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IEEE P802.3dg 100BASE-T1L PHY PAM-3 8B6T Partial Response with Bounded Running Disparity Time Domain Simulations

Brian Murray
Philip Curran

Introduction

- This a presentation of time domain simulation results of a 100BASE-T1L PHY architecture using PAM-3 8B6T coding with partial response (PR) and bounded running disparity
  - The simulations are run under the same conditions as previous time domain simulation results by the authors
  - Alien cross-talk is modelled with AWGN
- 8B6T has a larger codebook of available symbols which allows the selection of the set of code group symbols to improve the properties of the line code
  - curran_3dg_01_05132024 has given the background to this code, its construction and properties
    - In particular, the one-to-one mapping from the PR sequences to the 6D ternary code group which eliminates error propagation
    - The $\sqrt{2}$ minimum distance between any two PR sequences to allow an effective SNR gain of up to 3 dB
  - The code has 256 6T data symbols / pairs of 6T symbols with balanced running disparity
  - Additional codes are available for control codes and idle
- The time domain simulation uses the AWGN Noise models for PHY Evaluation
  - *zimmerman_3dgah_01b_01292024*
  - This approximates to a flat AWGN Noise source at -113 dBm/Hz over 0 to 100 MHz for a 75 MSym/s baud rate which is 7 mV rms

Challenge of Reaching 500 m

- The big challenge of 100BASE-T1L is how to achieve sufficient performance margin at 500 m in the Industrial Ethernet noise environment to meet a 10^{-10} bit error rate
  - Previous simulations have shown that the SNR margin using a standard DFE is not sufficient and some performance gain is required to have margin to the 10^{-10} bit error rate requirement
  - The nature of the channel is approximately (1 + D); at longer lengths and higher noise the 1st tap of the DFE becomes larger that 0.5 and can be even greater than 1.0 resulting in error propagation
- The 8B6T partial response code has properties to address both of these challenges

100BASE-T1L PAM-3 Time Domain Simulation

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- 100BASE-T1L PAM-3 8B6T with partial response (PR) and bounded running disparity
- Generic 100BASE-T1L Architecture with following parameters
  - PAM-3 using the 802.3cg Scrambler and 8B6T PCS with running disparity at 75 MSym/s
  - Ideal DAC & line driver, 2.4V Tx, 12-bit ADC
  - DFE using 48 feed forward taps and 64 feedback taps, ideal data path
- 802.3cg and 802.3dg Insertion Loss model

802.3dg IL	$IL(f) \le \left(5.42 \times \sqrt{f} + 0.044 \times f + \frac{1.76}{\sqrt{f}}\right) + 5 \times 0.02 \times \sqrt{f} \quad \text{(dB)}$
802.3cg IL	$IL(f) \le 10\left(1.23 \times \sqrt{f} + 0.01 \times f + \frac{0.2}{\sqrt{f}}\right) + 10 \times 0.02 \times \sqrt{f} \quad \text{(dB)}$

- External Noise Model proposed by *zimmerman*
  - Noise with a Gaussian distribution and magnitude of **–113 dBm/Hz**
  - 7 mV rms over a flat 100 MHz

