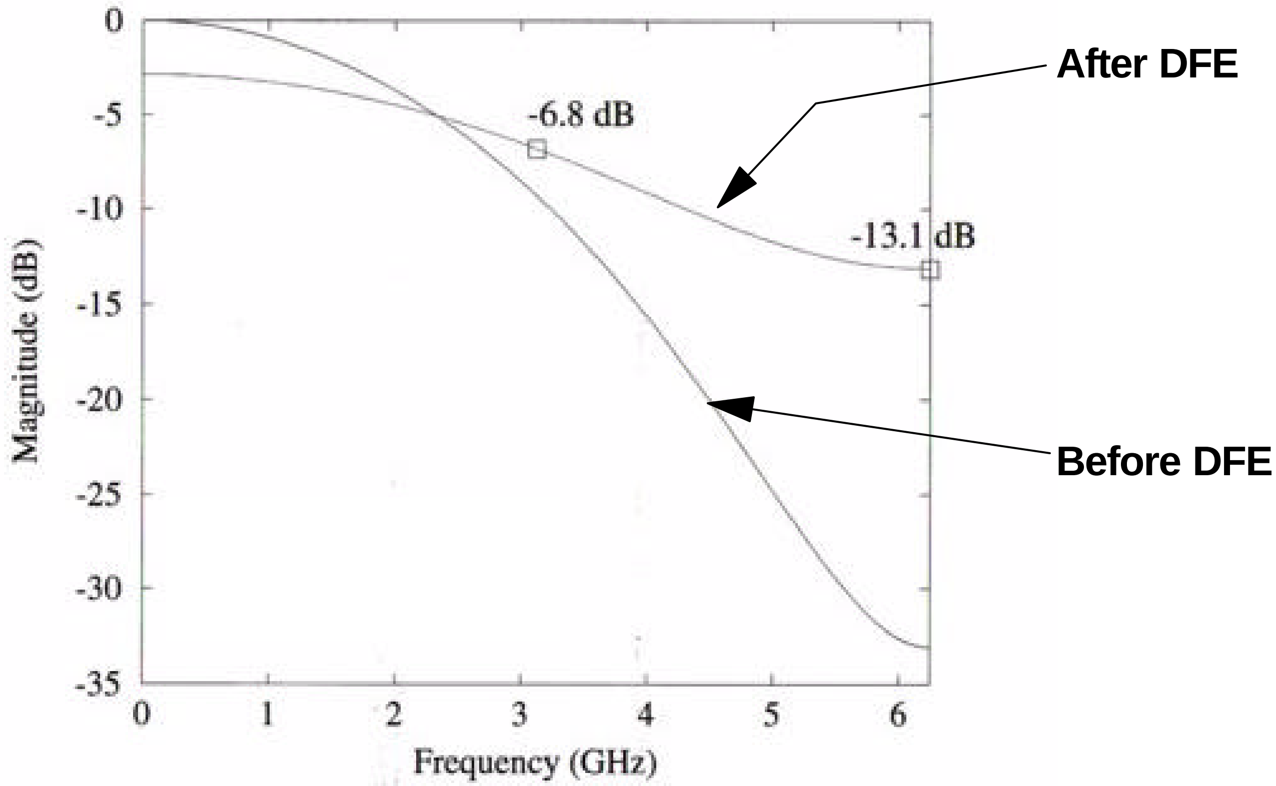
Sampled Response: Bessel Filter Channel





- To observe effect of DFE, compare discrete Fourier transforms of sampled response before and after eliminating post-cursors.

