Feasibility Study and DSP Considerations for 400G/lane PAM4 Co-Packaged Optics

802.3 400GPL Study Group

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400G optical signaling architectures

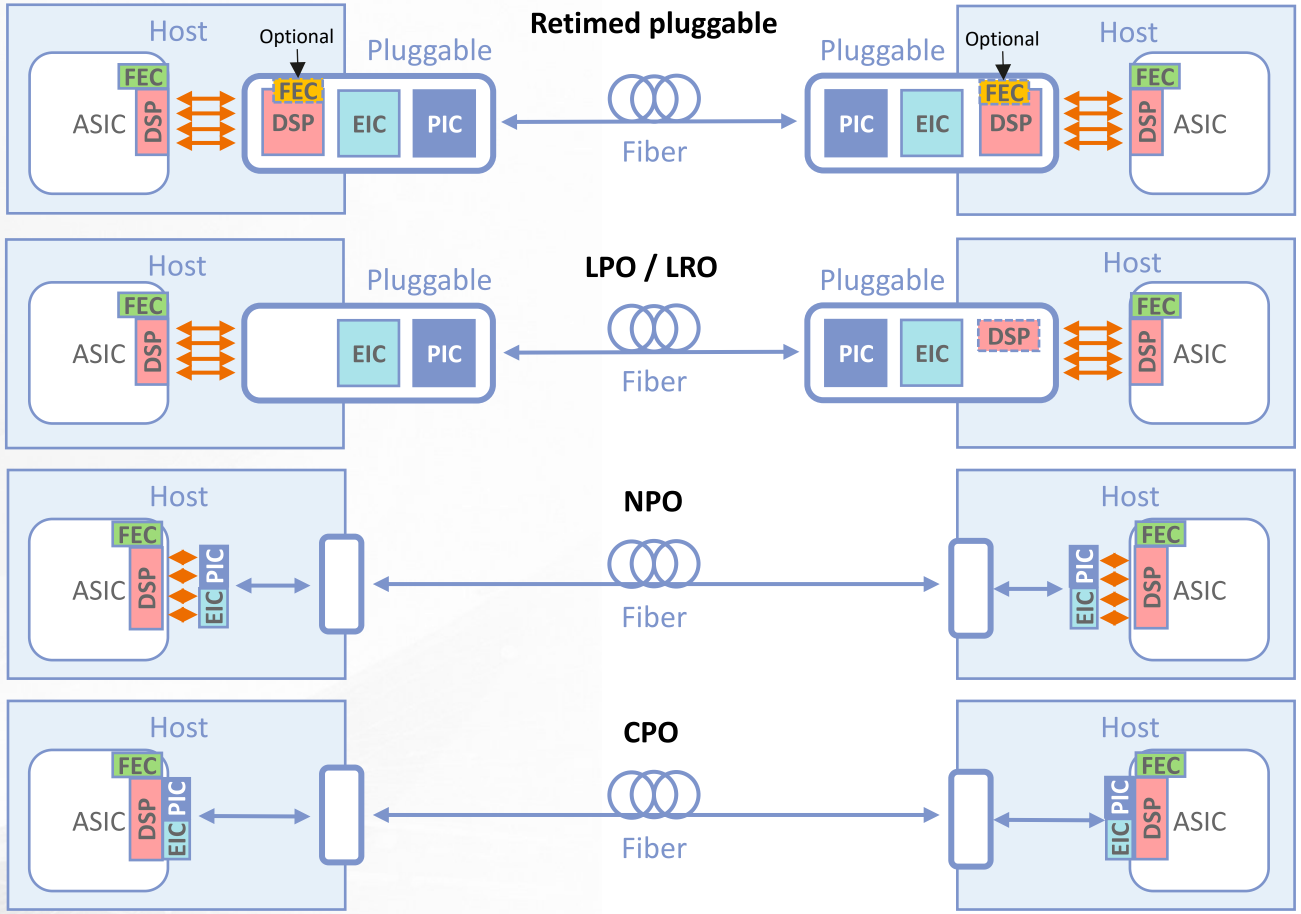
Retimed & linear drive needs to be supported by PAM4

Optical modulation

- PAM4 is the preferred choice due to higher SNR, MPI tolerance and lower error floor
- Industry-first 400G PAM4 DSP presented at OFC 2026 for retimed applications
- KP4 FEC is the desired path forward