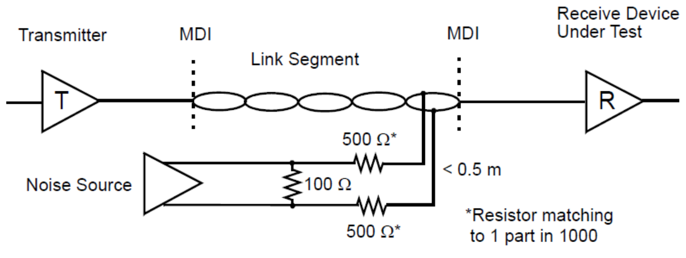


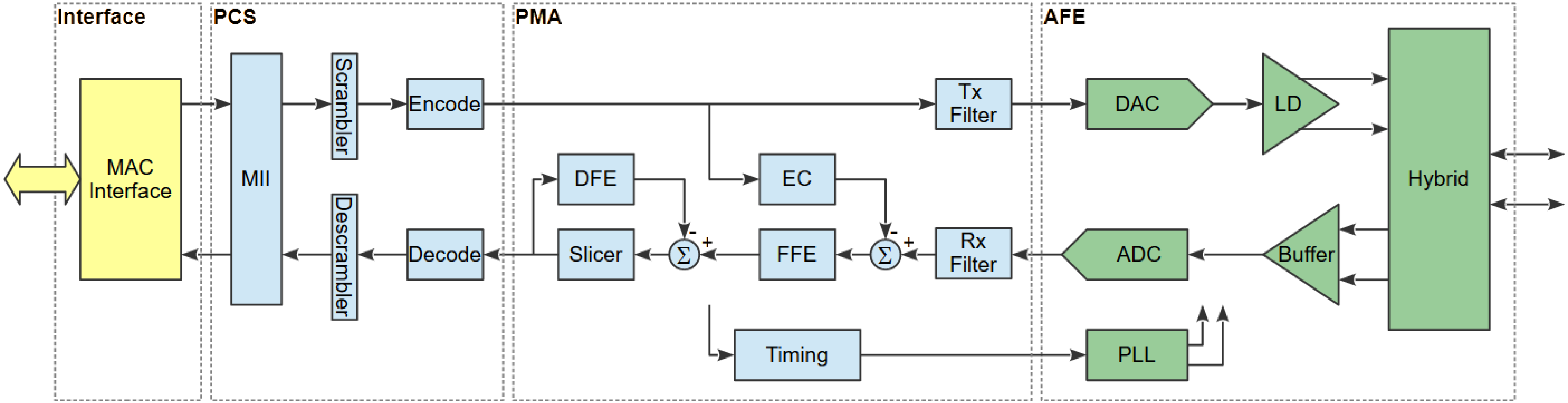
Figure 146–24—Alien crosstalk noise rejection test set-up

100BASE-T1L SNR vs Ext Noise

- Plot SNR versus external Gaussian noise
  - For values of 3, 5, 7 and 9 rms
  - For Insertion Loss model proposed for 802.3dg and IL model used in 802.3cg
    - For cable lengths 300, 350, 400, 450, 475 and 500 m derived from a scaled IL model
    - Scaling relative to the Insertion Loss model will be worse than a typical cable model
  - At 2.4V transmit level
  - After 1536K symbols of start-up, idle and data (~ 20000 μs)
    - Enter data after 300K symbols

