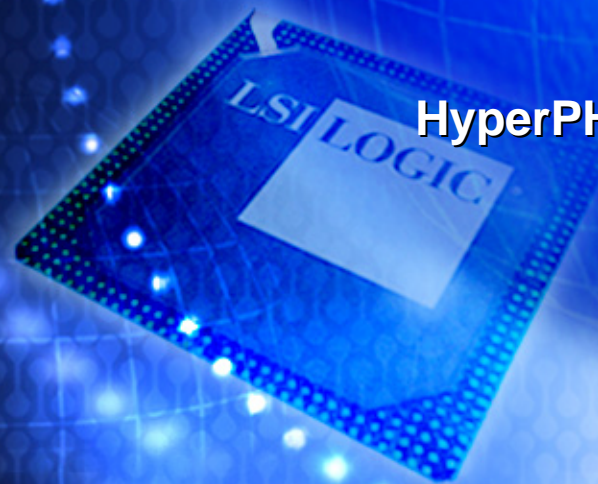# Comparison of NRZ and PAM-4 with the IEEE Channel Model

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LSI LOGIC

- **NRZ and PAM-4 with a linear FIR feedforward (FF) filter and a decision feedback (FB) equalizer are compared.**

- **The number of taps in the feedforward and feedback equalizers are varied.**

- **Response is from real channel close to the IEEE channel model.**

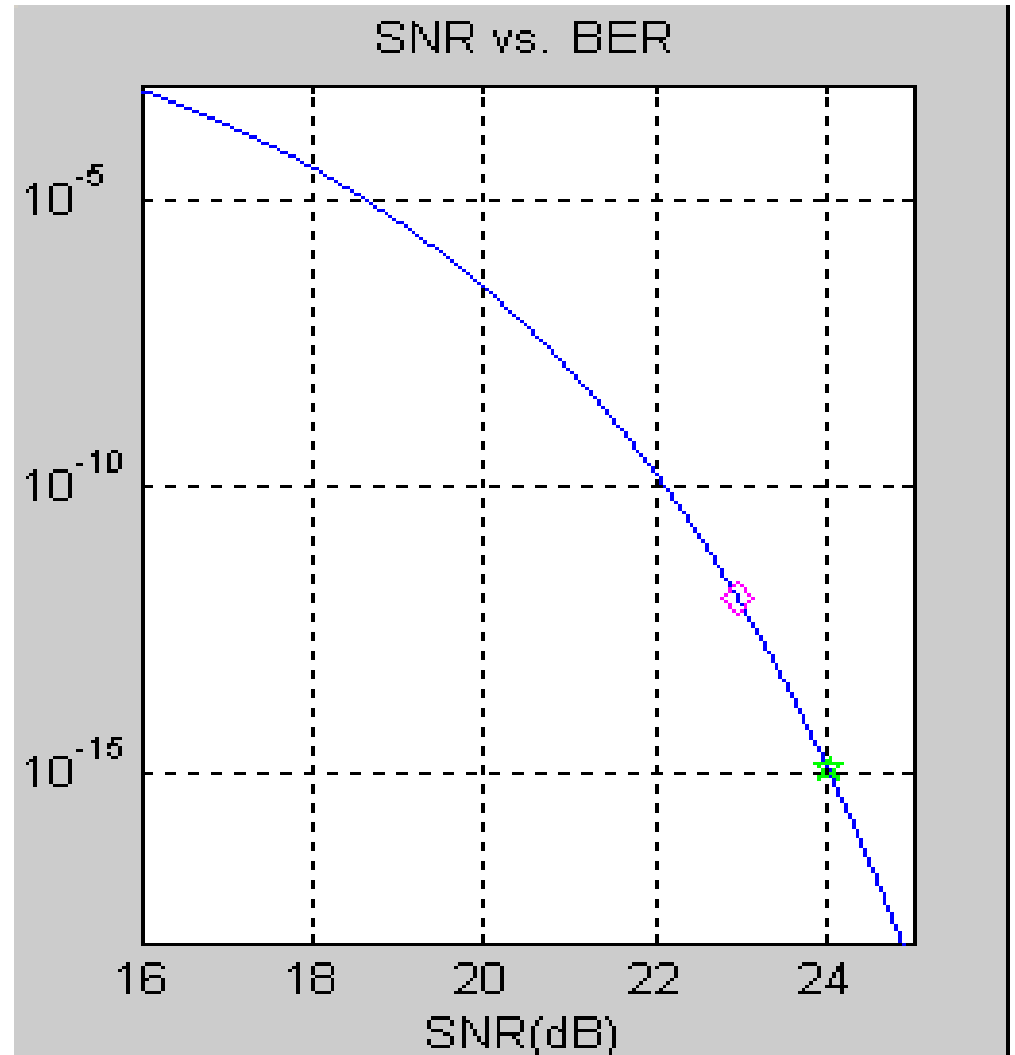- **The effect of near-end crosstalk is observed.**

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

$$SNR = \frac{d_{\min}^2}{\boldsymbol{s}^2}$$

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

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


SNR vs. BER

Parameters Used

- **Only DJ is from ISI**
  - ◆ **No DCD, PJ included**
- **0.01UI s RJ added**
- **Signal-to-Electronics Noise Ratio 45dB**
- **Crosstalk added as noted**
- **Ideal receiver sensitivity assumed**

Description of Results

- **Only NRZ with DFE and PAM-4 with DFE are considered**

- **SNR at optimal sampling point is shown**

- **x-axis shows number of feedback taps used**

- **Each line represents a different number of feed-forward (FF) equalizer taps used in the TX**

