Title: Overview of Signaling and Equalization Methods Considered in OIF and IEEE 802.3 ap for 6G and 10 Gbps

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LSI Logic

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Abstract:
The presentation gives an overview and comparison of signaling methods and equalization techniques considered for backplane transceivers at 6 and 10 Gbps in other standards bodies. In particular, NRZ, PAM-4 Duobinary, and PR4 are the signaling schemes considered and linear and decision feedback equalization are discussed.

Introduction

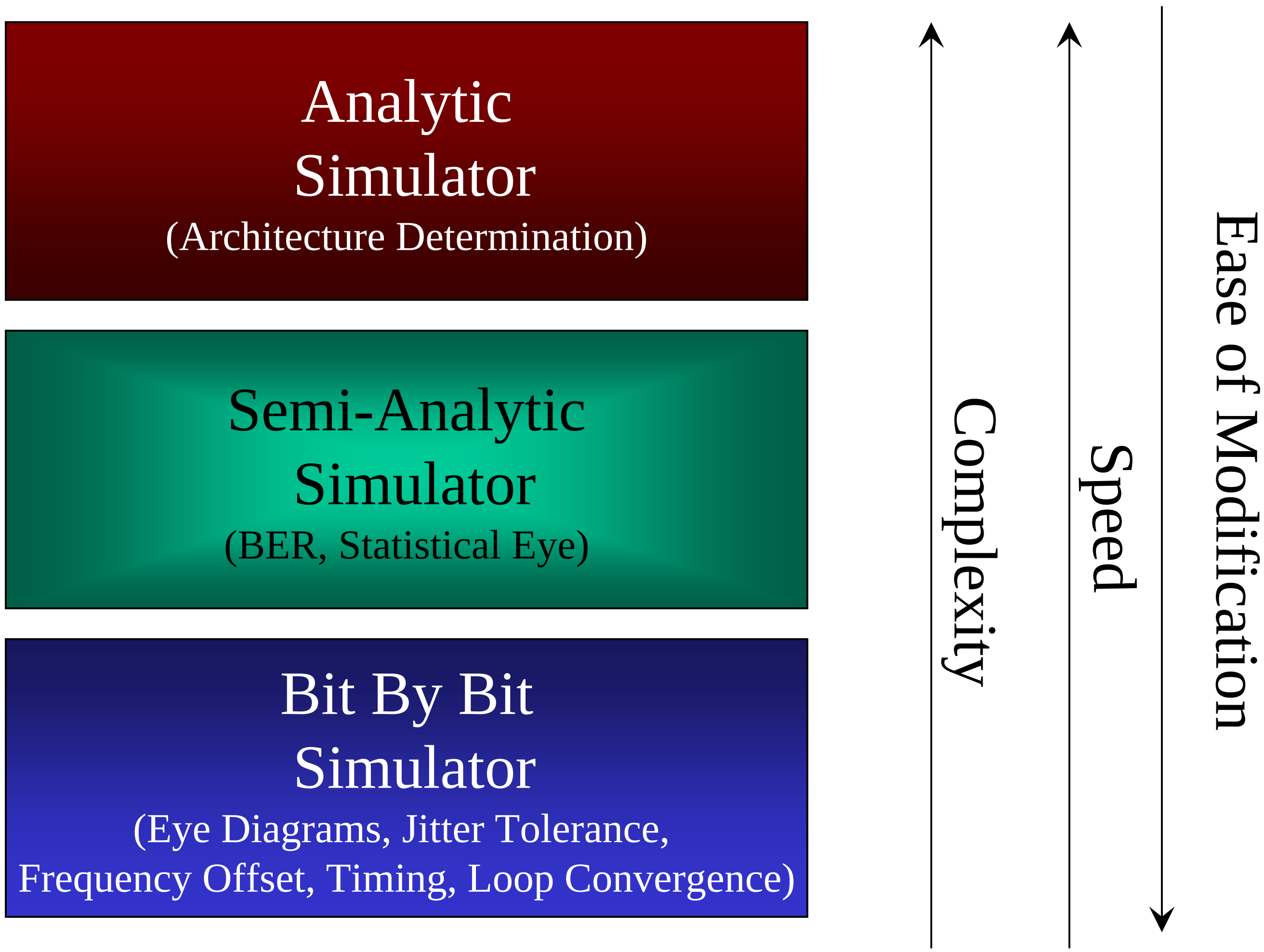
- Many signaling techniques have been examined
  - NRZ
  - PAM-4
  - Duobinary
  - PR4
- Several equalization techniques have been considered
  - FIR linear filter on TX or RX
  - Continuous time linear equalizer in Rx
  - Decision Feedback Equalizer in Rx

Introduction

- Simulation Model Overview
- Linear Equalizer versus Decision Feedback Equalization (DFE)
- NRZ vs. PAM-4
- NRZ, Duobinary, and PR4

Simulator Overview

Three System Modeling Approach



Analytic Model

- Includes
  - Inter-symbol Interference
  - Tx Jitter
  - Electronics (White) Noise
  - Crosstalk
- Does Not Include
  - Receiver Sensitivity
  - Duty Cycle Distortion
  - Other Sources of DJ

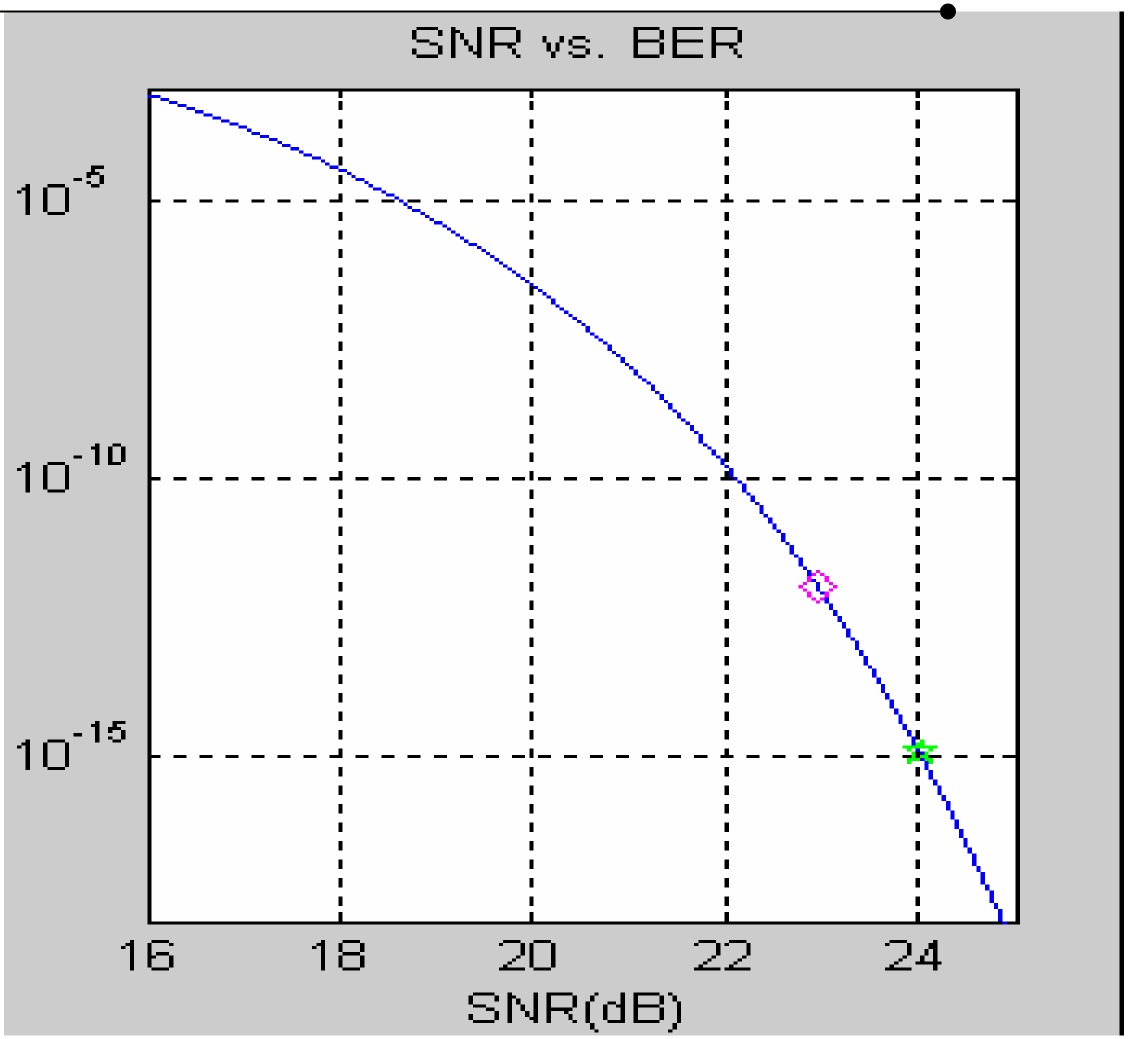
Required SNR

SNR Required at Slicer for 10^{-15} BER

$$SNR = \frac{d_{\min}^2}{\sigma^2}$$

$$\Pr_{err} \approx \frac{1}{2} erfc\left(\frac{\sqrt{SNR}}{2\sqrt{2}}\right)$$

- Approximately 24dB is required for an error rate of 10^{-15}



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Overview of Simulations

- Equalization architectures with a linear FIR feedforward (FF) filter in the TX, and a decision feedback (FB) equalizer in the Rx are compared.
- The number of taps in the feedforward and feedback equalizers are varied.
- The effect of one worst-case near-end crosstalk aggressor is considered.
- A simple RC model with pole at 0.75*baud rate is used for the transmitter.
- Mellitz capacitor-like package model included on both transmitter and receiver.

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Parameters Used

- Only DJ is from ISI
  - No DCD, PJ included
- 0.010UI σ RJ added, unless otherwise noted
  - Not more than 13.4ps peak-to-peak RJ at 8.5Gbps data rate with probability $1-10^{-12}$
  - Not more than 15.6ps peak-to-peak RJ max at 8.5Gbps data rate with probability $1-10^{-15}$
- Signal-To-Electronics Noise Ratio 45dB, unless otherwise noted
- Crosstalk added as noted
- Ideal receiver sensitivity assumed

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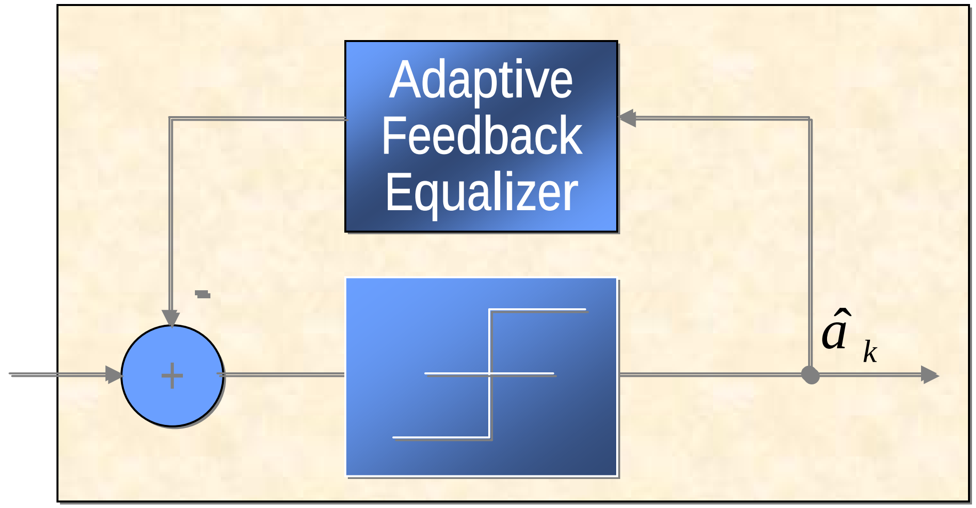
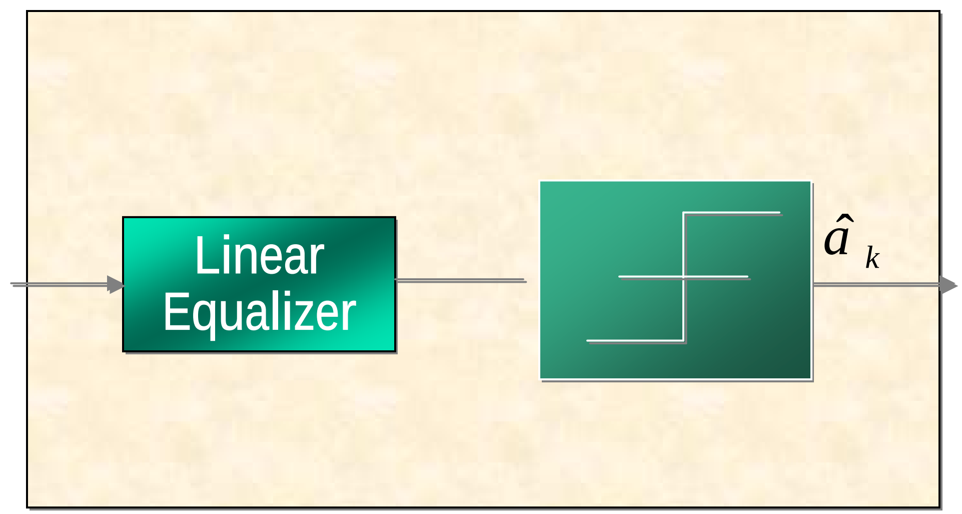
Decision Feedback Equalization versus Linear Feedforward Equalization