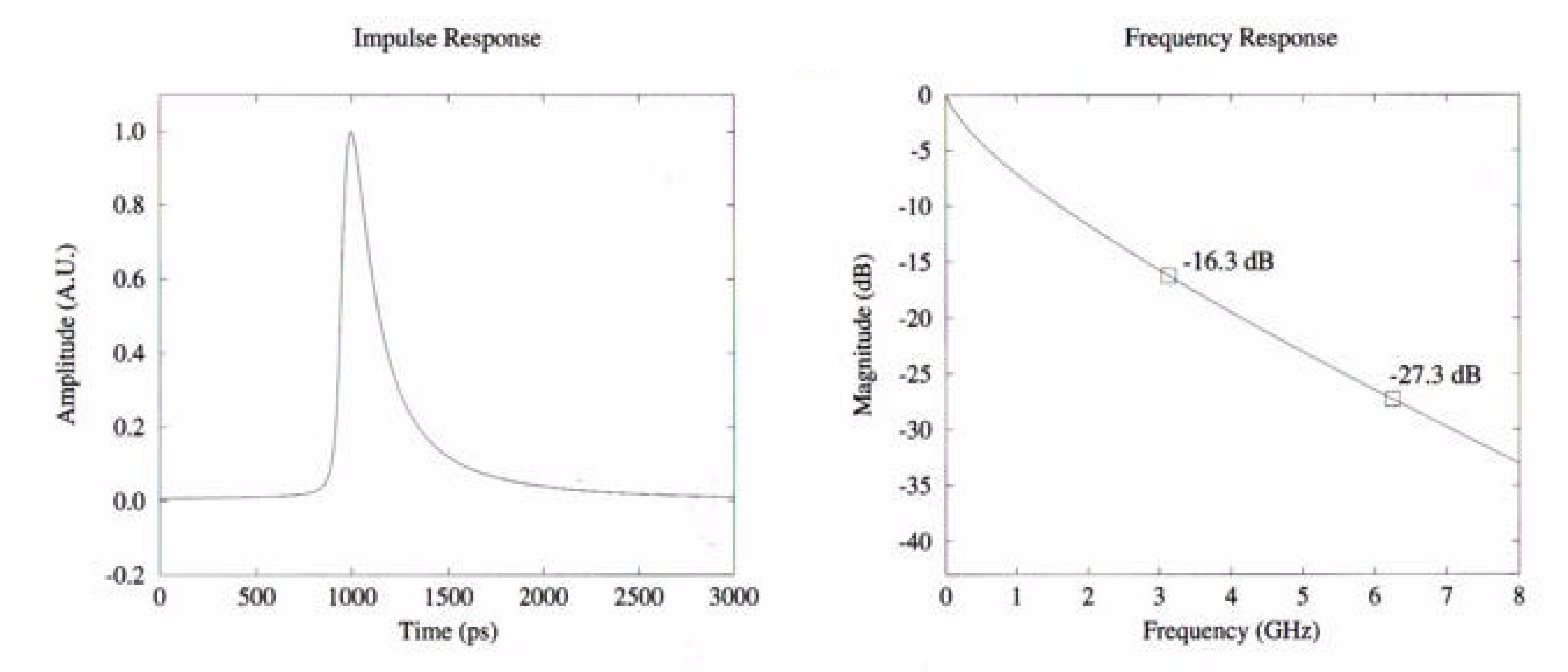
Impact of DFE on Channel Response



- DFE flattens channel response so that loss at 6.25 GHz is only 6.3 dB greater than at 3.125 GHz.
- Result is that NRZ performs better than PAM-4.