- **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.**

Frequency Response
Actual Channel with response close to IEEE Channel Model (from Xilinx)

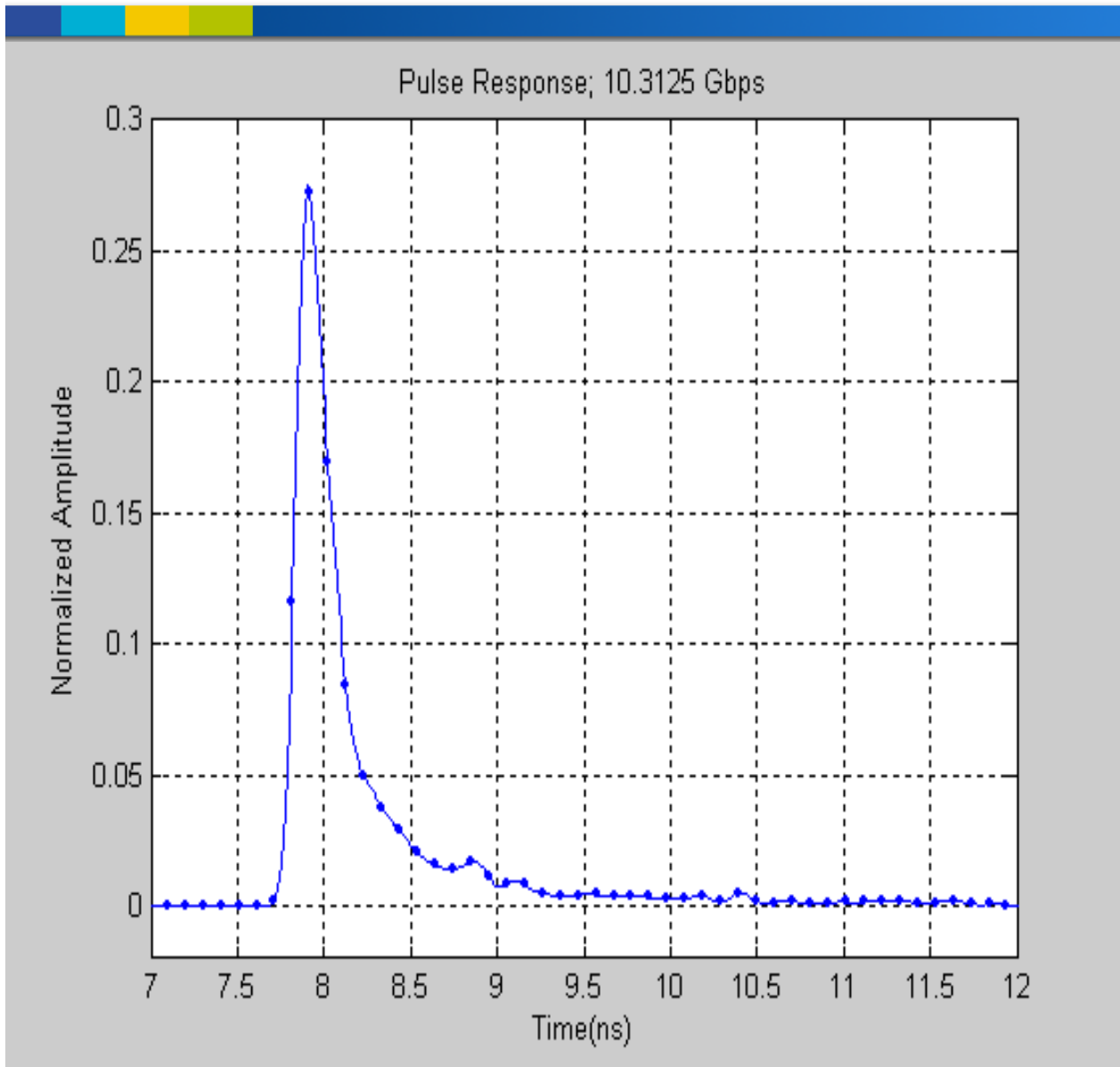Normalized Frequency Response

- IEEE Channel Model
- Real Channel
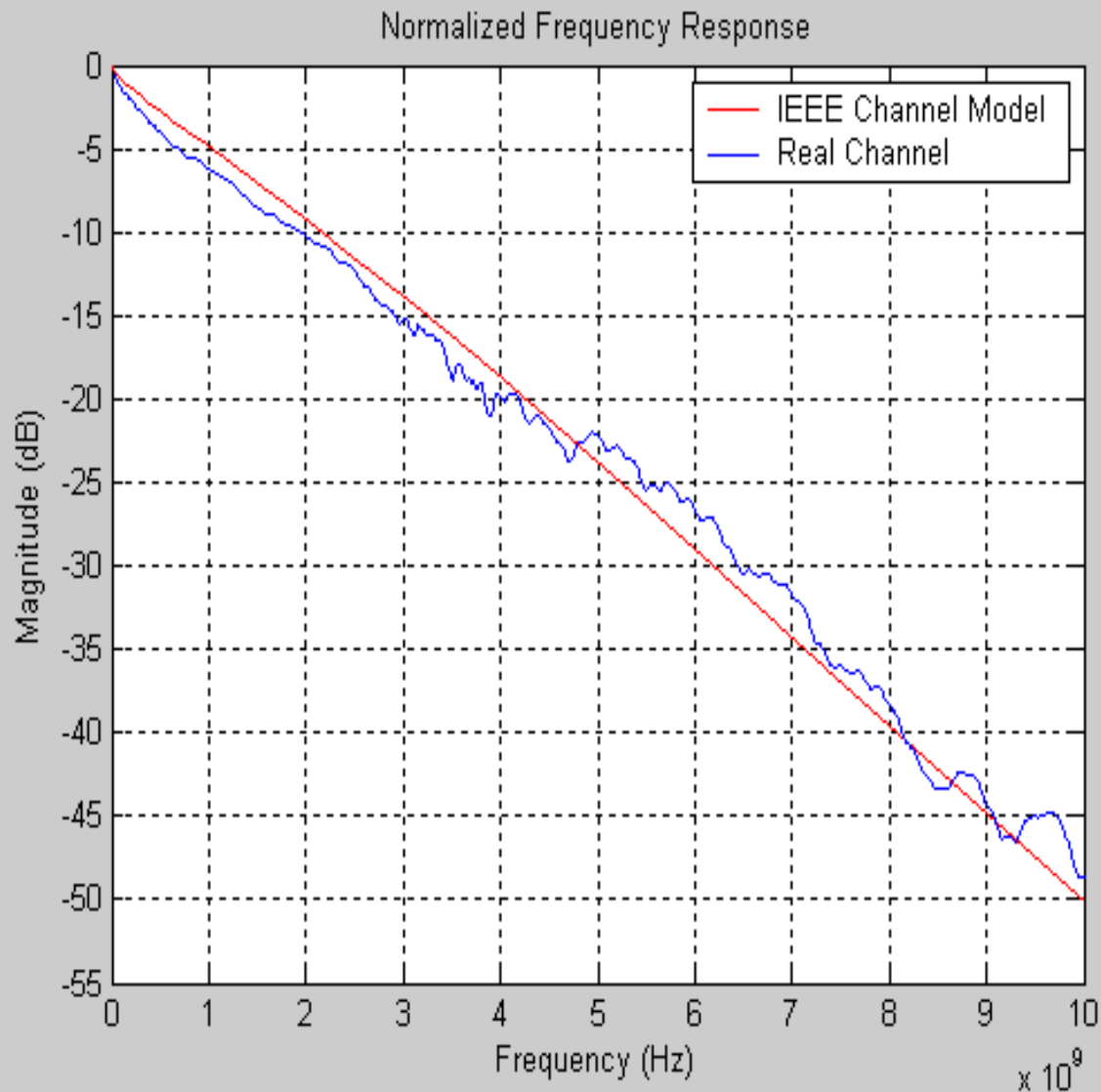
•Difference between response at 5GHz (Nyquist frequency of NRZ) and 2.5GHz (Nyquist frequency of PAM-4) is about 11dB.

