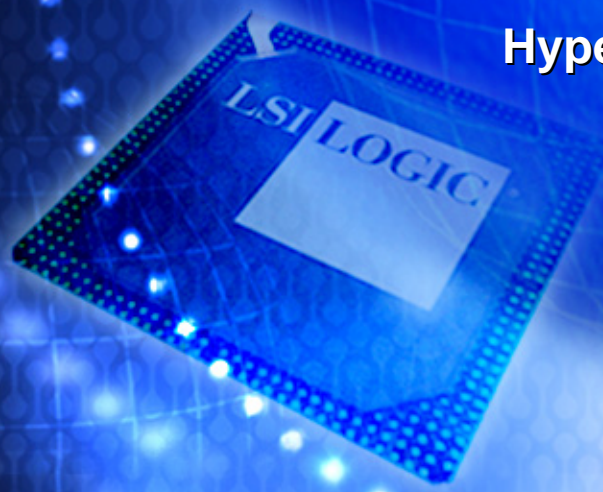


Performance of NRZ and PAM-4 with IEEE 802.3ap Test Channels

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- **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.**
- **Responses are from Tyco-provided measured channels and Xilinx-provided modeled channel.**
- **The effect of near-end crosstalk is observed.**

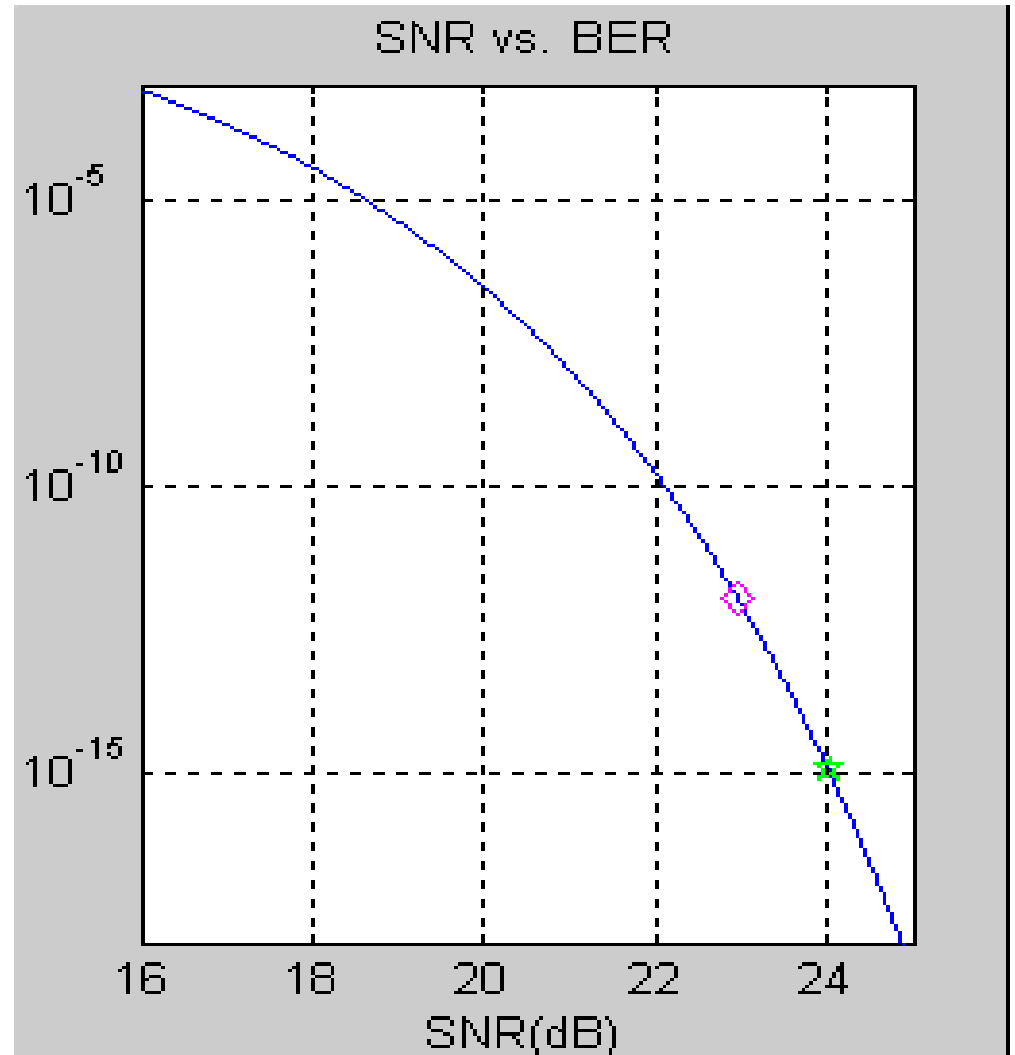
Required SNR

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

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

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

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