Generic 100BASE-T1L PHY Architecture

- Generic block diagram of a BASE-T PHY architecture

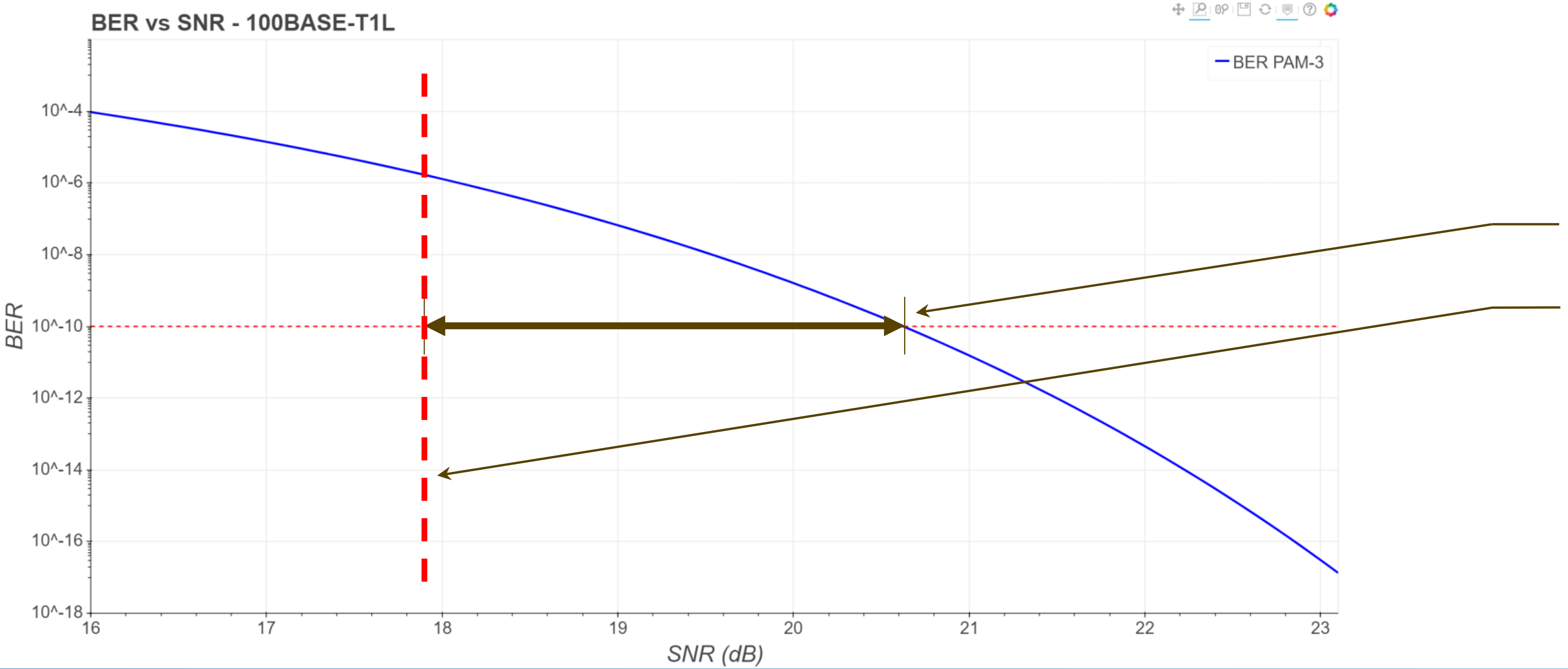


- A time domain simulation is run for a range of cable lengths / noise to determine SNR margin verses reach

Other example PHY architecture diagrams
10BASE-T1L [.cg Jan 2017 Graber_10SPE_10_0117.pdf]

SNR versus BER or Packet Error Rate

- 802.3dg standard mandates a BER ≤ 10^{-10}
  - The PAM-3 8B6T partial response ternary code has an idle symbol power of 0.7122*
    - The probability of an error at the ternary slicer of a conventional DFE is $1.2982 \times 0.5 \times \mathrm{erfc}\left(\frac{1}{2\sqrt{2}\sigma}\right)$
    - The probability of an error at the quinary slicer of a partial response DFE is $1.7818 \times 0.5 \times \mathrm{erfc}\left(\frac{1}{2\sqrt{2}\sigma}\right)$
  - The ratio of the mse noise to meet a BER ≤ 10^{-10} to the idle symbol power measured in dB is 20.6 dB and 20.7 dB
  - Including an effective SNR gain of 2.8 dB using Maximum Likelihood the SNR target for a BER ≤ 10^{-10} is **17.9 dB**