DFE Receiver

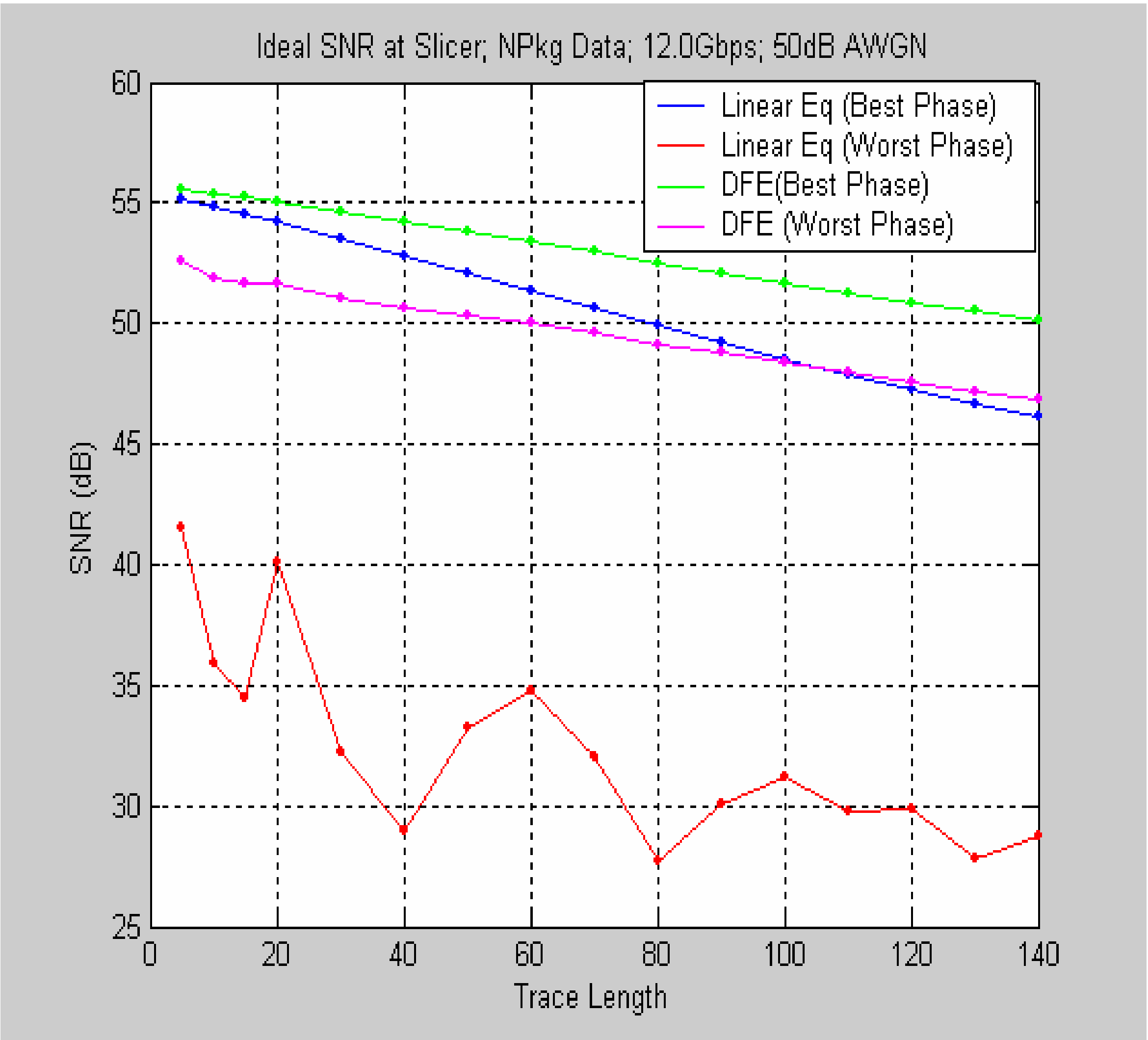


Receiver with Linear Equalization



Ideal DFE versus Ideal Linear Equalization

Best and Worst Case Phases Versus Distance; No Jitter or XT



- DFE has an advantage over linear equalizer at the ideal sampling phase because it results in less noise enhancement.
- DFE is less affected by choice of sampling phase and thus more resistant to jitter.

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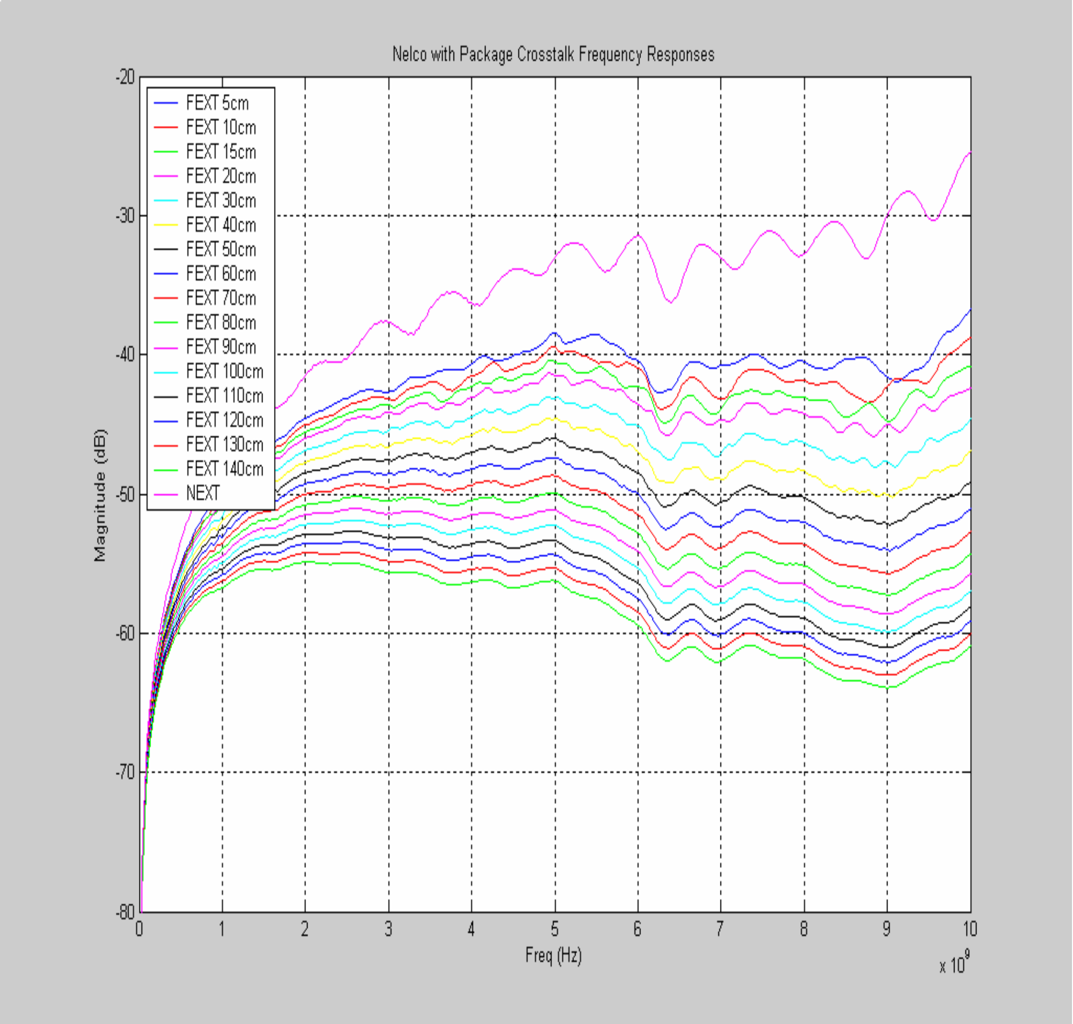
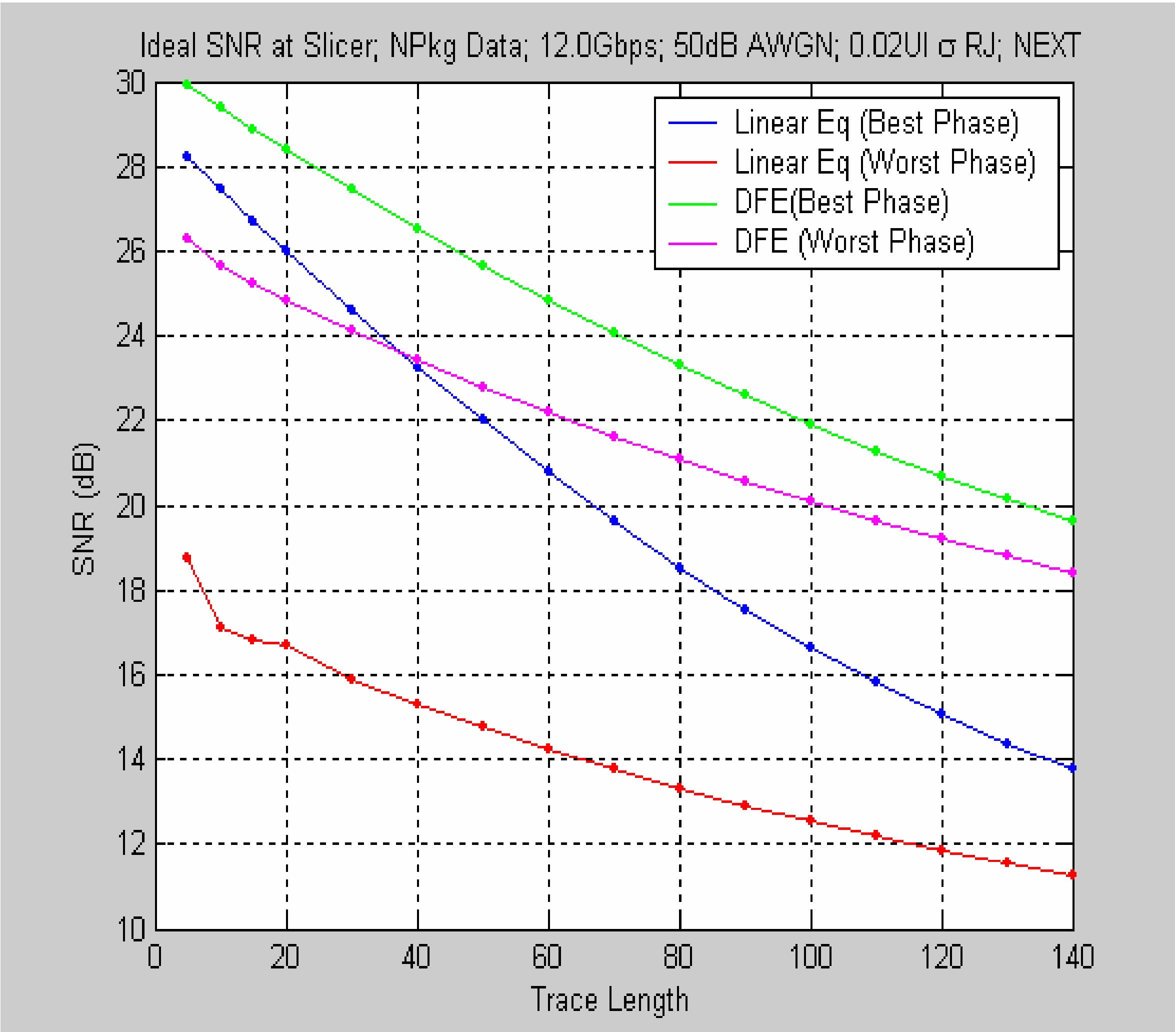
Crosstalk

Near-End and Far-End Crosstalk Frequency Responses



Ideal DFE versus Ideal Linear Equalization

Best and Worst Case Phases Versus Distance with Jitter and NEXT



- The benefit of DFE is shown to grow with the amount of high frequency noise and the amount of high frequency boost required to compensate for the channel's attenuation.

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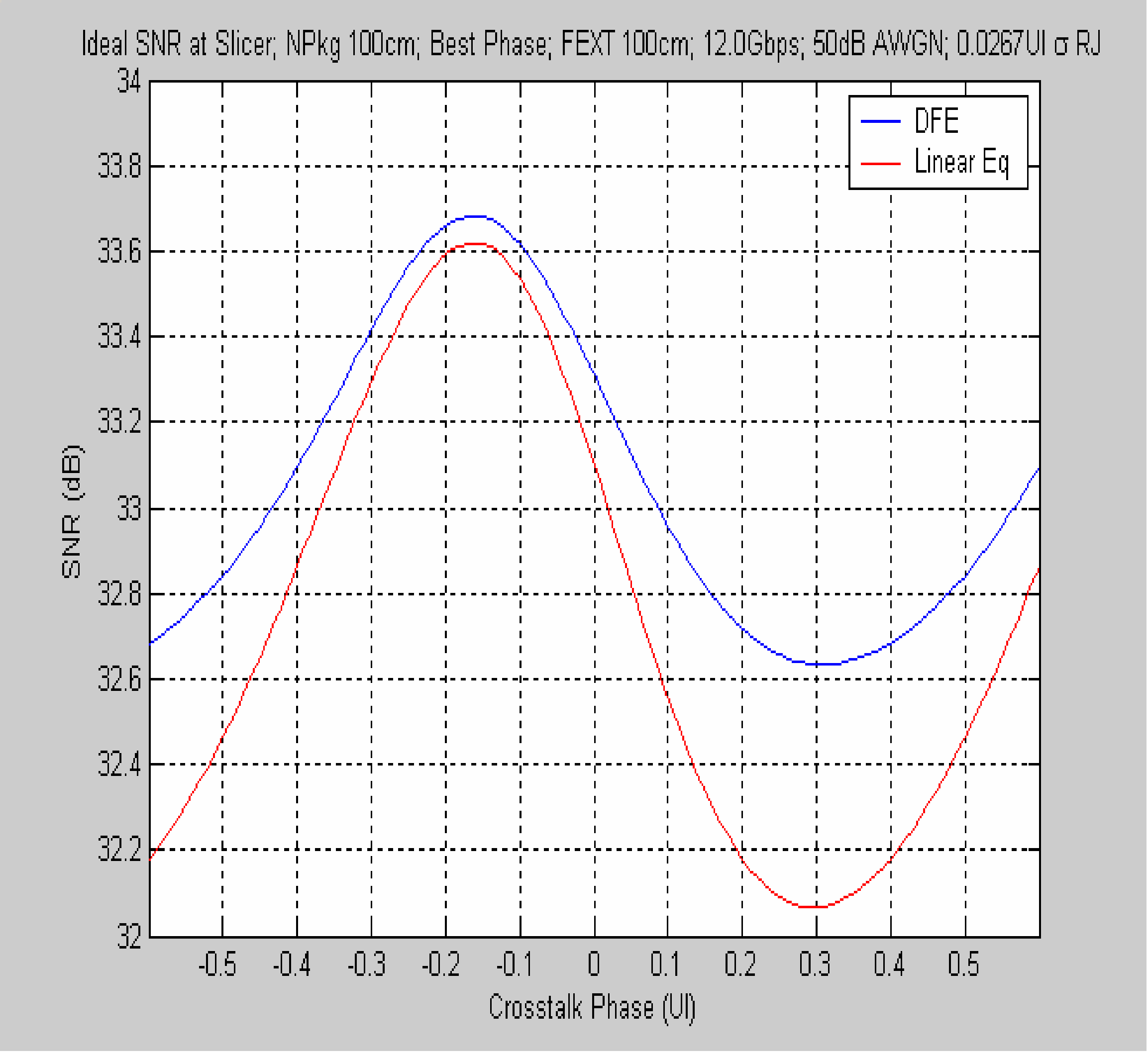
Far-End Crosstalk