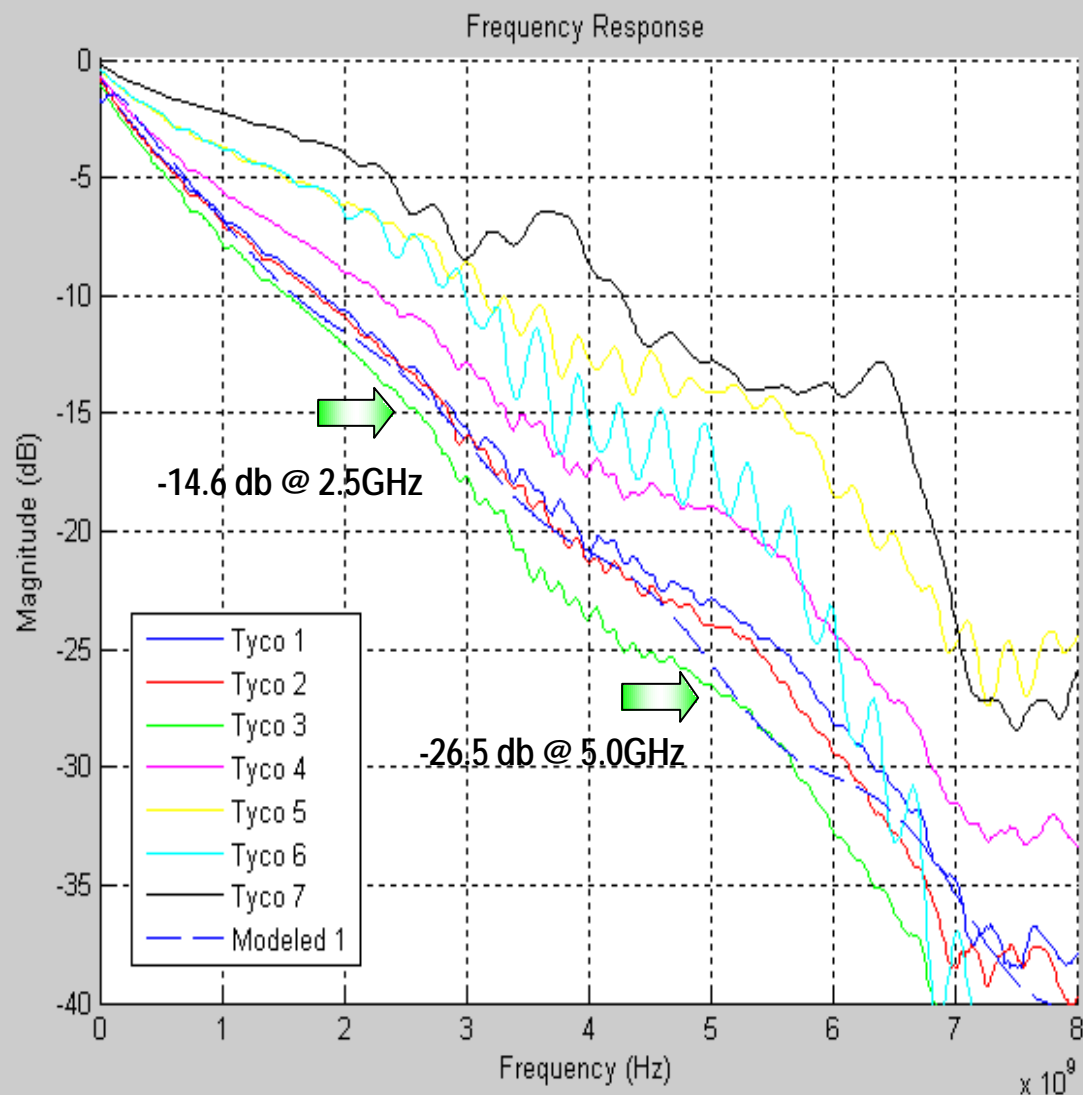
Parameters Used

- 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

- 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 Responses

Measured Channels from Tyco and Modeled Channel from Xilinx

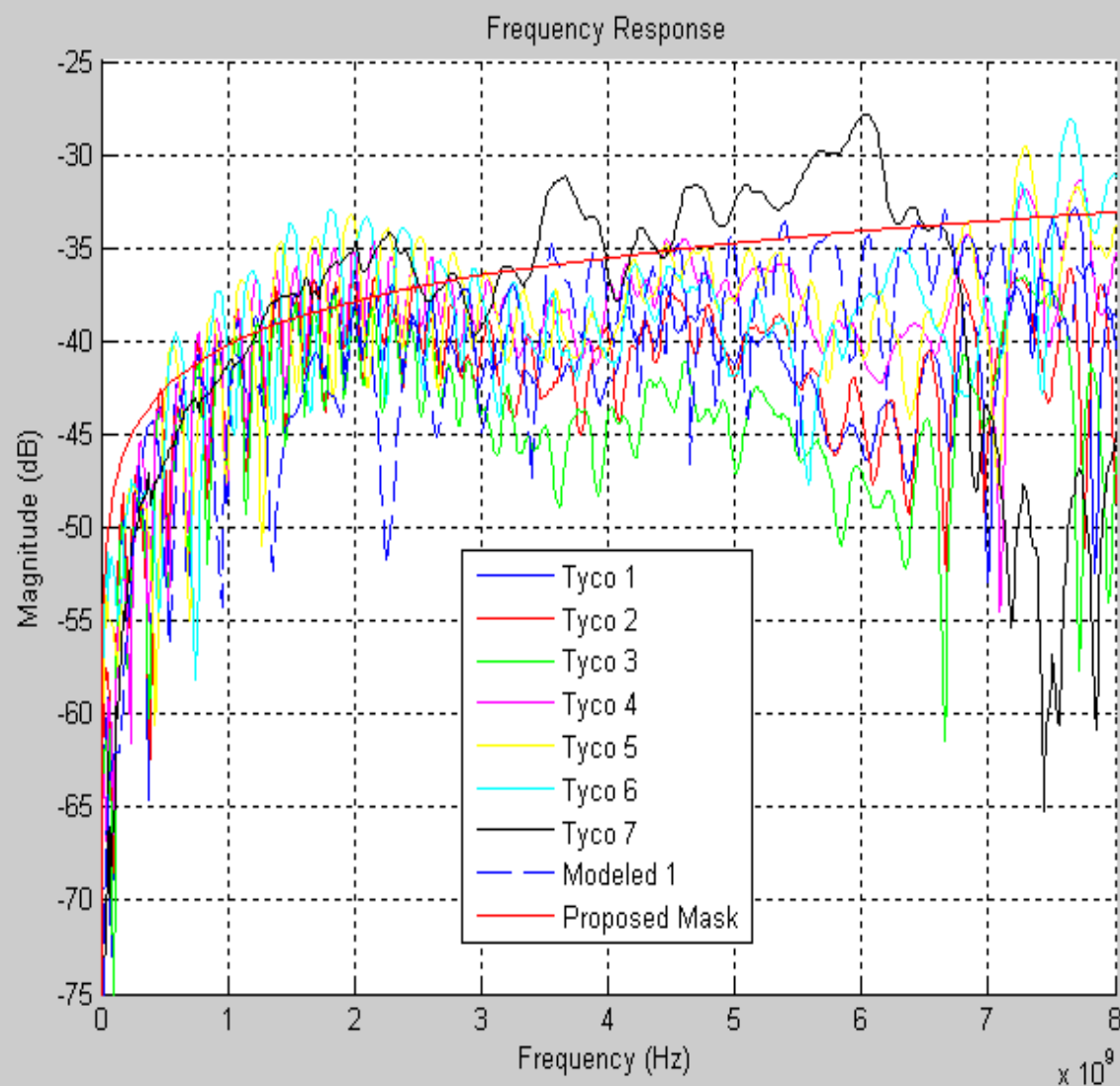


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- Tyco 3 exhibits largest difference of the measured channels between response at 5GHz (Nyquist frequency of NRZ) and 2.5GHz (Nyquist frequency of PAM-4). It is about 11.9 dB.
- The modeled Xilinx channel exhibited larger difference between response at 5GHz (Nyquist frequency of NRZ) and 2.5GHz (Nyquist frequency of PAM-4) than any of the measured channels. It is about 12.1 dB.