Architectures

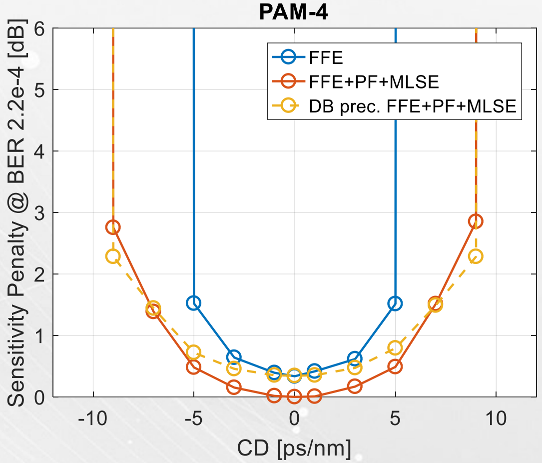
- E2E PAM4 signaling required for linear drive architectures
- Technical feasibility of CPO and E/O/E channels using advanced analog and digital equalization techniques is of interest

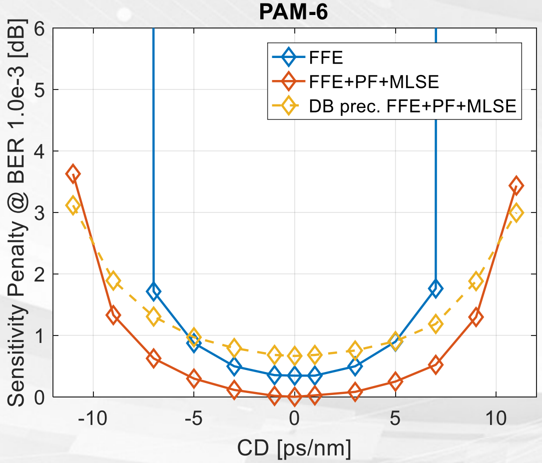


400G PAM4 vs. PAM6

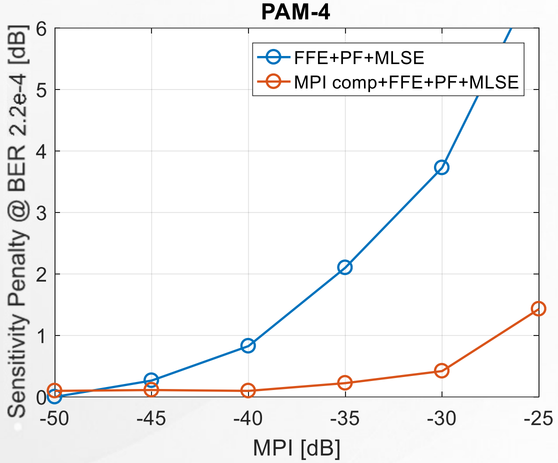
Does the electrical channel advantage of PAM6 translate to the optical domain?