Effect of Crosstalk Phase



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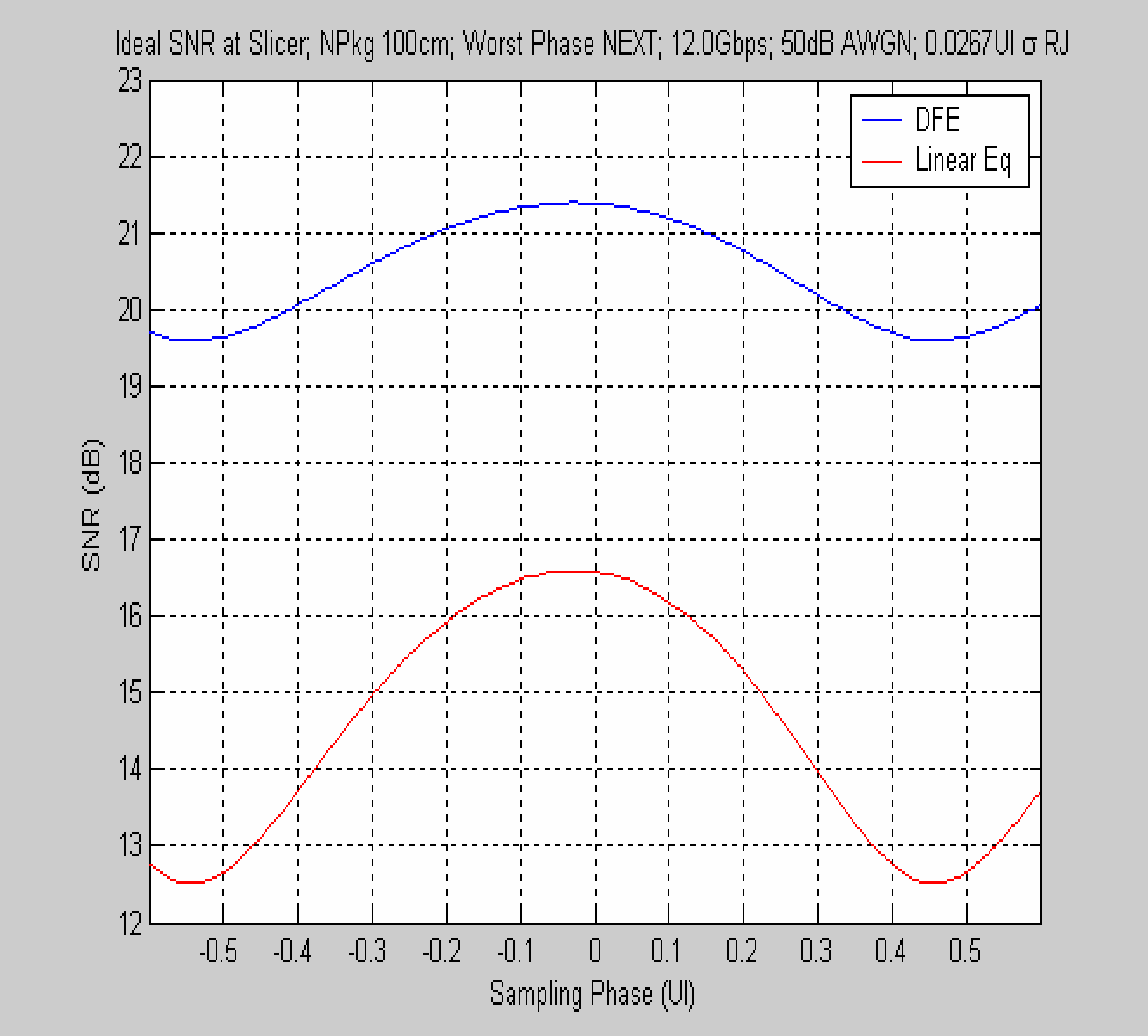
Near-End Crosstalk

Effect of Worst Phase NEXT



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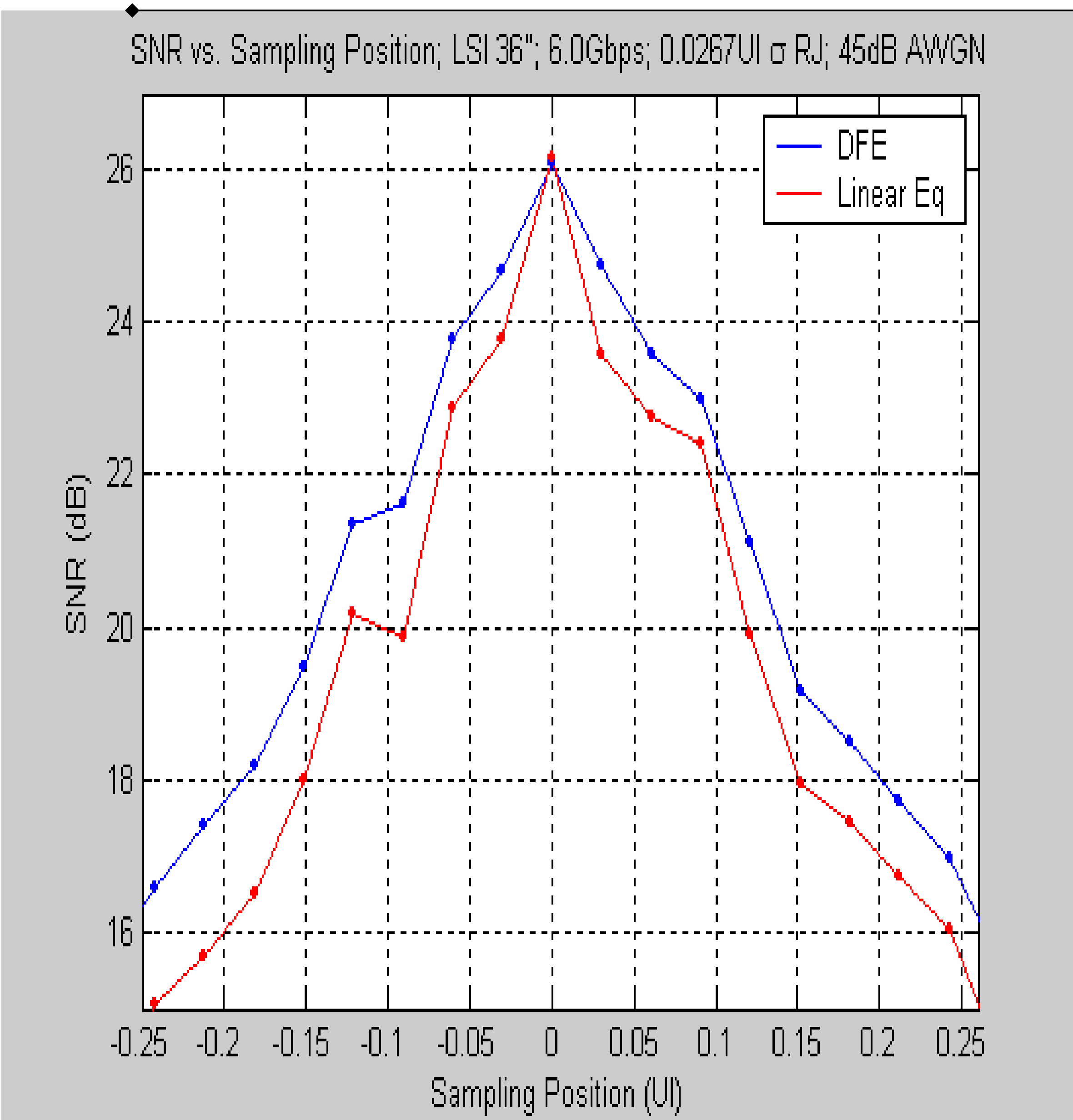
SNR at Slicer vs. Sampling Position

LSI 36” Trace, 6.0 Gbps; 0.026UI Random Jitter



•Even without crosstalk, the benefit of DFE can be seen as the sampling position moves away from the center of the eye. This results in improved jitter tolerance.

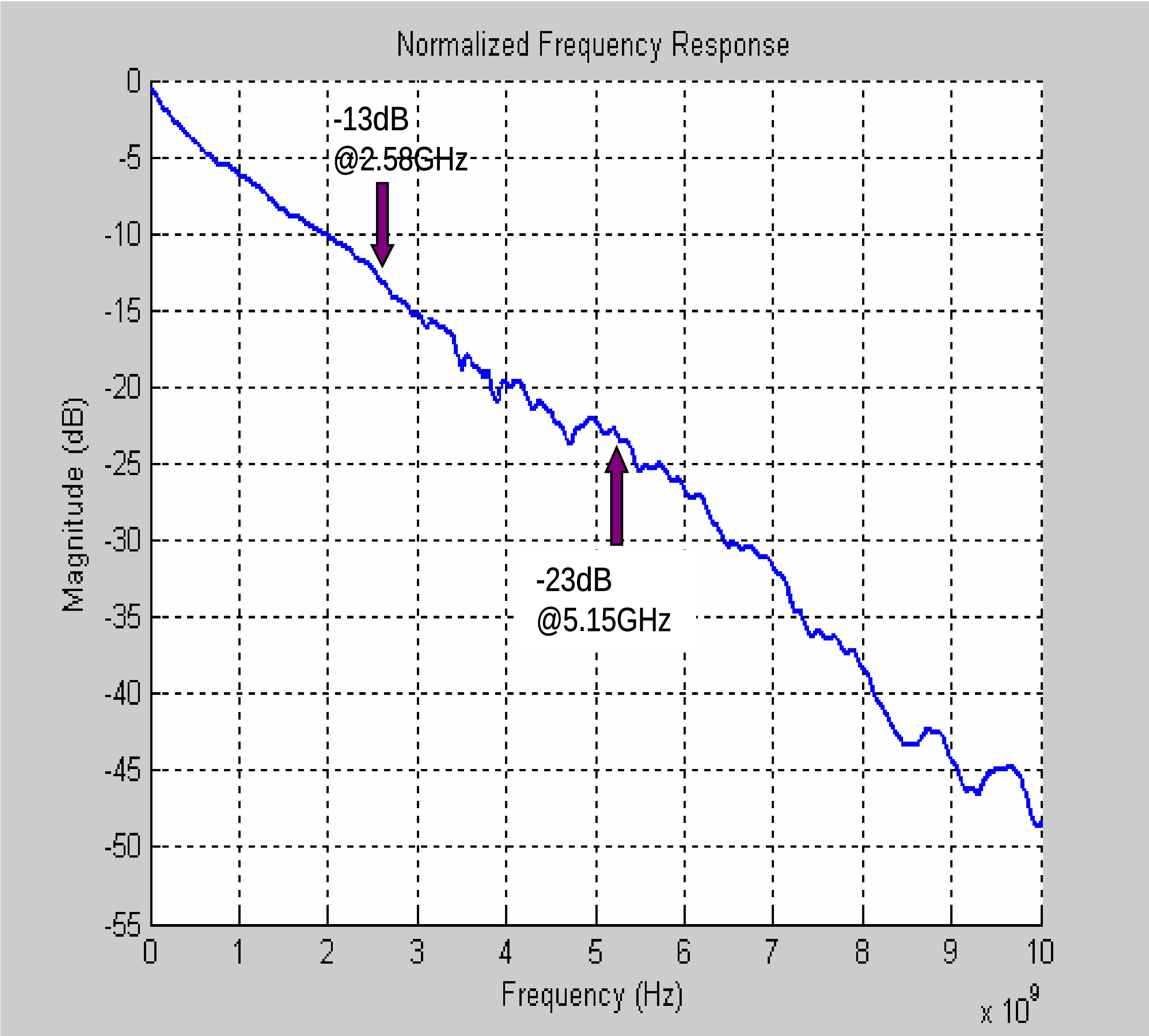
NRZ vs. PAM-4

Introduction

- NRZ is standard 2–level signaling used in most backplane transceivers today.
- PAM-4 is four level signaling at half the bit rate with each level corresponding determined by two consecutive bits.
- NRZ can perform better than PAM-4 even when the channel loss between the Nyquist frequency of PAM-4 and that of NRZ is greater than 9.5dB.
- NRZ and PAM-4 with a linear FIR feedforward (FF) filter and a decision feedback (FB) equalizer are compared for such a channel.
- The number of taps in the feedforward and feedback equalizers are varied.
- The effect of near-end crosstalk is observed.

Frequency Response

Actual Channel (from Steve Anderson, Xilinx)

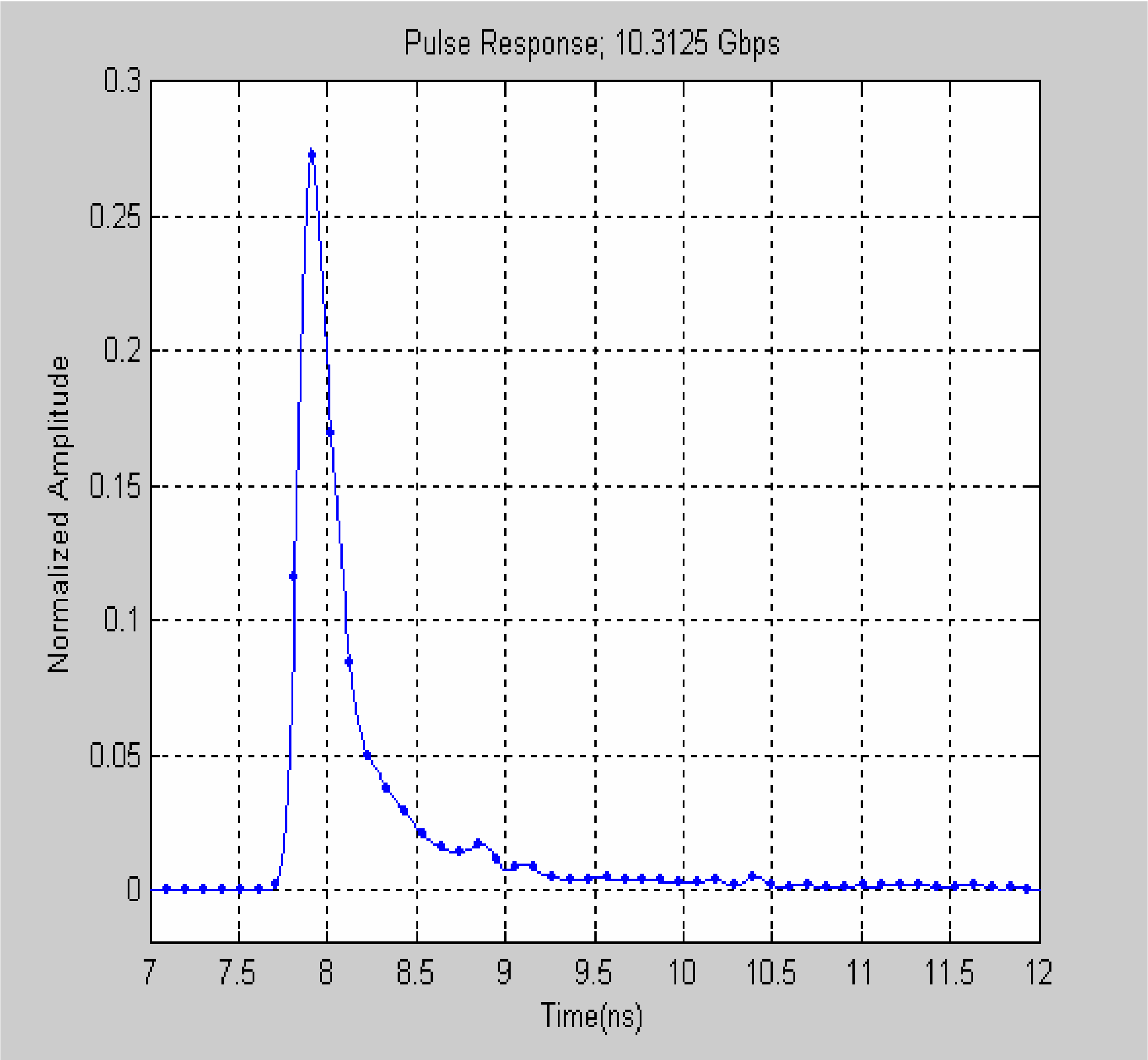


- Difference between response at 5.15GHz (Nyquist frequency of NRZ) and 2.58GHz (Nyquist frequency of PAM-4) is about 10dB.
- PAM-4 is often thought to perform better if the difference is greater >9.5dB.[1] This figure comes from the fact that an ideal PAM-4 signal has three eyes each of which have roughly 1/3 the vertical opening of an ideal NRZ eye.