- PAM-4 has often been thought to perform better if the difference is greater >9.5dB.

Near-End Crosstalk Frequency Responses

Worst Case NEXT from each Tyco measured case and NEXT from modeled Xilinx data

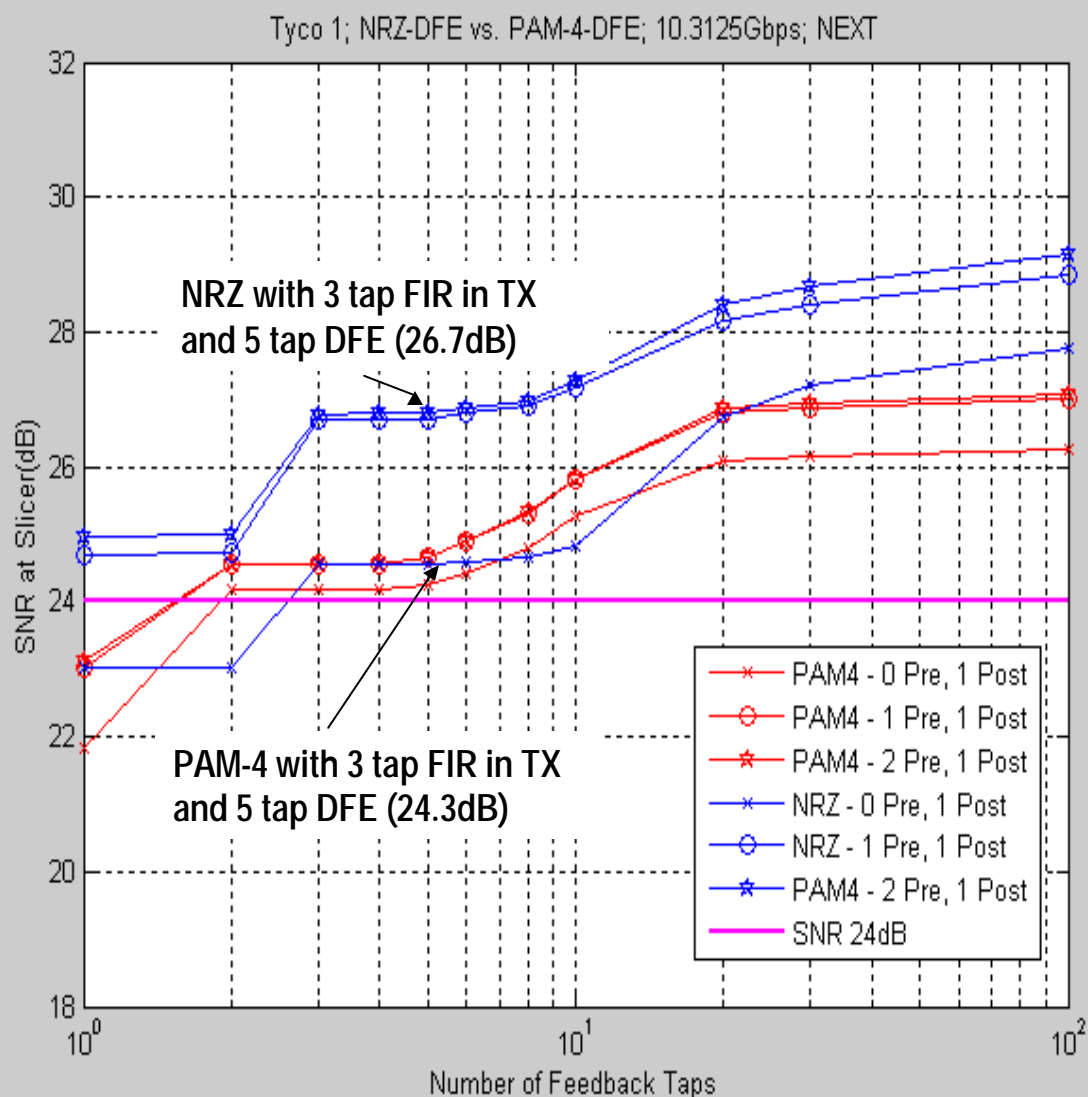


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- One NEXT aggressor will be considered for each case: the worst case provided for each channel. Usually, one aggressor was significantly worse than the others.
- Crosstalk is assumed to occur at the same frequency as the signal.
- The worst case crosstalk phase at the ideal sampling point is selected.