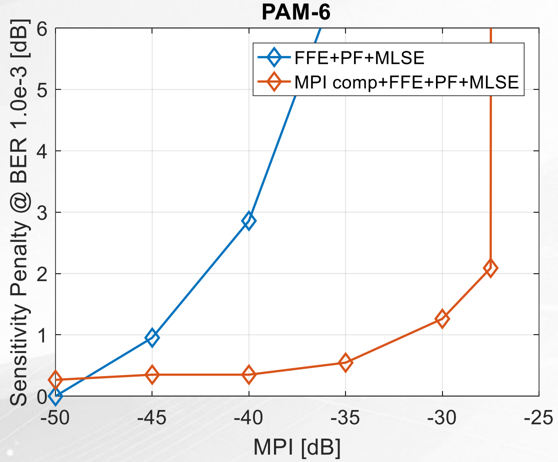
CD – both only support LWDM



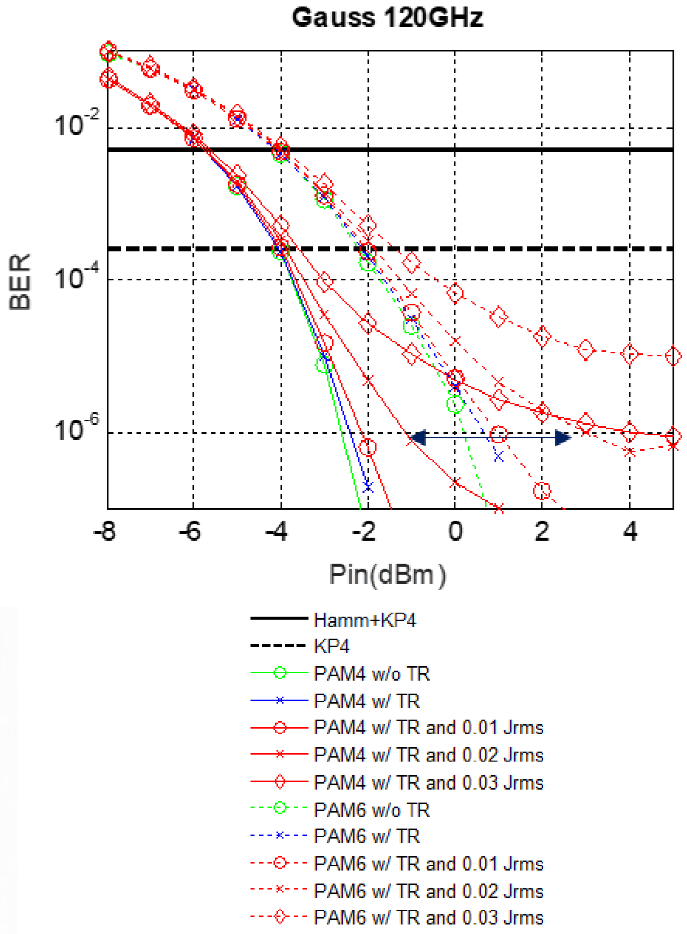


MPI – Higher tolerance to link flaps for PAM4



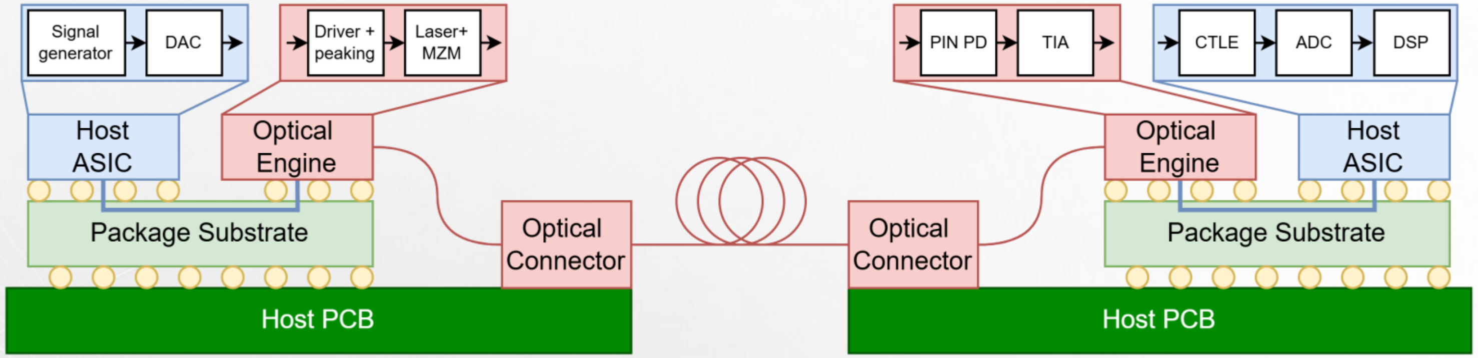


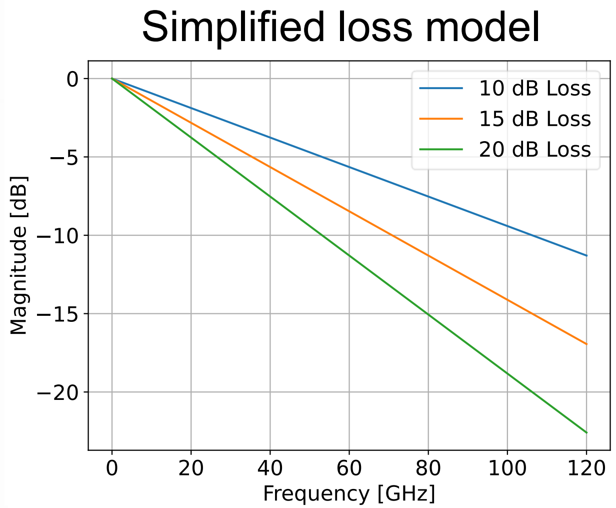
Clock jitter tolerance – PAM6 with higher error floor



