A Performance Analysis for TDD-based Physical Layer Transceiver

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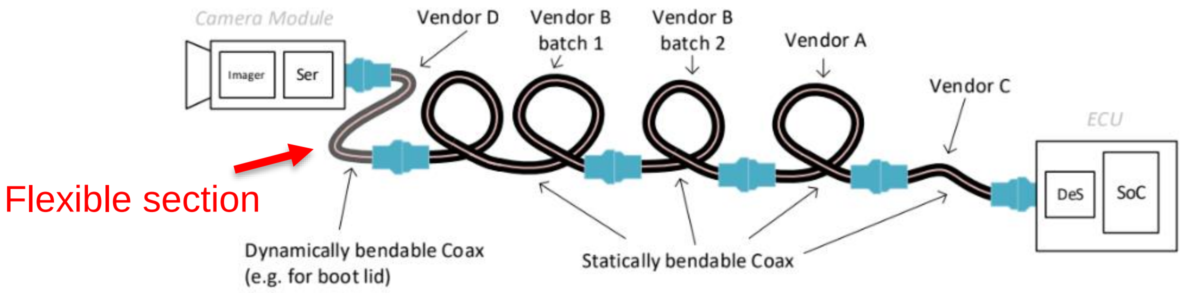
Forewords

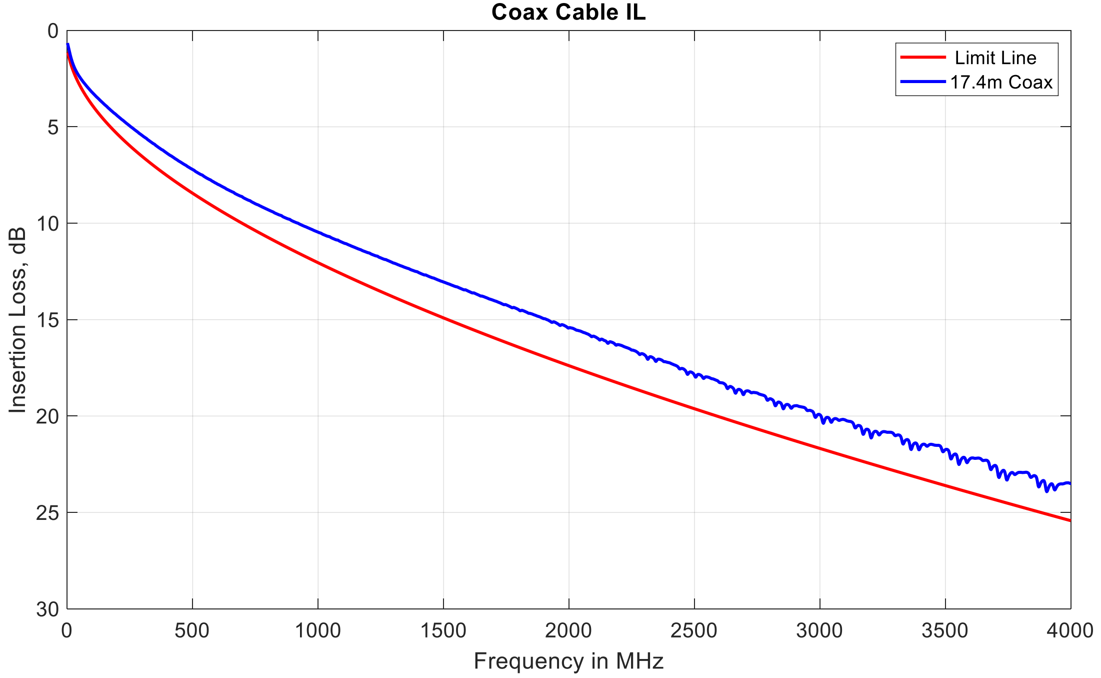
- 802.3dm Task Force has received proposals for an asymmetric link for image sensor applications with emphasis on automotive applications.
- It is essential to investigate performance of such proposals for the type of noise that are typical in automotive applications.
- The proposed solutions differ from each other on the modulation type (PAM2 vs PAM4). A performance analysis for these two modulation is provided in this presentation.
- The insertion loss in the link segment as well as board components and PHY termination is considered in this analysis.
- This analysis includes the effect of “practical receiver” implementation limits.
- This presentation is mainly focused on 2.5Gbps and 5Gbps links where a different modulation is proposed for TDD and ACT-based architectures.
- The performance limitation for a 10Gbps link is also discussed.

Outline

- Link segment Insertion Loss assumed for performance analysis
- Implied MDI Insertion Loss
- BER and SNR calculation and noise margin
- Eye height referred to the receive input for PAM2 vs PAM4
- Eye Height considering receiver implementation
- Single ended transmit PSD
- Adaptive notch filtering and its limitations
- PAM4 justification for 802.3ch
- Summary and conclusions

Coax Link Segment Insertion Loss





- The blue line in the plot is a 17.4m link segment, measured at room temperature. It has 6 in-line connectors and uses a RTK031 coax cable type.
- The red line in the plot, is a 15m coaxial link segment limit line proposed in previous 802.3dm presentations[1,2] :

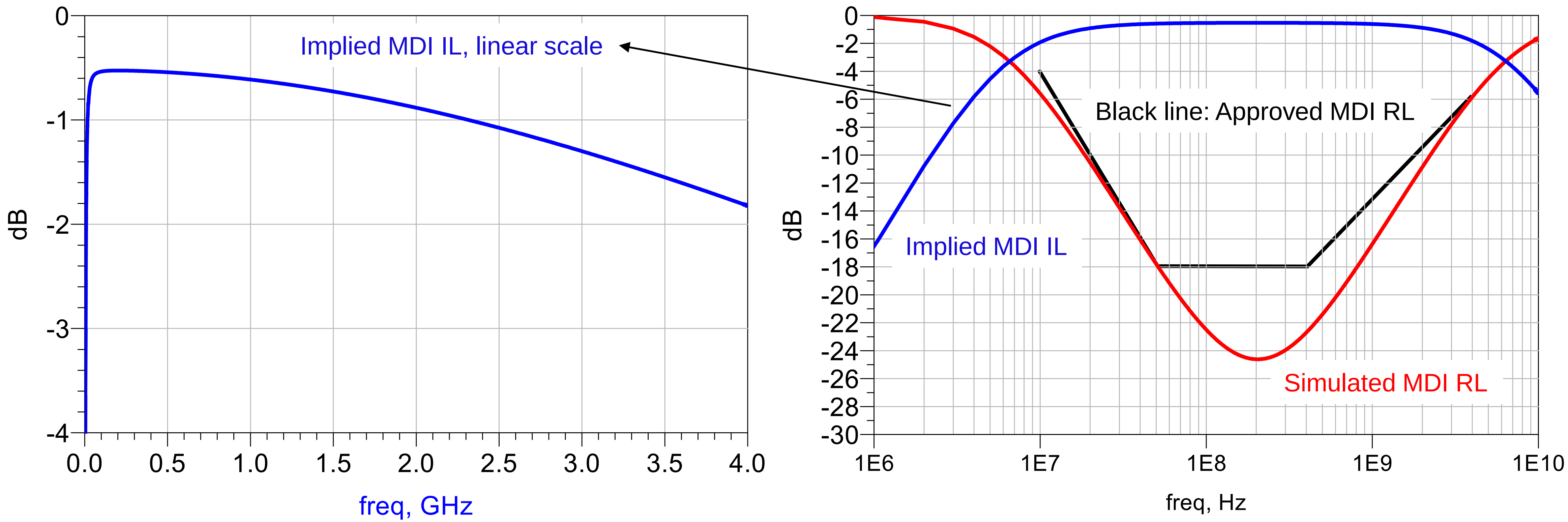
$$\text{IL (dB)} = 0.3 + \frac{0.48}{\sqrt{f}} + 0.345\sqrt{f} + 0.000825f$$