NRZ vs PAM-4

Tyco Channel 1; 10.3125Gbps; NEXT;

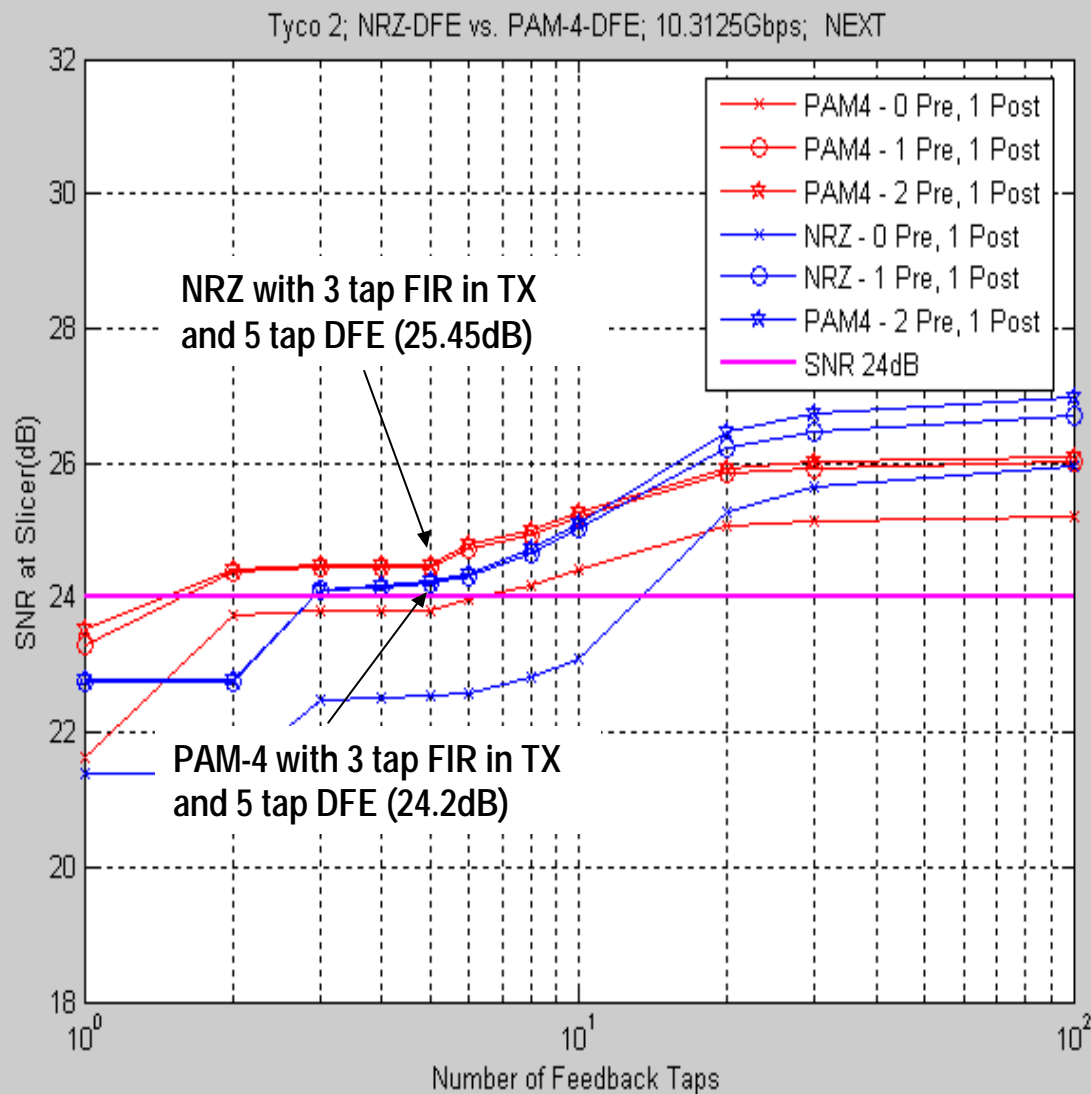


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- This channel exhibited 9.2dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).
- With NEXT and three tap FIR, NRZ meets SNR goal with one DFE tap and PAM-4 requires two.
- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows about 3.4dB improvement over PAM-4.

NRZ vs PAM-4

Tyco Channel 2; 10.3125Gbps; NEXT;



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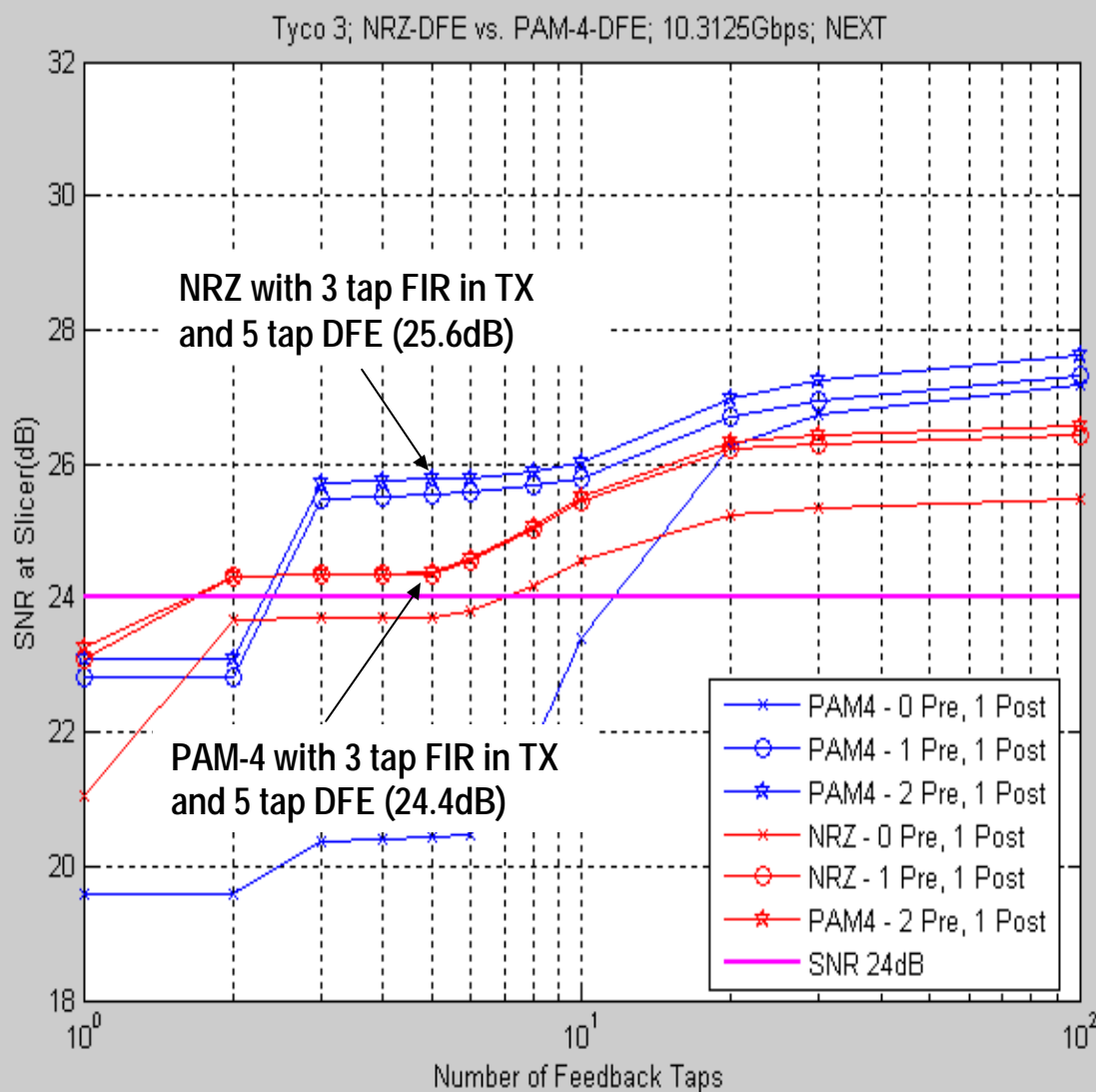
•This channel exhibited 10.9dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).