Overview

400G CPO/NPO simulation system



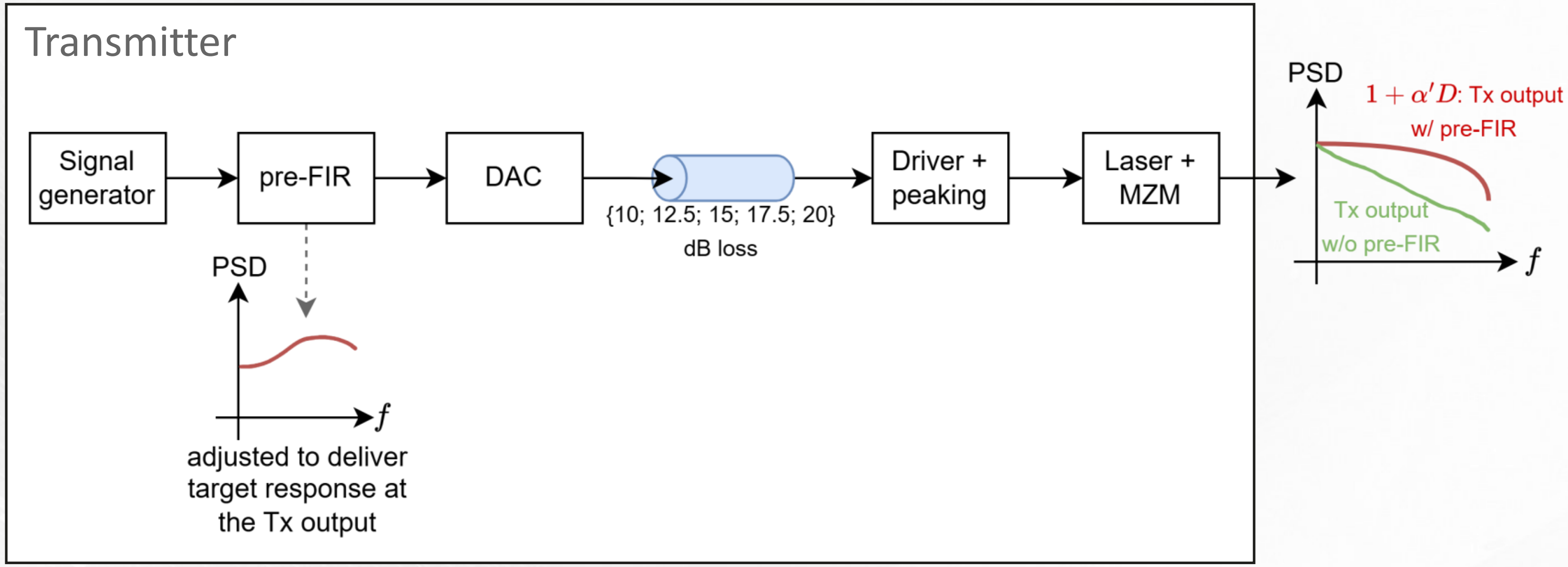


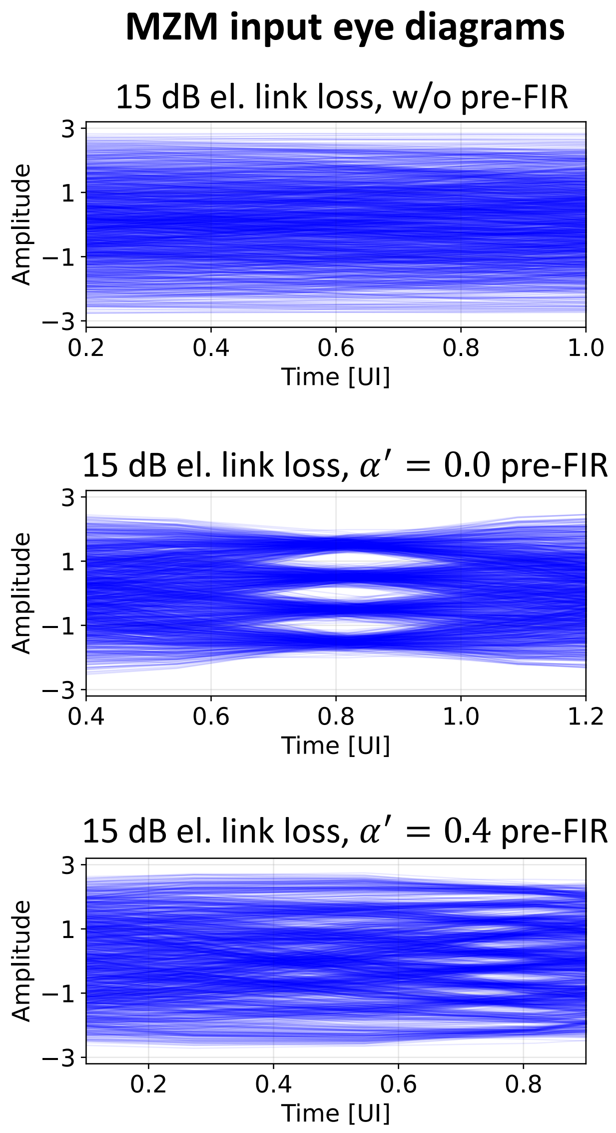
- 400 Gb/s/lane CPO/NPO feasibility for next-gen optical systems
  - Key parameters currently remain open.
  - Minimizing PCB trace insertion loss (Host ASIC ↔ Optical Engine) is critical for feasibility.
- Scope of investigation
  - Feasibility dependence on Tx digital and analog equalization techniques.
  - Interaction with Rx DSP