[1] Howard Johnson, "Multi-Level Signaling," DesignCon 2000.

Pulse Response

Based on Channel similar to IEEE 802.3ap Channel Model



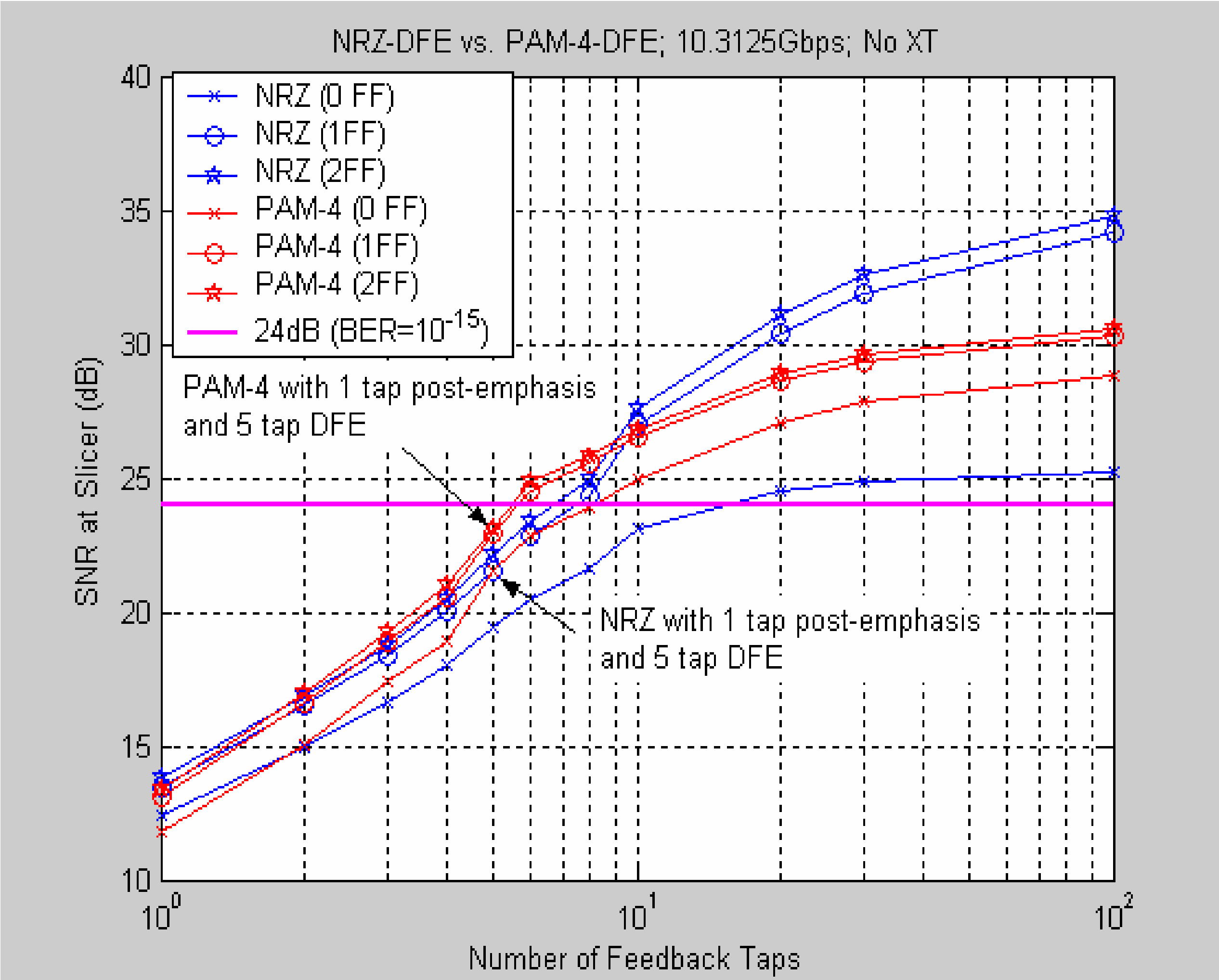
- Pulse response generated assuming single pole TX lowpass filter with corner at ¾ * baud rate.
- Dots are separated by one UI and therefore represent potential ISI.
- Only one significant point of pre-cursor ISI.
- Has long slowly decaying tail with many points of post-cursor ISI. This would require >15 DFE taps to completely address.

Description of Results

- SNR at optimal sampling point is shown. No measurement of horizontal eye opening is presented.
- x-axis shows number of feedback taps used
- Each line represents a different number of feed-forward (FF) equalizer taps used in the TX
- Each color represents a different signaling scheme.
- Crosstalk is assumed to occur at the same frequency as the signal. The worst case crosstalk phase at the ideal sampling point is selected.
- All tap values are ideal.

NRZ vs PAM-4

10.3125Gbps; No Crosstalk



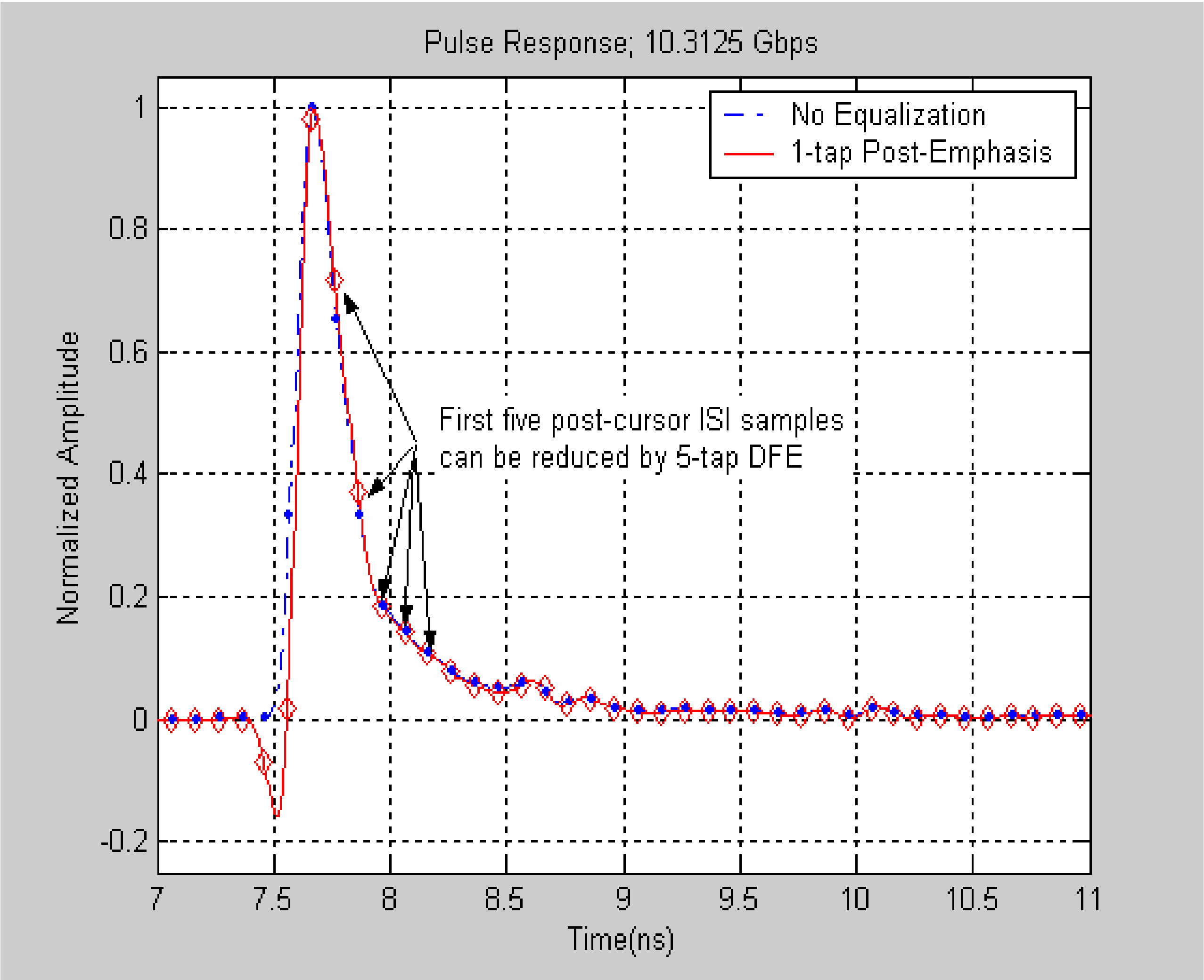
- Transmit equalization is FIR with varying number of taps to address pre-cursor ISI.

$$\frac{D^k - \sum_{n=0}^{n=k-1} \alpha_n D^{(k-1)-n}}{1 + \sum_{n=0}^{k-1} abs(\alpha_n)}$$

- With one tap post-emphasis (D-α) and 5 feedback taps, neither PAM-4 nor NRZ provides enough SNR to function. However,PAM4 has about 1.5dB more SNR.
- To get BER <10^{-15} with one tap post-emphasis, PAM-4 requires 6 feedback taps while NRZ requires 8.
- As number of DFE taps increases, performance of NRZ relative to PAM4 increases.

Pulse Response at 10.3125Gbps

One Tap Post-Emphasis



- Transmit equalization is two tap FIR to address pre-cursor ISI (one tap post-emphasis).
- Precursor ISI is greatly reduced.
- First five post-cursor ISI samples can be reduced by a 5-tap DFE.
- A long slowly decaying tail of post-cursor ISI still remains.

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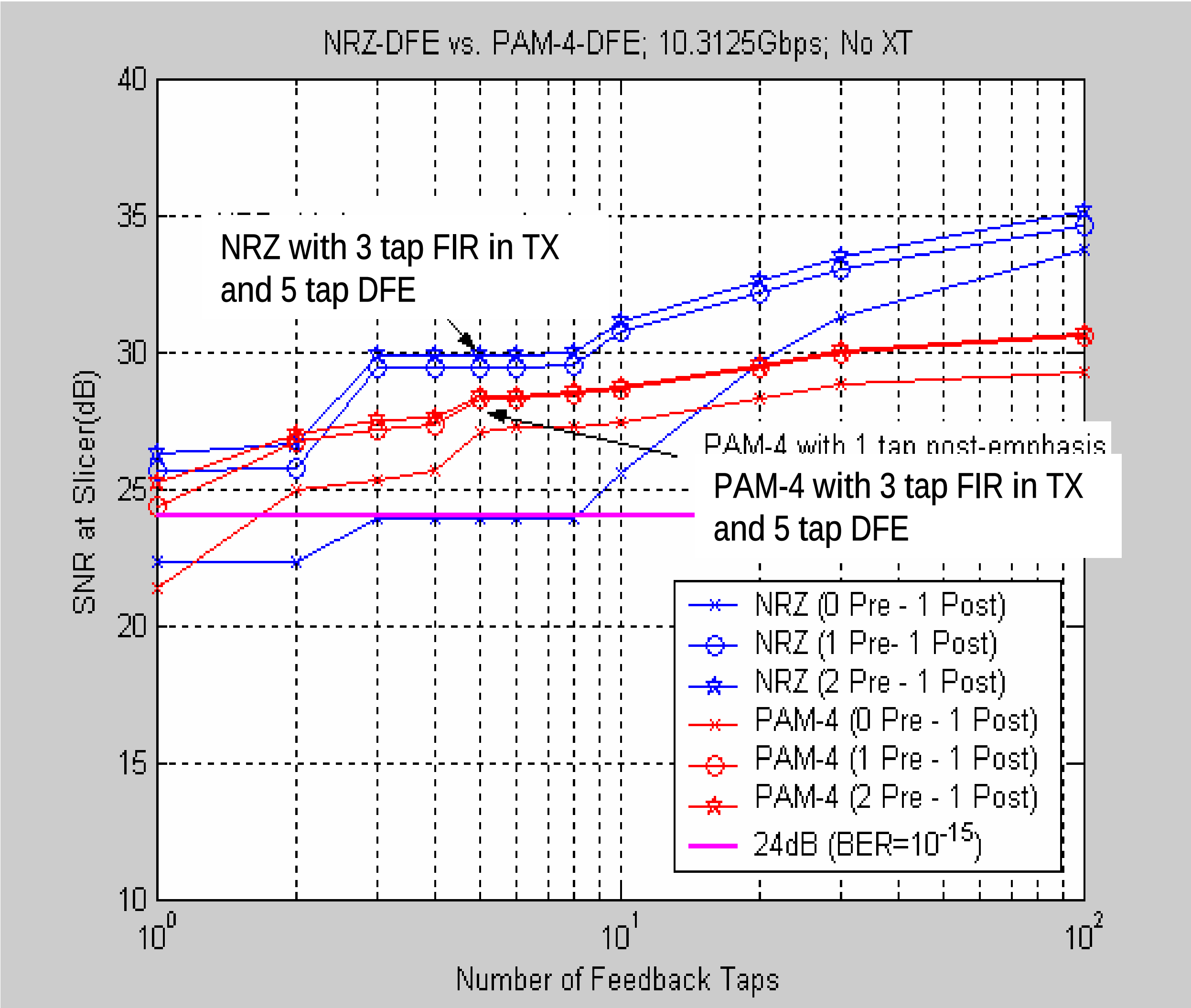
NRZ vs PAM-4

10.3125Gbps; No Crosstalk; With One Tap PostCursor FF Equalization



- Transmit equalization is a FIR with one tap to address post-cursor ISI and varying number of taps to address pre-cursor ISI.
- With one tap post-emphasis and one tap pre-emphasis

$$(-\beta D^2 + D - \alpha)$$

and 5 feedback taps, both PAM-4 and NRZ provide enough SNR to function. However, NRZ has about 1dB more SNR than PAM-4.