•PAM-4 is often thought to perform better if the difference is greater >9.5dB.

Pulse Response
Based on Channel similar to IEEE Channel Model

Pulse Response; 10.3125 Gbps

- 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.

NRZ vs PAM-4
10.3125Gbps; No Crosstalk

NRZ-DFE vs. PAM-4-DFE; 10.3125Gbps; No XT
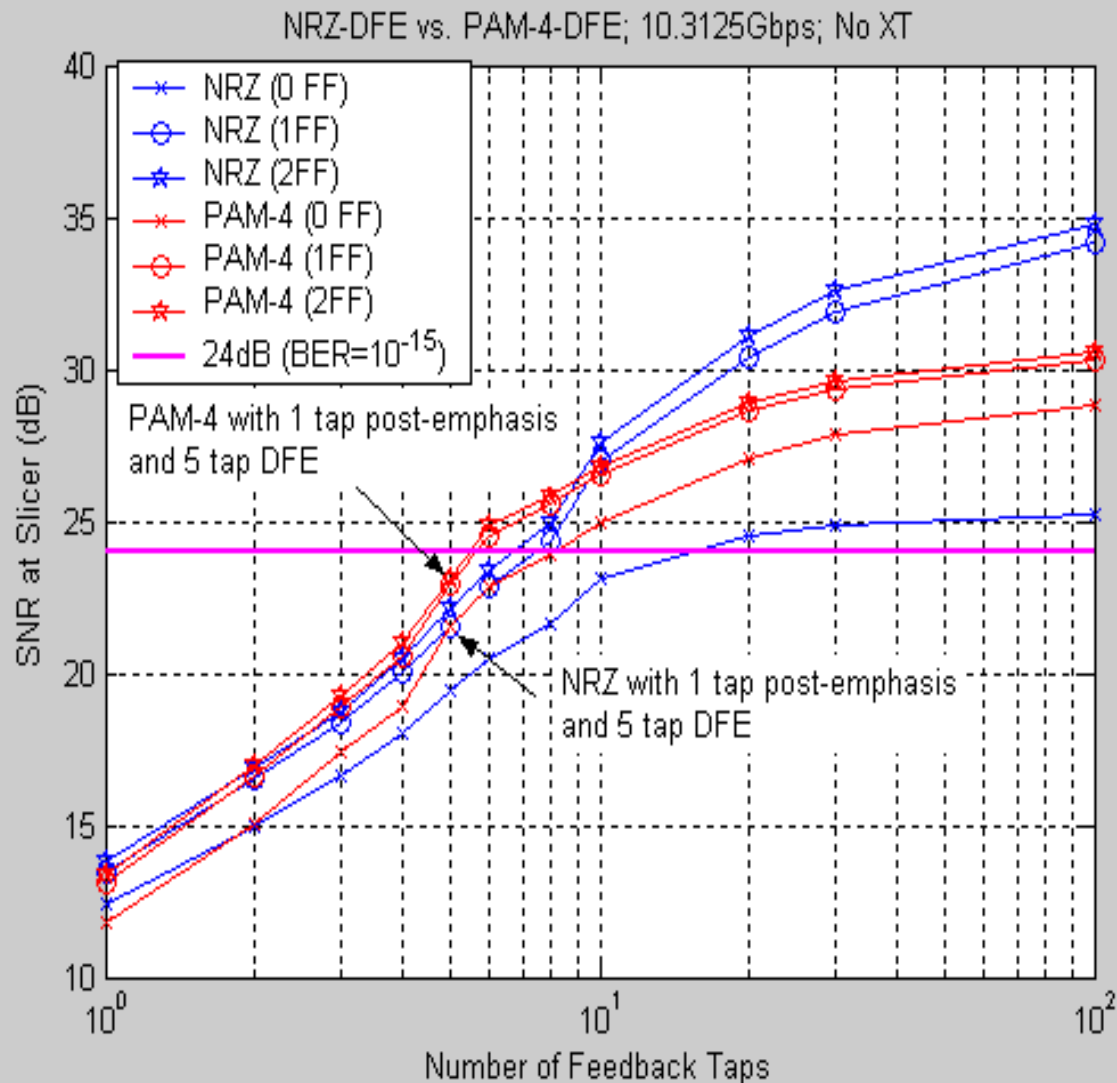
- •Transmit equalization is FIR with varying number of taps to address pre-cursor ISI.