Component	Key parameters in simulation
Tx DSP	pre-FIR 7 taps
DAC	1 sps, ENoB 5.0
Tx PCB	10 – 20 dB link loss @ Nyquist
Driver Peaking	{0; 5; 10} dB
Laser	-152 dB/Hz RIN, 10 MHz linewidth
Tx Bandwidth	110 GHz 4th order Bessel
Fiber	<500 m; no CD, DGD, MPI
PD + TIA	Responsivity 0.5 A/W, 25 pA/√Hz noise
Rx PCB	10 – 20 dB link loss @ Nyquist
Rx CTLE	10 dB
ADC	1 sps, ENoB 6.0
Rx Bandwidth	110 GHz 4th order Bessel
Rx DSP	FFE 41 taps, optional 2 tap noise whitening filter + memory 1 MLSE

Tx Pre-FIR Calibration

Controlling the tradeoff between emphasis and PAPR

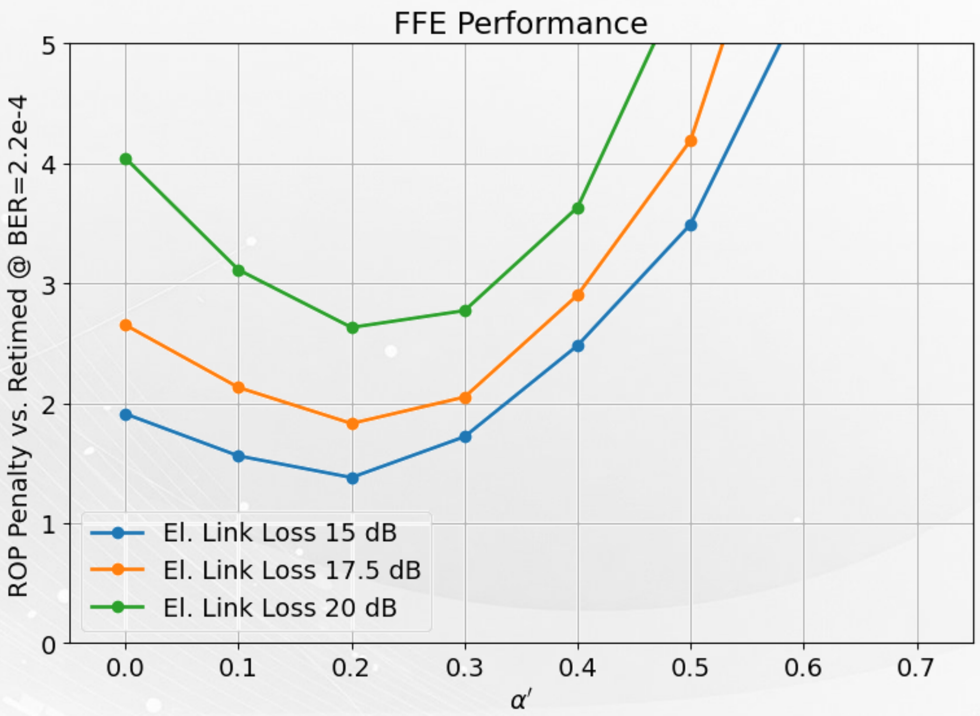


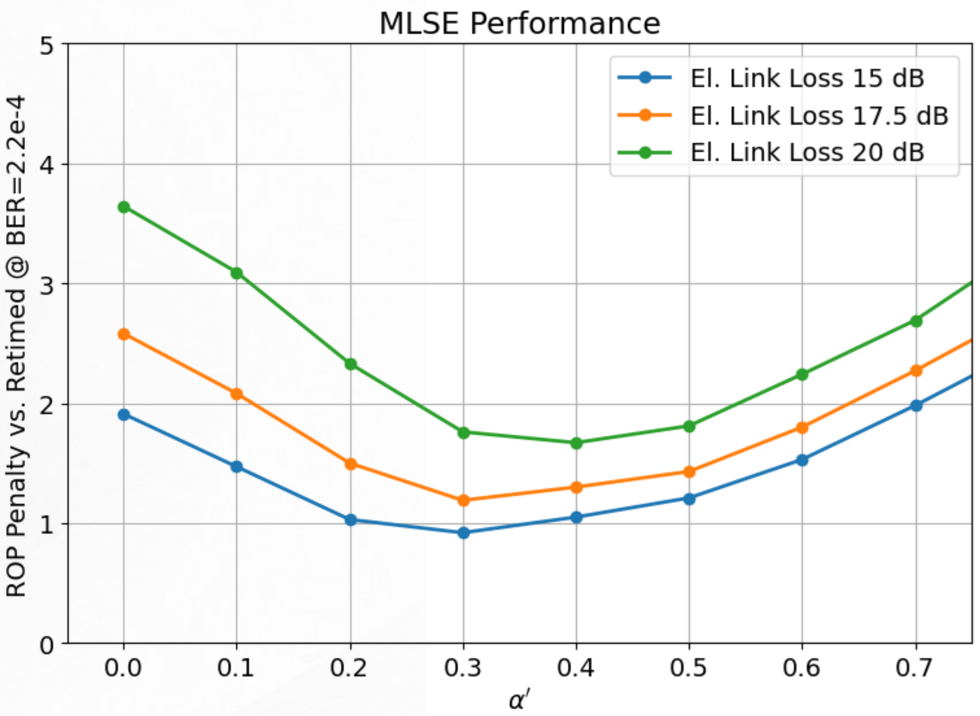


- Pre-FIR optimization: Target is a partial response (PR) of the type $1 + \alpha' D$ at the output of the transmitter.