•With NEXT and three tap FIR, NRZ meets SNR goal with three DFE taps and PAM-4 requires two.

•With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows about a 0.25dB loss as PAM-4.

NRZ vs PAM-4

Tyco Channel 3; 10.3125Gbps; NEXT;

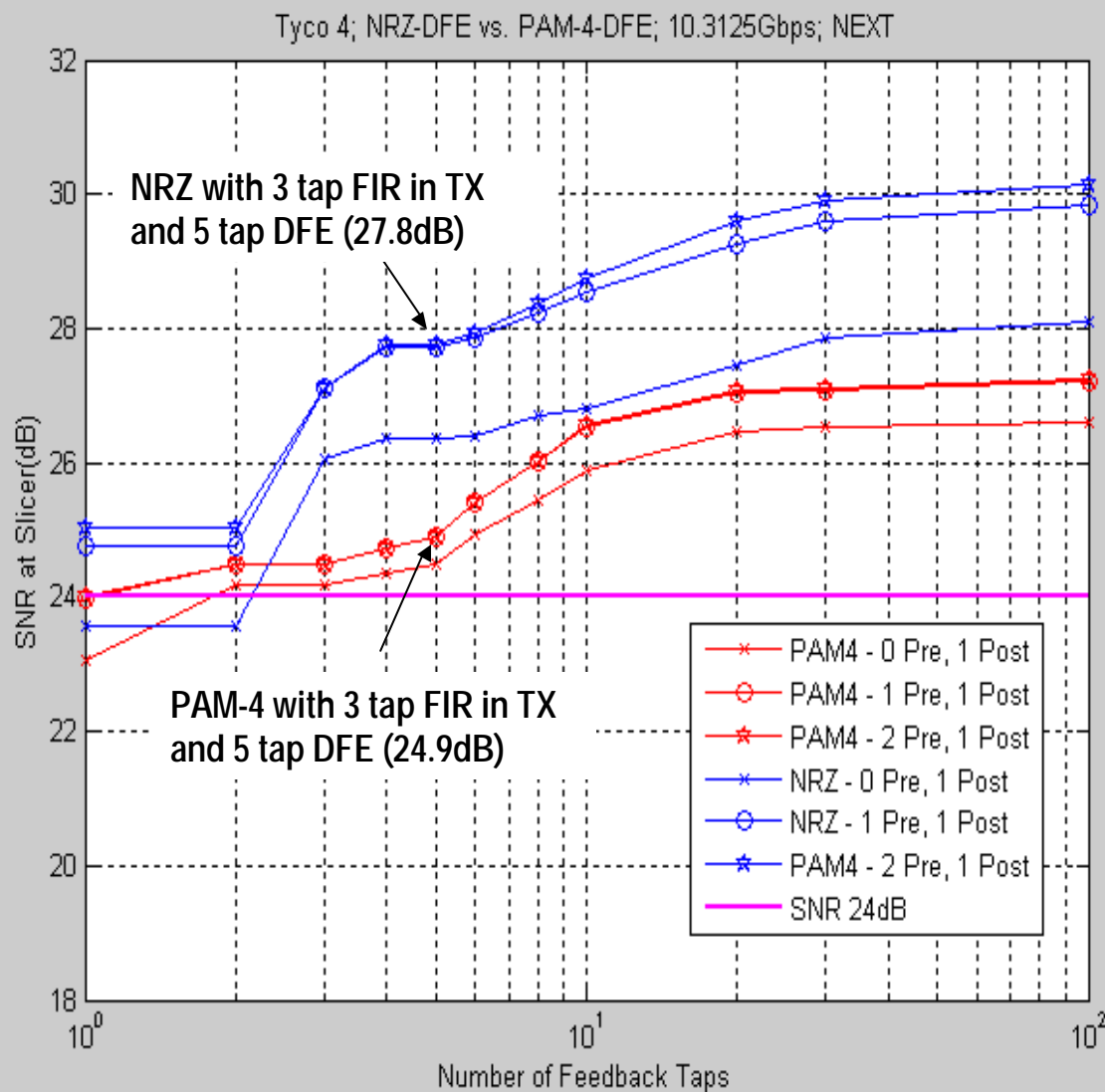


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- This channel exhibited 11.9dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).
- With NEXT and three tap FIR, NRZ meets SNR goal with three DFE taps and PAM-4 requires two.
- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 1.2dB margin over PAM-4.