$$1\text{MHz} \leq f \leq 4000\text{MHz} \qquad f \text{ in MHz}$$

- The analysis provided in this presentation, are based on the red limit line shown and scaled for cable lengths below 15m.

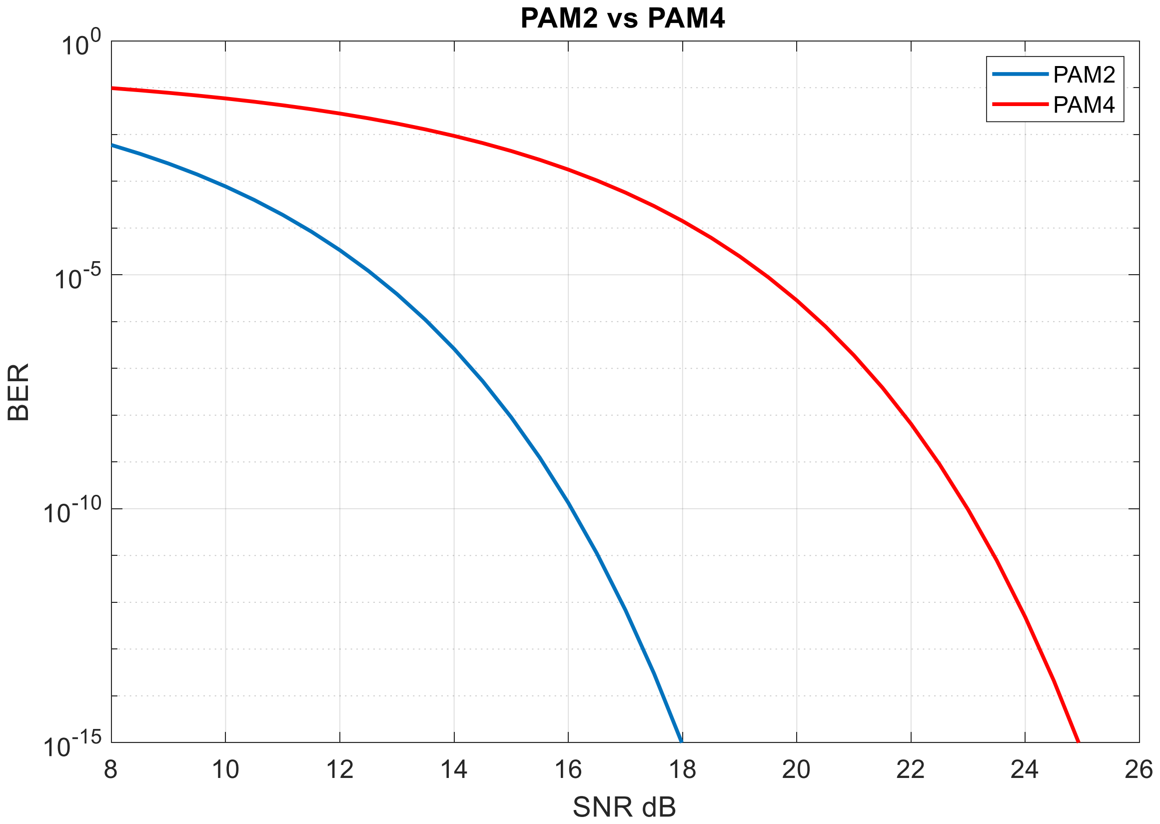
1. https://www.ieee802.org/3/dm/public/0924/Zerna_802.3dm_01_240918_IL_Limit_Proposal.pdf
2. https://www.ieee802.org/3/dm/public/0724/Zerna_802.3dm_01b_240717_IL_RL_Limits.pdf

MDI Insertion Loss



- For a PHY that meets the approved MDI RL, there is an implied MDI Insertion Loss (board components and PHY termination).
- The circuit simulation is used to generate worst MDI RL and from there the implied “MDI Insertion Loss” (PHY termination of 45Ω , Inductance of 680nH and total capacitance of 1pF)

