E-O Link Analyses of PAM4, PAM6, and PAM8 at 448Gbps/λ

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Introduction

- A critical element for 448 Gbps/λ Electro-Optical Link Transmission is achievable bandwidth of the linear driver, optical modulator, photodetector, TIA, and supporting SerDes elements.

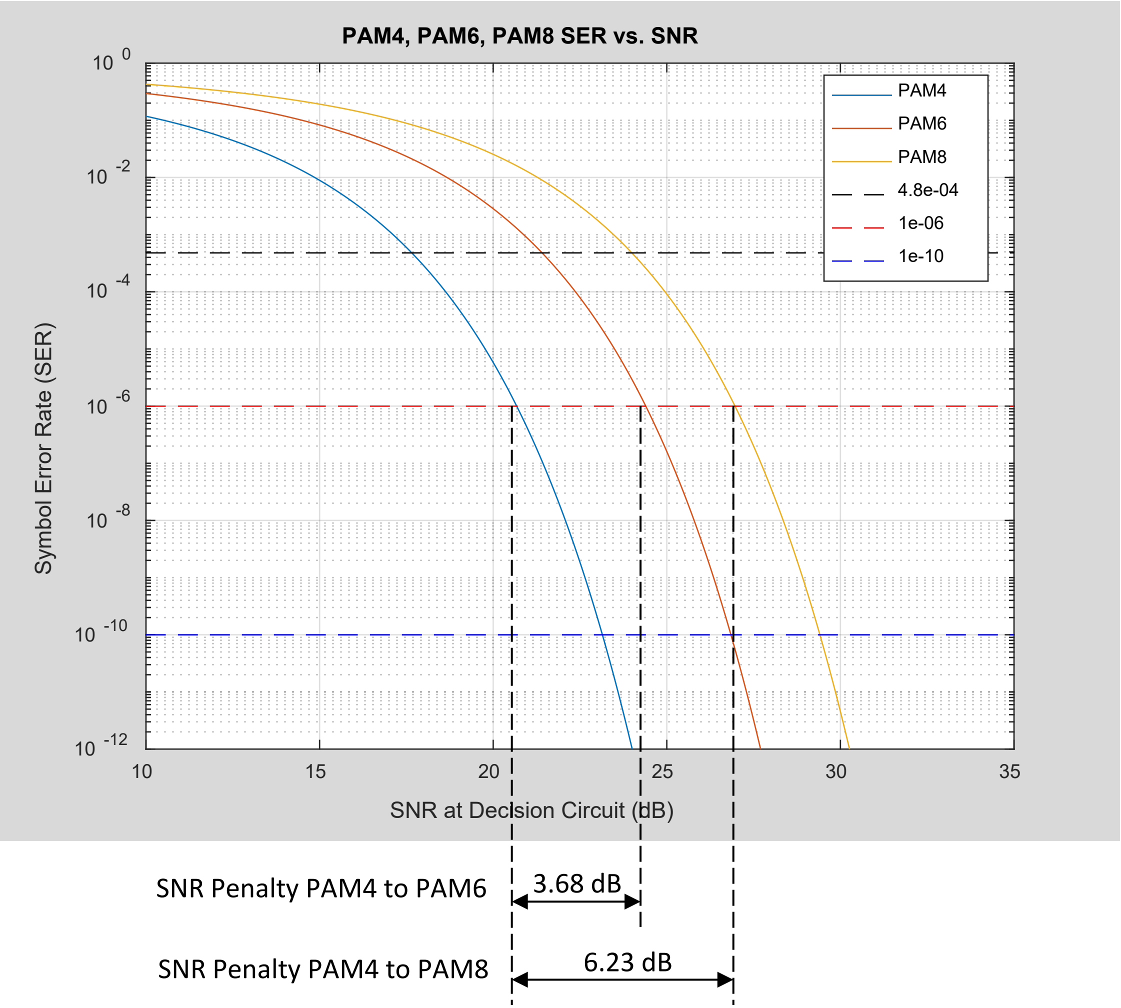
- Compare PAM4, PAM6, and PAM8 link performance in an Additive White Gaussian Noise (AWGN) environment:
  - SER vs. SNR
  - SER vs. OMA at photo-detector (PD) input receiver input in a reference receiver

- Reference receiver for evaluating impact of transmit link bandwidth on the received signal
  - Estimate noise enhancement in a reference receiver as function of driver and modulator bandwidth
  - Evaluate corresponding impact on OMA at PD for a targeted SER ≈ 1e-6

- List minimum driver and modulator bandwidths for direct detection of PAM4, PAM6, and PAM8 signals in a reference receiver environment.