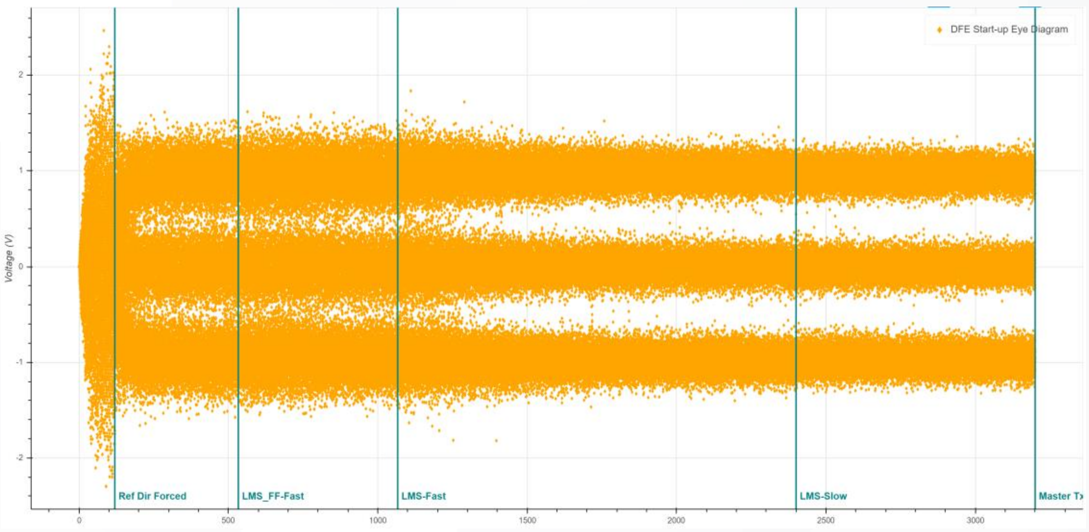


SNR Target to meet 10^{-10} BER
- PAM-3 8B6T with a conventional DFE requires 20.6 dB
- With Maximum Likelihood estimation requires 17.9 dB

*see curran_3dg_01_05132024

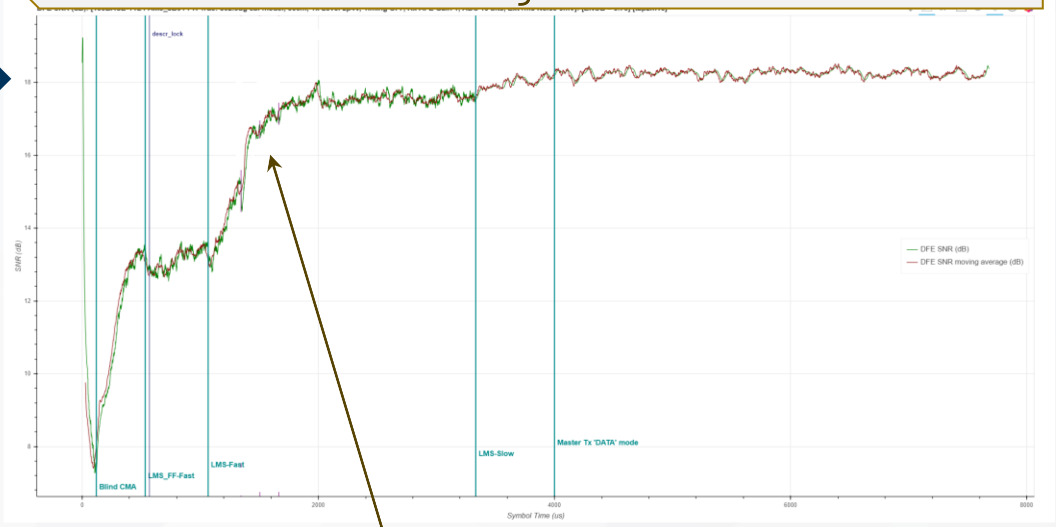
100BASE-T1L PAM-3 8B6T 802.3dg IL - 500m / 9 mV rms Noise