NRZ vs PAM-4

Tyco Channel 4; 10.3125Gbps; NEXT;



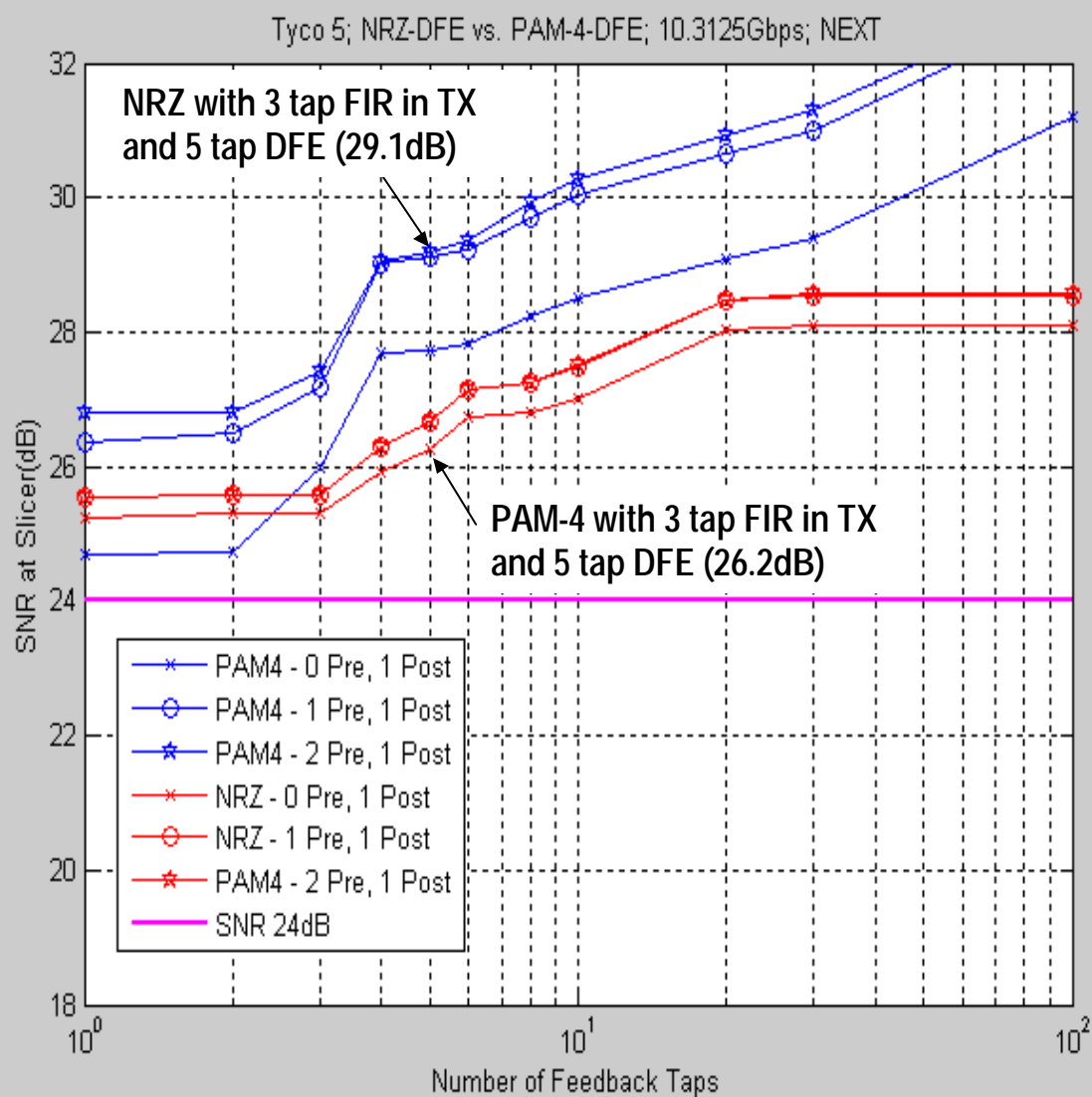
- This channel exhibited 8.0dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).

- With NEXT and three tap FIR, NRZ meets SNR goal with one DFE tap and PAM-4 requires two taps.

- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 2.9dB margin over PAM-4.

NRZ vs PAM-4

Tyco Channel 5; 10.3125Gbps; NEXT;

