Further Consideration on Modulation Formats of 400Gbps per lane Optical Signaling

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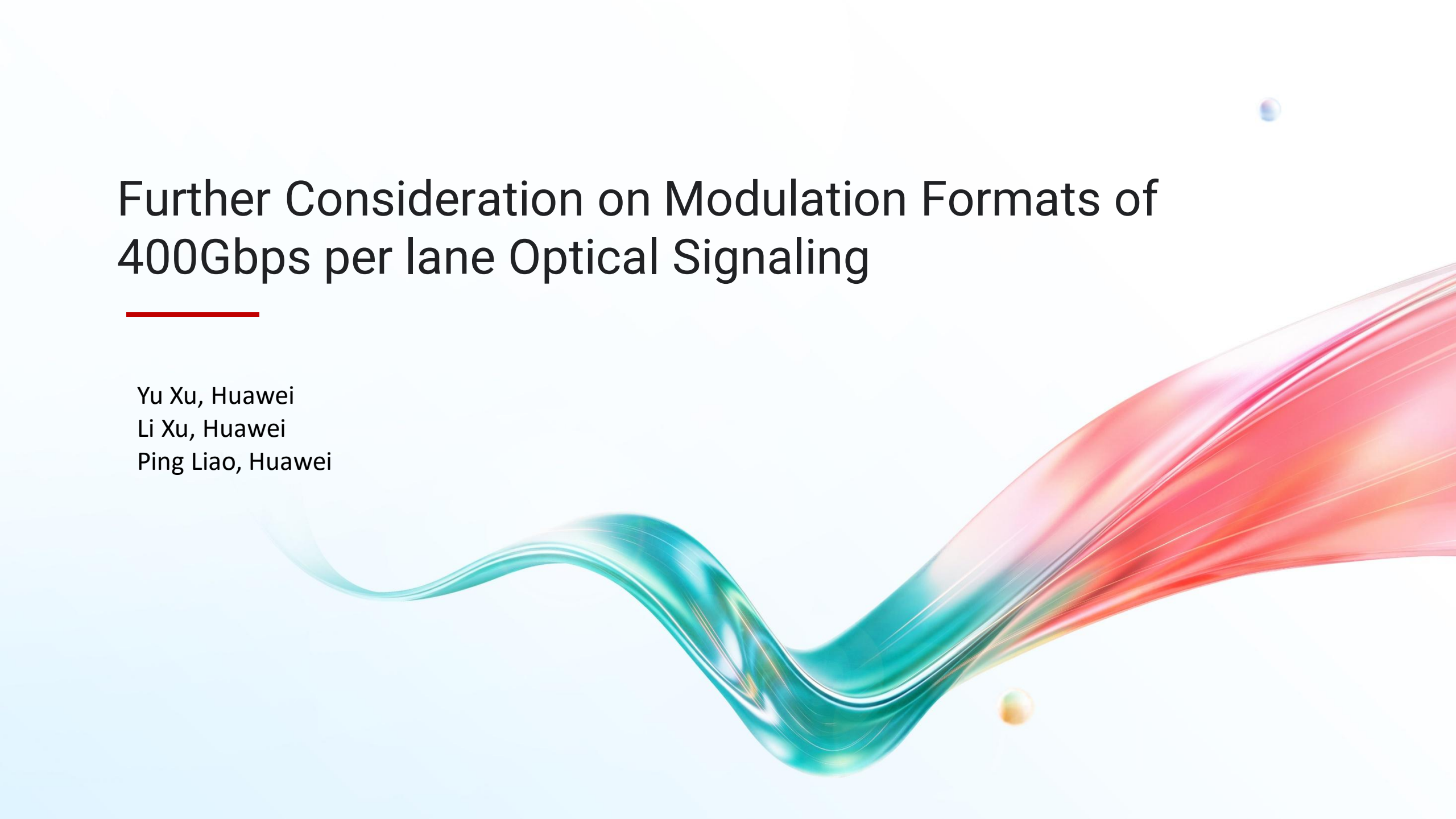