- As the number of feedback taps increases, advantage of NRZ over PAM4 increases.

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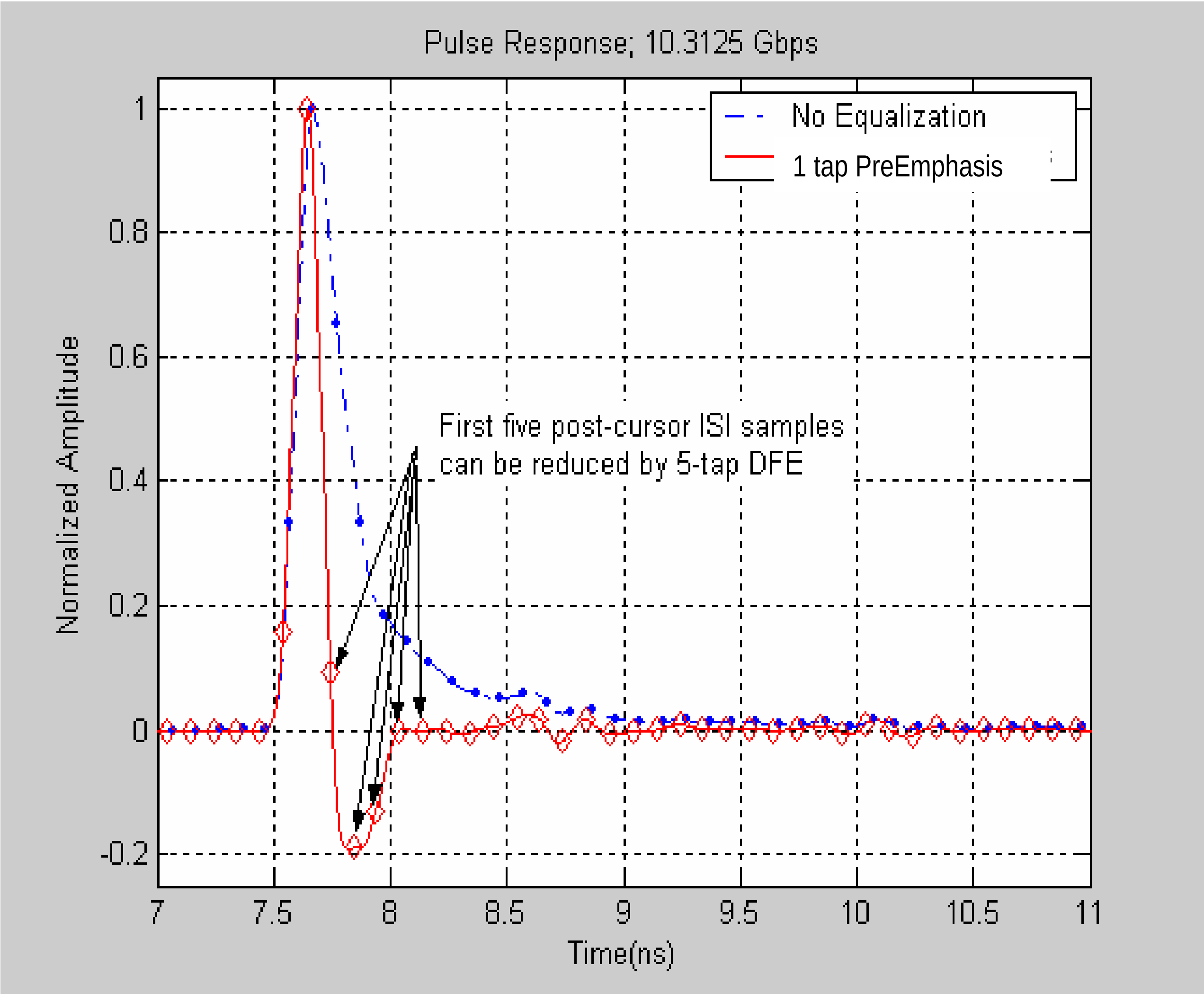
Pulse Response at 10.3125Gbps

One Tap Pre-Emphasis



- Transmit equalization is two tap FIR to address post-cursor ISI (one tap pre-emphasis).
- Post-cursor ISI is greatly reduced so that only three significant post-cursor ISI points remain.
- One tap of pre-emphasis can almost completely remove long tail that would require almost 15 taps of DFE.
- Pre-cursor ISI is reduced but still significant.

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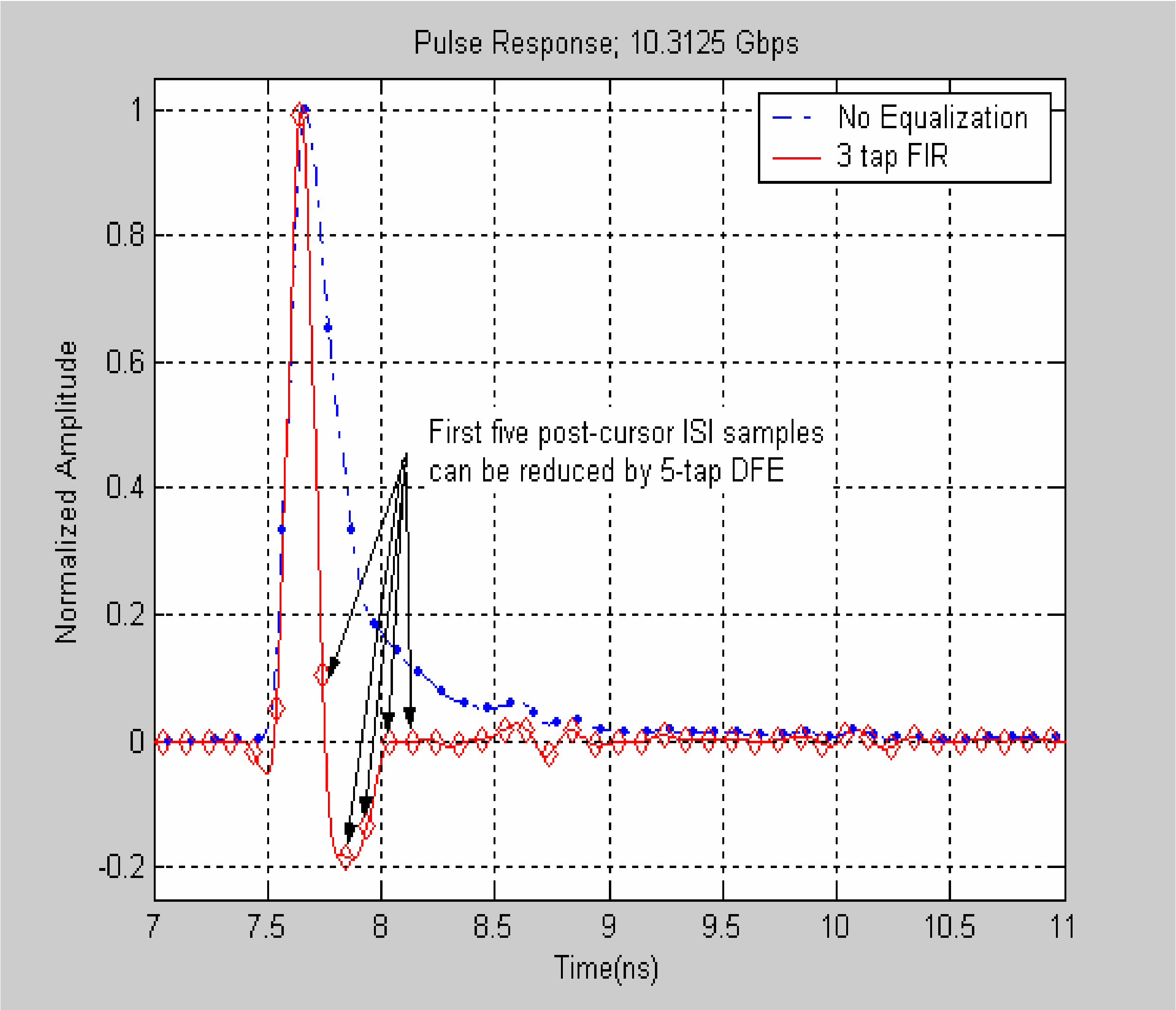
Pulse Response at 10.3125Gbps

Three Tap FIR (One Tap Pre-Emphasis and One Tap Post-Emphasis)



- Transmit equalization is three tap FIR with one tap to address pre-cursor ISI and one tap to address post-cursor ISI. (One tap post-emphasis and one tap pre-emphasis.)
- Pre-cursor ISI is now also significantly reduced.

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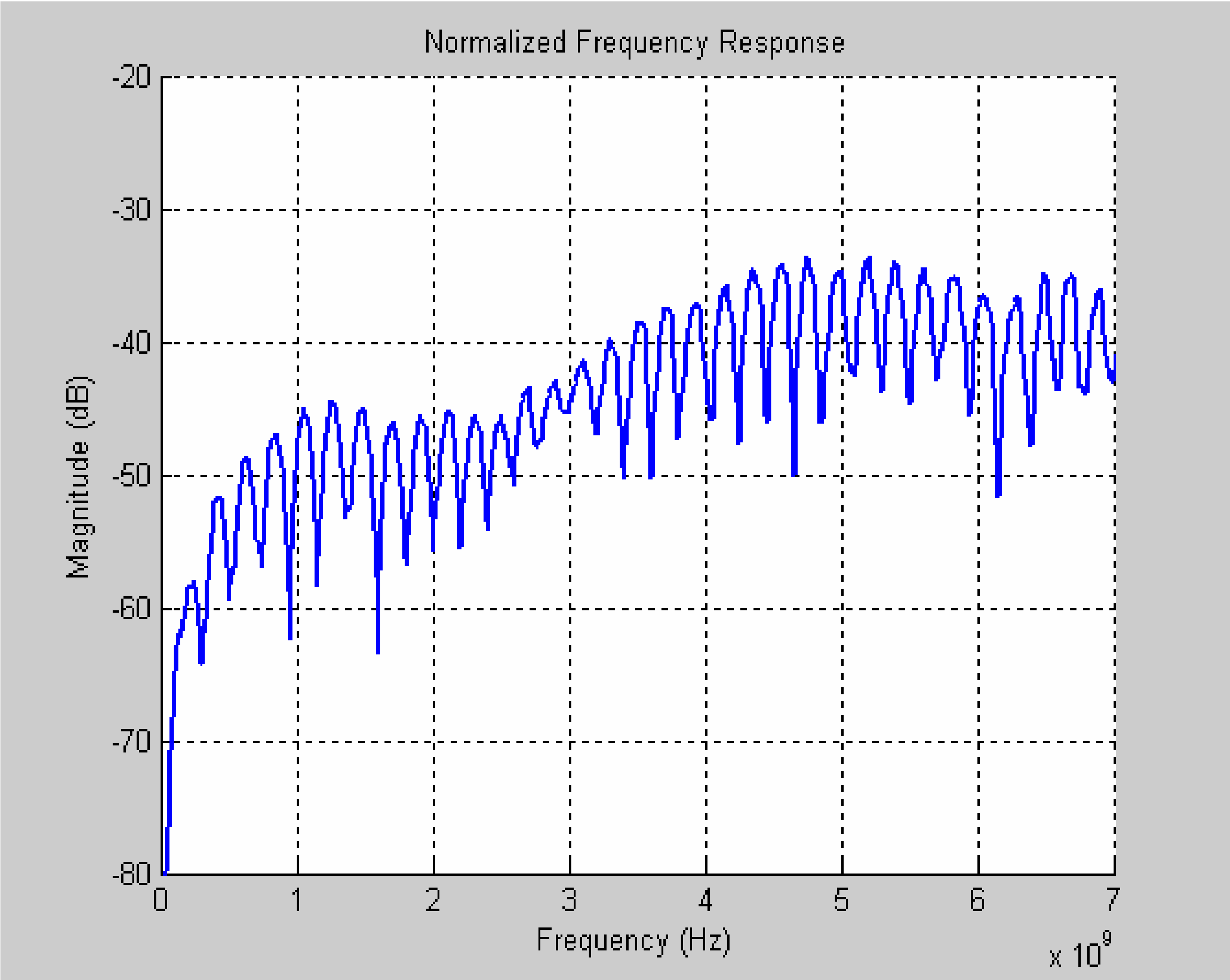
Near-End Crosstalk Frequency Responses

From Xilinx



- •One channel of NEXT will be added to the simulations.
- •Crosstalk is assumed to occur at the same frequency as the signal.
- •The worst case crosstalk phase at the ideal sampling point is selected.