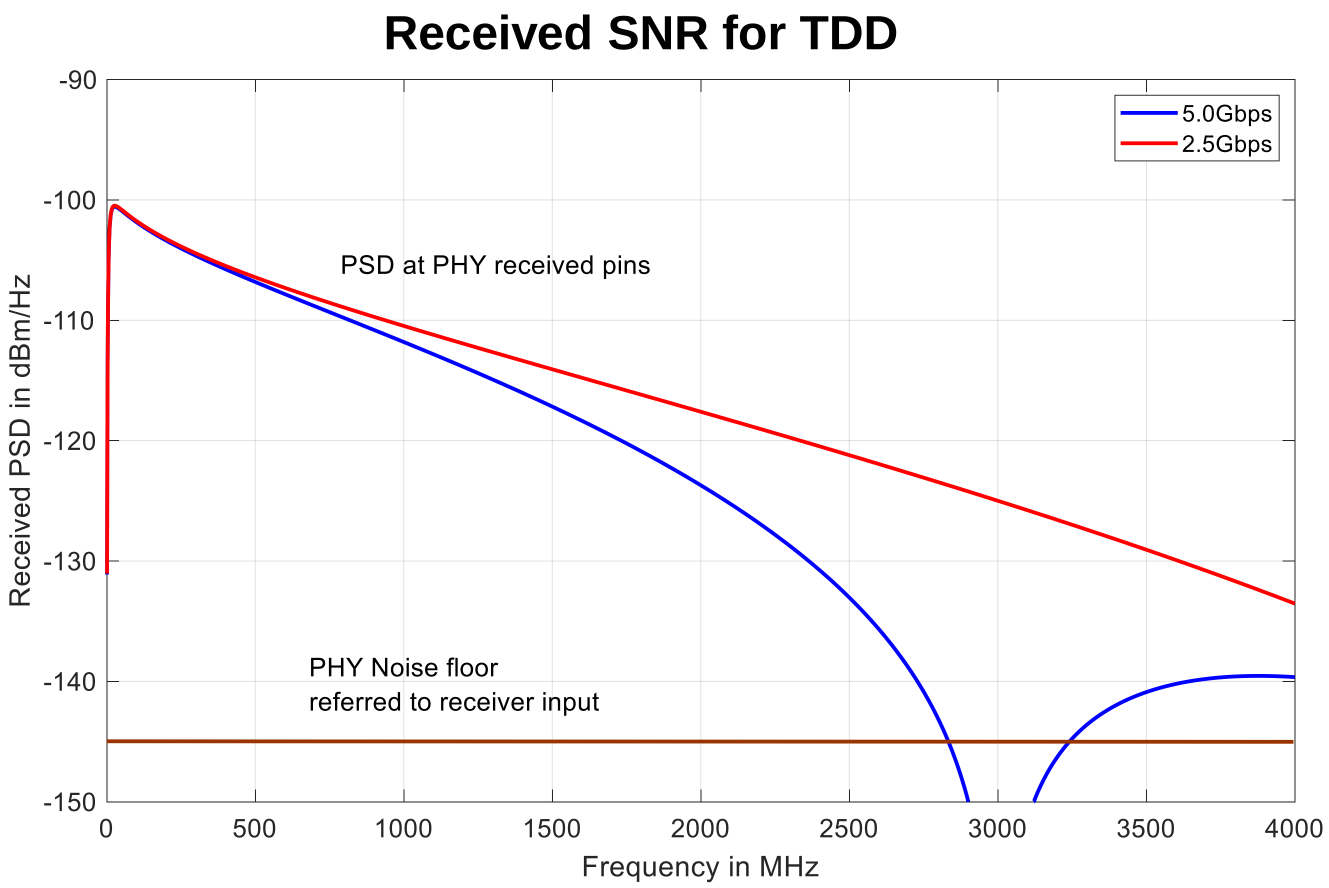
BER vs SNR for PAM2 and PAM4



	PAM2 SNR	PAM4 SNR
BER @ 1e-10	16dB	23dB
BER @ 1e-12	17dB	24dB
BER @ 1e-15	18dB	25dB

- The BER plot shows un-coded performance.
- SNR requirement drops by FEC coding gain at the target BER.

SNR Calculation Based on Received PSD



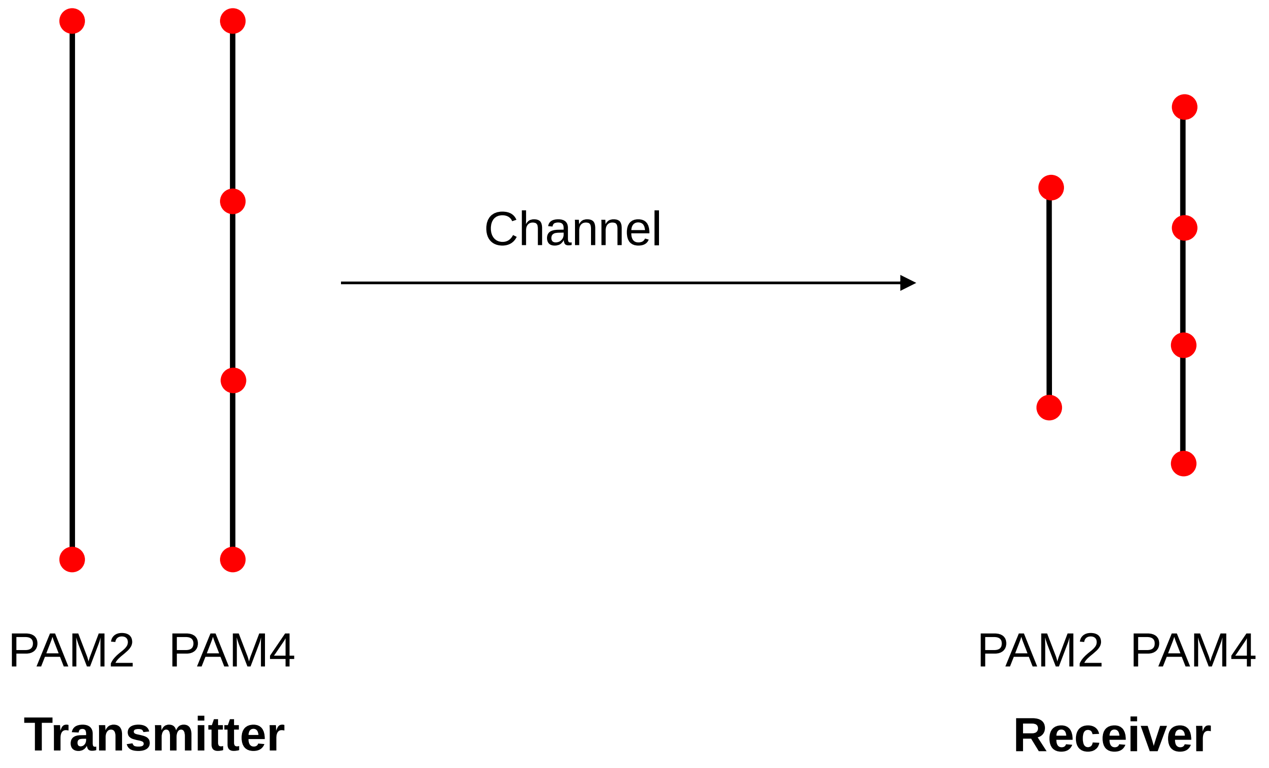
- When there is no ingress noise, the SALZ SNR for a 15m link is calculated to be:

	SNR for 2.5Gbps	SNR for 5.0Gbps
Received SNR	35.7dB	31.2dB
Margin to 1e-12 BER	18.7dB	14.2dB

- Even without FEC, there is a large noise margin for both 2.5Gbps and 5.0Gbps link with respect to the PHY internal noise level.
- XTALK was not considered in the calculation.

- Not shown here, the calculated noise margin to 1e-12 for ACT–PAM4 is 18.7dB at 2.5Gbps and 12.9dB at 5.0Gbps, before FEC (XTALK not included).

Eye Height: PAM2 versus PAM4 for 2.5Gbps and 5Gbps Link



- This depiction shows PAM2 signal is attenuated more in the channel than PAM4 (due to higher baud rate) but still Euclidean distance is larger for PAM2.
- A larger Euclidean distance results in larger eye height at the receiver, providing more protection against automotive ingress noise.

- Eye height referred to the receiver input is further analyzed using the well known SALZ SNR.