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

- •With one tap post-emphasis (D-**a**) and 5 feedback taps, neither PAM-4 nor NRZ provides enough SNR to function. However,PAM4 has about 1.5dB more SNR.
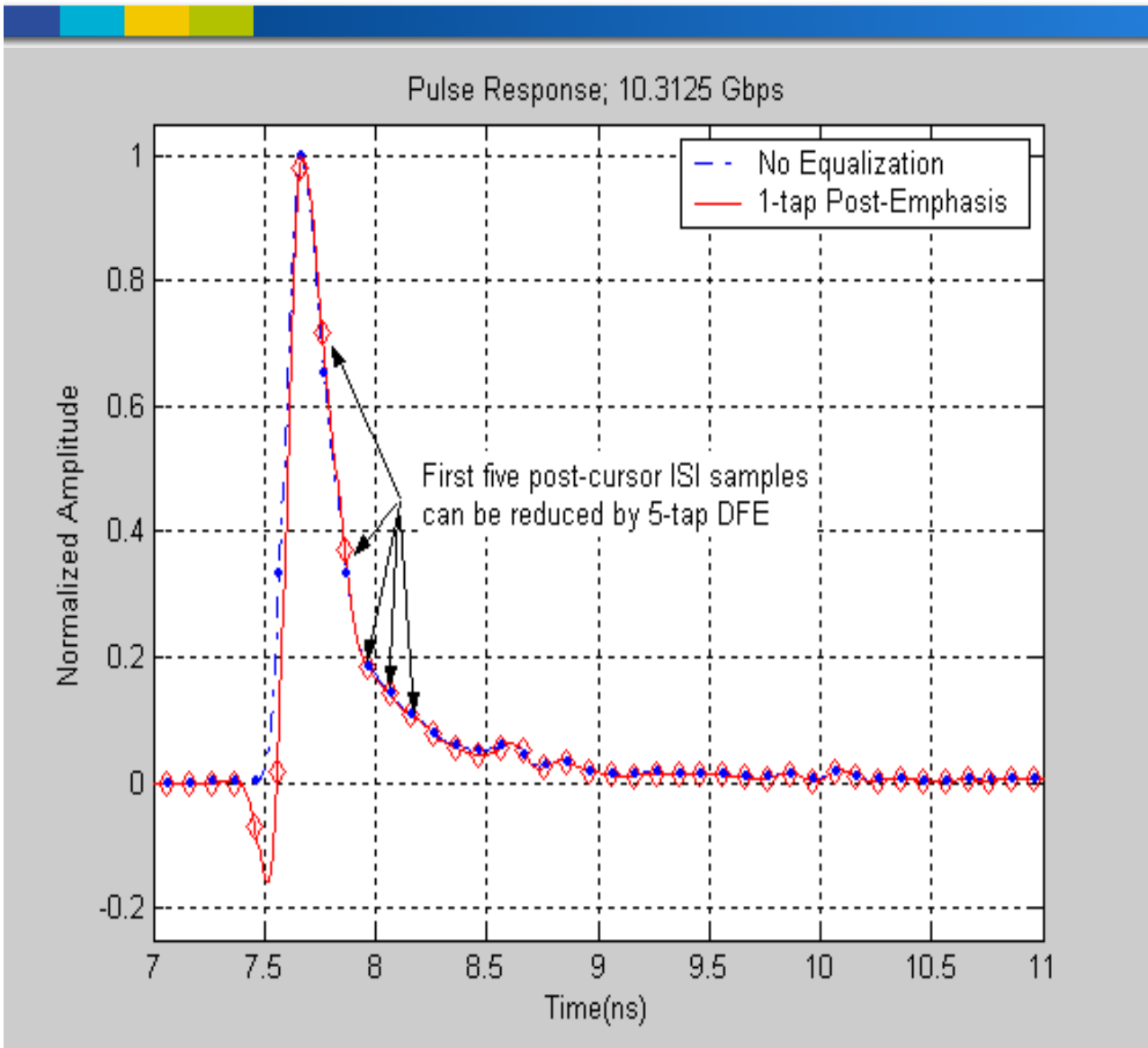
- •To get BER $<10^{-15}$ with one tap post-emphasis, PAM-4 requires 6 feedback taps while NRZ requires 8.

- •As number of DFE taps increases, performance of NRZ relative to PAM4 increases.

