PAM-N Tutorial Material

802.3bj 100 Gb/s Backplane and Copper Cable Task Force

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- Objectives
- PAM-N Ideal Channel Simulations
- PAM-N Optimum Receiver Analysis
- PAM-N Realizable Receiver Simulations
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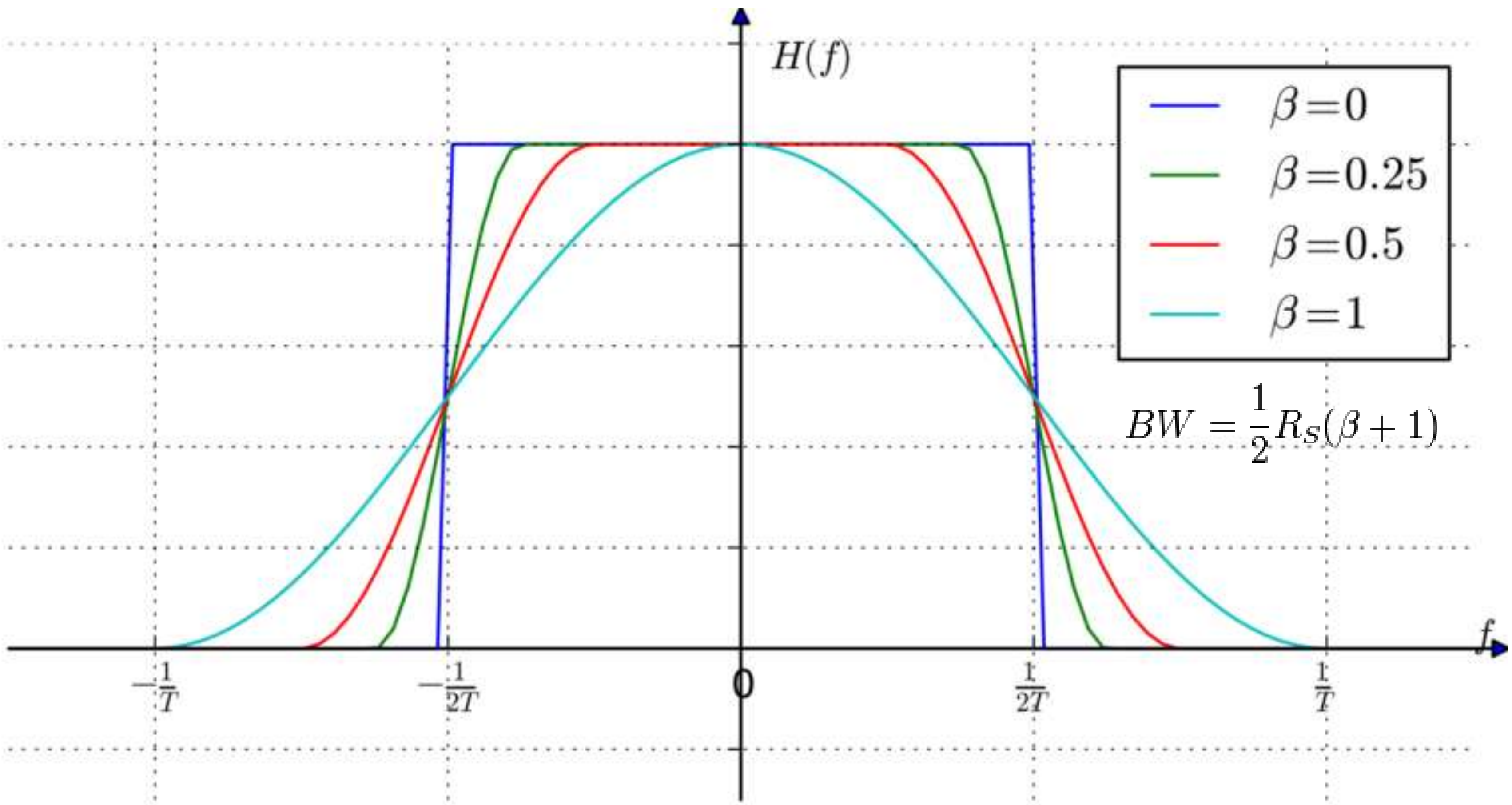
Introduction

- 25Gb/s modulation alternatives are being debated in 802.3bj
- Higher order modulation will be required in future standards to support bandwidth and density growth
- It is critical that there is a broad understanding of PAM-N (amplitude) and more generally QAM (amplitude and phase) modulation to enable informed debate about technology choices for present and future standards