Introduction

- The objective 400 Gb/s/Lane Signaling has been accepted at July meeting.
  - *Define a physical layer specification that supports 400 Gb/s operation over 1 pair of SMF with lengths up to at least 500 m*
  - *Define a physical layer specification that supports 800 Gb/s operation over 2 pairs of SMF with lengths up to at least 500 m*
  - *Define a physical layer specification that supports 1.6 Tb/s operation over 4 pairs of SMF with lengths up to at least 500 m*
- The solution of 400G/L signaling is critical and there seems different preferences on modulation formats for optical signaling.
- At the last May Meeting, we provided a presentation with the conclusion that the bandwidth of optoelectronic devices is no longer a bottleneck with the improvements in fabrication processes and device designs for PAM4/6/8.
- For this contribution, we analyze the performance and penalty of the two modulation formats with more critical parameters e.g. MPI, ER, BER etc., to help the decision making in the optical signaling.

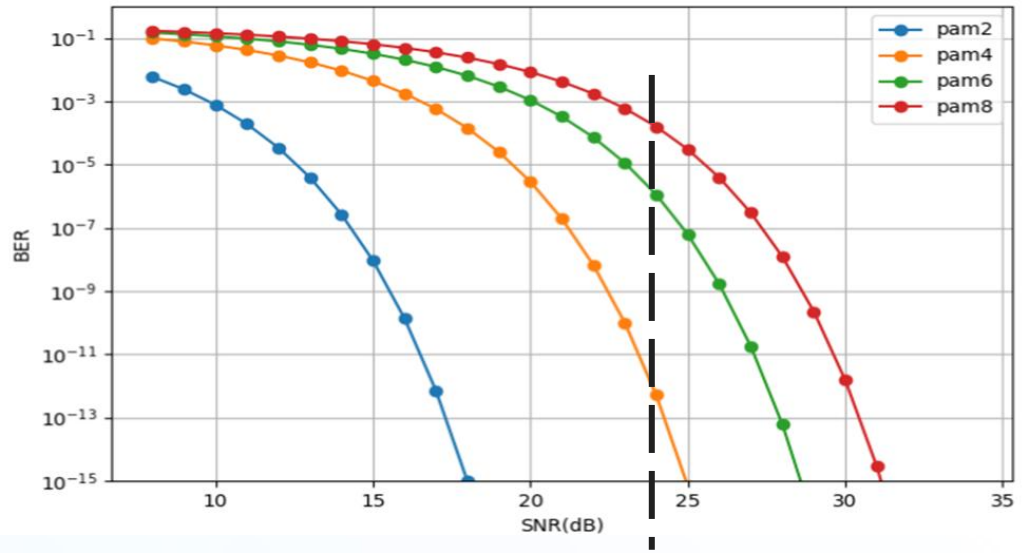
SNR Penalty—Theoretical Analysis

- SNR requirement strongly depends on Modulation format. Higher Modulation format needs more SNR to achieve the same BER due to more levels of signals that higher modulation format introduced.

  For PAM-M

$$\mathrm{BER} = \frac{2(M-1)}{M log_2 M} Q\left(\sqrt{\frac{3}{M^2-1}\mathrm{SNR}}\right)$$

$$\mathrm{and}\ Q(\mathrm{x}) = \frac{1}{\sqrt{2\pi}} \int_{\mathrm{x}}^{\infty} \mathrm{e}^{-\mathrm{u}^2/2}\, du$$



- Under the assumption of AWGN channels, the theoretical SNR gap is about 3/6dB between PAM6/8 and PAM4.
- With the same SNR condition like 24dB, theoretically PAM4 could achieve a BER of 1e-12, while PAM6 can only achieve ~1e-6.