Receiver Eye Height Estimation

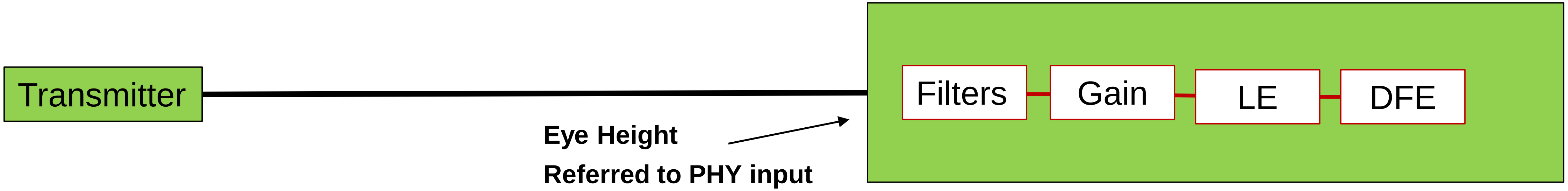
- SNR performance for a sufficiently long DFE equalizer when target SNR is >> 1 is estimated as:

$$SNR_{Salz} \approx \text{Mean} [\, SNR_{dB}(\, f\,)\,] = \text{Mean} [\, S_{dB,\, rx}(\, f\,)\,] - \text{Mean} [\, N_{dB,\, rx}(\, f\,)\,]$$

- The received signal in dB is calculated as:

$$\text{Mean} [\, S_{dB,\, rx}(\, f\,)\,] = \text{Mean} [\, S_{dB,\, tx}(\, f\,) - IL_{db}(\, f\,)\,] = \text{Mean} [\, S_{dB,\, tx}(\, f\,)\,] - \text{Mean} [\, IL_{db}(\, f\,)\,]$$

- Given $IL_{db}(\, f\,)$, Eye Height at the receiver input is estimated by scaling the transmit signal with the average of the channel Insertion Loss in the dB scale.

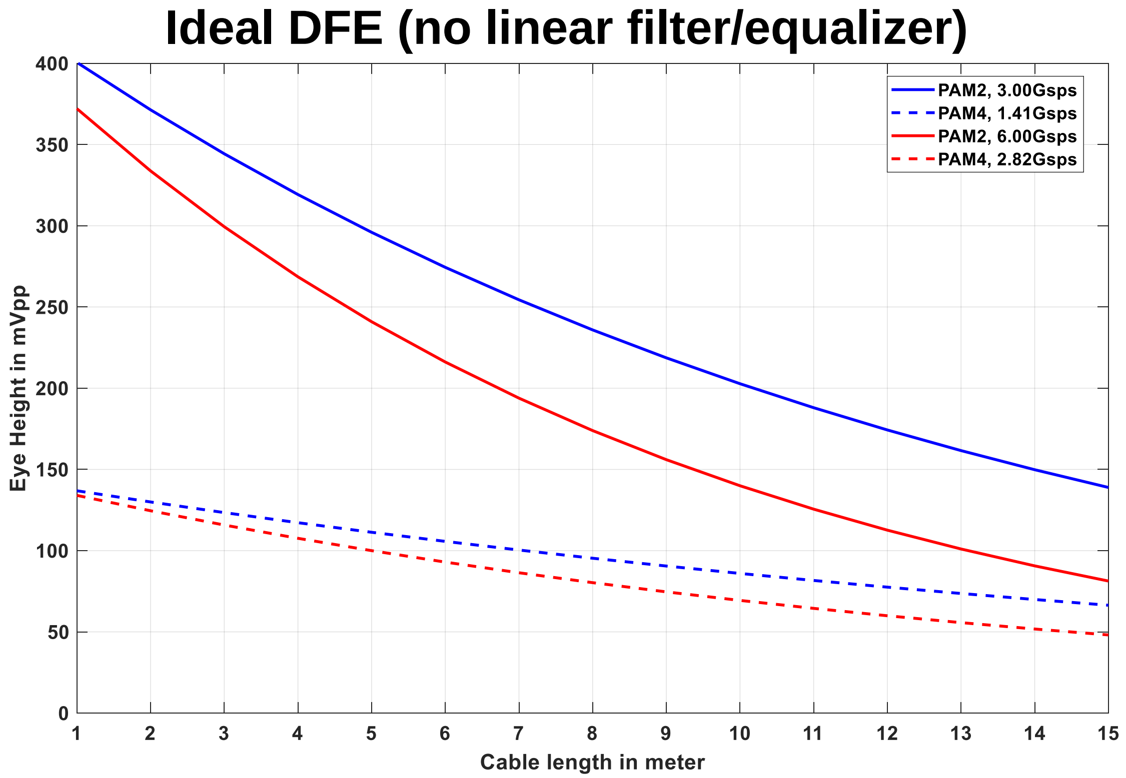


Linear equalizer maybe a CTLE or a FFE or a combination of both

Eye Height = Vpp/(m-1)/10^(ILA/20)

Where m is Modulation level (2 or 4)
Vpp is transmit single ended Voltage Peak to Peak
ILA (in dB) is mean insertion loss from PHY transmit pins to the DFE in the receiver

Modulation Level Effect on Eye Height



	Modulation	Baud Rate
2.5Gbps	PAM2	3.0Gsps
	PAM4	1.406Gsps
5.0Gbps	PAM2	6.0Gsps
	PAM4	2.812Gsps