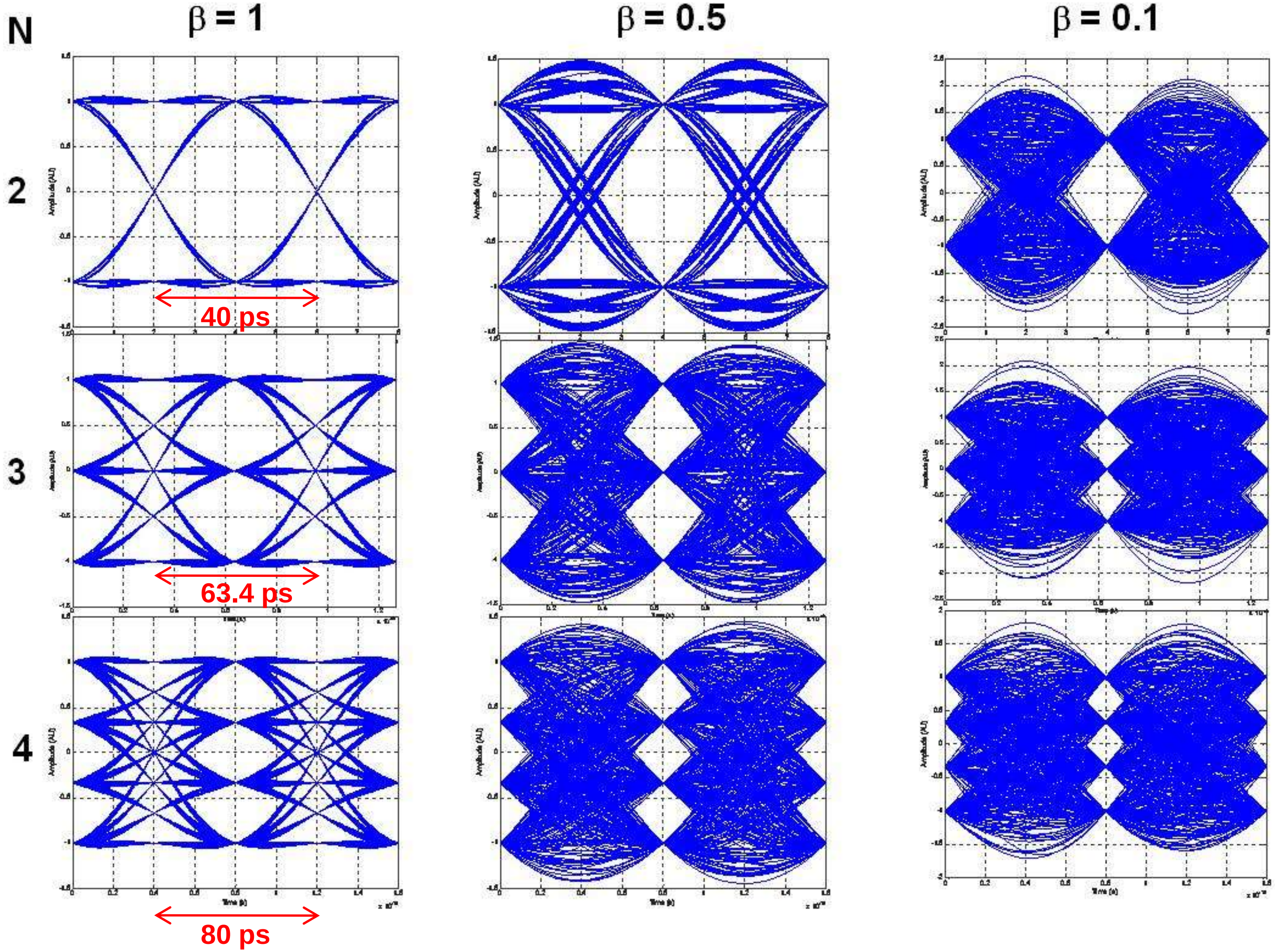
Objectives

- Develop PAM-N modulation tutorial material
- Solicit PAM-N modulation tutorial contributions
- Develop PAM-N performance understanding from:
  - Ideal channel models
  - Fundamental theory
- Compare PAM-2 (NRZ) & PAM-4 performance