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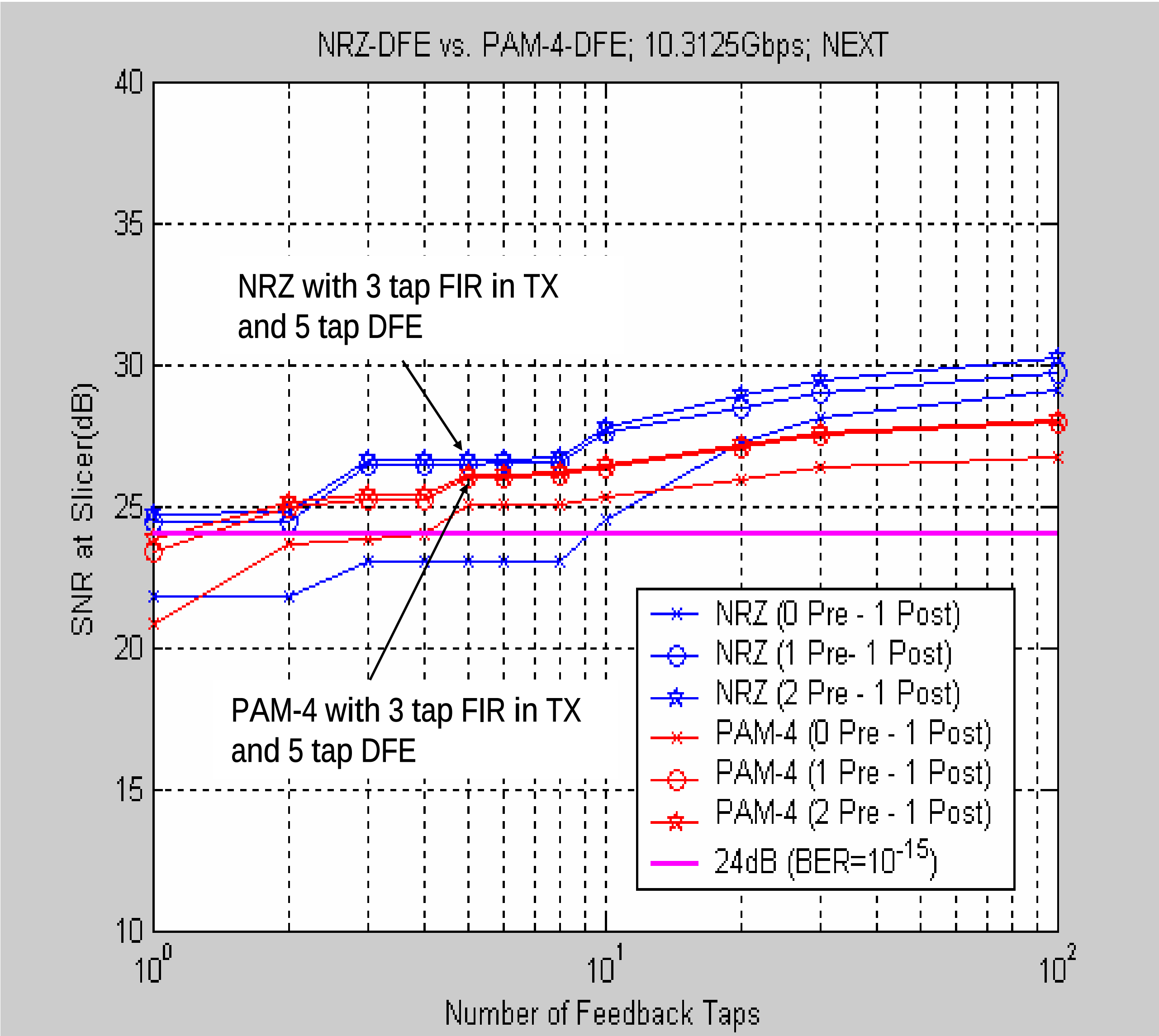
NRZ vs PAM-4

10.3125Gbps; NEXT; With One Tap PostCursor FF Equalization



- With NEXT and three tap FIR, NRZ meets SNR goal with one DFE tap and PAM-4 requires two.
- With NEXT, performance of three tap FIR and 5 DFE taps decreases about 2.5dB.
- NRZ advantage over PAM-4 has decreased to about 0.5dB with 5 tap DFE.

Conclusion

NRZ vs. PAM-4

- Although channel has greater than 9.5dB loss between Nyquist frequencies of PAM-4 and NRZ, NRZ can perform better depending on the detection scheme.
- Performance of NRZ improves relative to PAM-4 as the number of DFE taps increase.
- A three tap FIR with one tap dedicated to post-emphasis and one tap devoted to pre-emphasis is recommended. This can greatly reduce pre-cursor ISI and mostly remove a long slowly decaying tail on the pulse response. A few points of significant post-cursor ISI remain and can be removed with a few taps of DFE.
- With pre-emphasis tap, number and weight of feedback taps is reduced resulting in improved error propagation.

NRZ, Duobinary, and PR4 Overview

Introduction

- Overview of signaling schemes
  - NRZ, Duobinary, and PR4
- Presentation of results

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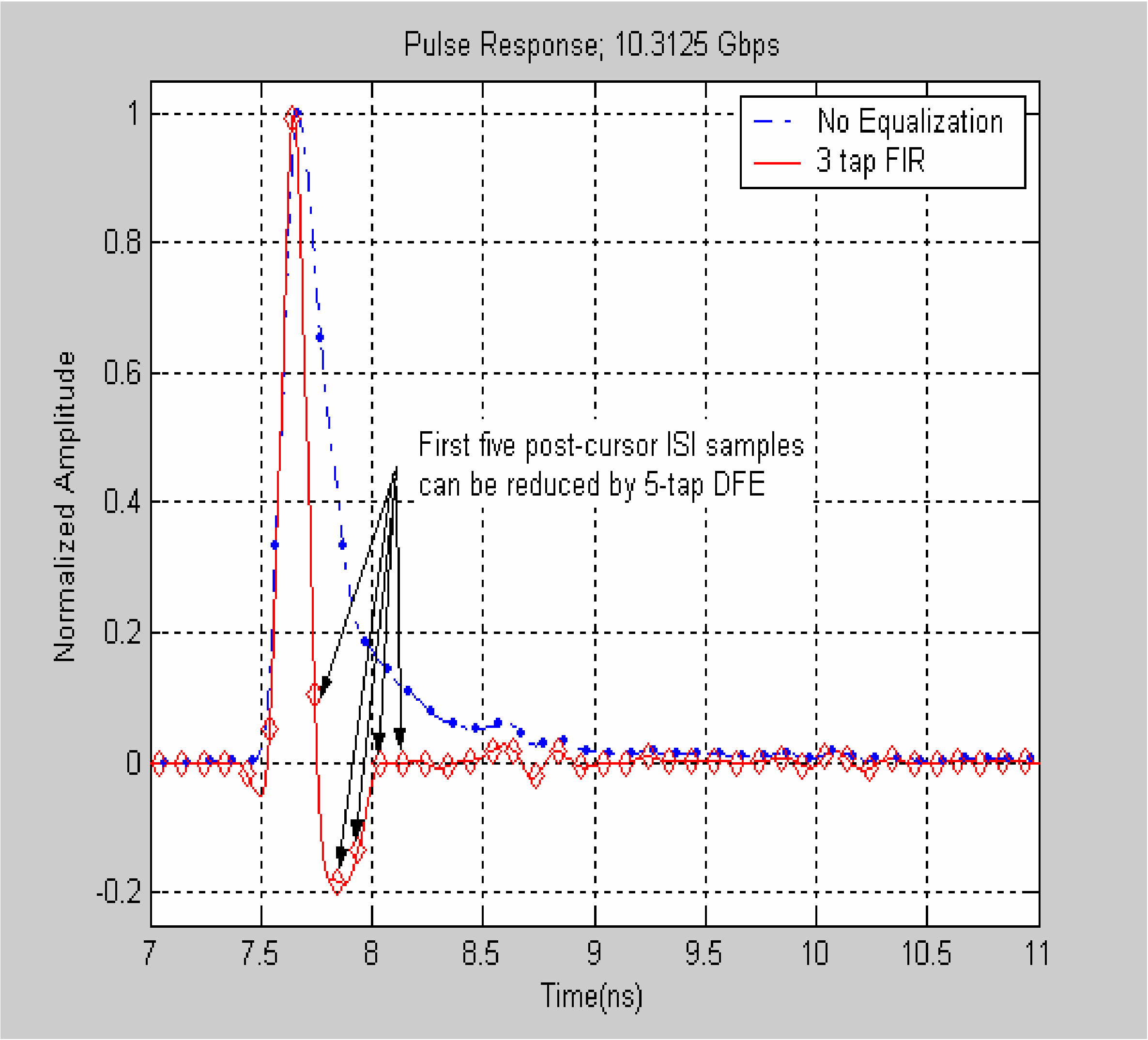
NRZ Signaling

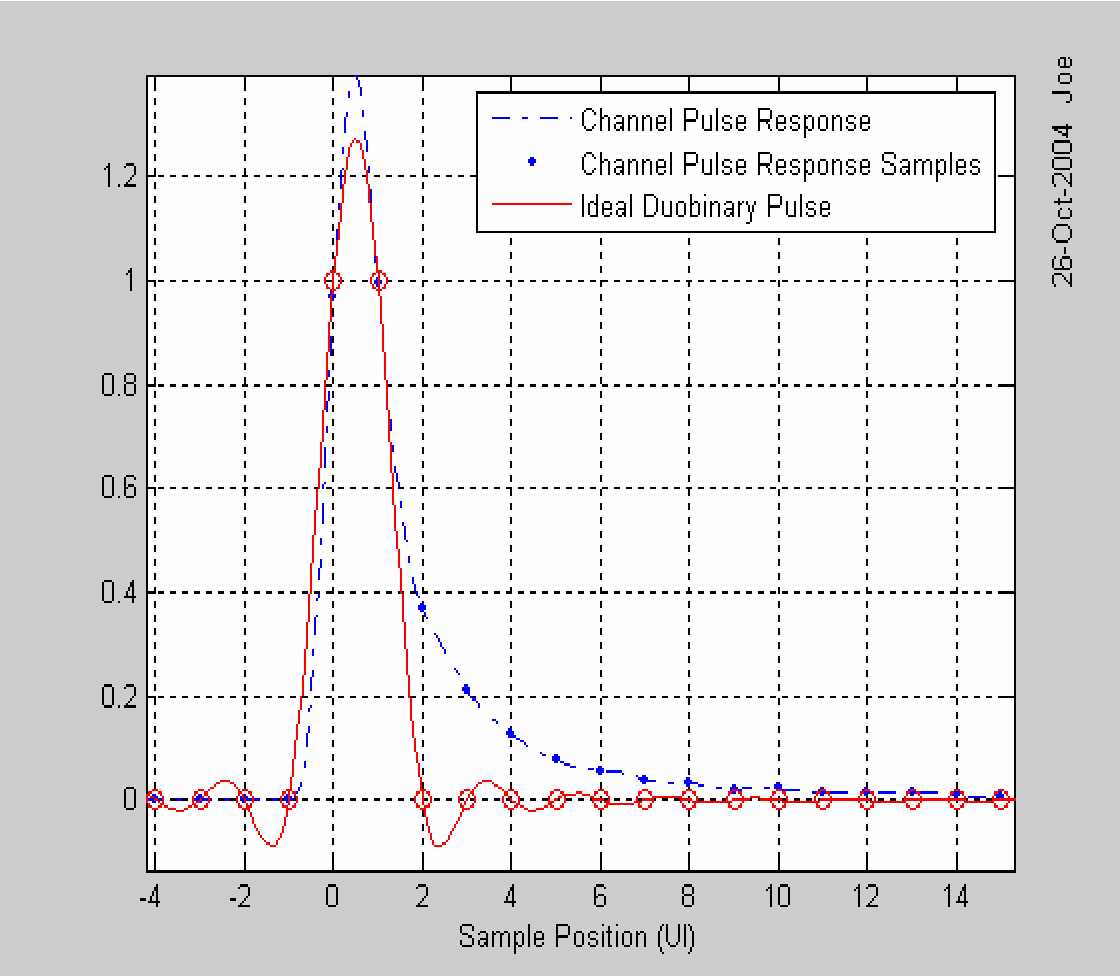
Trying to Removing All ISI Through Equalization



- Our primary equalization goal has been to eliminate intersymbol interference (ISI).
- A combination of a TX FIR filter and a DFE in the Rx are used to mitigate the ISI.
- The goal of removing ISI is to make detection possible with a reasonable complexity.

Duobinary

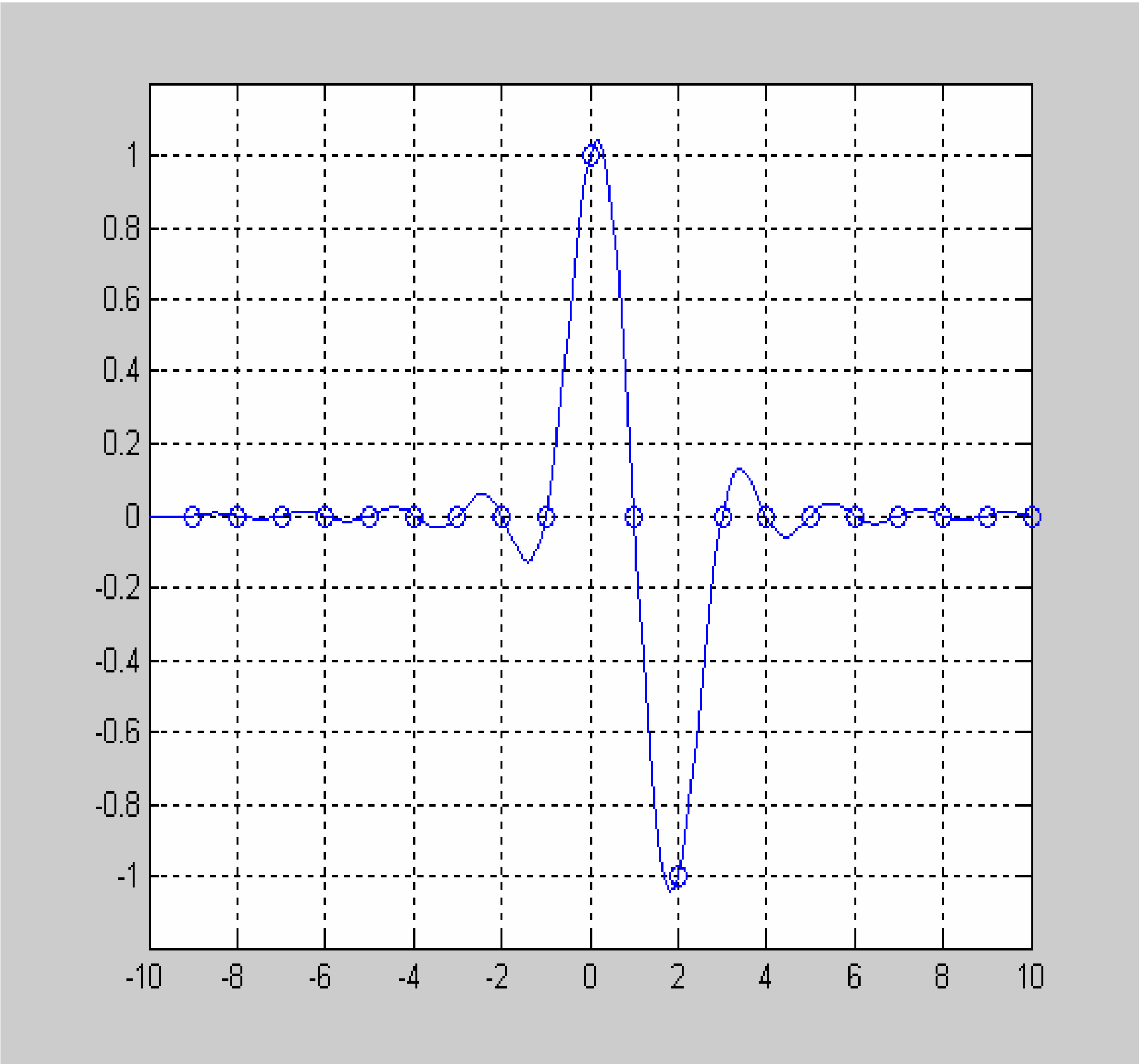
Ideal versus Channel Pulse Response



- 1+D Channel
  - Samples at
    - time 0 and 1 are 1
    - 0 everywhere else.
- Appears to be a reasonable fit for channels at this data rate.