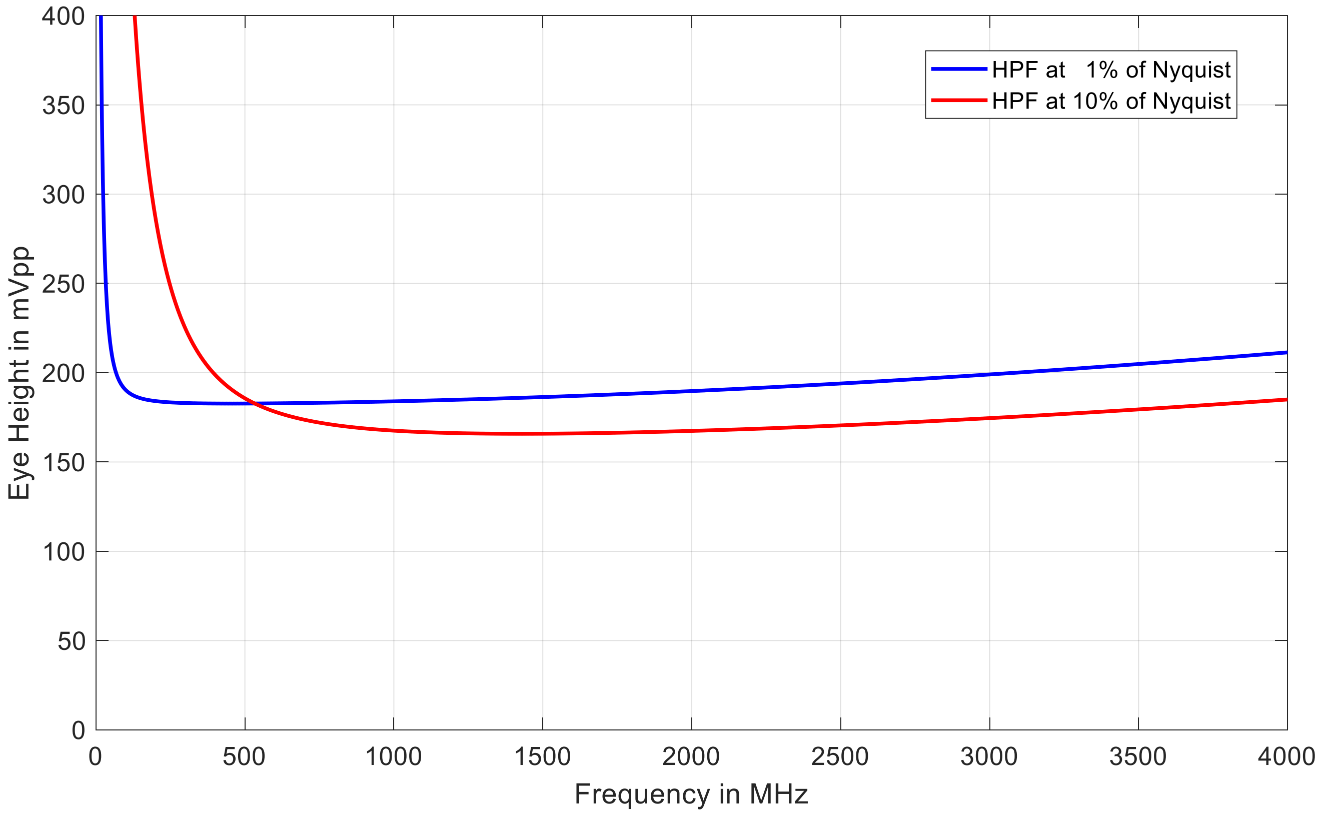
- The plots are produced for a transmit Voltage of 1Vppd (differential).
- The cable IL is scaled from the IL limit for a particular length.

- These plots show significant advantage for PAM2 vs PAM4 for 2.5Gbps and 5Gbps for more frequently installed cable lengths[1] (e.g. for some use cases[1], the max installed length is less than 9m).

1. https://www.ieee802.org/3/ISAAC/public/1123/matheus_ISAAC_03_1411202327_v1.0b.pdf

Receiver HPF Effect on Eye Height

referred to the receiver input



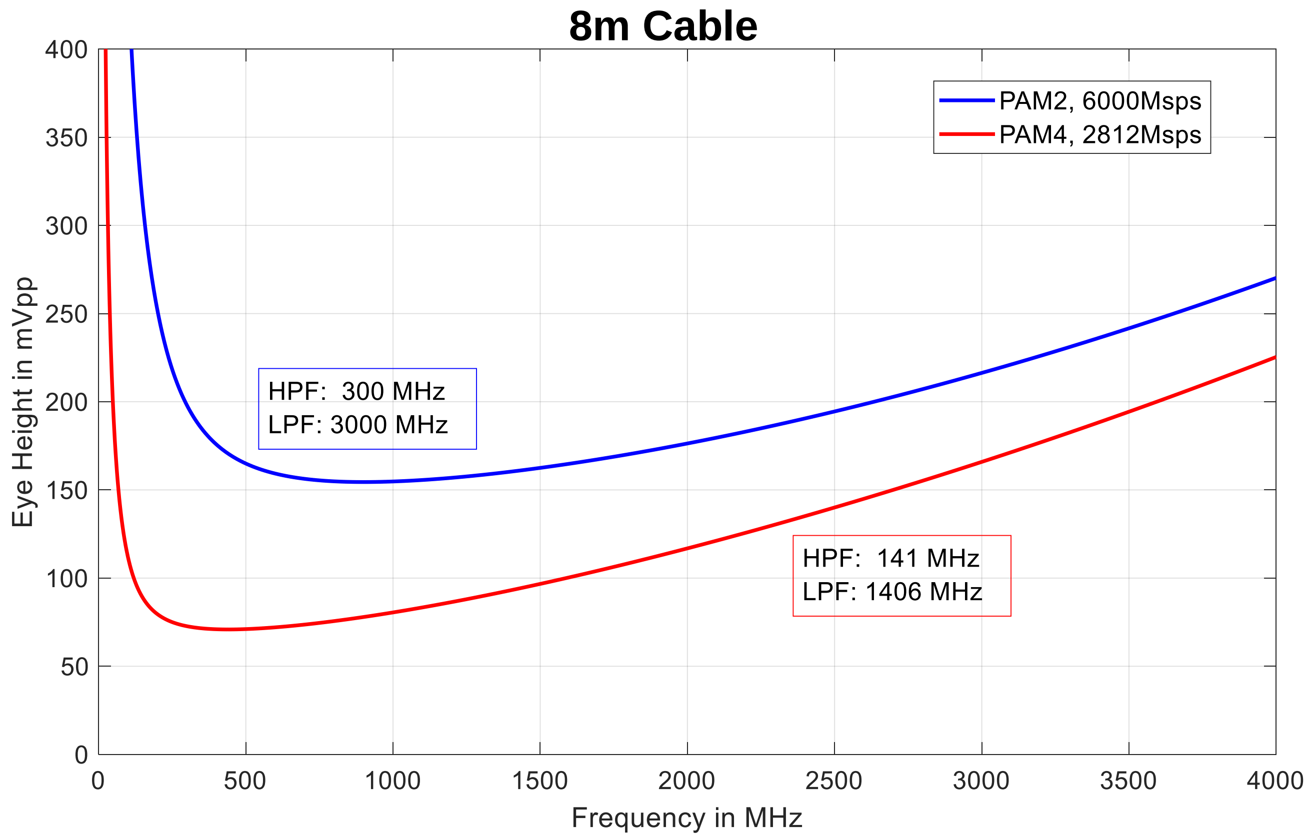
Modulation: PAM2, 1Vpp differential
Baud Rate: 6Gsps
Receiver HPF: 1% vs 10% of Nyquist bandwidth.
Cable Length: 8m (scaled from limit line)

- Any linear filter before DFE, including high pass, low pass, CTLE or FFE may result in noise enhancement (i.e. reduced eye height referred to the receiver input) but they are essential for practical implementations with a limited number of DFE taps for high speed.

- A High Pass Filter (HPF) with a higher BW helps shorten the length of impulse response and thus lowers the number of DFE taps which helps the implementation.
- A HPF with a higher BW also helps removing low frequency transient noises.