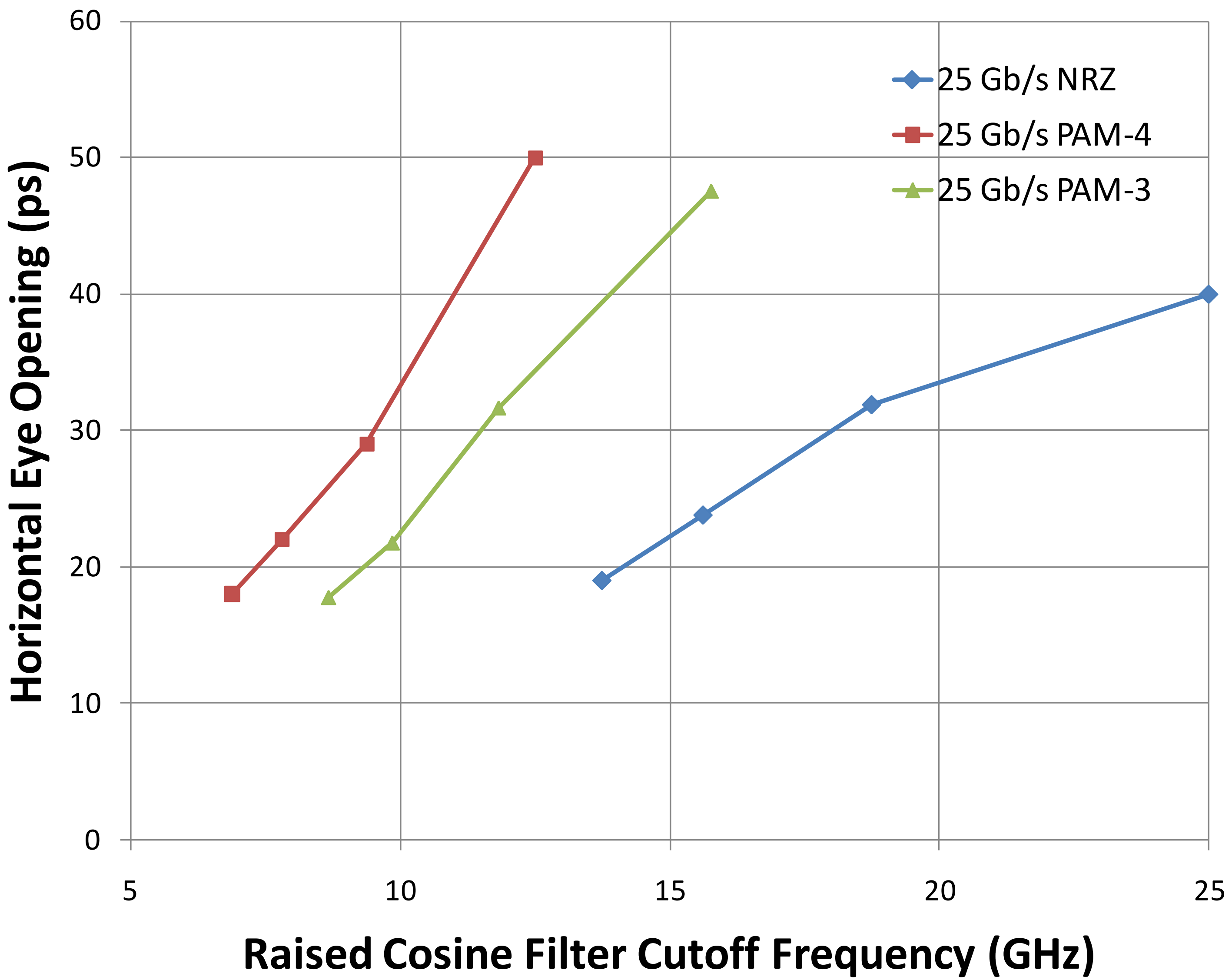
Matlab Model 1: Raised Cosine Channel



PAM-N Eye Diagrams



PAM-N Horizontal Eye Opening



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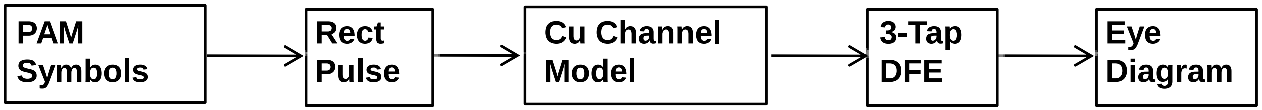
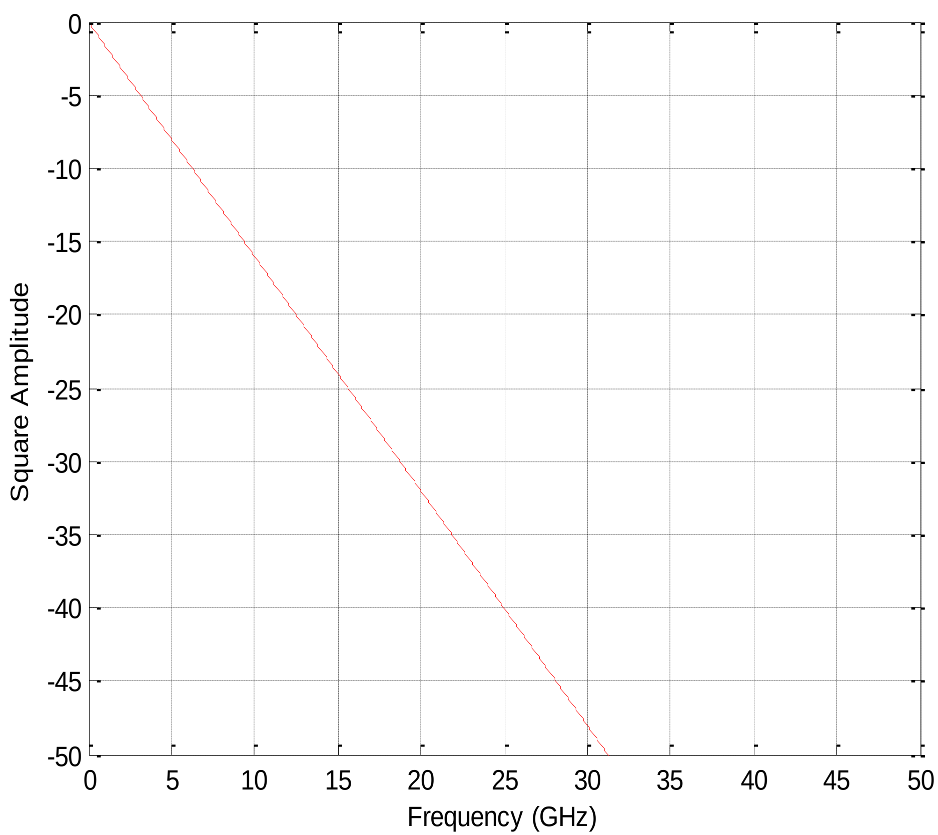