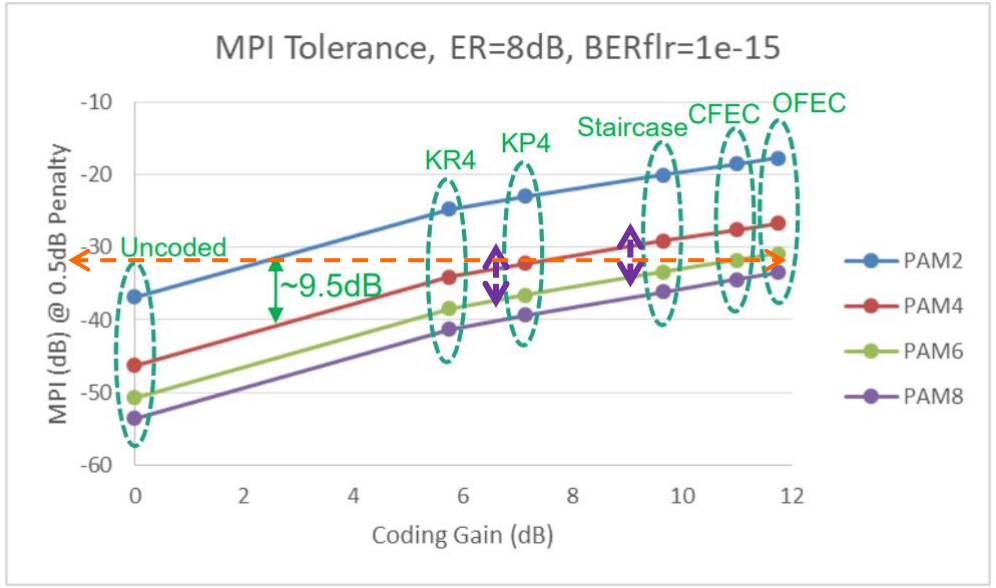
Metric	MF	BER					
		1.00E-04	1.00E-05	1.00E-06	1.00E-07	1.00E-09	1.00E-12
SNR requirement	PAM4	18.21	19.43	20.40	21.20	22.45	23.87
	PAM6	21.79	23.06	24.04	24.84	26.11	27.51
	PAM8	24.28	25.54	26.53	27.34	28.63	30.07

MPI Tolerance —Theoretical Analysis(1/2)

- MPI tolerance is a critical performance metric for optical solution.
- zhang_3df_01_220524 provided an analytical MPI model and discussed MPI penalty with different modulation formats. Following the same Gaussian noise approximation, MPI penalty is calculated as:

$$\Delta P_{dB} = -5\lg\left(1 - \frac{2\cos^2\alpha}{\mu_2\left(\frac{1}{SNR_{th}} - \frac{1}{SNR_{flr}}\right)} 10^{\frac{MPI_{dB}}{10}}\right)$$

- With KP4 FEC, under the assumption of 8dB ER, BER floor 1e-15 and 0.5dB sensitivity penalty, MPI tolerance gap is about 5dB (-32dB VS -37dB) between PAM4 and PAM6.
- For the same MPI power, to achieve the same BER target, PAM6 needs high performance FEC like CFEC, where FEC Overhead and complexity increase.

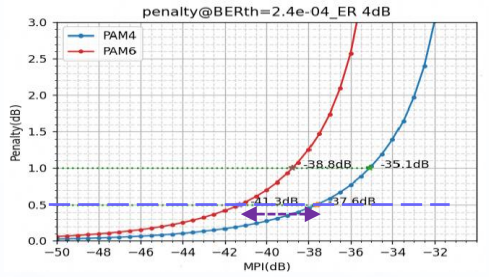


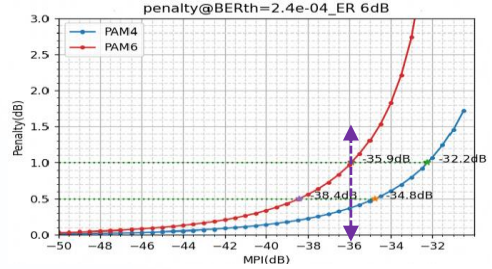
Ref: zhang_3df_01_220524

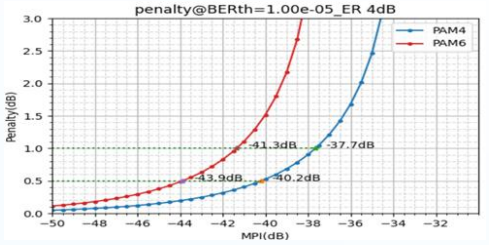
Ref: Modeling MPI penalty and its implication for next generation PAMx systems, IEEE802.3df