Partial Response – Class IV

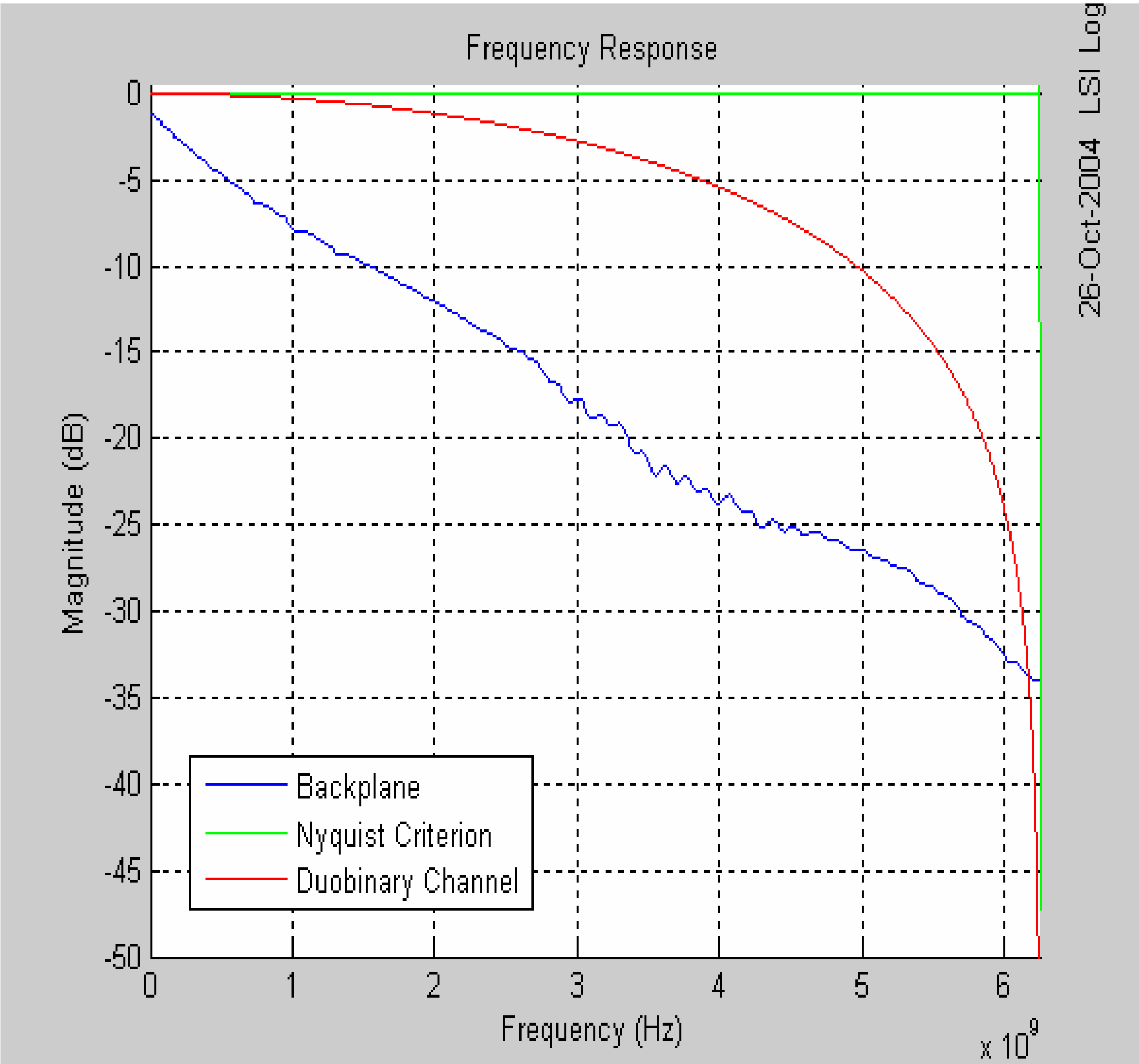
Pulse Response



- Does not resemble our channel pulse response.

Frequency Response Comparison

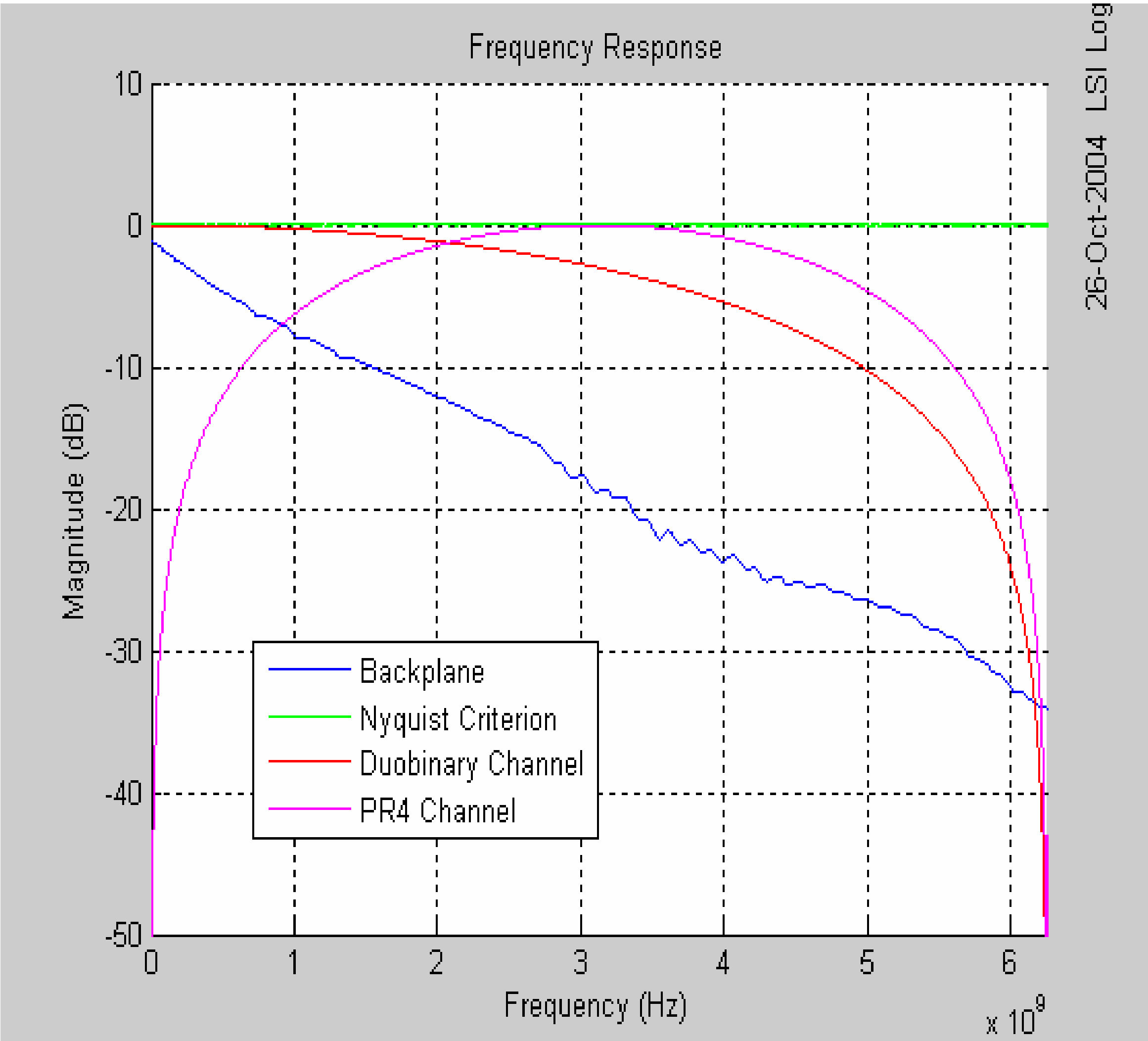
NRZ and Duobinary



- Ideal NRZ equalization target is flat spectrum.
- NRZ requires a lot of high frequency boost.
- Duobinary's 1+D equalization target has a null at the Nyquist frequency. It is a better match to the channel at high frequencies and consequently requires less high frequency boost.

Frequency Response Comparison

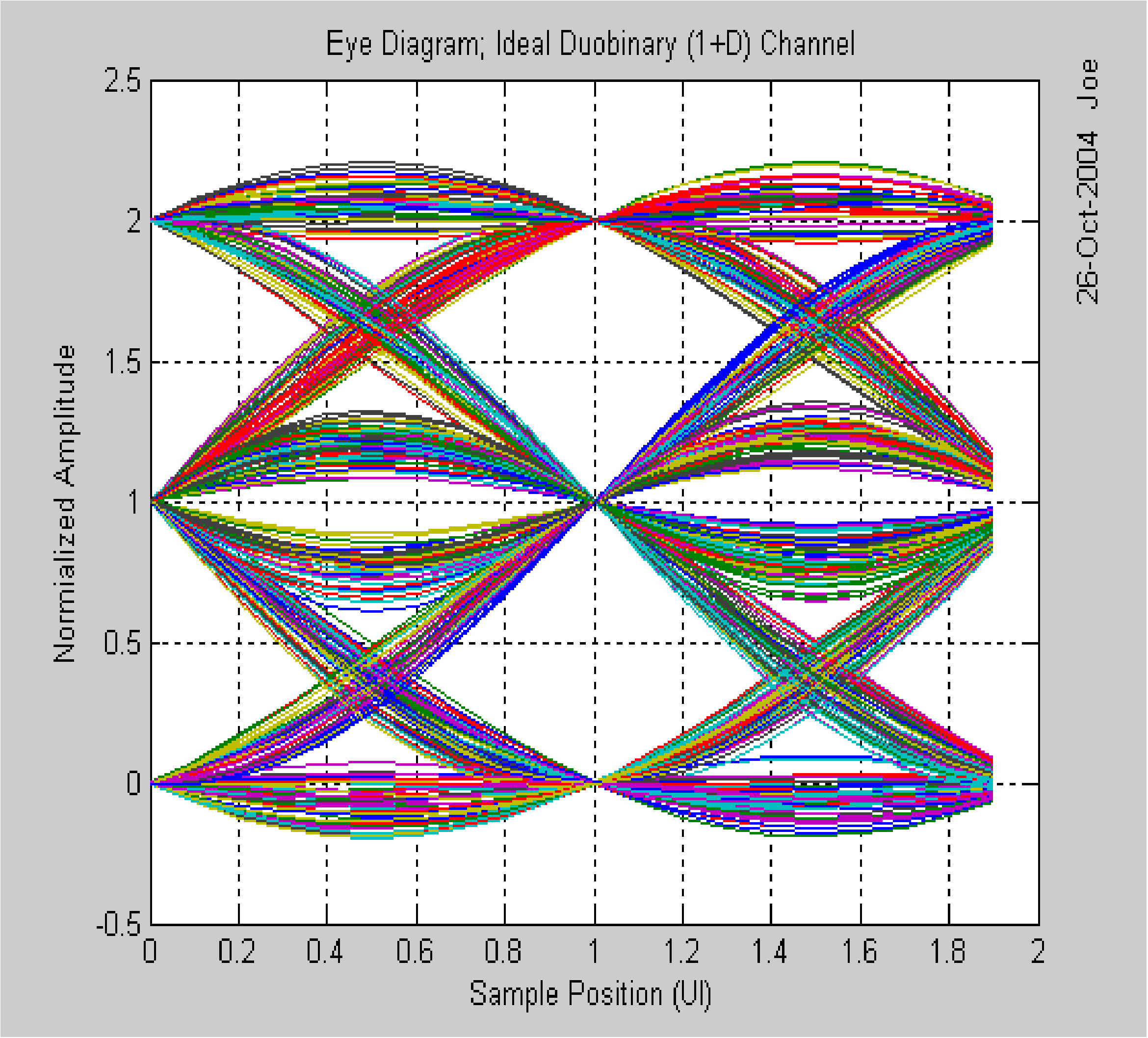
NRZ, Duobinary, and PR4



- Has nulls at both DC and Nyquist
- Null at DC may match DC-null in AC coupled systems, but PR-4's DC null is much deeper.
- Equalizing to PR4 results in throwing away the signal in the low frequency range where the SNR is strongest.

Duobinary

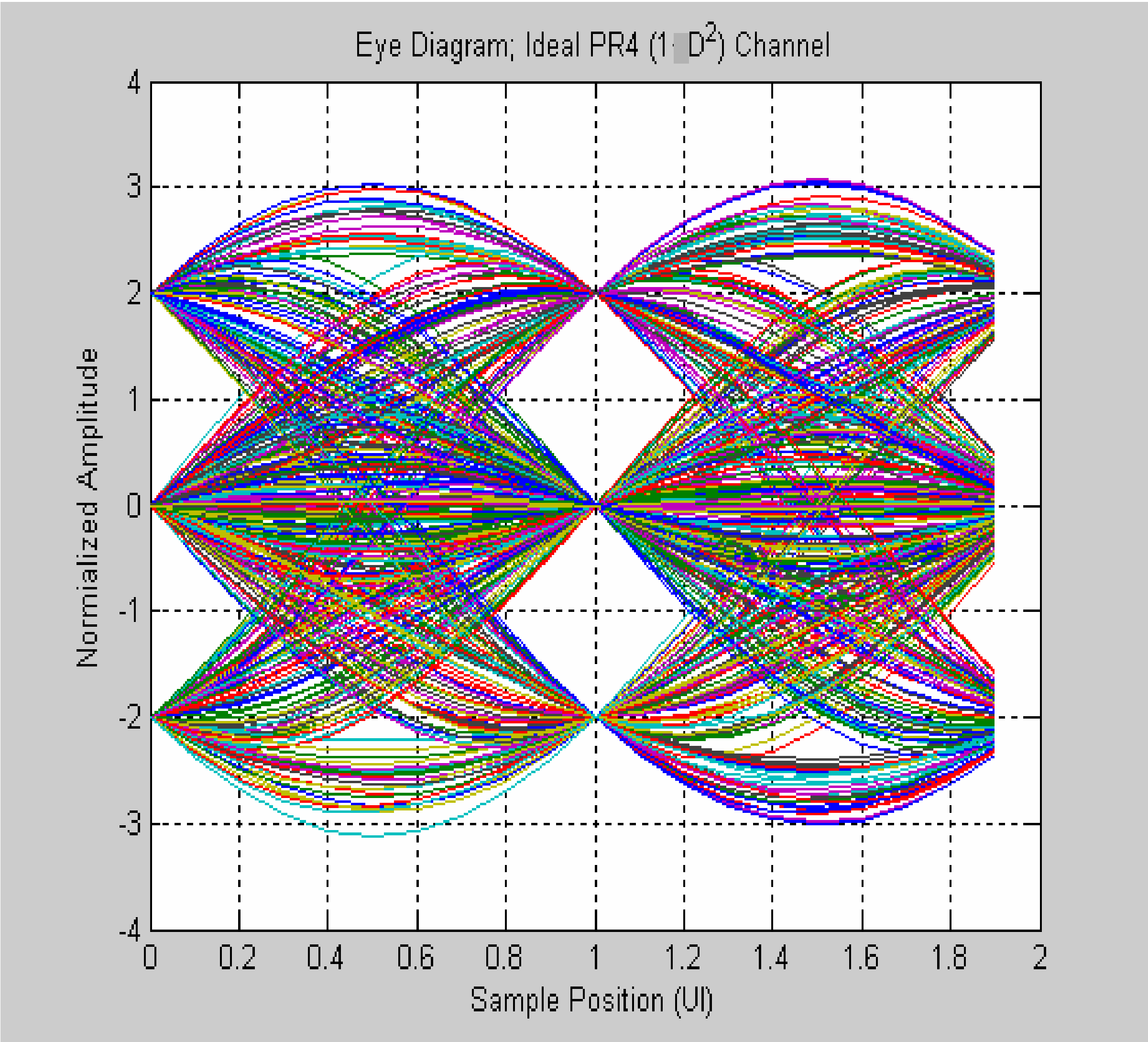
Ideal Eye Diagram



- No transitions from highest to lowest signal levels in adjacent bits.
- Notice that slicer value that results in highest jitter tolerance is not the slicer level that results in best noise tolerance.