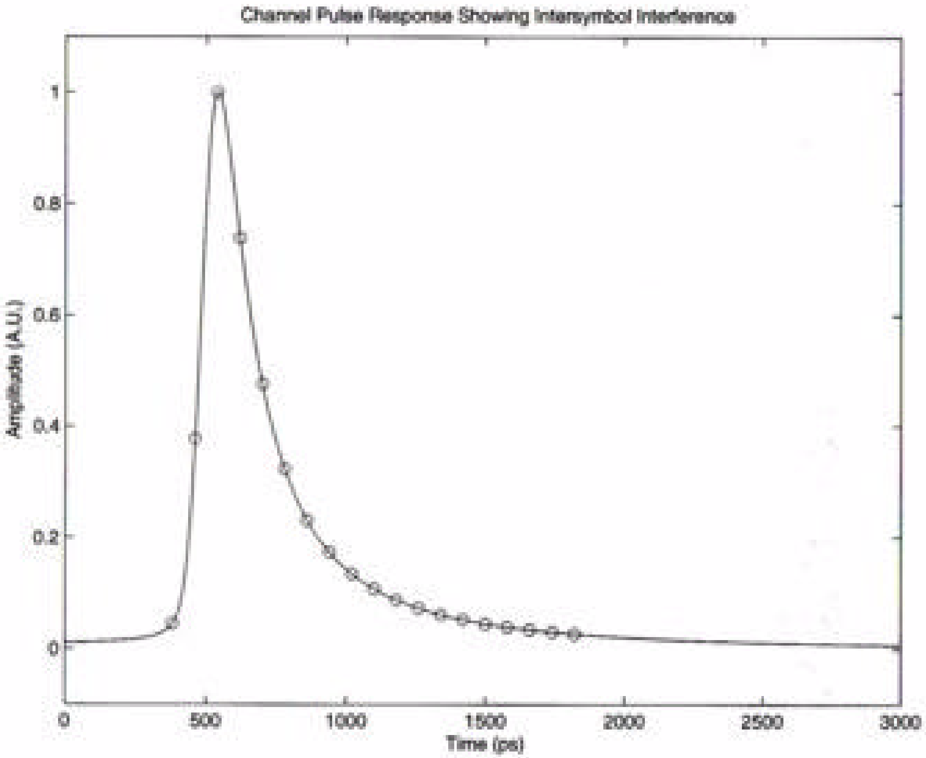
Lossy Transmission Line Channels

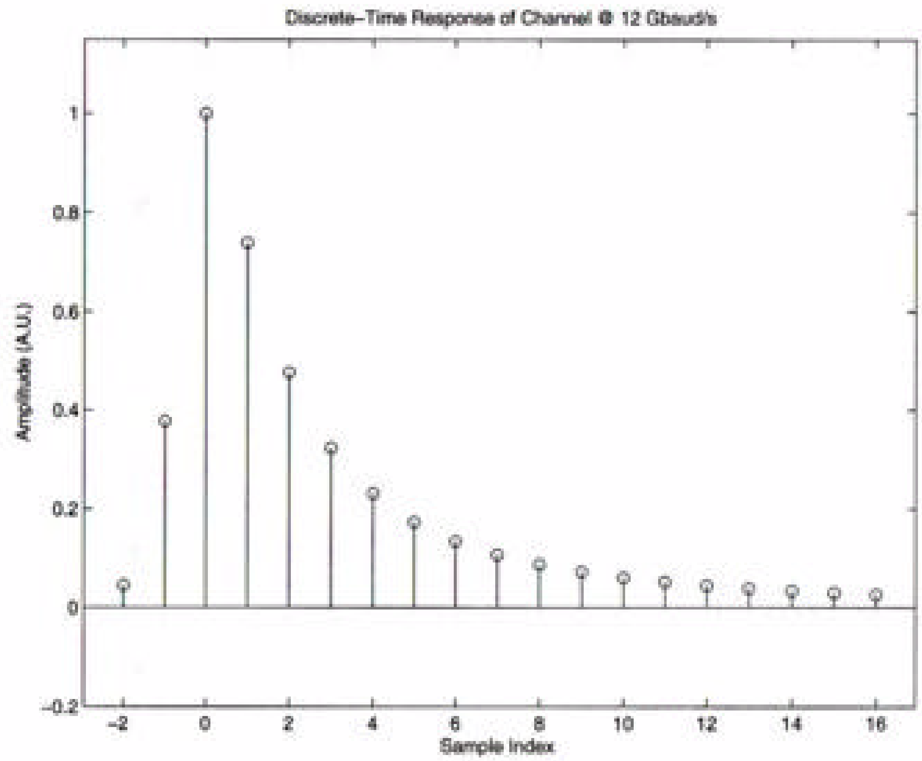
Consider lossy transmission line channel: 50" Nelco (w/o package)