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Pulse Response at 10.3125Gbps
One Tap Post-Emphasis

Pulse Response; 10.3125 Gbps

- No Equalization
- 1-tap Post-Emphasis

First five post-cursor ISI samples can be reduced by 5-tap DFE
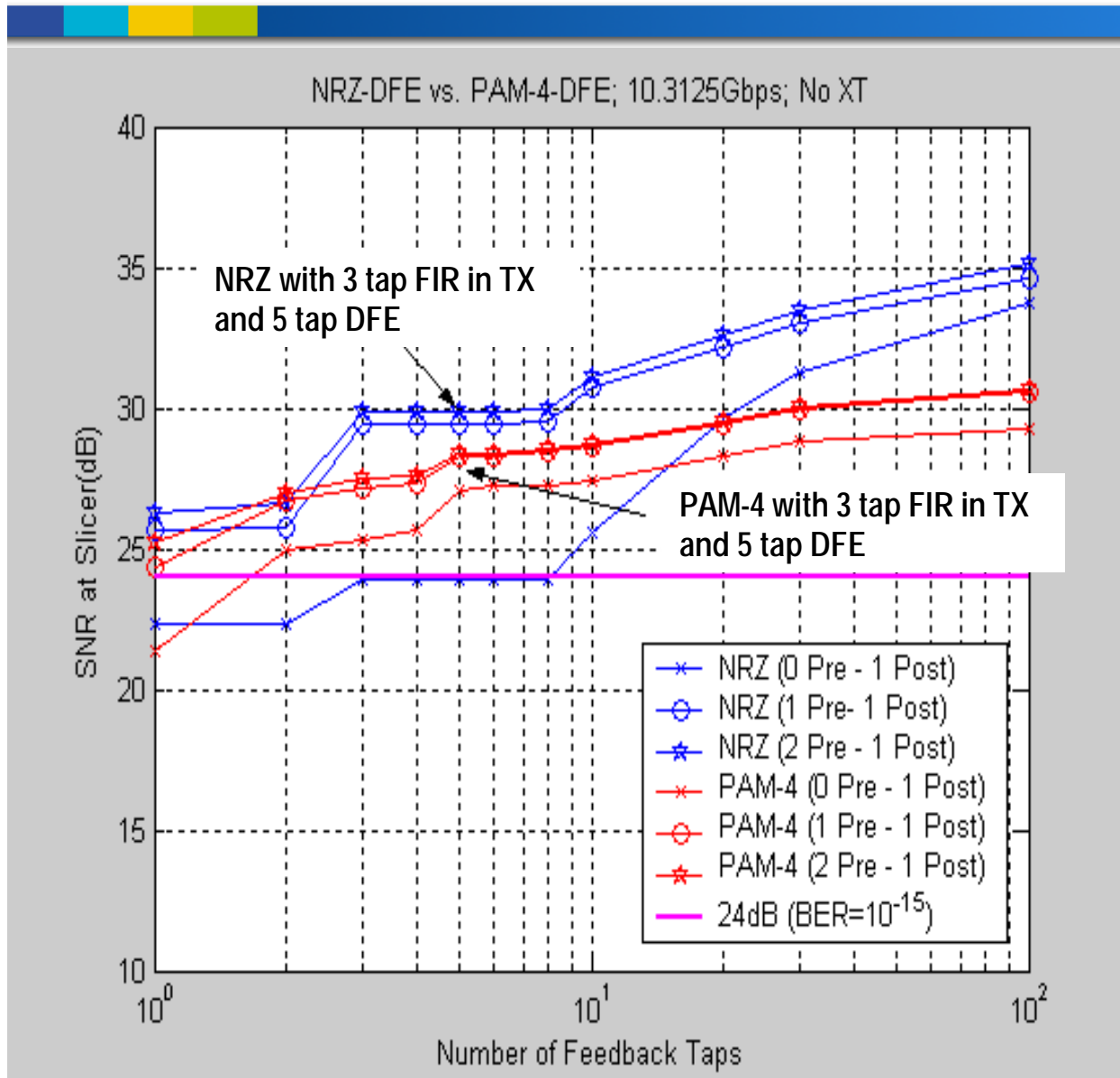
- Transmit equalization is two tap FIR to address pre-cursor ISI (one tap post-emphasis).

- 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

NRZ-DFE vs. PAM-4-DFE; 10.3125Gbps; No XT

NRZ with 3 tap FIR in TX and 5 tap DFE

PAM-4 with 3 tap FIR in TX and 5 tap DFE

Legend:
- NRZ (0 Pre - 1 Post)
- NRZ (1 Pre - 1 Post)
- NRZ (2 Pre - 1 Post)
- PAM-4 (0 Pre - 1 Post)
- PAM-4 (1 Pre - 1 Post)
- PAM-4 (2 Pre - 1 Post)
- 24dB (BER=10^{-15})

•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

$$(-\mathbf{b}D^2 + D - \mathbf{a})$$

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.