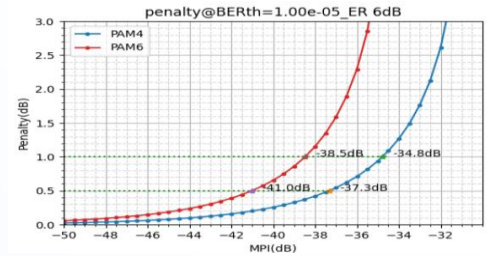
MPI Tolerance —Theoretical Analysis(2/2)

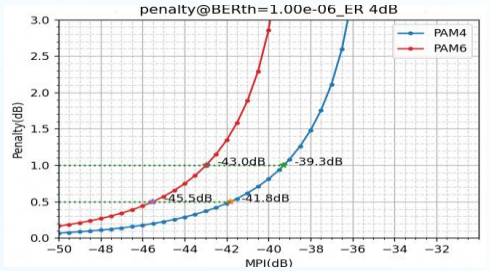
- Following the same formulation as in zhang_3df_01_220524, under the assumption of $\boldsymbol{cos^2\alpha = 0.8}$, BER floor of 1e-12, ER=4dB, and 0.5dB sensitivity penalty, the MPI tolerance gap is about 3.7dB@2.4e-4/1e-5/1e-6 between PAM4 and PAM6.
- Specifically for PMA6, when ER=4dB, MPI power should be kept under around -41dB@0.5dB sensitivity penalty at BER=2e-4, -43.9dB@0.5dB sensitivity penalty at BER=1e-5, and -45.5dB@0.5dB sensitivity penalty at BER=1e-6.
- If higher MPI power is hard to achieve, increasing ER may also help alleviate the sensitivity penalty brought by PAM6.
- But if ER is increased, driver amplitude should also be increased, which may cause more power consumption. And for ER=6dB, there is a risk about technical feasibility given the usual ER values of 4.5~5dB.