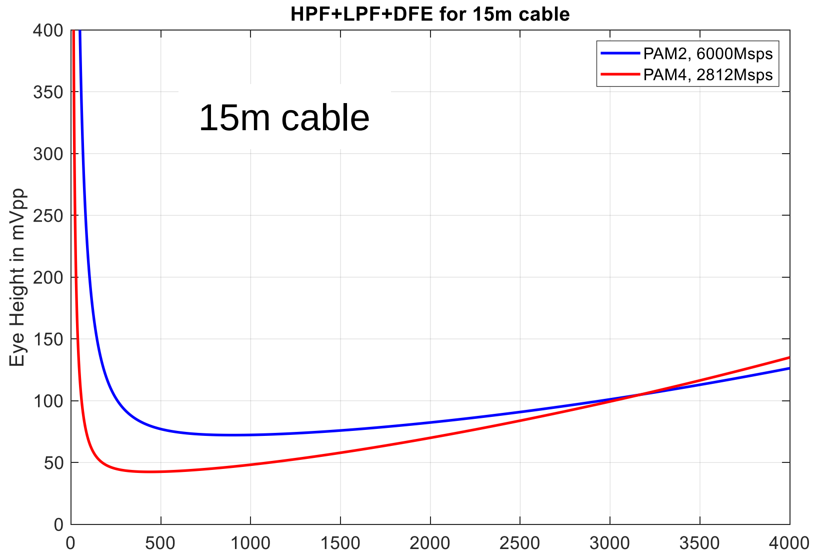
Eye Height When Using Both a HPF and a LPF

referred to the receiver input



Modulation: PAM2 vs PAM4
Baud Rate: 6000Msps vs 2812.5Msps
Receiver HPF: 10% of Nyquist bandwidth
Receiver LPF: Nyquist bandwidth
Cable Length: 8m (scaled from limit line)

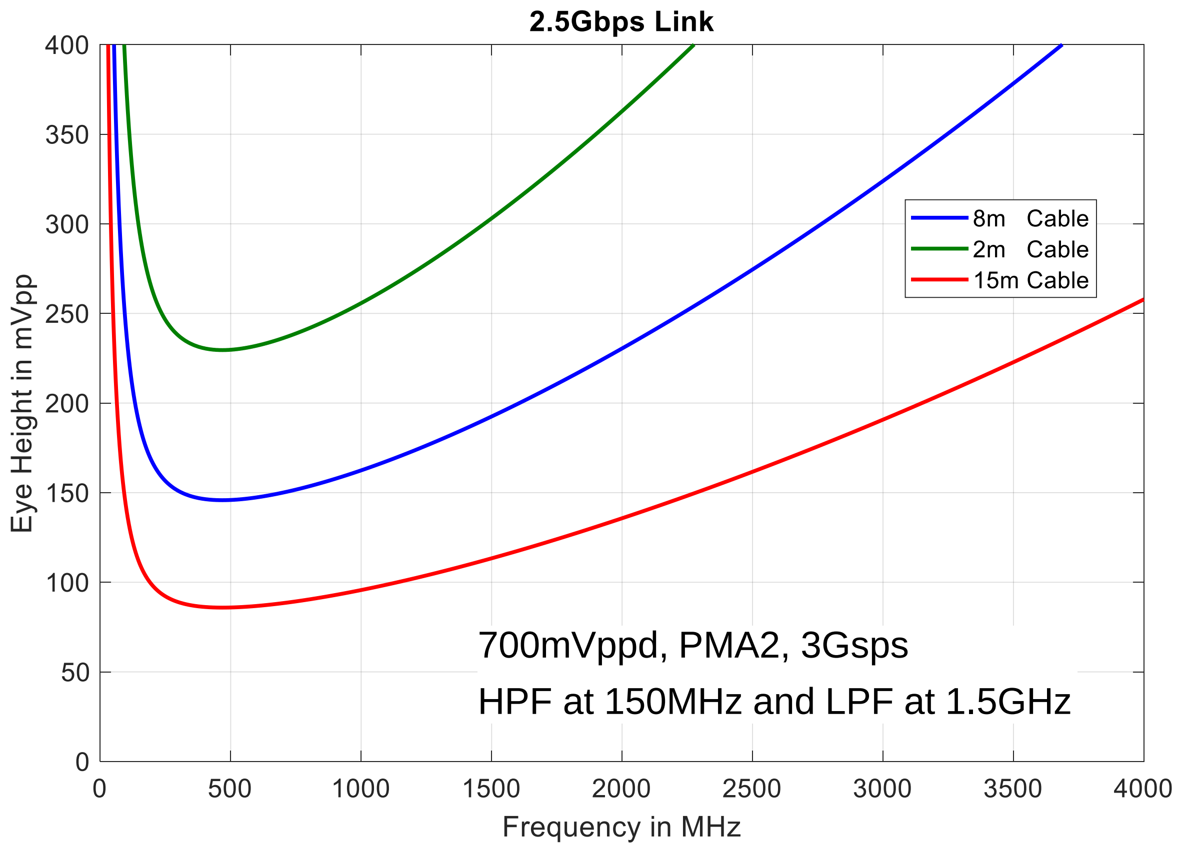
- The LPF helps reduce out of band ingress noise.