  - Degree of freedom for optimization
    - $\alpha' = 0$: inversion of the Tx electrical link (including driver peaking)
    - $\alpha' > 0$: Intentional residual ISI allocated to Rx DSP. Reduces pre-FIR emphasis, lowering DAC quantization noise.

Tx Pre-FIR Sweep Curves w/ 5 dB Tx Driver Peaking

Optimization depends on Rx DSP

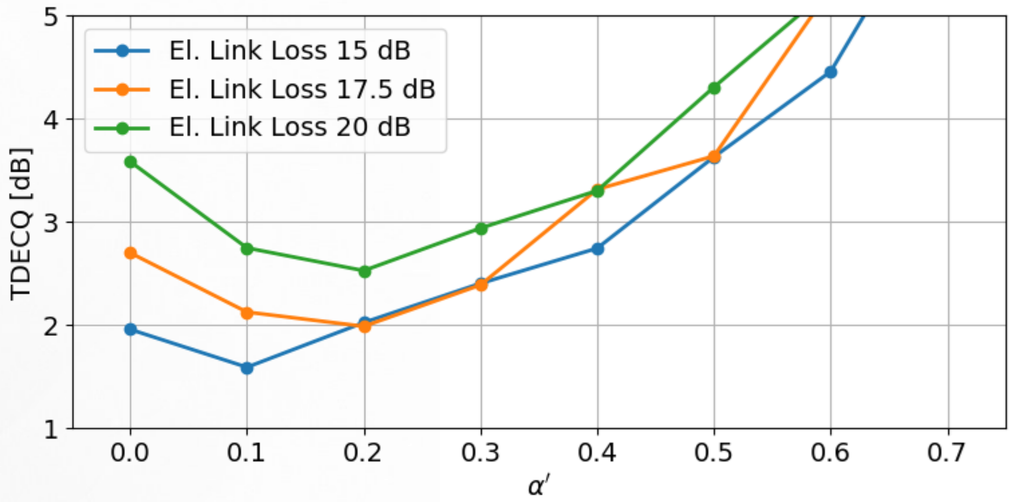




- Rx DSP performance after full CPO system (parameters in page 4): Comparison of FFE and MLSE
  - ROP penalty vs. pre-FIR parameter α' dependent on the electrical link loss.
- Pre-FIR requirements: Optimization varies by Rx DSP type.
  - FFE performance is optimal at $\alpha' = 0.2$ for various electrical links losses.
  - MLSE performance is optimal at $\alpha' = 0.3$ and $\alpha' = 0.4$.