- Summary: 448Gb/s Bandwidth Challenges – Driver, Modulator, Photodetector, and TIA

SER vs. SNR: PAM4, PAM6, and PAM8



$$\text{SNR Penalty to PAM}-\text{L (dB)} = 10\log_{10}\left(\frac{1}{5}\cdot\frac{L^2-1}{3}\right)$$

$$\textbf{PAM4}:\ SER = \frac{3}{2}\cdot \mathrm{Q}\left(\frac{d}{\sigma}\right) = \frac{3}{2}\cdot Q\left(\sqrt{\frac{SNR}{5}}\right)$$

$$\textbf{PAM6}:\ SER = \frac{5}{3}\cdot \mathrm{Q}\left(\frac{d}{\sigma}\right) = \frac{5}{3}\cdot Q\left(\sqrt{\frac{3\cdot SNR}{35}}\right)$$

$$\textbf{PAM8}:\ SER = \frac{7}{4}\cdot \mathrm{Q}\left(\frac{d}{\sigma}\right) = \frac{7}{4}\cdot Q\left(\sqrt{\frac{SNR}{21}}\right)$$

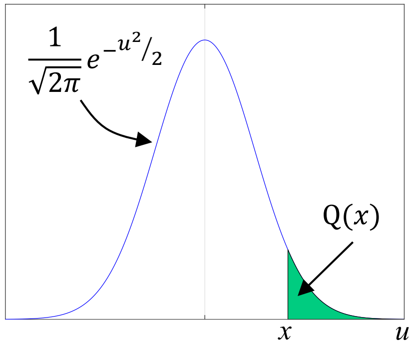
$$SNR = \frac{\text{Signal Power}}{\text{Noise Power}} = \frac{P_S}{P_N} \qquad \begin{cases} P_S = \dfrac{L^2-1}{3}d^2 \\ P_N = \sigma^2 \end{cases}$$

SNR Penalty w.r.t. PAM4

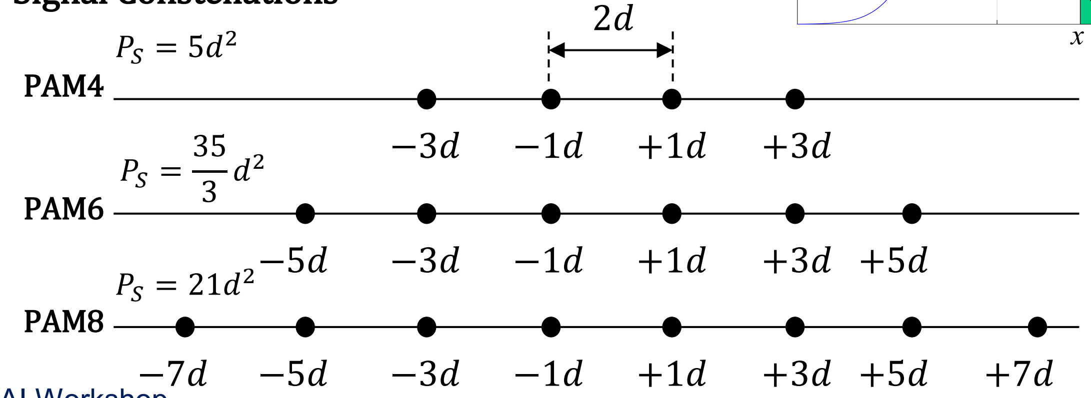
Line Code	SNR Penalty
PAM4	---
PAM6	3.68 dB
PAM8	6.23 dB