Start-up Eye Diagram

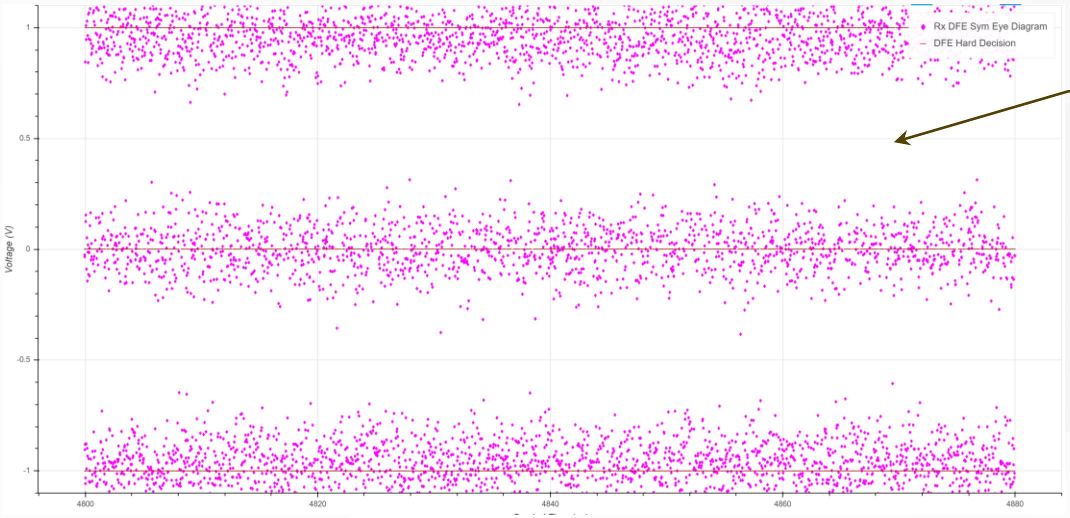


SNR Convergence 0 – 8 ms

18dB →



PAM-3 Eye Diagram During Data



- At 500m and 9 mV of noise the DFE is still very well behaved