Matlab Model 2: Exponential Loss Channel

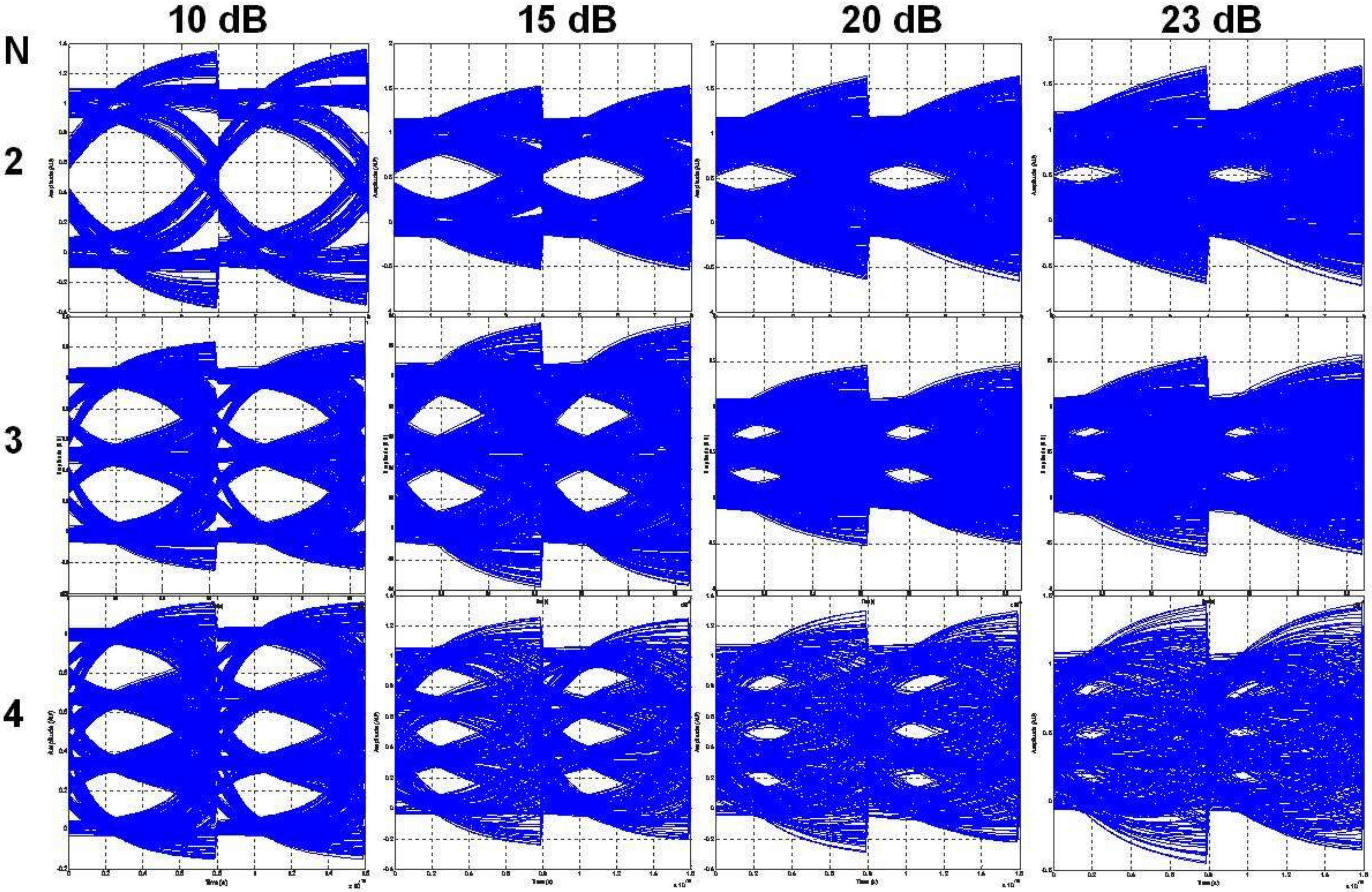


Channel Model



- Ideal Linear Phase Channel
- 20dB loss @12.5GHz
- FFE equalizer not included to gain PAM-N performance understanding from DFE only equalizer output