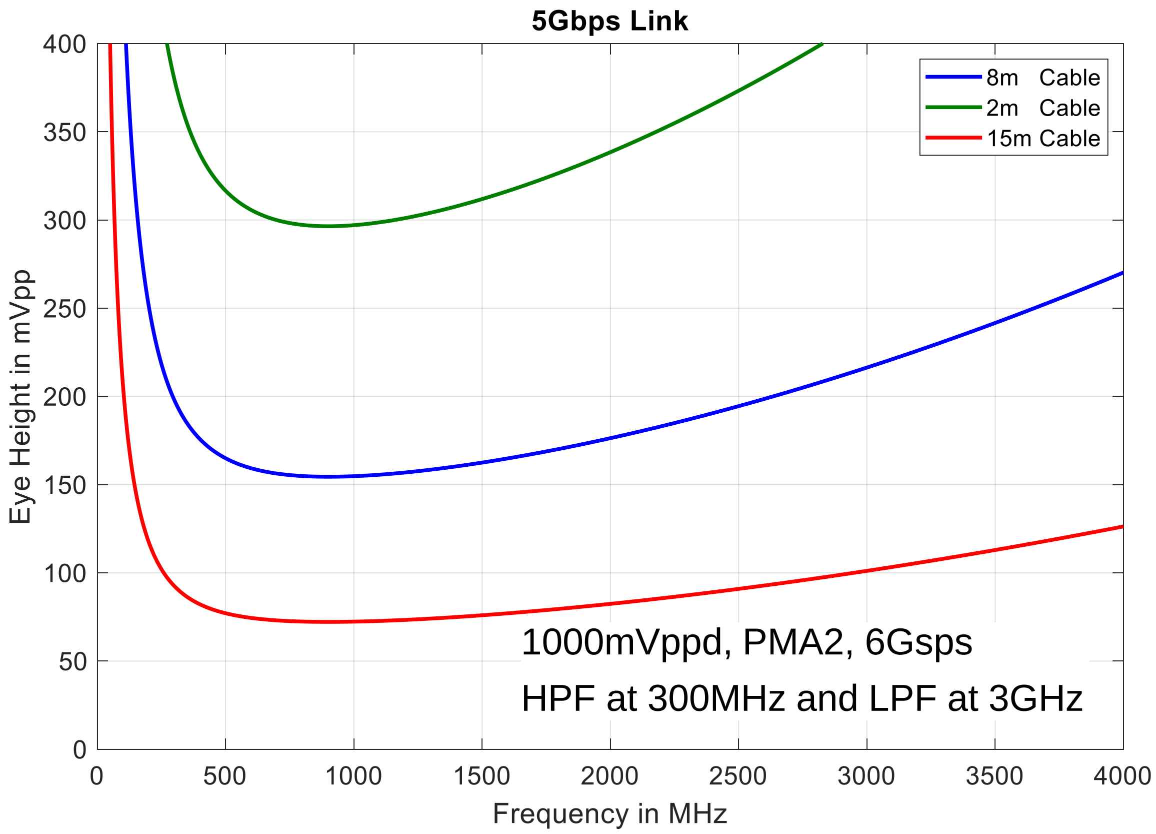


- PAM2 provides the highest Eye Height referred to the receiver input even after a HPF and a LPF applied (1st order).

Eye Height for 2.5Gbps and 5Gbps for TDD

referred to the receiver input, Receiver with HPF+LPF

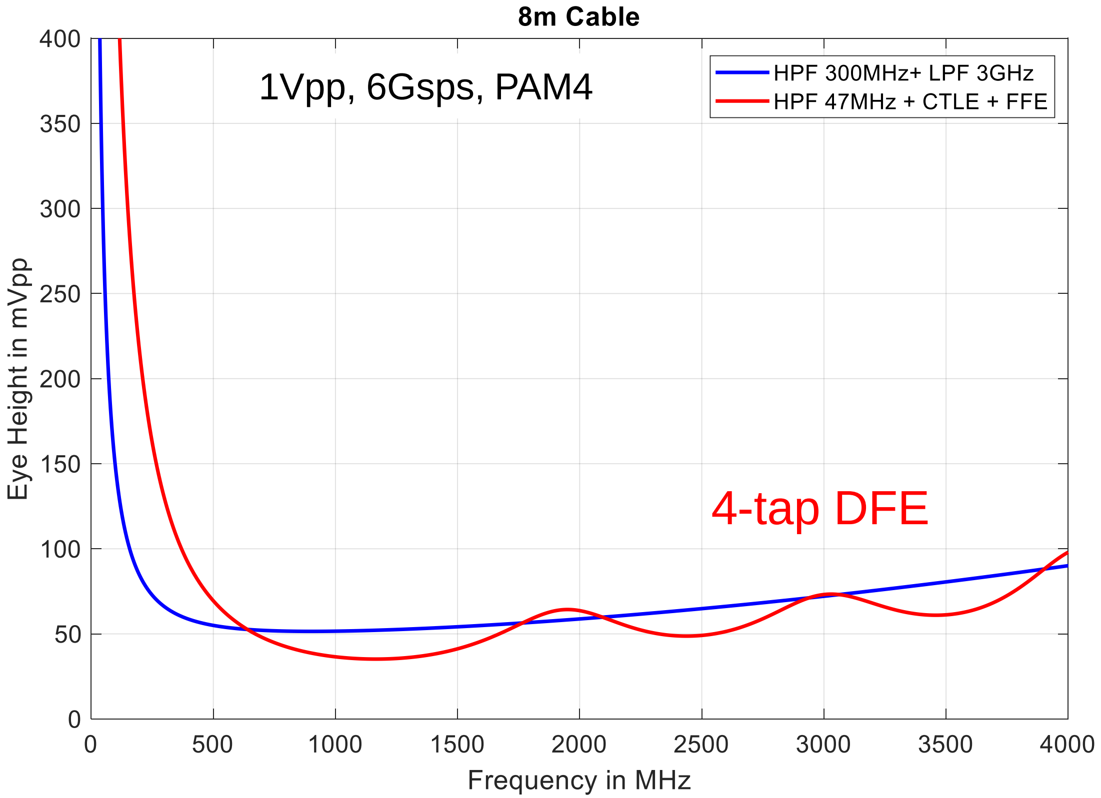




- It is fair to say that for frequently installed link segments, an ingress noise up to 100mVpp is tolerated in the proposed TDD solution at 2.5Gbps and 5Gbps.
- The assumed receiver parameters are an example and not a suggestion for implementation.

Eye Height for 10Gbps PAM4

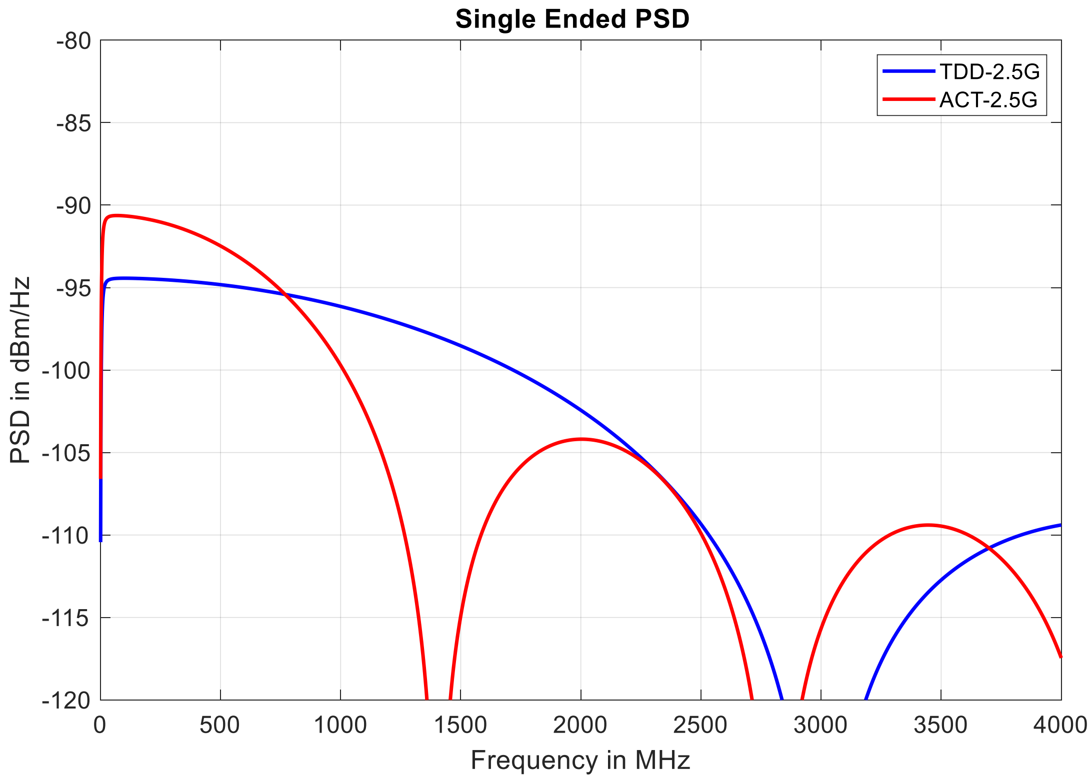
referred to the receiver input, 4tap DFE , MMSE solution