Pulse Response at 10.3125Gbps
One Tap Pre-Emphasis

Pulse Response; 10.3125 Gbps

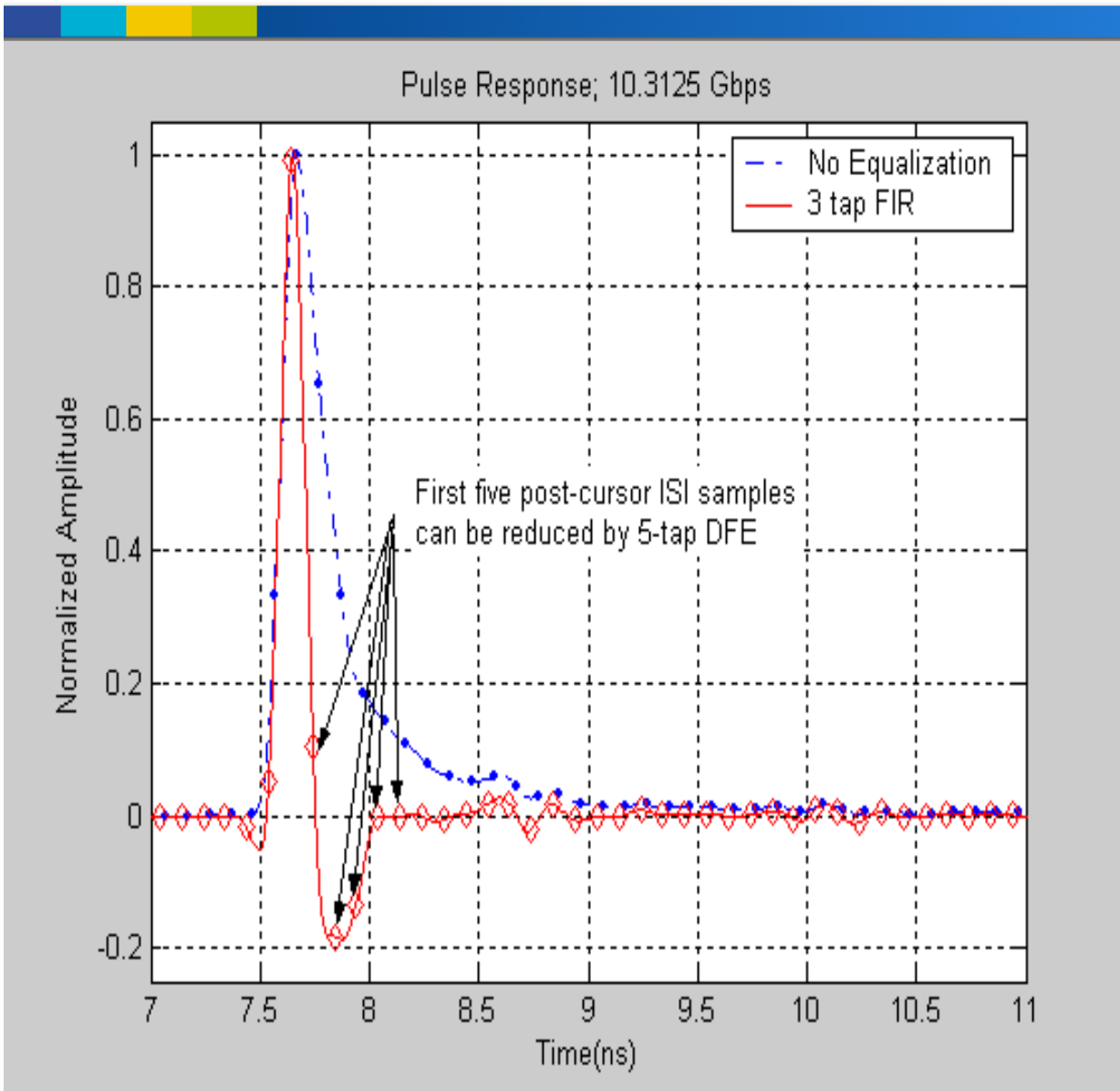First five post-cursor ISI samples can be reduced by 5-tap DFE
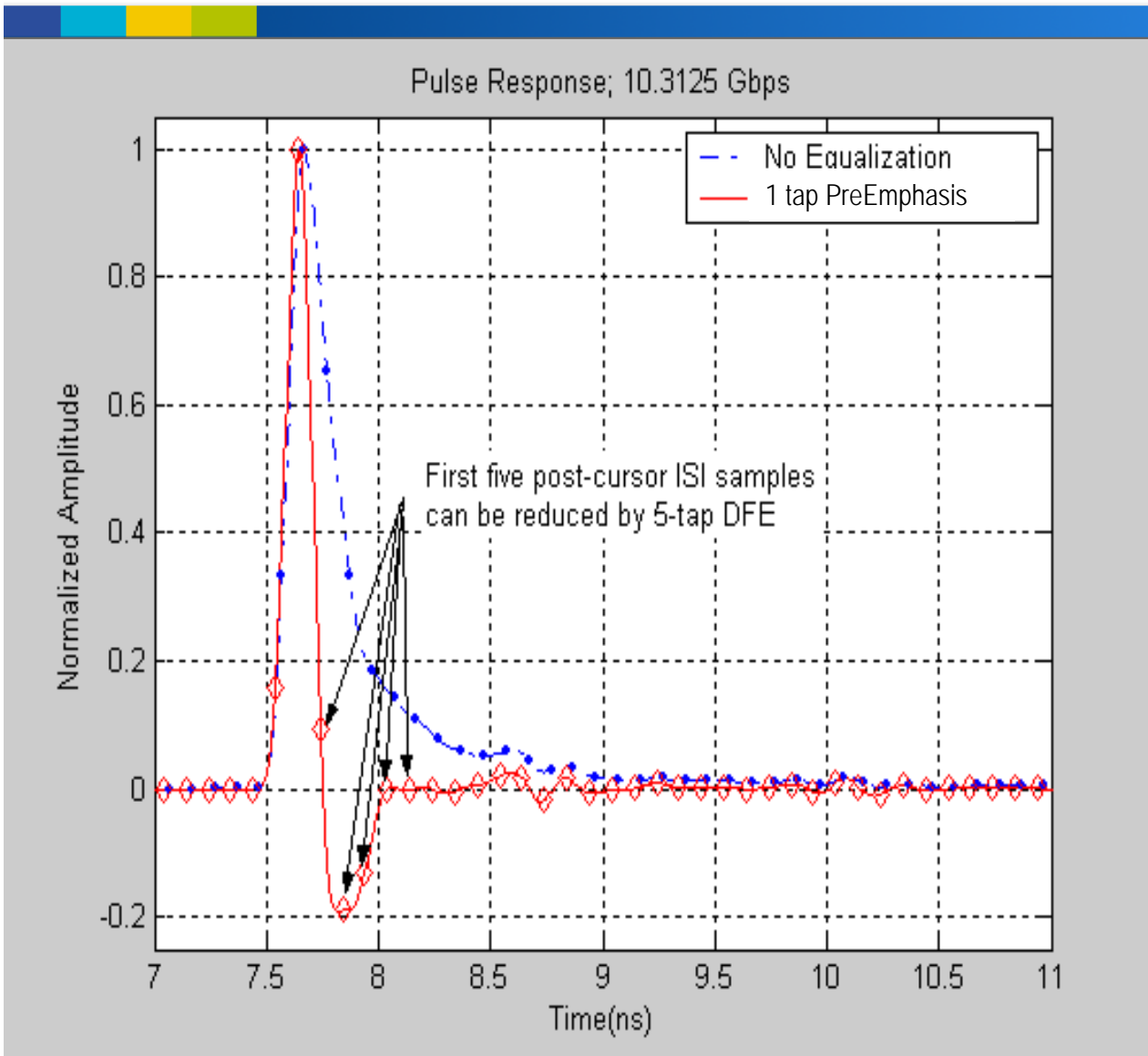
- Transmit equalization is two tap FIR to address post-cursor ISI (one tap pre-emphasis).