PAM-N Eye Diagrams after DFE



Addition of FFE equalizer will significantly increase the vertical eye opening

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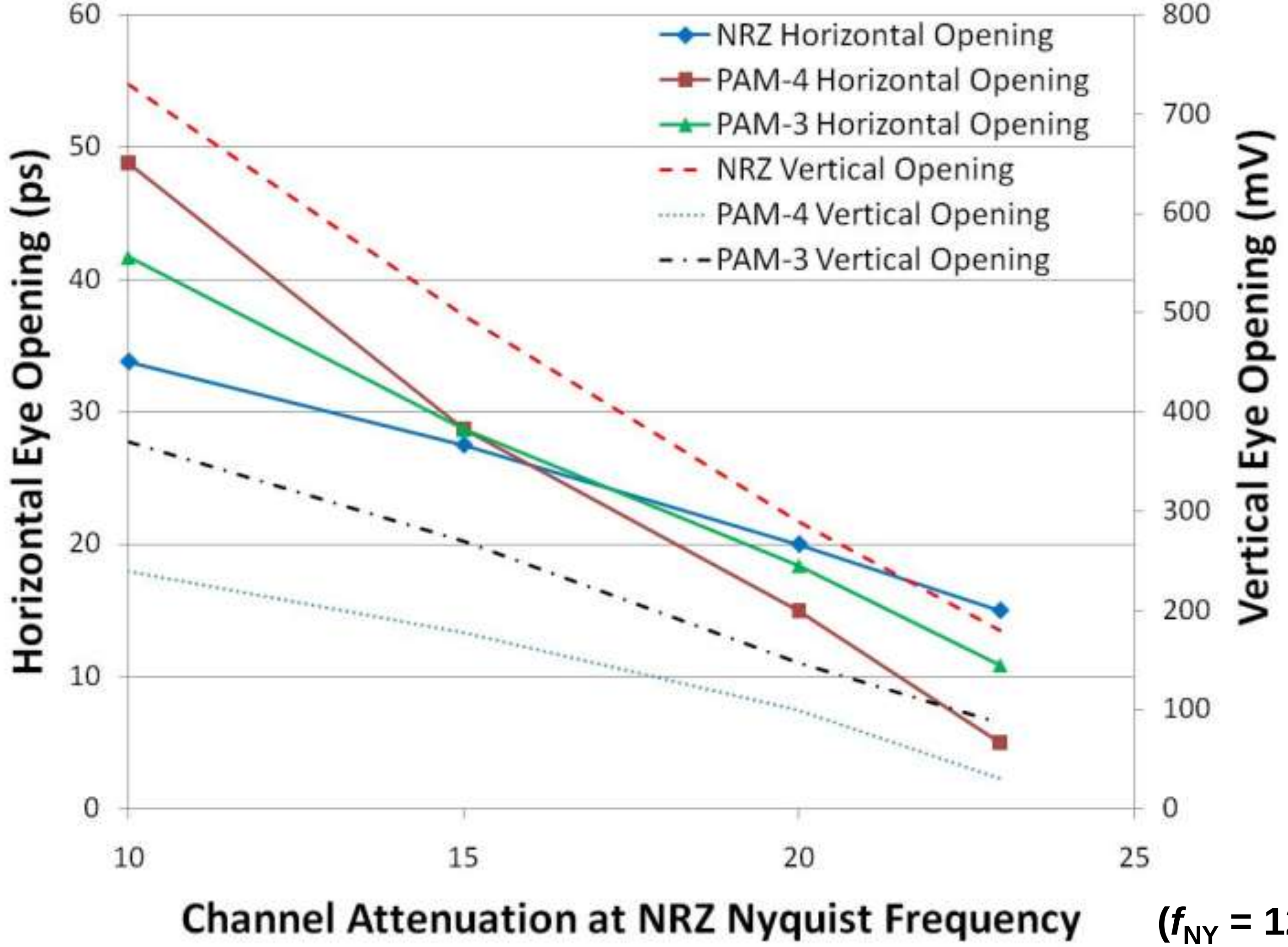
PAM-N Eye Opening

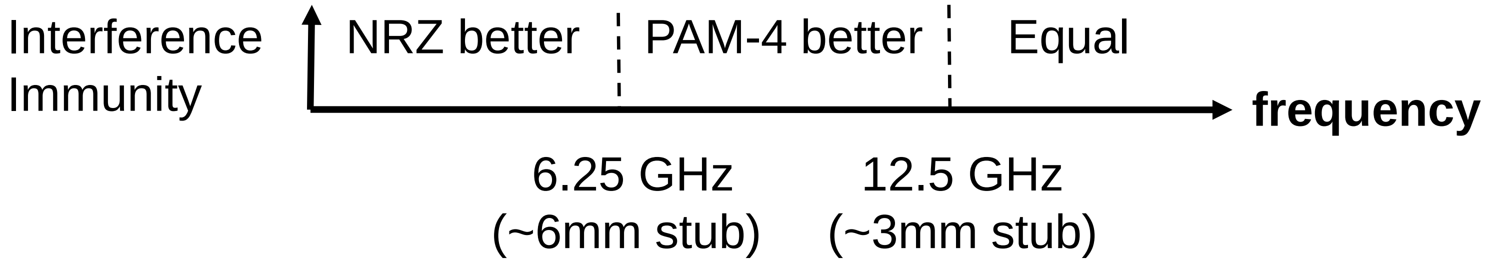


(f_{NY} = 12.5 GHz)

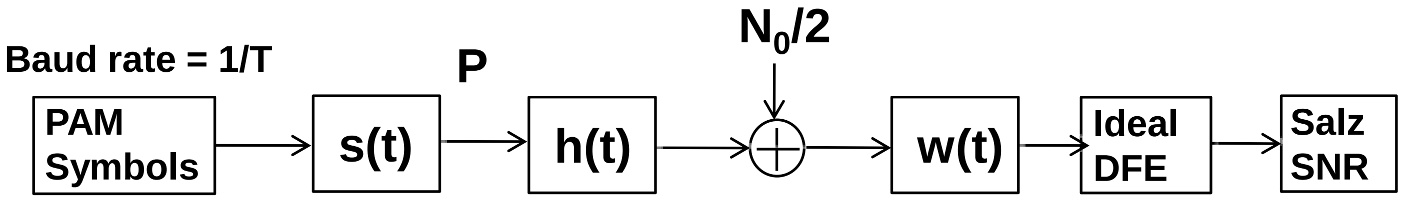
Horizontal and vertical eye openings defined as "inner eye opening"