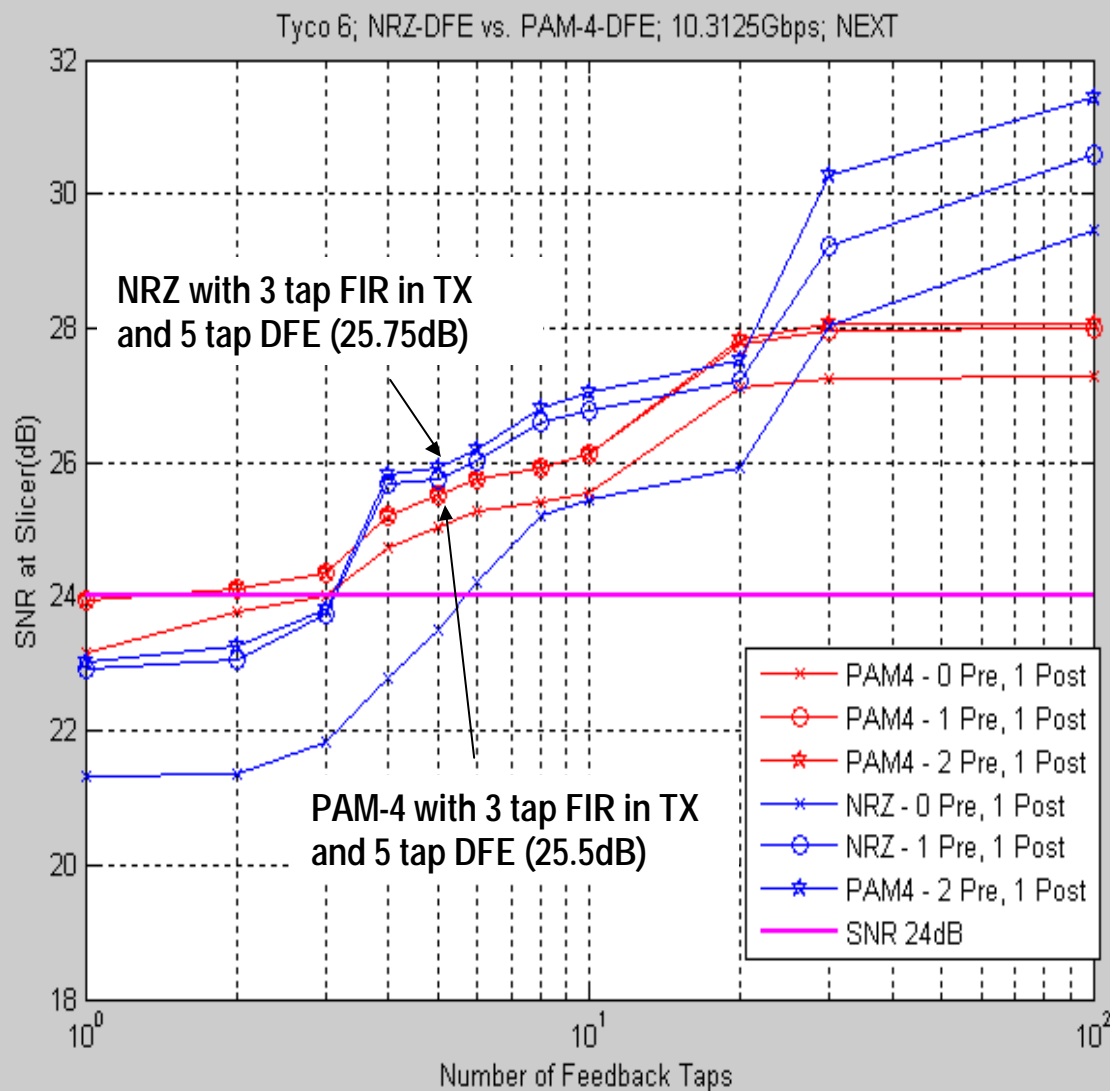


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- This channel exhibited 6.6dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).
- All equalization and signaling strategies considered meet SNR goal.
- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 2.9dB margin over PAM-4.

NRZ vs PAM-4

Tyco Channel 6; 10.3125Gbps; NEXT;



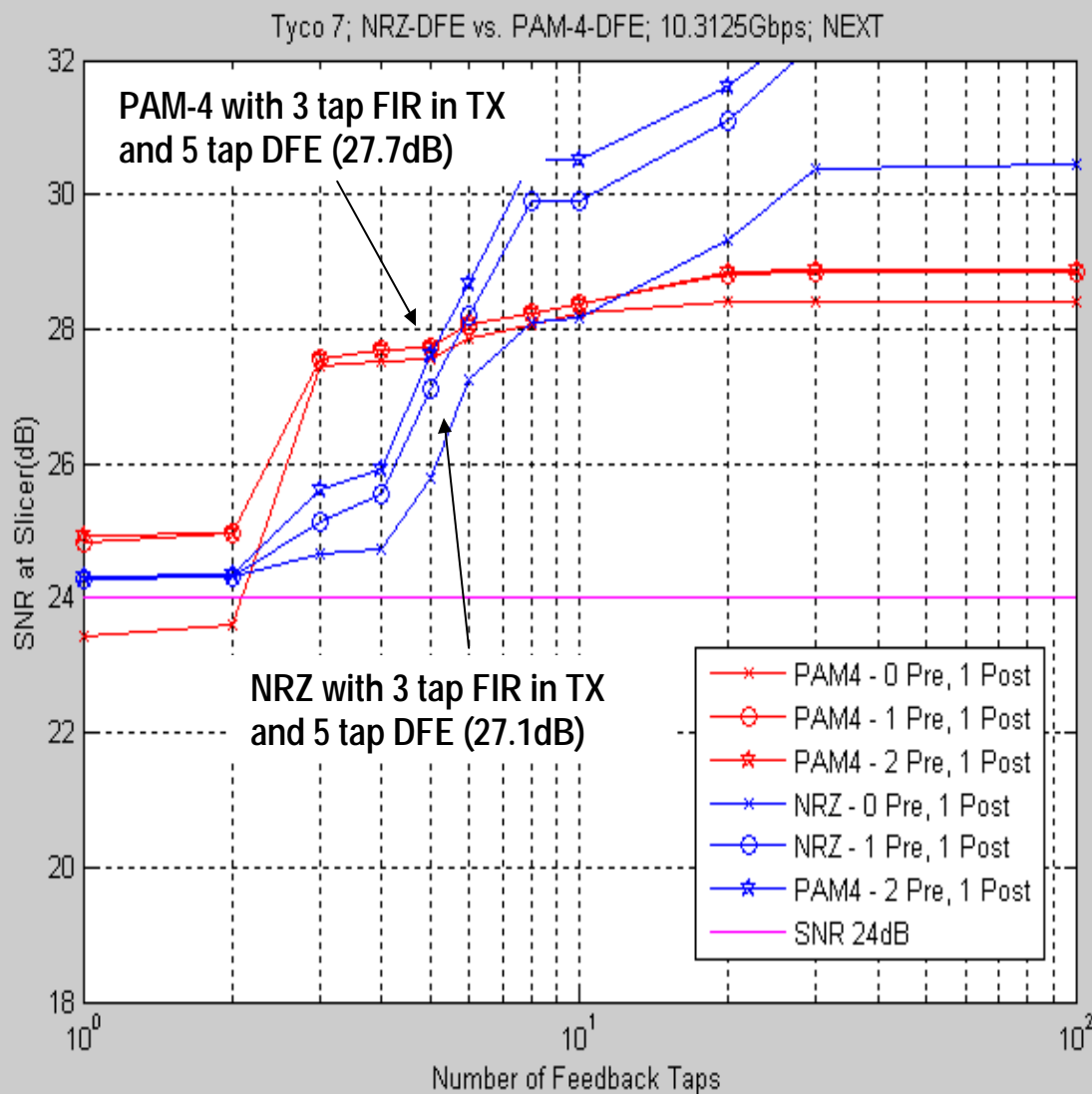
- This channel exhibited 8.0dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz). (Difficult to estimate due to ringing.)

- With NEXT and three tap FIR, NRZ meets SNR goal with four DFE taps and PAM-4 requires two taps.

- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 0.25dB margin over PAM-4.

NRZ vs PAM-4

Tyco Channel 7; 10.3125Gbps; NEXT;

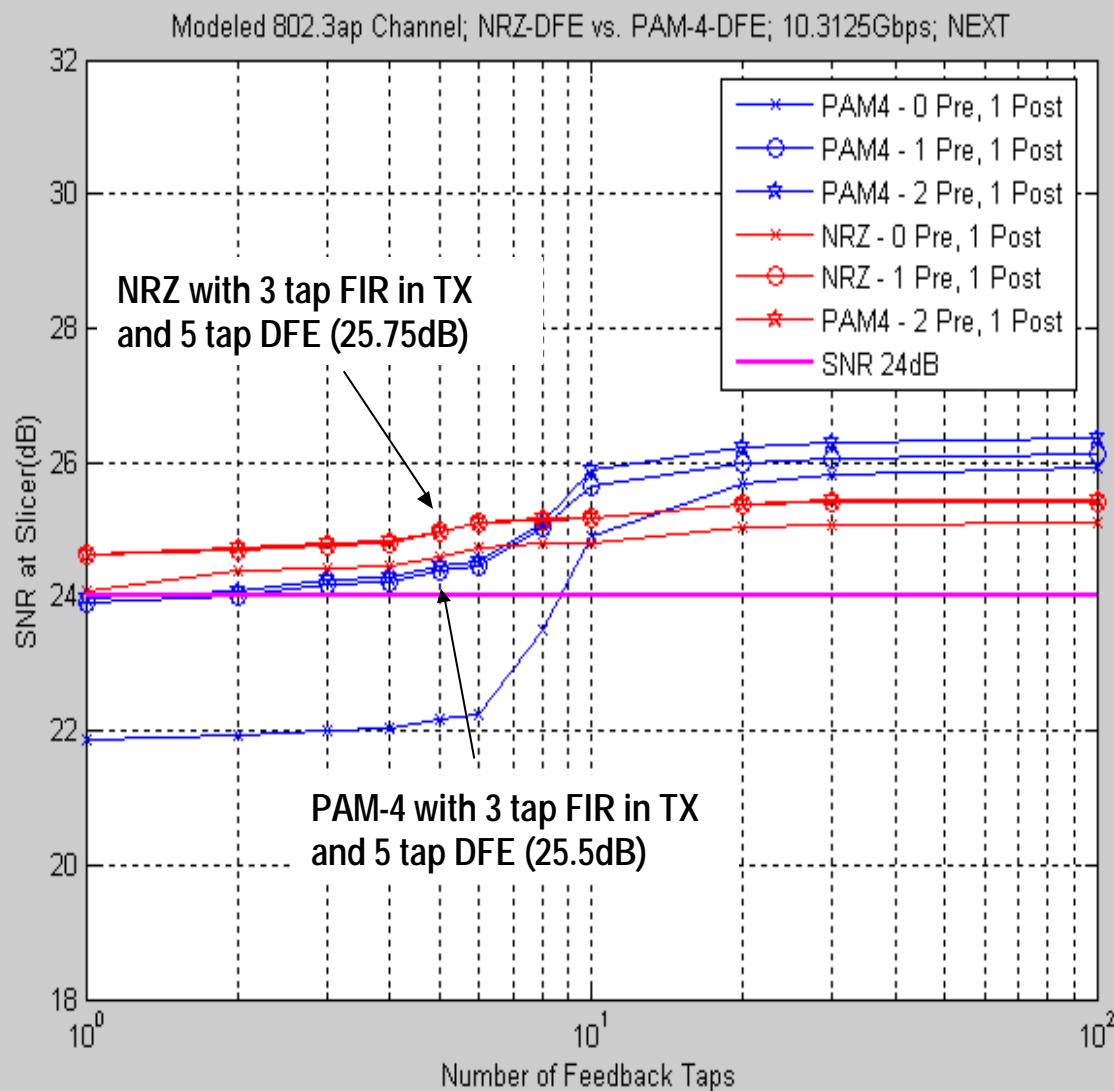


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- This channel exhibited 6.5dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz).
- With NEXT and three tap FIR, both NRZ and PAM-4 meet SNR goal with one DFE tap.
- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 0.6dB loss relative to PAM-4.

NRZ vs PAM-4

Modeled Channel (Xilinx); 10.3125Gbps; NEXT;



24-Sep-2004 LSI Logic

- This channel exhibited 12.1dB loss between the Nyquist frequency for PAM-4 (2.5GHz) and that for NRZ (5.0GHz). (Difficult to estimate due to ringing.)

- With NEXT and three tap FIR, NRZ meets SNR goal with two DFE taps and PAM-4 requires one taps.

- With NEXT, performance of three tap FIR and 5 DFE taps, NRZ shows 0.25dB loss relative to PAM-4.



Results Summary

Channel	Loss (2.5GHz to 5.0GHz)	NRZ # of FB taps for 24dB	PAM-4 #of FB taps for 24dB	NRZ v. PAM-4 3 tap FIR 5 tap DFE
Tyco 1	9.2 dB	1	2	3.4dB NRZ
Tyco 2	10.9 dB	3	2	0.25dB PAM-4
Tyco 3	11.9 dB	3	2	1.2dB NRZ
Tyco 4	8.0 dB	1	2	2.9dB NRZ
Tyco 5	6.6 dB	1	1	2.9dB NRZ
Tyco 6	8.0 dB	4	2	0.25dB NRZ
Tyco 7	6.5 dB	1	1	0.6dB PAM-4
Xilinx 1	12.1 dB	2	1	0.25dB PAM-4

Conclusion

- Although some channels have greater than 9.5dB loss between Nyquist frequencies of PAM-4 and NRZ, NRZ can perform better depending on the detection scheme.
- NRZ and PAM-4 were found to require similar complexity equalization to meet SNR target.
- Performance of NRZ improves relative to PAM-4 as the number of DFE taps increase.
- Channel loss between Nyquist frequencies for NRZ and PAM-4 did not appear to directly correlate to relative performance.