100BASE-T1L SNR vs Ext Noise – PAM-3 dg IL Model

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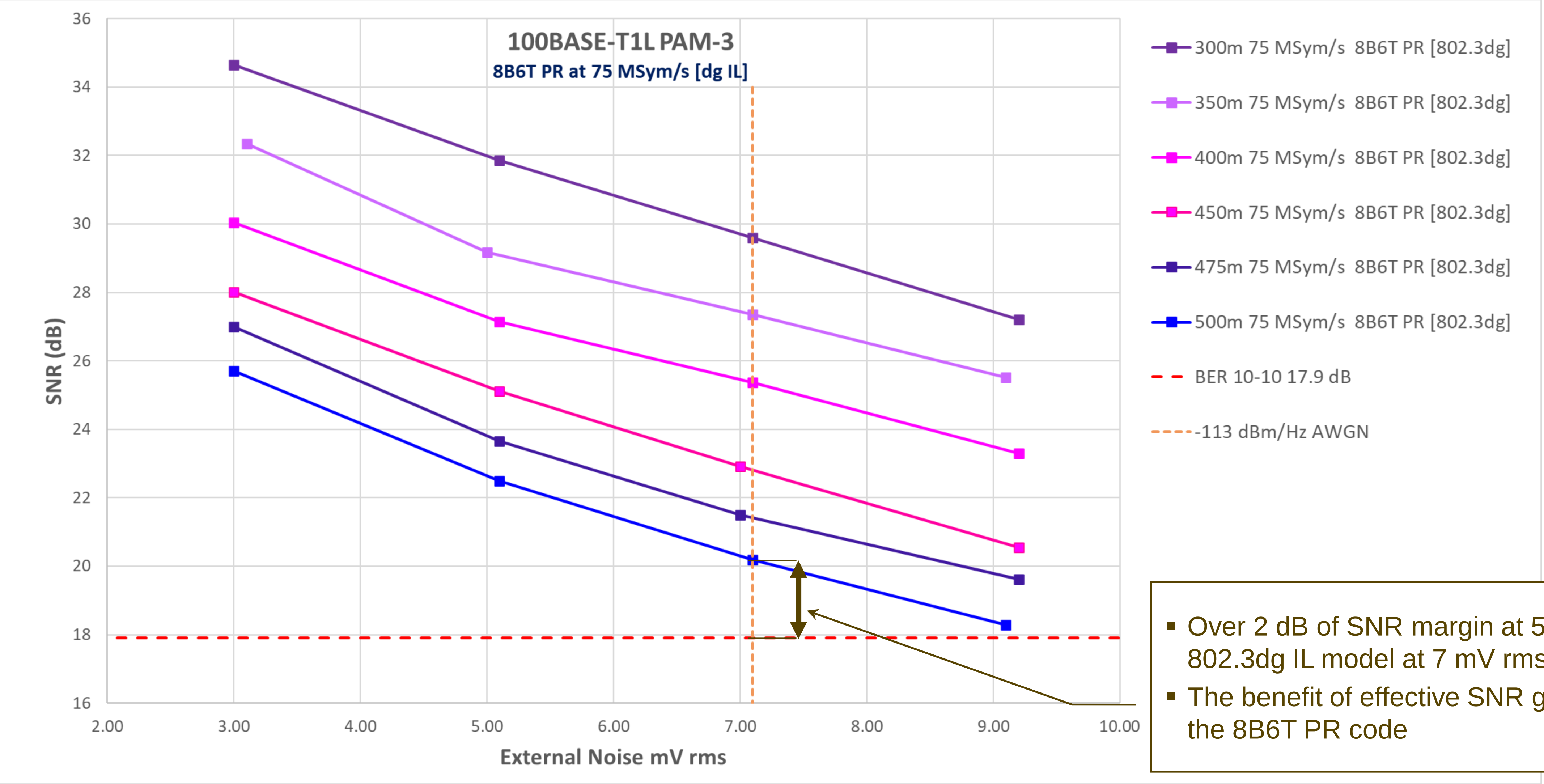
100BASE-T1L 75 MSym/s 8B6T PR: SNR versus External Noise – 2.4V Tx Amplitude