PAM-N Eye Diagram Observations

- PAM-N has zero ISI at the ideal sampling point with a raised cosine channel response
- For an ideal Nyquist channel, PAM-4 has twice the horizontal eye opening versus NRZ
- In practice ideal sampling never happens; performance is limited by horizontal eye closure due to ISI
- Horizontal eye closure rate with increasing channel loss is faster for PAM-4 than NRZ; ~15dB crossover w/ 3-Tap DFE
- For an ideal Nyquist channel, PAM-4 has better immunity to interferers, like suck-outs and crosstalk, from $F_{PAM\text{-}4\_Nyquist}$ to $F_{NRZ\_Nyquist}$



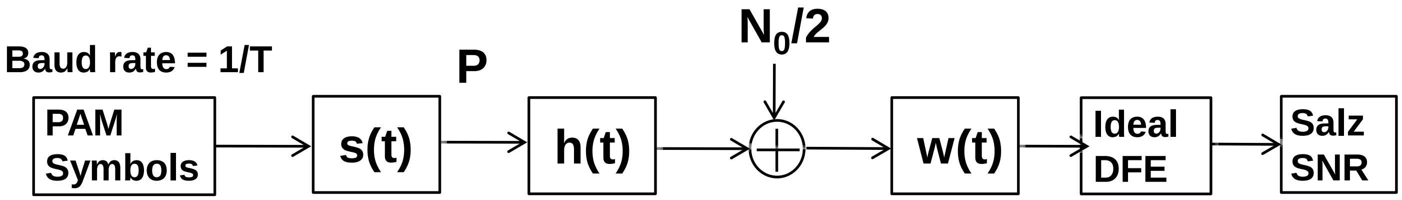
Salz Model



Model Assumptions:

1. Ideal DFE (infinite taps)
2. Matched filter W(t) using ideal FFE (infinite taps)
3. DFE decision errors ignored (i.e. SNR is high enough)
4. Noise is AWGN
5. Nyquist pulse shaping TX filter S(t)
6. Exponential loss channel modeled as $H(f) = \exp(-\alpha f)$

Salz Model, cont.



Analytical solution for normalized Mean Square Error (MSE) at output of DFE (Salz SNR bound):

$$SNR = e^{\left[\frac{T}{\pi} \int_0^{\frac{\pi}{T}} \ln\left(\rho e^{-\frac{\alpha\omega}{\pi}} + 1 \right) d\omega \right]}$$

$\rho = P*T/(N_0/2)$ = TX SNR

Salz Model, cont.

In the limit of high TX SNR, Taylor series expansion can be used to obtain a remarkably simple formula for Salz SNR:

$$SNR_{dB} = \rho_{dB} - \frac{1}{2}(IL_{f_{NY}})$$

The effective SNR at DFE output is approximately the TX SNR decreased by ½ the IL (channel insertion loss) in dB at the Nyquist frequency.

$$f_{NY} = 1 / 2T$$

Salz Model NRZ & PAM-4 Comparison

$$SNR_{dB} = \rho_{dB} - \frac{1}{2}(IL_{f_{NY}})$$

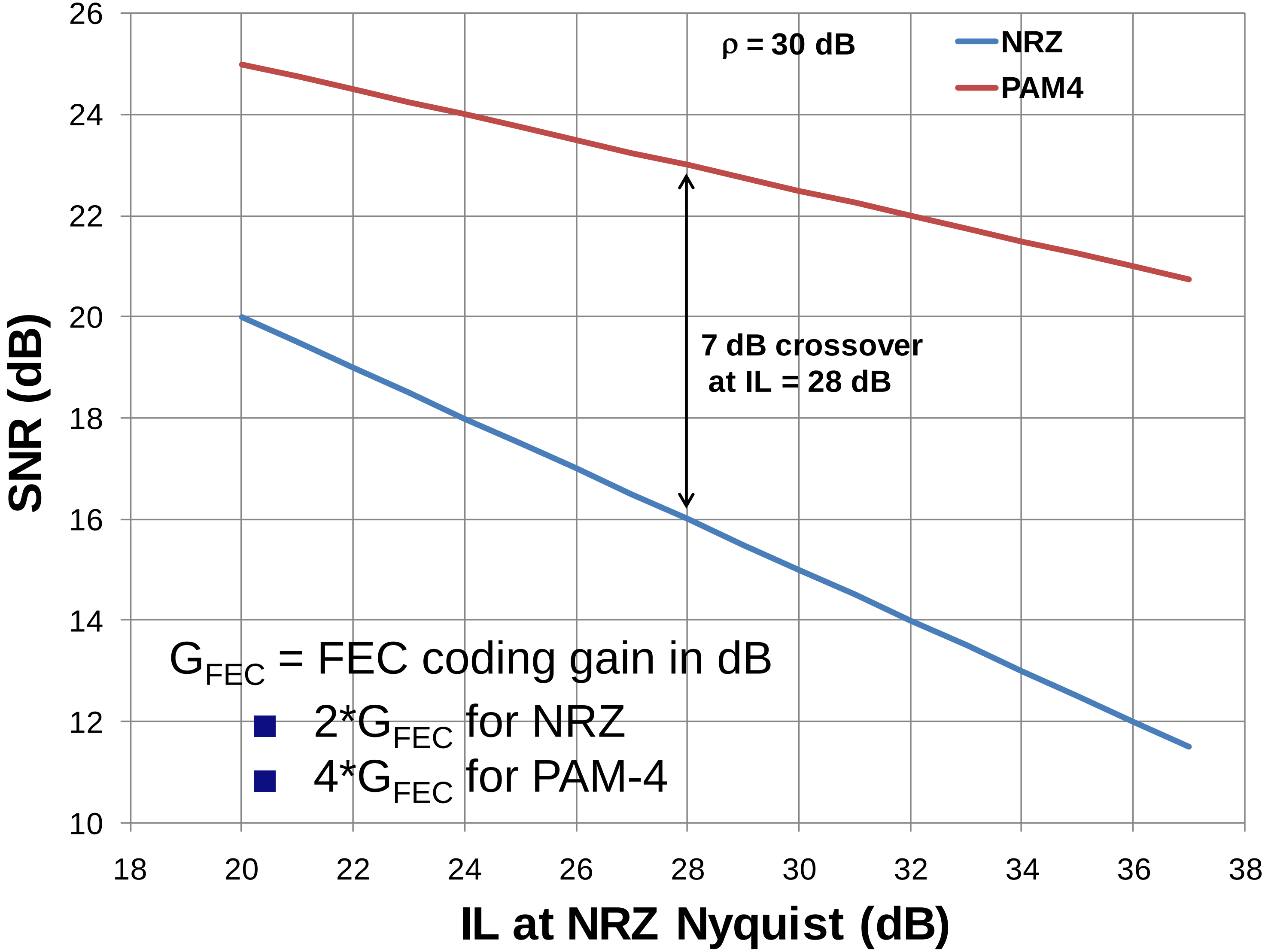
- PAM-4 f_{NY} = ½ NRZ f_{NY}
- PAM-4 IL = ½ NRZ IL
- Theoretical NRZ SNR in dB at equal TX SNR:

  NRZ SNR = ¼ PAM-4 SNR (4x PAM-4 advantage)
- To achieve the same BER:

  NRZ SNR = PAM-4 SNR - 7dB (7dB NRZ advantage)
- Therefore PAM-4 is better than NRZ for:

  IL > 28dB (i.e. NRZ is better for IL < 28dB)

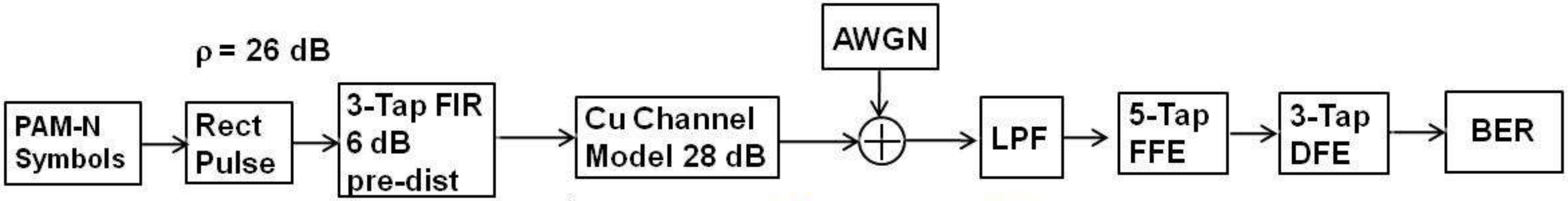
Salz Model NRZ & PAM-4 Comparison

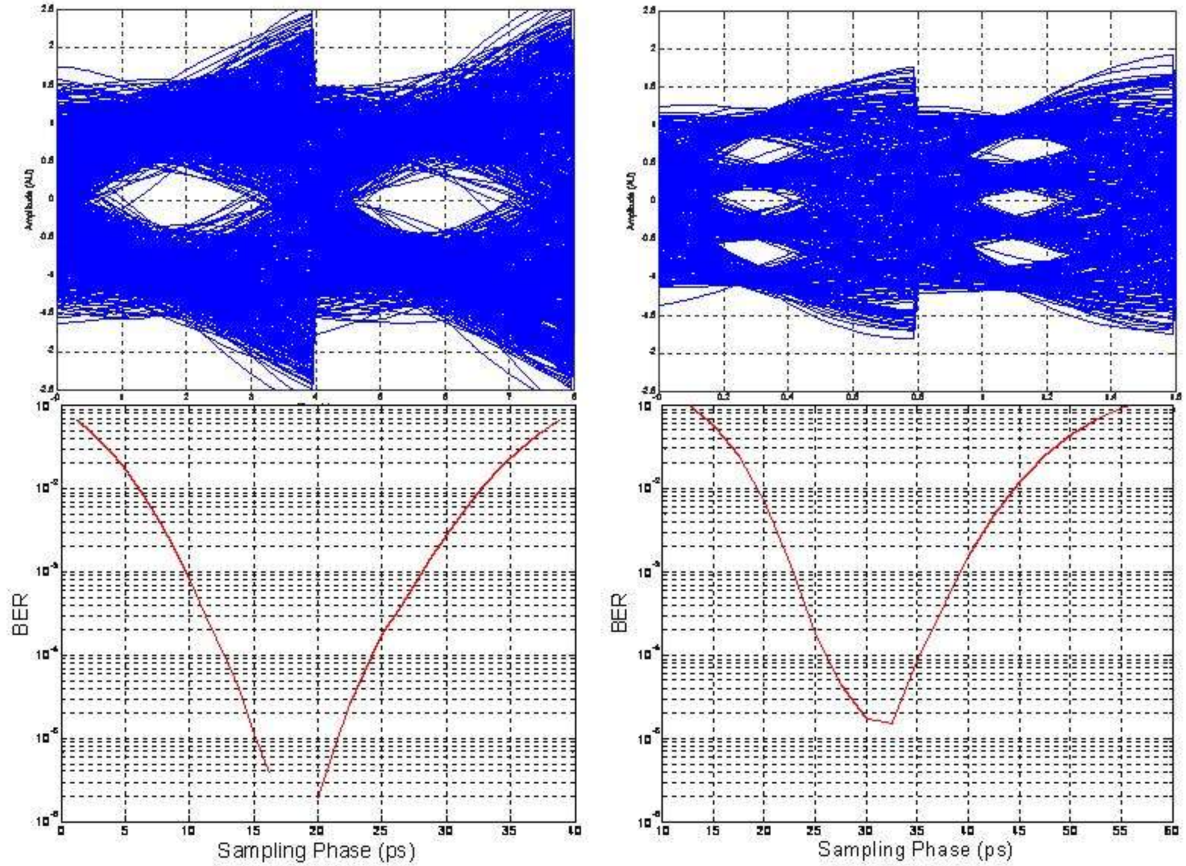


G_{FEC} = FEC coding gain in dB

- $2*G_{FEC}$ for NRZ
- $4*G_{FEC}$ for PAM-4

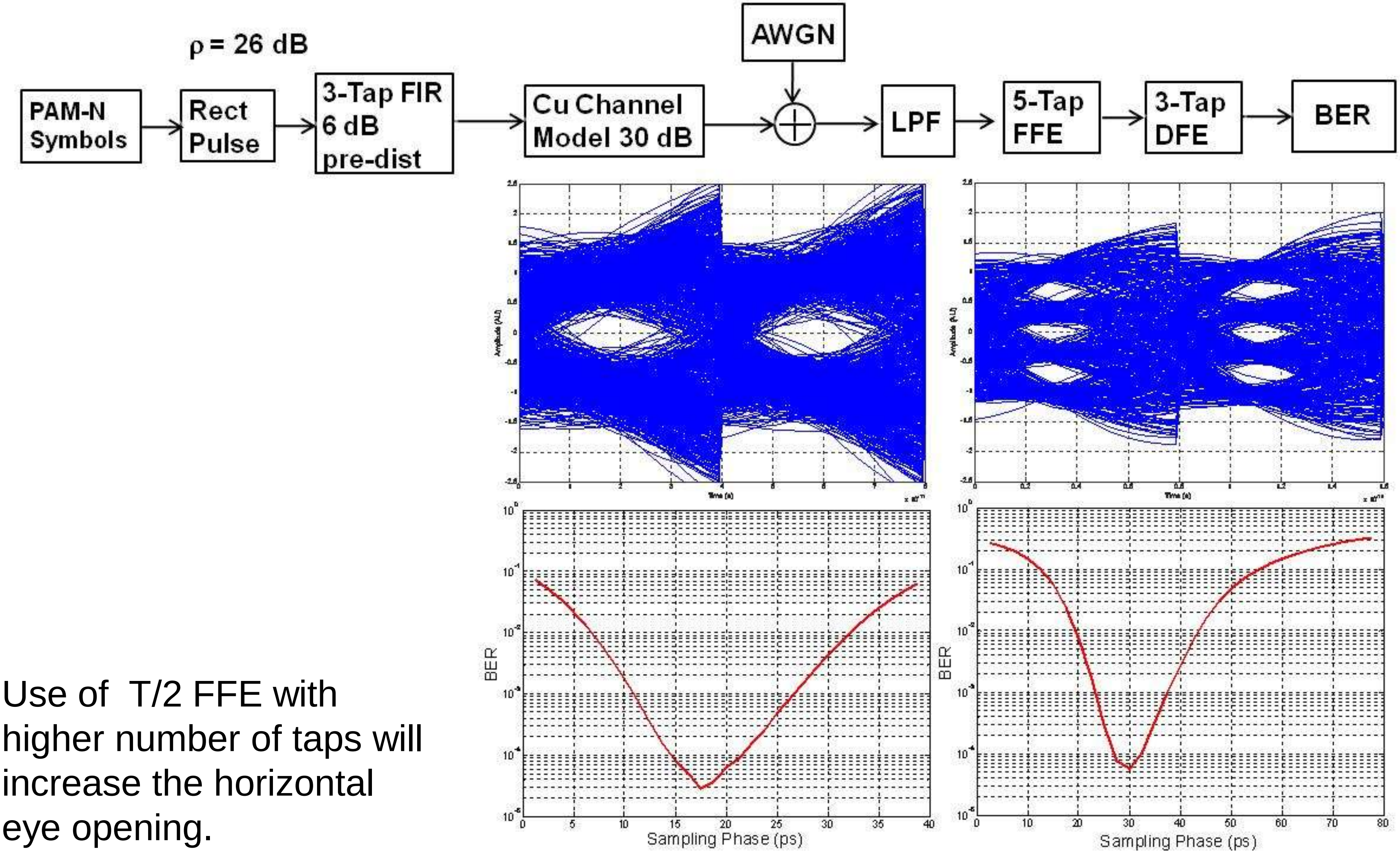
Matlab Model 3: FFE+DFE RX w/ 28dB IL





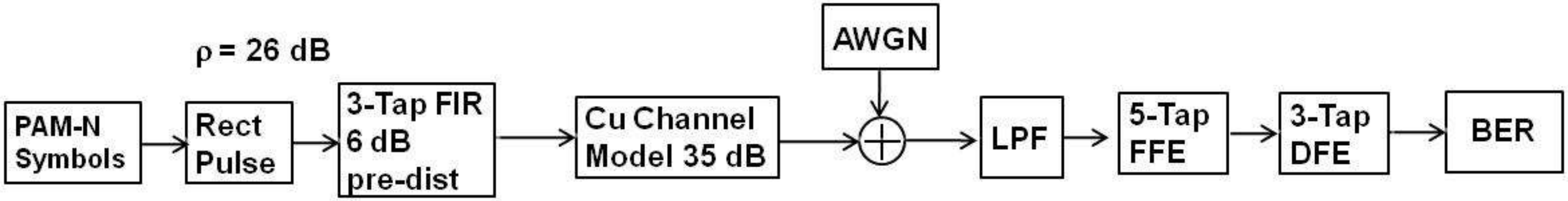
Use of T/2 FFE with higher number of taps will increase the horizontal eye opening.