TDECQ Analysis w/ 5 dB Tx Driver Peaking

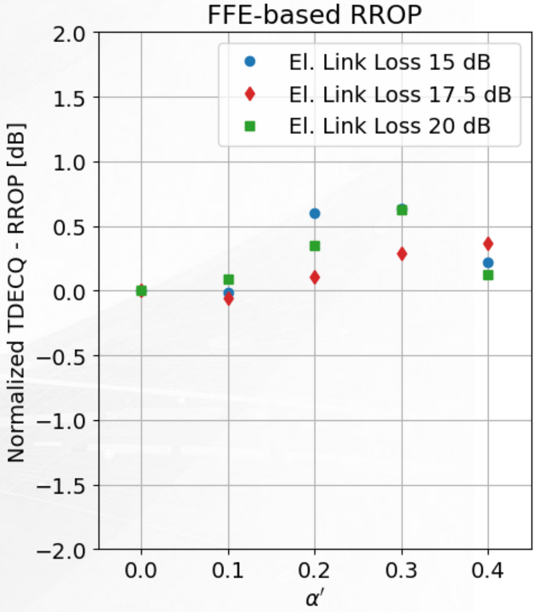
Conflict with MLSE performance optimization

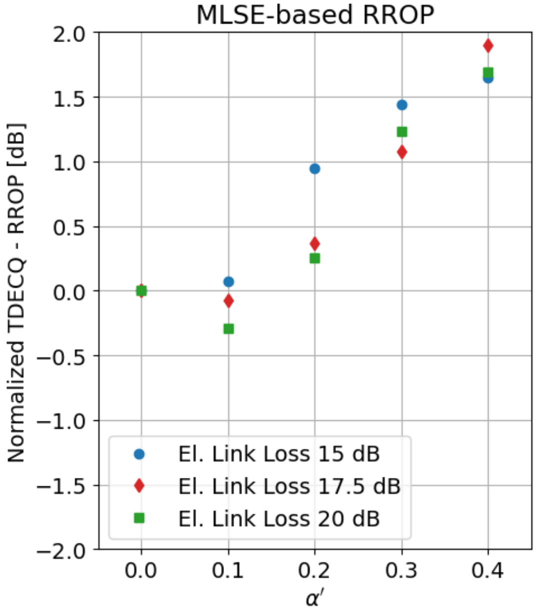


Metric validity and optimization conflict

- As a transmitter quality metric, TDECQ should correlate with final link performance.
  - Inherent problem for linear drive systems: reference receiver is different from linear receiver.
  - Increased difference if MLSE is used in the receiver: Optimizing for TDECQ yields pre-FIR coefficients differing from those optimal for MLSE performance.
- A conflict exists between minimizing TDECQ and optimizing for specific Rx DSP configurations.

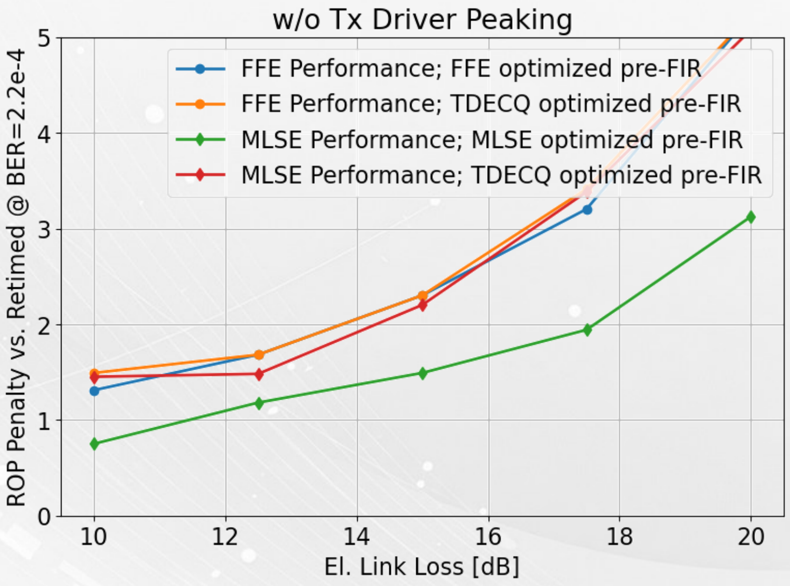
Optimization metric	Best α' @ 20 dB el. link loss
TDECQ	0.2
FFE Performance	0.2
MLSE Performance	0.4