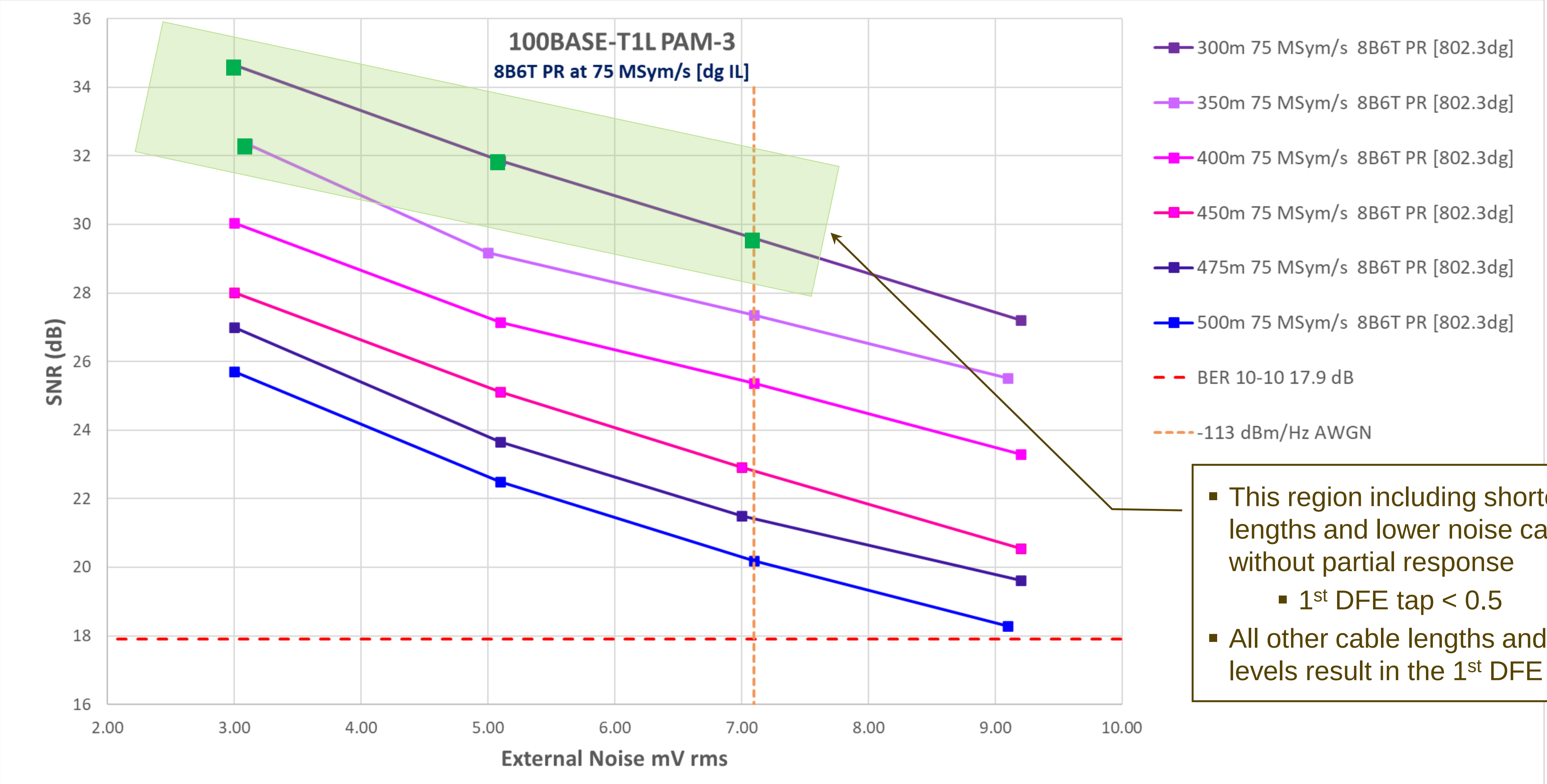
- Over 2 dB of SNR margin at 500m and 802.3dg IL model at 7 mV rms
- The benefit of effective SNR gain using the 8B6T PR code