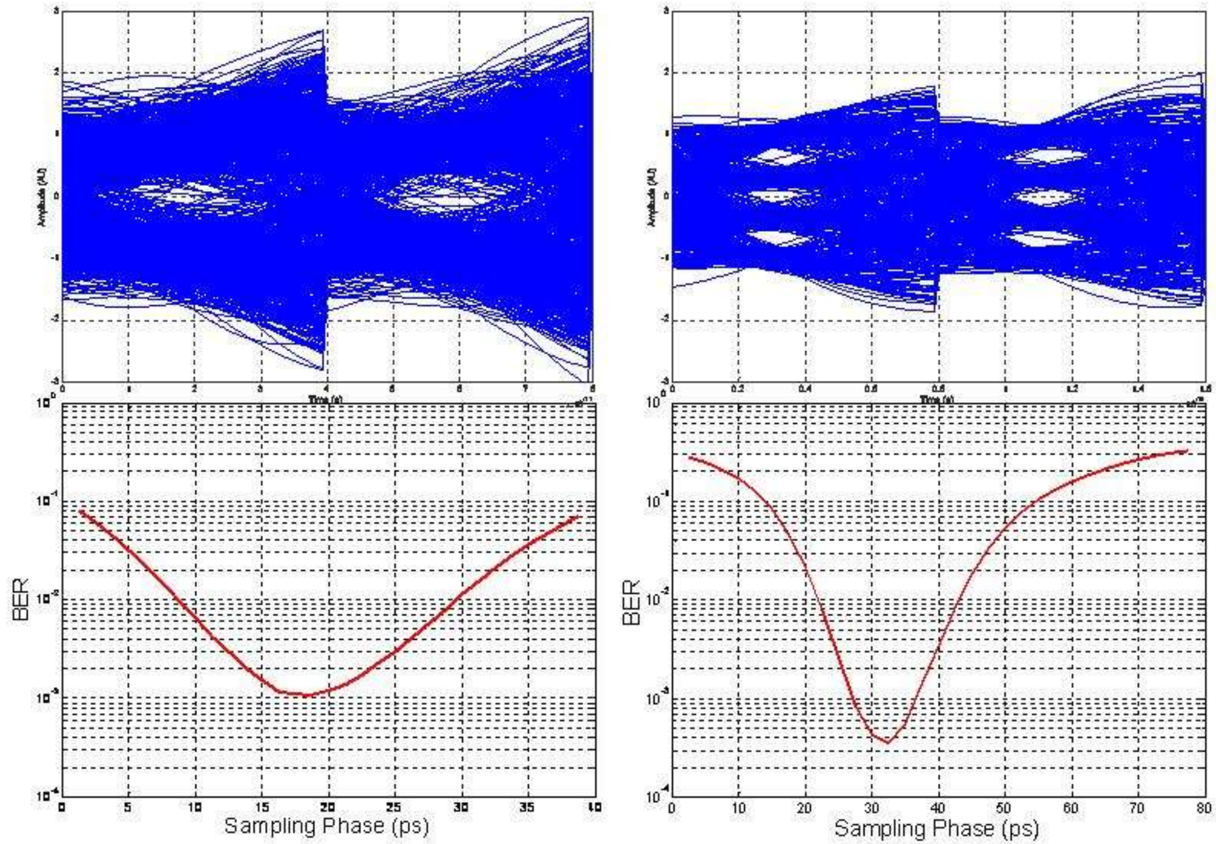
Matlab Model 4: FFE+DFE RX w/ 30dB IL



Use of T/2 FFE with higher number of taps will increase the horizontal eye opening.

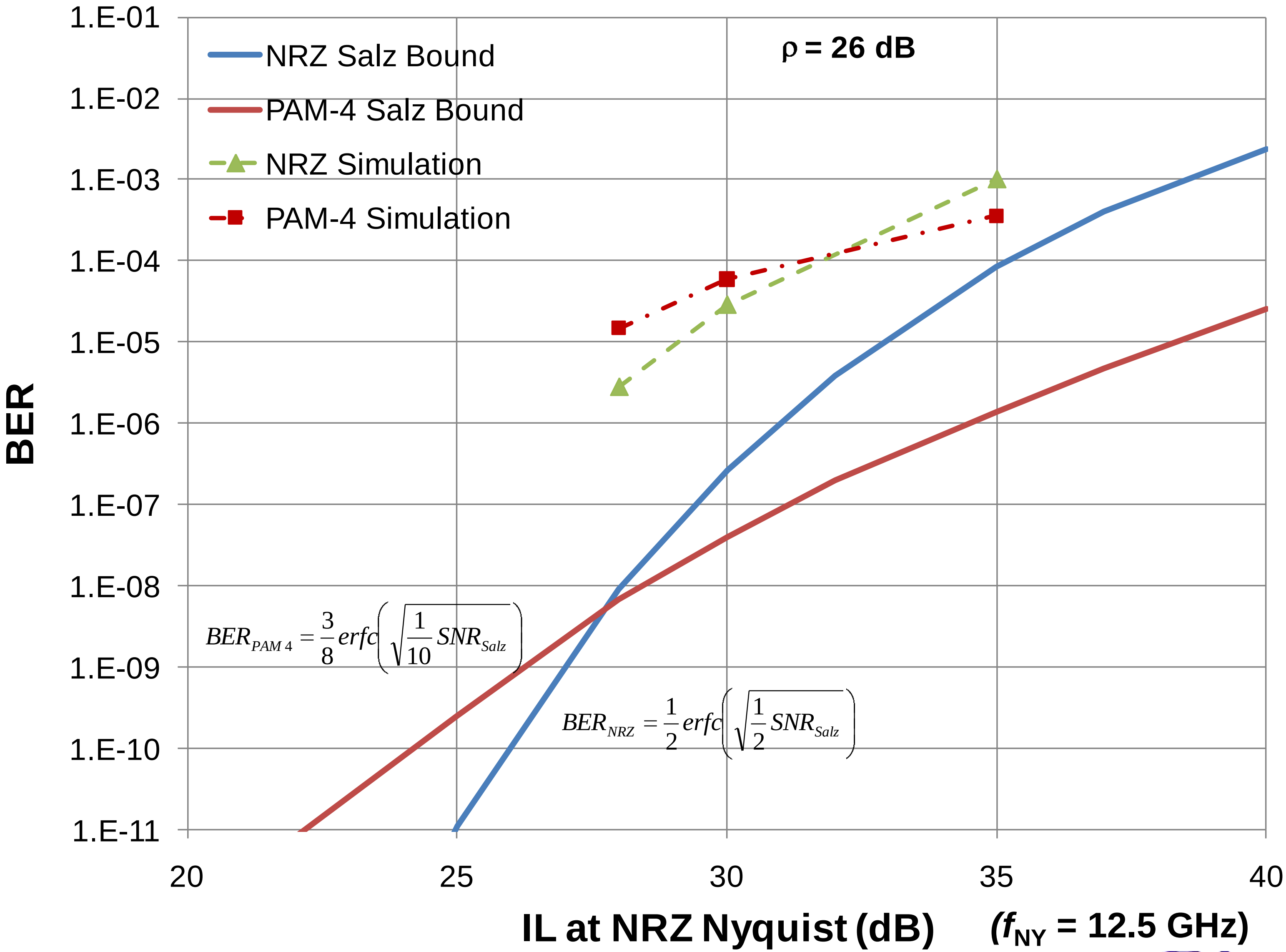
Matlab Model 5: FFE+DFE RX w/ 35dB IL





Use of T/2 FFE with higher number of taps will increase the horizontal eye opening.

Salz RX & FFE+DFE RX Comparison



Summary Results

- Salz Model over an exponential loss channel shows better PAM-4 versus NRZ performance for:
  - $IL_{12.5GHz} > 28dB$ (i.e. NRZ is better for $IL_{12.5GHz} < 28dB$)
  - $IL_{12.5GHz} > 32dB$ (for moderate FFE+DFE RX Model)
- For IL ~ 30dB, small implementation differences can shift the crossover, explaining conflicting Task Force results
- Salz Model does not include random jitter and timing errors
- PAM-N differences in sensitivity to timing jitter and errors may substantially change the IL crossover value

  The timing penalty will be quantified in future work

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- References without url are available for download at:

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