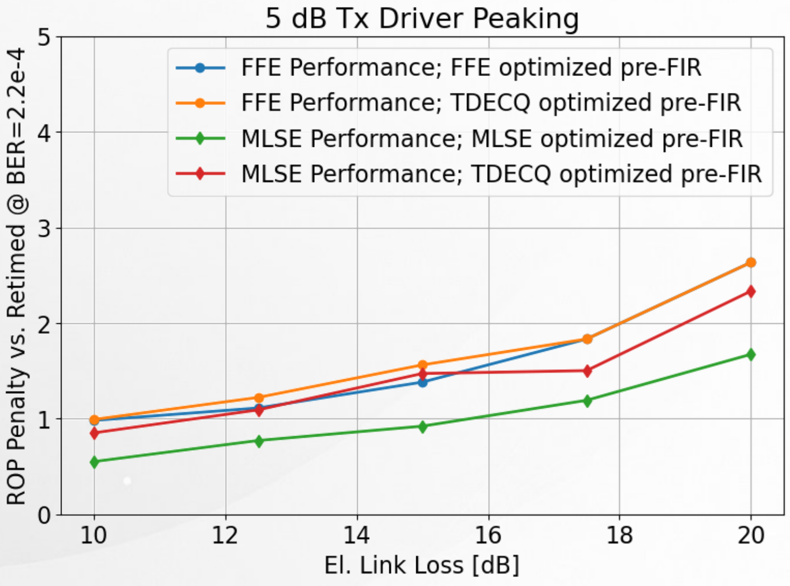


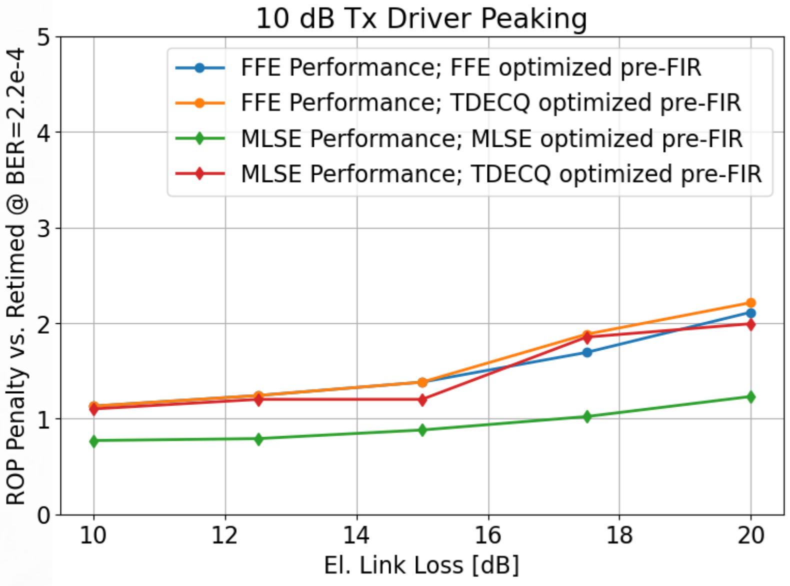


Tx Pre-FIR and Analog Peaking Overview

Optimization metric is critical for the final performance







- With MLSE employed in the Rx DSP, TDECQ fails to accurately predict system performance.
  - An alternative transmitter quality metric is necessary.
  - An example would be MLSE TDECQ, proposed in https://www.ieee802.org/3/dj/public/23_07/stojanovic_3dj_01_2307.pdf
- Tx analog peaking is critical to minimize penalties in high-insertion-loss electrical links.

Conclusions

Digital and analog equalization require careful co-optimization

Feasibility

- 400 Gb/s/lane CPO/NPO feasibility depends on electrical link loss, analog peaking and Rx DSP.
    - For electrical link losses > 15 dB, strong Tx analog peaking and Rx MLSE are mandatory.

DSP Interaction

- Optimal pre-FIR configuration is strictly dependent on the Rx DSP (FFE vs. MLSE).

Metric Limitations

- Standard TDECQ is a poor predictor of link performance when Rx MLSE is used.
- An alternative metric (e.g., MLSE TDECQ) is required for accurate transmitter evaluation for E/O/E channels

Thank you