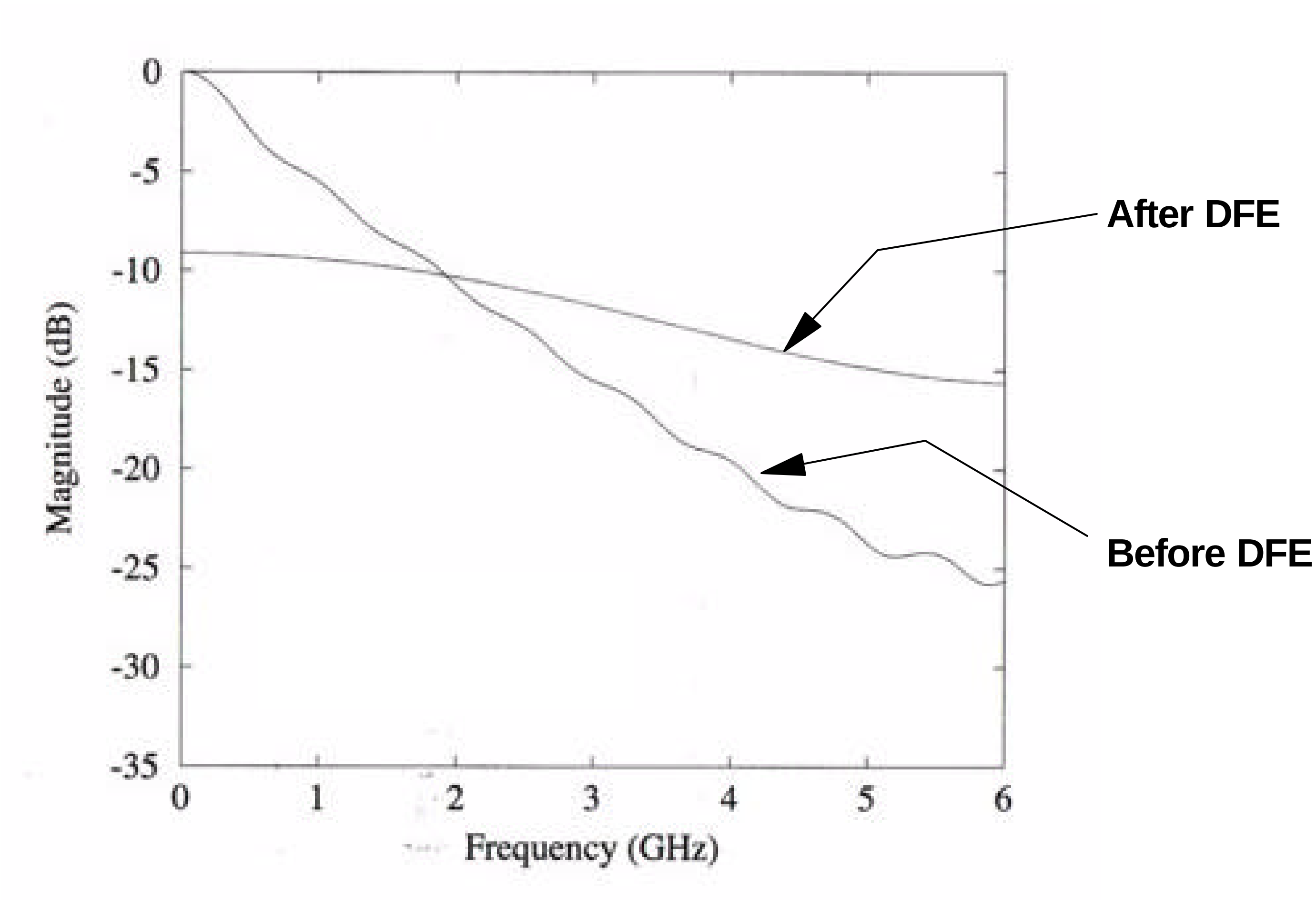
Loss in this example is 11dB greater at 6.25 GHz than at 3.125 GHz.
(Should be a candidate for PAM-4.)

Sampled Response: 50" Nelco Line (w/o Package)





Impact of DFE on Channel Response



- DFE flattens channel response of 50" Nelco line.