Partial Response Simulations

- Simulations are run for both conventional and PR DFE
  - A Ternary slice and conventional DFE including the 1st tap to decode each 1T symbol
  - A partial response DFE using a Quinary slice and lookup table to decode the 6T symbol
- Identical results are achieved for both approaches when there are no symbol errors
  - At marginal SNR very small differences are observed between the two approaches when there are symbol errors due to the effect of error propagation
  - The partial response DFE using a Quinary slice has lower error propagation between 6T symbols
    - An example of a longer simulation run of 320 ms of data at 18 dB of SNR (9 mV rms) where the conventional DFE had 29 error events and a total of 46 errors with 17 error events with error propagation by 1 or 2; in this case about 55% of the errors propagate
    - With a PR DFE and Quinary slice, the 17 error propagating events reduced to 3 cases of error propagation by 1; in this case about 10% of the error propagate

100BASE-T1L SNR vs Ext Noise – PAM-3 dg IL Model

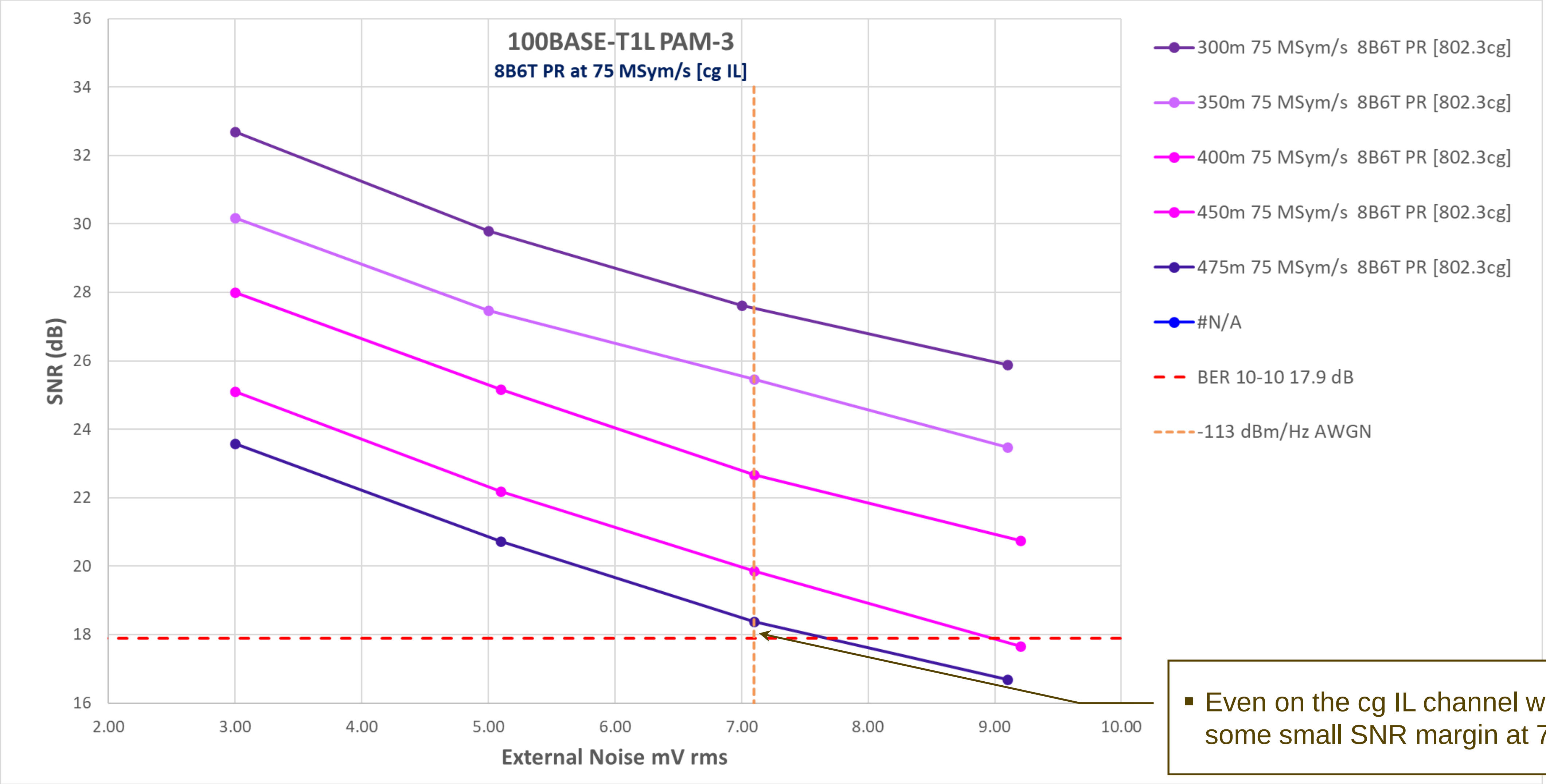
100BASE-T1L 75 MSym/s 8B6T PR: SNR versus External Noise – 2.4V Tx Amplitude



- This region including shorter cable lengths and lower noise can operate without partial response
  - 1st DFE tap < 0.5
- All other cable lengths and noise levels result in the 1st DFE tap > 0.5

100BASE-T1L SNR vs Ext Noise – PAM-3 cg IL Model

100BASE-T1L 75 MSym/s PAM-3 4B3T and 8B6T: SNR versus External Noise – 2.4V Tx Amplitude



- Even on the cg IL channel we now have some small SNR margin at 7 mV rms

Summary

- PAM-3 coding using 8B6T with partial response meets the reach requirements of 500 m on the proposed link segment specifications with over 2 dB of SNR margin
- PAM-3 has the advantage of wider spacing of decision thresholds which gives the greatest immunity to impulse noise
- PAM-3 8B6T with partial response has the advantage of up to 3 dB of effective SNR gain due to the $\sqrt{2}$ minimum distance between any two partial response sequences
- PAM-3 coding schemes can be implemented with very low latency by adopting similar approaches to other PHYs like 10BASE-T1L and 1000BASE-T and embed the control codes in the constellation

Questions ?