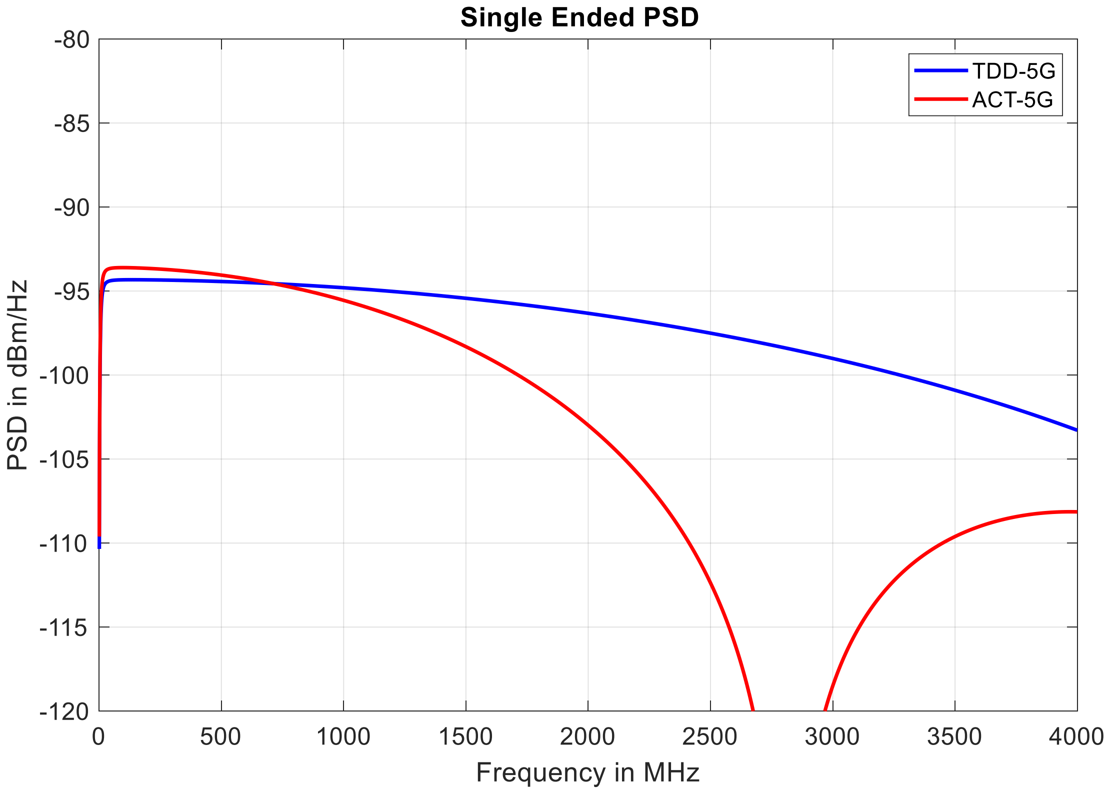


- The Blue Line shows a reference analog type equalizer without notching capability.
- Red line shows digital CTLE+ FFE + 4-tap DFE , MMSE solution with notching capability (notch not shown).
- The oscillatory behavior is due to low number of DFE taps which is limited due to unrolling requirement of PAM4 with digital ADC-based implementation.
- With such a low eye height even at 8m, it is meaningful to allow higher transmit Voltage levels.

- The SNR at 15m is calculated to be about 29dB. While this is sufficient for full length link segment performance on a bench, the in-car performance may be limited for certain type of installations and noises.

Single Ended TX PSD for TDD and ACT 2.5Gbps/5.0Gbps





- A typical single ended PSD of PAM2 modulated TDD at 2.5Gbps and 5Gbps is **below -94dBm/Hz** which is more assuring for emission in FM and DAB bands[1] which is a well known issue for in-car measurements.

1- This is not a conclusion that PAM4 transmitter necessarily causes emission problem.

Adaptive Narrow Band Noise Cancellation

- The adaptive notch filtering is shown to improve performance of a receiver that is subject to CW and AM automotive noises (slow ramp-up as compared to the speed of equalizer adaptation) .
- The notch filtering requires high speed adaptation and it is typically implemented in digital domain (needs high speed ADC).
- The DFE requires unrolling in the digital domain which is more practical and cost efficient with PAM2 rather than PAM4 to implement.
- The notch filtering is limited by the receiver dynamic range and not all noise types can be removed with notch filtering. Therefore a larger eye height is still an advantage for performance in noisy automotive applications.
- For 2.5Gbps and 5Gbps, simpler SerDes type equalizers[1] with no notching have been implemented. However, there may be still cases notching helps performance at 5Gbps.
- 10Gbps is more challenging and notching may be necessary to achieve some level of performance.

1. https://www.ieee802.org/3/dm/public/0724/Chini_Tazebay_3dm_01a_0724.pdf

802.3ch PAM4 Modulation

- **PAM4 is justified for 802.3ch but not necessarily for 802.3dm at 2.5bps/5Gbps**
  - The Insertion Loss for STP is much more than typical Coaxial cables used for Image Sensors. Therefore, less improvement is seen using PAM2.
  - It is well known that the STP cable type provides better noise protection than Coaxial. Thus, PAM4 was decided by 802.3ch Task Force to be sufficient for noise protection.
  - More static use cases for STP versus flexible Coax portions which are subject to more aging effect.
  - The full signal swing in differential transmission versus single ended transmission yields to 6dB loss for the signal.
  - Full speed, full duplex PHY would require more complex echo canceller with an increased baud rates when using PAM2 (this is not the case for TDD).

Summary and Conclusions

- Based on white Gaussian noise, the BER and SNR analysis for PAM2 and PAM4 shows a tie between the two modulation techniques.
- In this presentation, the analysis of eye height referred to the receiver input is performed as a measure of ingress noise tolerance. The analysis shows significant advantage for PAM2 over PAM4 for 2.5Gbps and 5.0Gbps links.
- Even with some aspect of a “practical receiver” implementation, the ingress noise tolerance of the proposed TDD signaling with PAM2 modulation is very promising at 2.5Gbps and 5Gbps.
- A typical single ended PSD of PAM2 transmitter at 2.5Gbps and 5Gbps is below -94dBm/Hz which is more assuring for emission than PAM4 transmitter with 4dB higher level in the FM and DAB bands.
- The ingress noise tolerance of 10Gbps PAM4 is not as impressive and is likely to be limited to shorter link segments. The adaptive notch filtering would help to achieve a certain level of performance but not all noise types can be rejected with such a technique.

Thank you for your attention

Questions?