50" Nelco Line Simulation Results

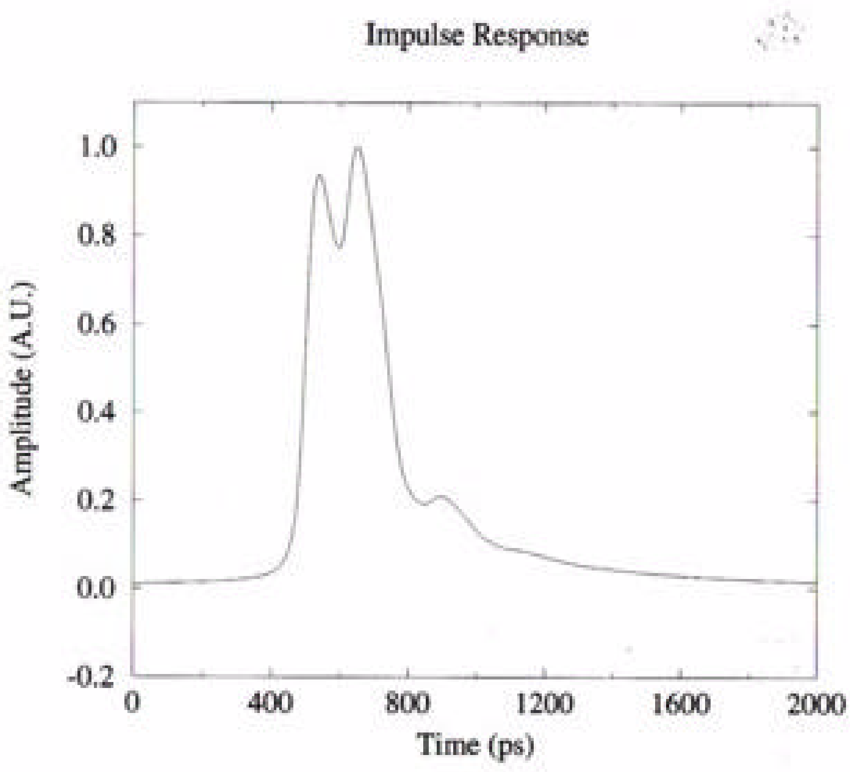
- **PAM-4 Simulation Conditions: 4-tap FFE, 8-tap of DFE**
  - **Vertical Eye = 65 mV**
  - **Horizontal Eye = 50 ps**

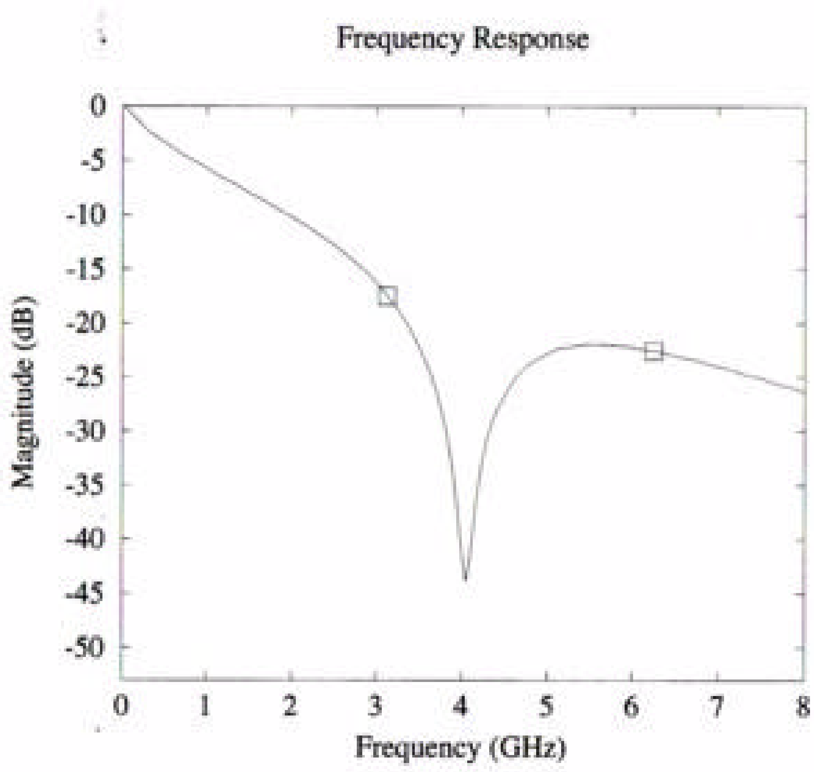
- **NRZ Simulation Conditions: 4-tap FFE, 20-tap of DFE**
  - **Vertical Eye = 84 mV**
  - **Horizontal Eye = 65 ps**

- **Once again NRZ Eye is larger despite conventional wisdom.....**

Transmission Line With Stub

Consider 40" Nelco line with 1 cm stub (w/o package)





Note notch at 4 GHz above range of interest for PAM-4.