- 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.

Pulse Response at 10.3125Gbps
Three Tap FIR (One Tap Pre-Emphasis and One Tap Post-Emphasis)

Pulse Response; 10.3125 Gbps

Legend:
- – – No Equalization
- —— 3 tap FIR

First five post-cursor ISI samples can be reduced by 5-tap DFE

X-axis: Time(ns), from 7 to 11
Y-axis: Normalized Amplitude, from -0.2 to 1

•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.)

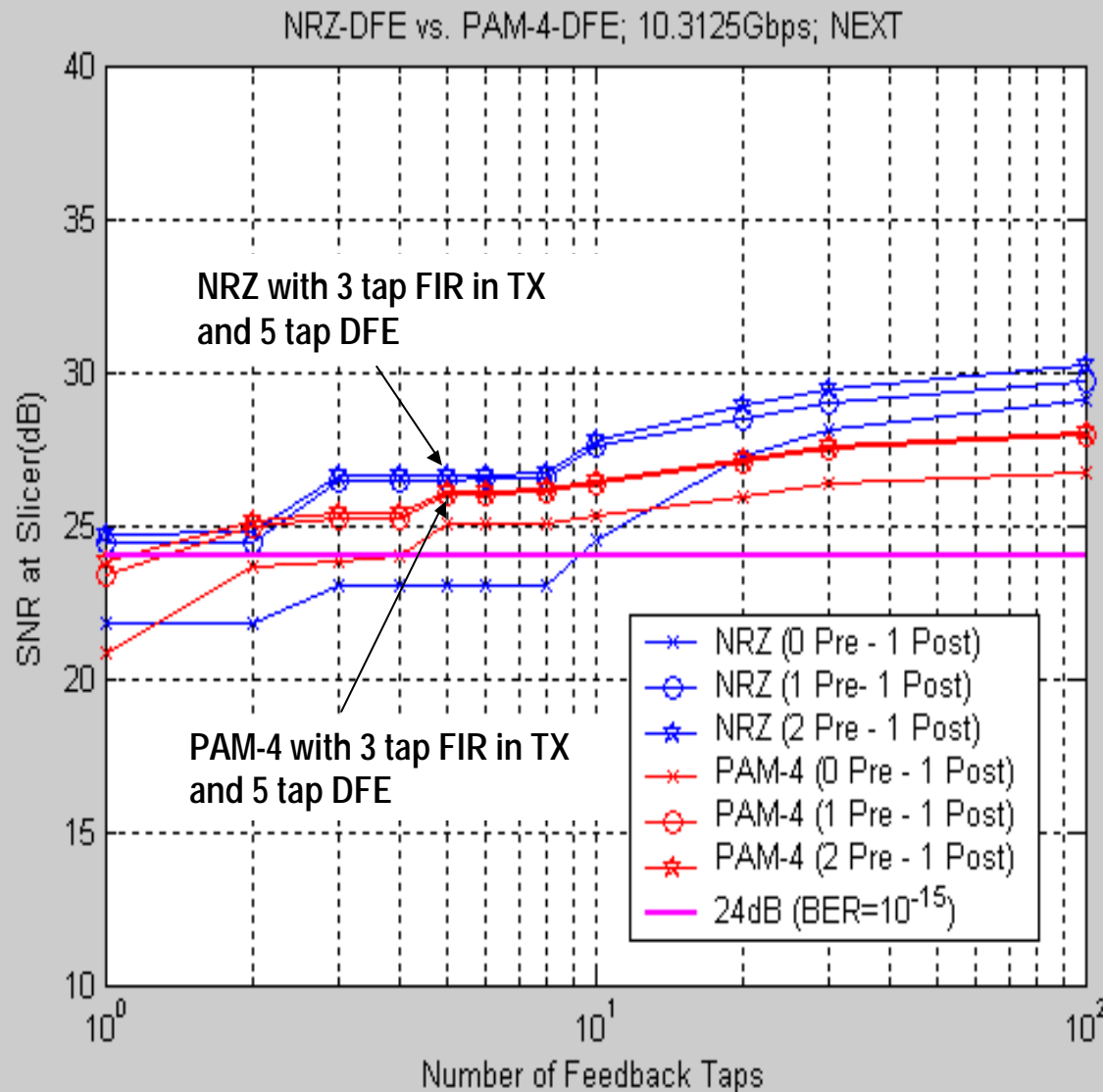•Pre-cursor ISI is now also significantly reduced.