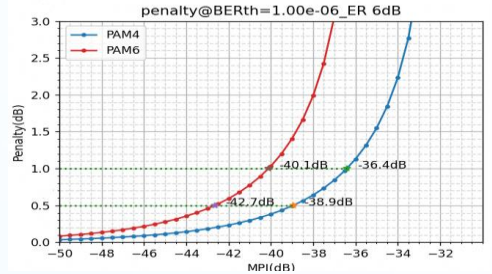




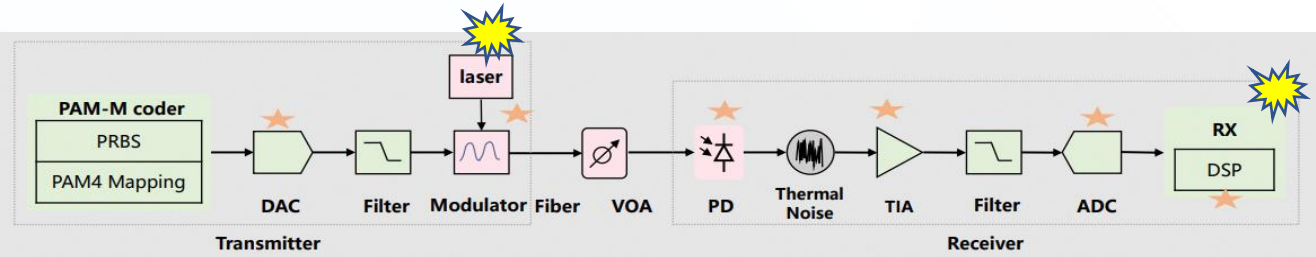




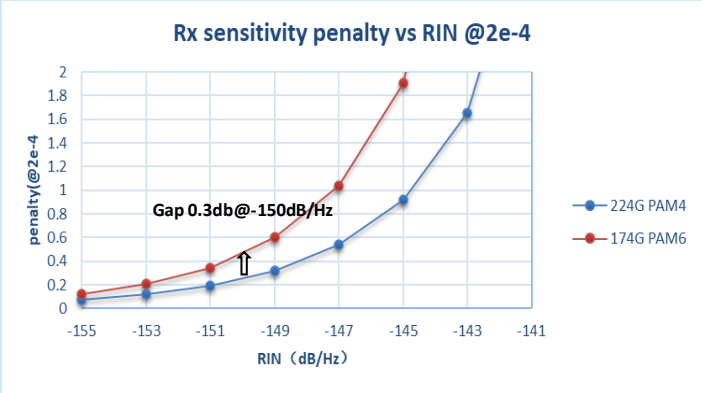


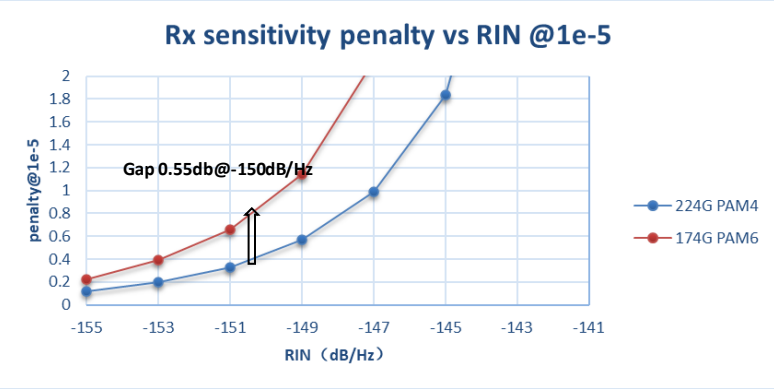


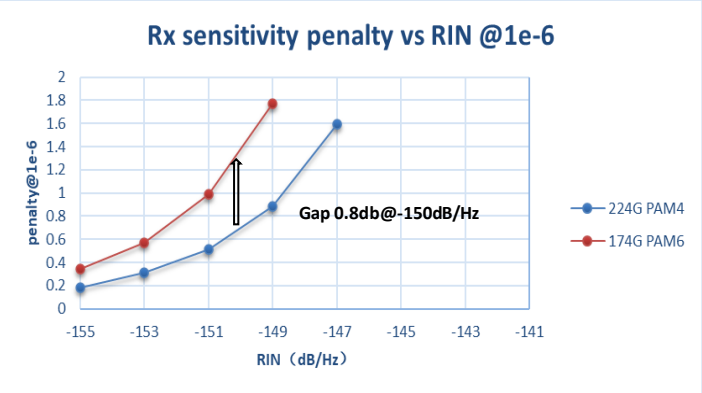
RIN Simulation with different BER Thresholds



- Due to reduced eye height and higher SNR requirement, PAM6 is more sensitive to RIN, which causes that sensitivity penalty increases more rapidly.
- At BER =2e-4, the gap is about 0.3dB @RIN=-150dB/Hz
- At BER =1e-5, the gap is about 0.55dB @RIN=-150dB/Hz
- At BER =1e-6, the gap is larger, which is about 0.8dB@RIN=-150dB/Hz







Further Considerations

- Nonlinearity
  - PAM6 has higher sensitivity to device nonlinearities compared to PAM4 due to the requirements of balance between signal levels, which are more sensitive to nonlinearity.
  - Comprehensive nonlinear analysis including component-level characterization and system-level impact assessment is ongoing and will be submitted as a follow-up contribution.

- FEC and DSP, higher-order modulation formation might need:
  - More efficient coding scheme
  - Higher-Coding Gain FEC
  - Higher-Performance DSP Algorithms
  - Increased power consumption and higher latency

Summary

- Based on current analysis, **PAM4 is more suitable as the modulation format for 400G/L over 500m applications**, offering the best balance among performance, complexity, and cost-effectiveness.

- We will provide follow-up contributions with detailed nonlinear analysis and component specifications to further support standard development.

Thank You