PR4

Eye Diagram



- Horizontal eye opening in ideal eye diagram is reduced compared to 1+D target.
- Any signal level can transition to any other signal level in adjacent bit.
- Even in ideal case, without MLSD, eye exhibits very little tolerance to jitter.

Summary of Results

SNR Comparison

Intel Backplanes

BP	NRZ 3FF+5DFE	DB 3FF+3DFE	DB 3FF+5DFE	DB 4FF+3DFE	DB 4FF+5DFE	PR4 3FF+3DFE	PR4 3FF+5DFE	PR4 5FF+3DFE	PR4 5FF+5DFE
Intel B1	25.75	23.7428	24.7189	23.8904	24.7194	10.02	10.5355	21.9916	22.148
Intel B12	25.4387	20.6647	24.2936	24.0673	25.5312	11.8722	12.9072	22.9701	23.5763
Intel B20	24.421	17.9337	21.4678	24.1036	24.7867	12.5534	13.6077	22.137	22.9709
Intel M1	24.2043	21.3843	21.8428	21.3882	22.1214	13.6615	14.3548	19.2269	20.565
Intel M20	24.2586	18.8378	20.1773	21.8866	22.3897	16.7028	17.1796	21.0436	21.0448
Intel T1	21.862	19.6715	20.0462	19.685	20.1262	11.684	11.8187	17.7951	19.4143
Intel T12	21.3521	17.8295	20.2168	18.696	20.4783	13.8084	15.0696	18.1711	18.9188
Intel T20	20.4595	16.3257	19.0451	18.4427	19.7304	14.0649	15.2461	17.3062	18.2698

SNR Comparison

Tyco Backplanes

BP	NRZ 3FF+5DFE	DB 3FF+3DFE	DB 3FF+5DFE	DB 4FF+3DFE	DB 4FF+5DFE	PR4 3FF+3DFE	PR4 3FF+5DFE	PR4 5FF+3DFE	PR4 5FF+5DFE
Tyco 1	26.4184	15.5579	18.0878	25.3081	25.3752	13.7218	15.3615	23.1624	23.6852
Tyco 2	26.7208	15.4417	17.8542	15.4474	17.8549	13.6503	15.4245	13.6559	15.4302
Tyco 3	24.7924	14.7412	17.0261	24.4904	24.6559	13.0619	14.8896	22.4596	23.1564
Tyco 4	27.3838	16.7213	19.9583	25.8848	26.1496	14.6765	16.383	23.8066	24.8202
Tyco 5	28.8032	20.5003	23.6176	27.3431	27.896	15.9264	17.4989	25.2065	26.7141
Tyco 6	25.4634	19.9357	22.3319	23.3344	24.3991	15.6349	17.0529	21.6006	23.0806
Tyco 7	26.6822	23.394	25.8662	23.7112	26.0652	16.9793	17.5009	22.5142	24.2921

SNR Comparison

Molex and Xilinx Backplanes

BP	NRZ 3FF+5DFE	DB 3FF+3DFE	DB 3FF+5DFE	DB 4FF+3DFE	DB 4FF+5DFE	PR4 3FF+3DFE	PR4 3FF+5DFE	PR4 5FF+3DFE	PR4 5FF+5DFE
MoLex i2	24.809	17.1815	18.9193	23.3004	23.8805	14.9248	16.8129	21.4513	22.3848
MoLex i3	24.7216	16.4369	18.7943	23.0948	23.7304	14.0673	15.9244	21.3092	22.3042
MoLex i4	24.635	16.8023	18.7352	23.0507	23.7563	14.504	16.5218	20.9664	22.278
MoLex i5	24.9085	16.0529	18.9518	23.5529	23.9459	13.7286	15.6399	21.5105	22.4099
Molex o2	25.224	17.5415	19.1214	23.9419	24.2682	15.4785	17.0011	22.3036	22.683
Molex o3	25.0651	16.75	18.8106	23.6832	24.0728	14.586	16.1901	22.0329	22.4956
Molex o4	25.1958	17.2071	18.9993	23.9024	24.2266	15.1239	16.7727	22.1454	22.6515
Molex o5	25.2929	17.2958	19.1175	24.1252	24.3047	15.3704	16.9238	22.3191	22.6489
Anderson	23.6875	15.3596	18.3673	22.8244	22.9803	13.3333	15.2358	20.2191	21.0405

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Required Number of DFE Taps

To Achieve 24dB SNR
Tyco Backplanes

BP	NRZ	DB	PR4
	3 tap FF	4 tap FF	5 tap FF
Tyco 1	<=1	3	6
Tyco 2	<=1	20	100
Tyco3	3	3	10
Tyco4	<=1	2	4
Tyco 5	<=1	<=1	<=1
Tyco 6	4	4	30

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Required Number of DFE Taps

To Achieve 24dB SNR

Intel Backplanes

BP	NRZ	DB	PR4
	3 tap FF	4 tap FF	5 tap FF
Intel B1	3	4	8
Intel B12	4	3	6
Intel B20	4	3	8
Intel M1	4	6	10
Intel M20	5	20	20
Intel T1	10	20	20
Intel T12	100	100	>100
Intel T20	>100	>100	>100

Required Number of DFE Taps

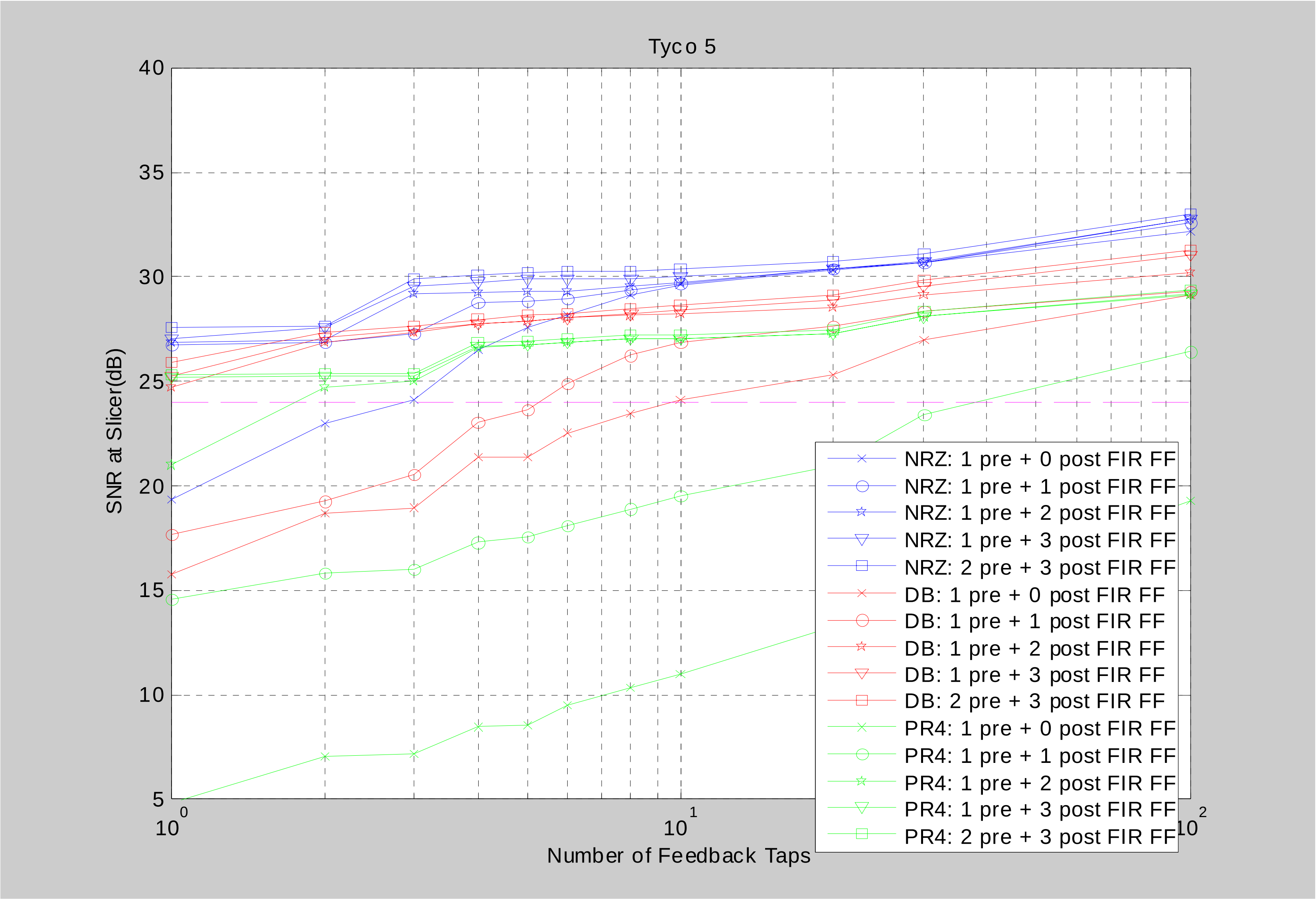
To Achieve 24dB SNR

Molex and Xilinx Backplanes

BP	NRZ	DB	PR4
	3 tap FF	**4 tap FF**	**5 tap FF**
Molex i2	2	6	100
Molex i3	2	8	100
Molex i4	2	10	100
Molex i5	2	6	100
Molex o2	<=1	4	100
Molex o3	<=1	5	100
Molex o4	<=1	4	100
Molex o5	<=1	3	100
Anderson	8	20	>100

Results

Tyco 5 Backplane



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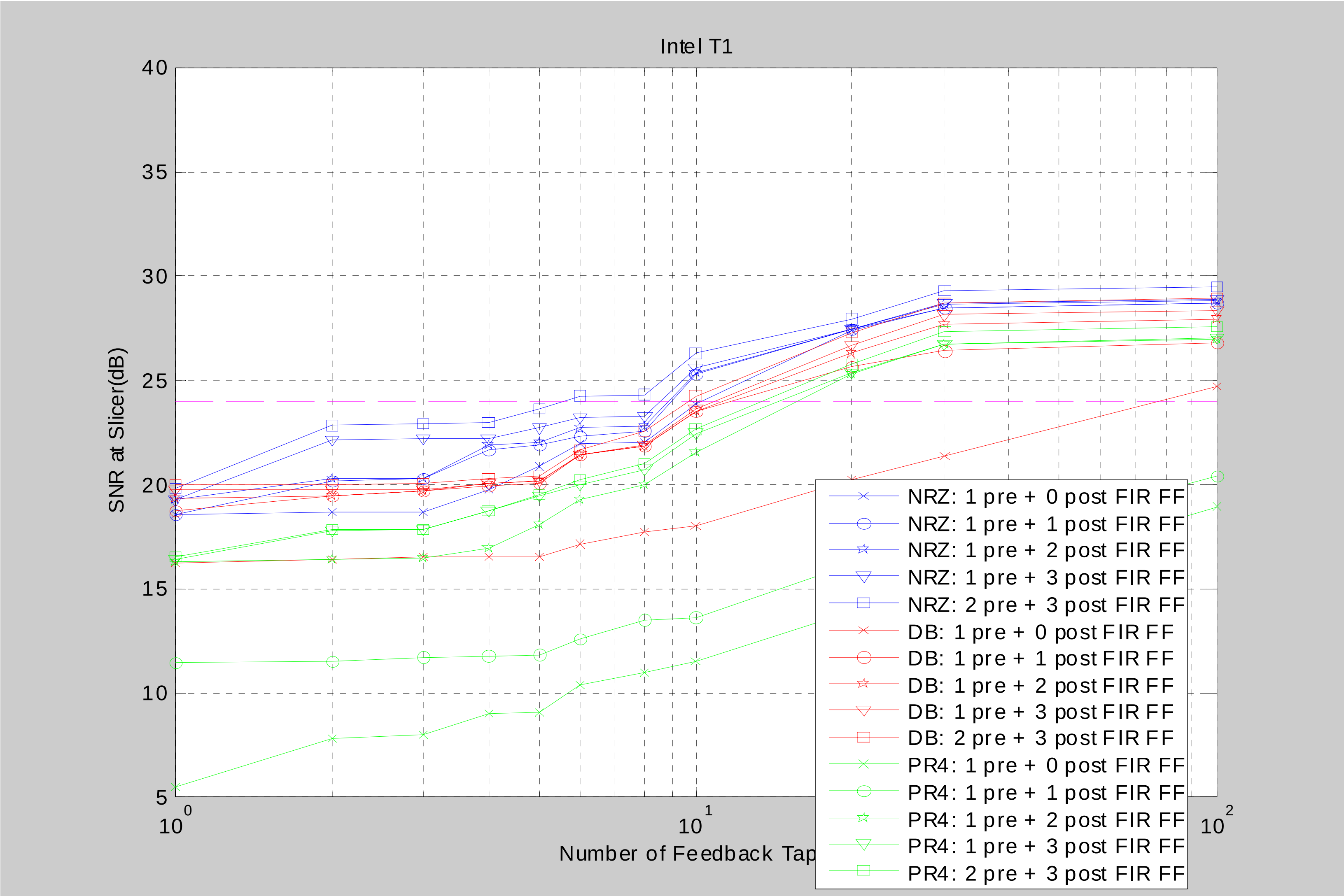
Results

Intel T1 Backplane



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Conclusions

NRZ, Duobinary, and PR4

- NRZ almost always outperformed Duobinary for similar equalization complexity.
- PR4 does not appear to be appropriate for this application.
- Intel T1 backplanes with large stubs are tremendously challenging to handle at these data rates.