Near-End Crosstalk Frequency Responses
From Xilinx
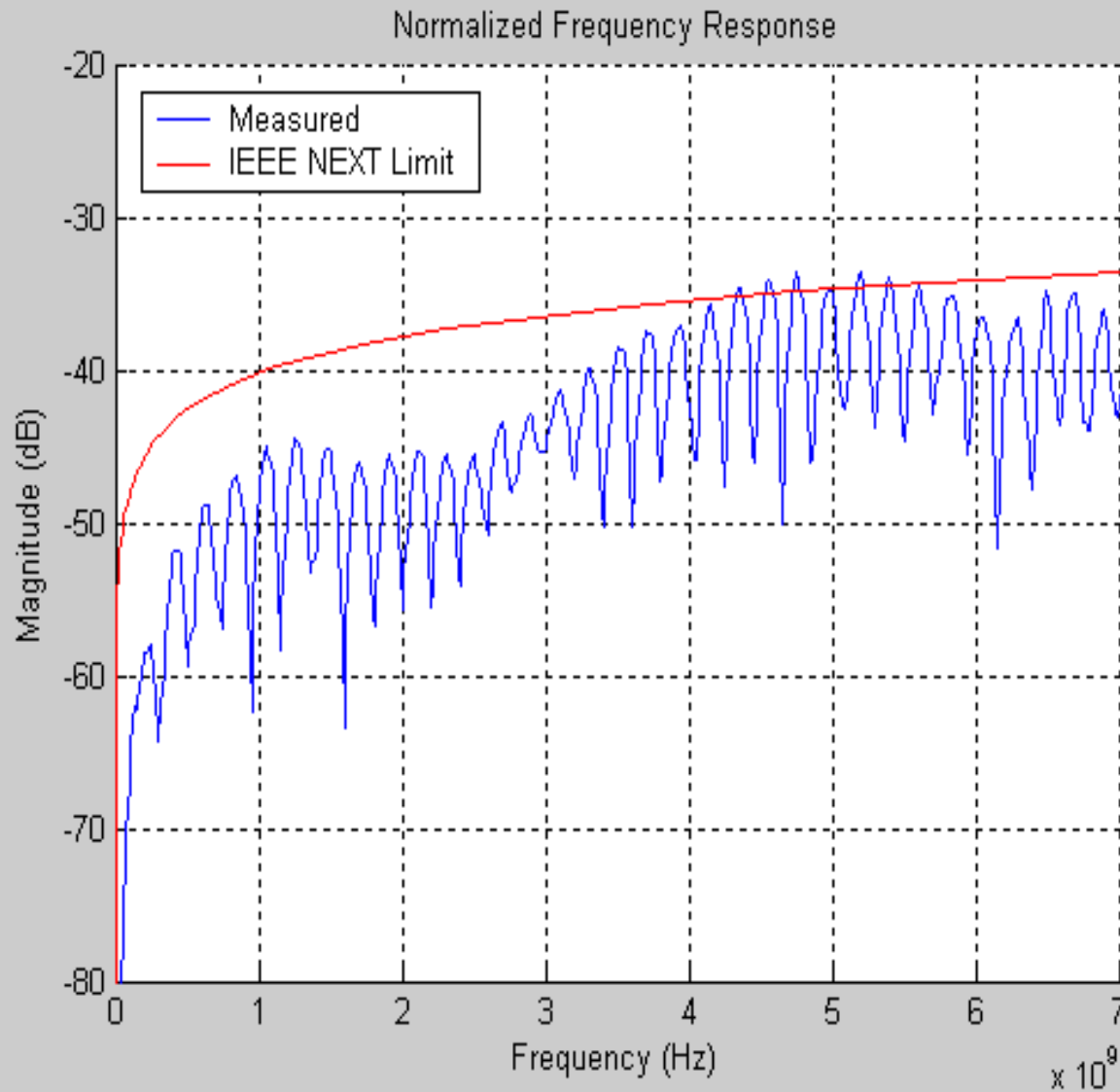
- One channel of NEXT will be added to the simulations.

- Crosstalk is assumed to occur at the same frequency as the signal.

- The worst case crosstalk phase at the ideal sampling point is selected.

NRZ vs PAM-4
10.3125Gbps; NEXT; With One Tap PostCursor FF Equalization

NRZ-DFE vs. PAM-4-DFE; 10.3125Gbps; NEXT

NRZ with 3 tap FIR in TX and 5 tap DFE

PAM-4 with 3 tap FIR in TX and 5 tap DFE

Legend:
- NRZ (0 Pre - 1 Post)
- NRZ (1 Pre- 1 Post)
- NRZ (2 Pre - 1 Post)
- PAM-4 (0 Pre - 1 Post)
- PAM-4 (1 Pre - 1 Post)
- PAM-4 (2 Pre - 1 Post)
- 24dB (BER=10^{-15})

Axes: SNR at Slicer(dB) vs Number of Feedback Taps

- 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.

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Conclusion

- 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.