Transmission Line with Stub Simulation Results

- Conventional wisdom is that notch is above frequency range of interest for PAM-4, but will impact NRZ performance.

- PAM-4 Simulation Conditions: 4-tap FFE, 10-tap of DFE
  - Vertical Eye = 77 mV
  - Horizontal Eye = 40 ps

- NRZ Simulation Conditions: 4-tap FFE, 20-tap of DFE
  - Vertical Eye = 82 mV
  - Horizontal Eye = 50 ps

- Once again NRZ Eye is larger despite conventional wisdom.....

Conclusion on NRZ vs. PAM Theory

- Conventional argument for using PAM-4 in high loss channels breaks down when DFE is being used in the system.
  - DFE flattens channel response without boosting noise or crosstalk.
- Analysis is consistent with observed simulation results for customer backplanes.
  - There is no significant advantage for PAM-4 over NRZ for any of the backplanes simulated by IBM to date.
- Analysis is consistent with hardware evaluations performed in customer labs.
  - Performance differences driven by implementation points
    - High performance NRZ implementation outperforms moderate performance PAM implementation, & vice-versa
- PAM does not offer a fundamental advantage over NRZ in backplane applications
  - In majority of cases NRZ has the performance advantage

Practical Considerations

- NRZ has proven to be a viable long-term technology
  - 20 Kbps signaling channels (RS-232-C) in 1969
  - >40 Gbps devices (OC768) shipping in production today
- High speed NRZ serdes cannot be displaced by PAM serdes in today's critical applications
  - 10Gbps Line Interfaces (XFP based Ethernet, FCS, OC192)
  - Area/power optimized chip to chip interfaces
  - Backplane extensions (VCSEL driven rack to rack interfaces)
- NRZ is shown to be extendable well into the future
  - >100 Gbps serdes circuits operational in labs today
  - Polymer embedded (in FR4) waveguide backplanes operational in labs today

The Case for Extending NRZ

- Extending NRZ provides synergy throughout the system design
  - Backwards interoperability to legacy interfaces with implementation of a single signaling type
  - Interoperability with 10 Gbps short reach interfaces
  - Straightforward auto-negotiation to 1Gbps Ethernet & XAUI over backplane
  - Backplane extensions with NRZ retimers and/or optical ribbon
- Extending NRZ provides synergy in development & test
  - Lab equipment
  - Manufacturing testers
  - Signal integrity skills
- Extending NRZ is consistent with other standards direction
  - 11 Gbps OIF CEI SR & LR
  - InfiniBand Technology Quad Data Rate
  - Fibre Channel 8.5 Gbps

Issues with PAM

- Can it be extended?
  - To advanced technologies with ever decreasing voltages?
    - PAM Vertical eye shuts down ~67% due to multiple levels
  - To higher data rates?
    - PAM Horizontal eye shuts down ~50% due to edge crossings

- Can it achieve high integration?
  - Switch chips exceeding 200 channels per device?
  - High integration ASICs with 10's or 100+ channels, inclusion of other NRZ serdes (PCI Express, XFI), a multitude of high speed SRAM banks, high frequency HSTL & other I/O external interfaces - at a design point operating off a 1.0V VDD supply?

- Does it fit the application?
  - PAM is suitable for 1000BaseT type applications where significant power & area can be dedicated to signal processing for integration of 1 to 4 channels in line card applications.
  - That's not the environment of backplane switches

Conclusion on NRZ vs. PAM Positioning

- NRZ is a long standing technology with proven extendability
  - Operating in excess of 100Gbps today
- 10+ Gbps NRZ technology will be developed (for XFI & other requirements) regardless of 10G EoBP signaling direction
  - NRZ based 10G EoBP would leverage these developments
  - PAM based 10G EoBP would compete for resources with this development, increasing TTM for both.
- PAM does not have a fundamental advantage over NRZ
  - No motivation to switch exists unless a SIGNIFICANT and SUSTAINABLE advantage can be shown
- The long term viability of PAM is a complete unknown
  - High integration in low voltage ASICs at 90nm and beyond
  - Extensions to higher speeds stressing an already compressed jitter budget