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

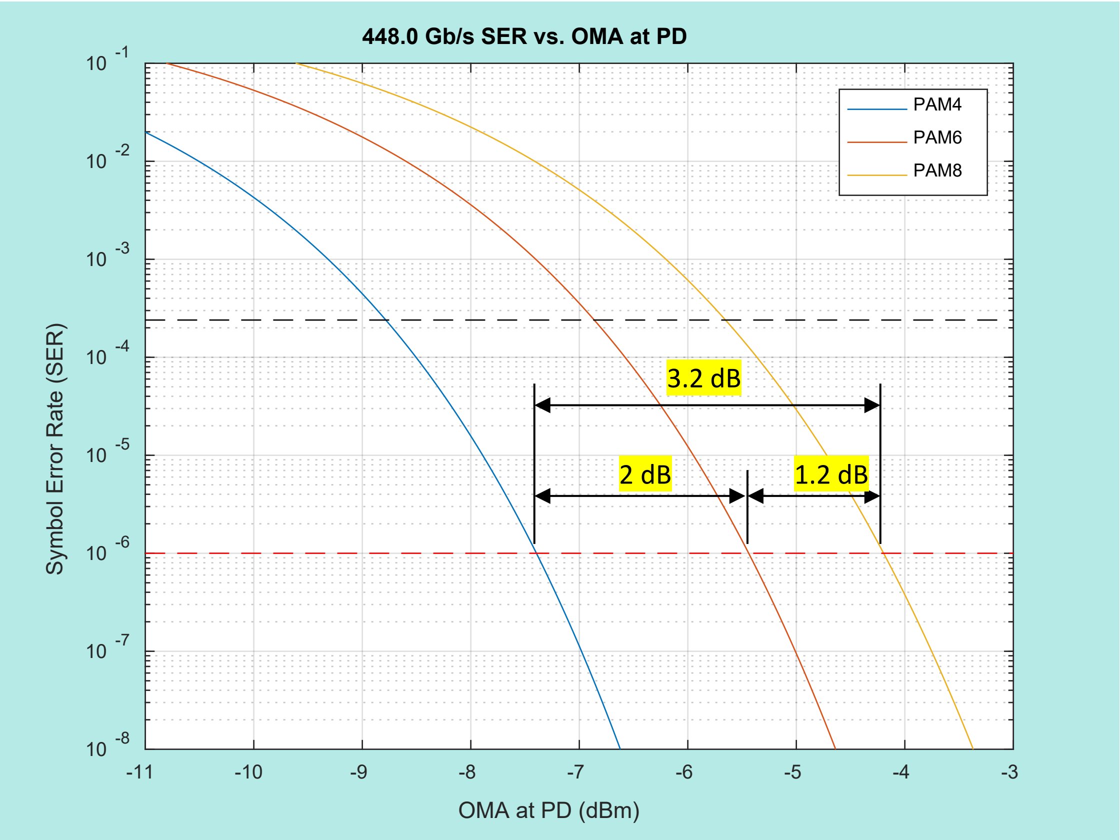
Probability of Symbol Error Q(x)

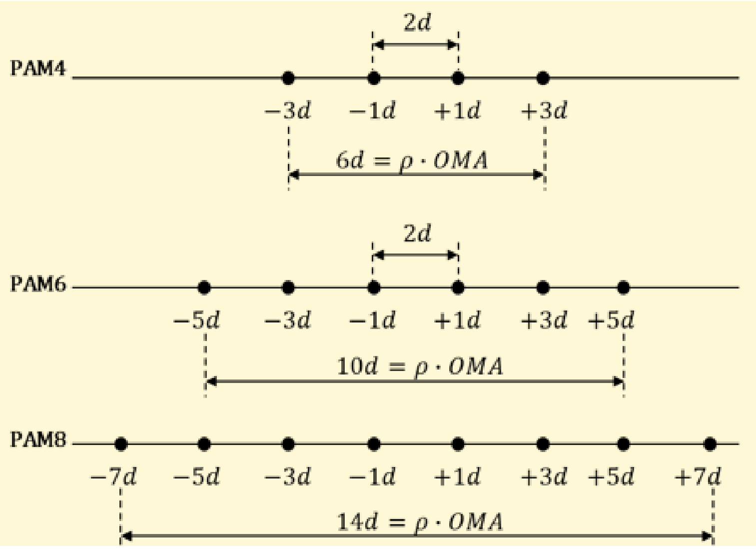


Signal Constellations



SER vs. OMA in AWGN for PAM-4, -6, and -8 (448 Gb/s)





Noise Environment:

- Thermal 15.3 pA/√Hz
- Shot Noise
- Noise BW = $f_{sym}/2$
- Extinction Ratio = 5 dB
- PD responsivity = 0.9A/W
- Not included:
  - RIN
  - Limited Tx Link BW

PAM4:

$$SER = \frac{3}{2} \cdot Q\left(\frac{d}{\sigma}\right) = \frac{3}{2} \cdot Q\left(\sqrt{\frac{SNR}{5}}\right) = \frac{3}{2} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 3 \cdot i_{rms}}\right)$$

$$\sigma = i_{rms} = \text{noise variance}$$

PAM6:

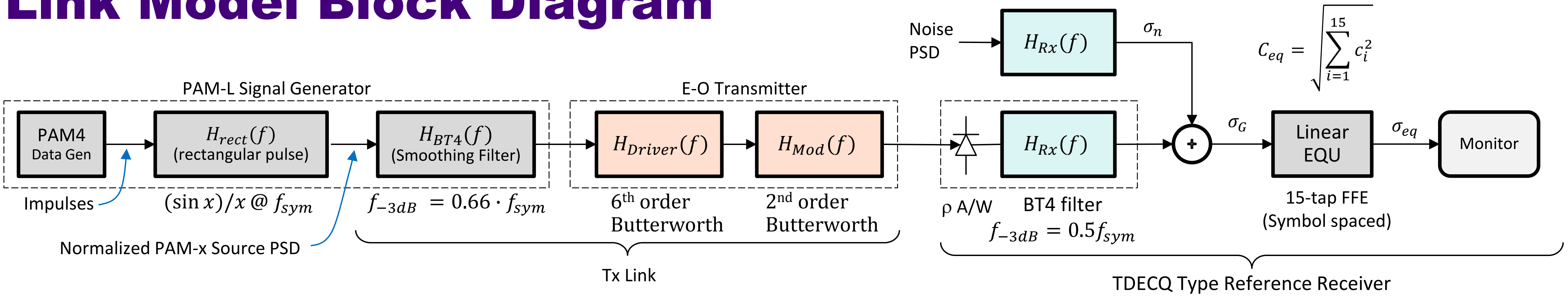
$$SER = \frac{5}{3} \cdot Q\left(\sqrt{\frac{3 \cdot SNR}{35}}\right) = \frac{5}{3} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 5 \cdot i_{rms}}\right)$$

PAM8:

$$SER = \frac{7}{4} \cdot Q\left(\sqrt{\frac{SNR}{21}}\right) = \frac{7}{4} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 7 \cdot i_{rms}}\right)$$

- Noise environment is Thermal + Shot AWGN (RIN not included)
- Noise BW = $f_{sym}/2$.
- Note: signal extinction ratio (ER) has impact on shot noise
- Link bandwidth limitations will enhance the noise requiring higher OMA for same SER

Link Model Block Diagram



- Transmit Link
  - Rectangular pulses are shaped with BT4 filter having max flat delay response up to the symbol rate (f_{sym})
  - Driver & Modulator modeled as 6th order & 2nd order Butterworth filters
- Reference receiver: TDECQ type receive structure
  - BT4 front-end noise limiting filter with $f_{-3dB} = f_{sym}$
  - 15-tap symbol space linear equalizer
- For each Driver & Modulator BW, measure equalizer MSE (σ_{eq}^2) and report corresponding noise enhancement (σ_{eq}/σ_n), where σ_n is the band limited noise at the receiver input

$$\text{Rx Noise Enhancement} = NE_{rx} \triangleq \frac{\sigma_{eq}}{\sigma_n}$$

$\sigma_n =$ Bandlimited noise at receiver input

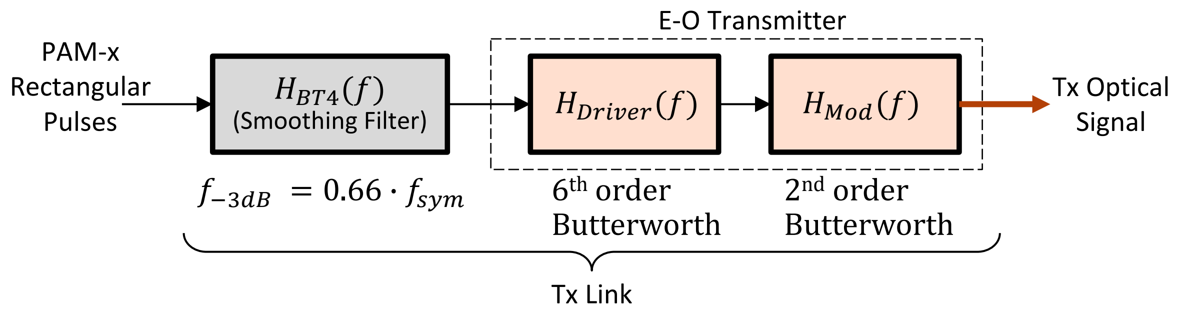
Noise BW $= f_{sym}/2$

$\sigma_{eq}^2 = MSE$ at the equalizer output

$$SNR = \frac{L^2 - 1}{3} \cdot \frac{1}{MSE} \quad \text{where } L = \{4, 6, 8\}$$

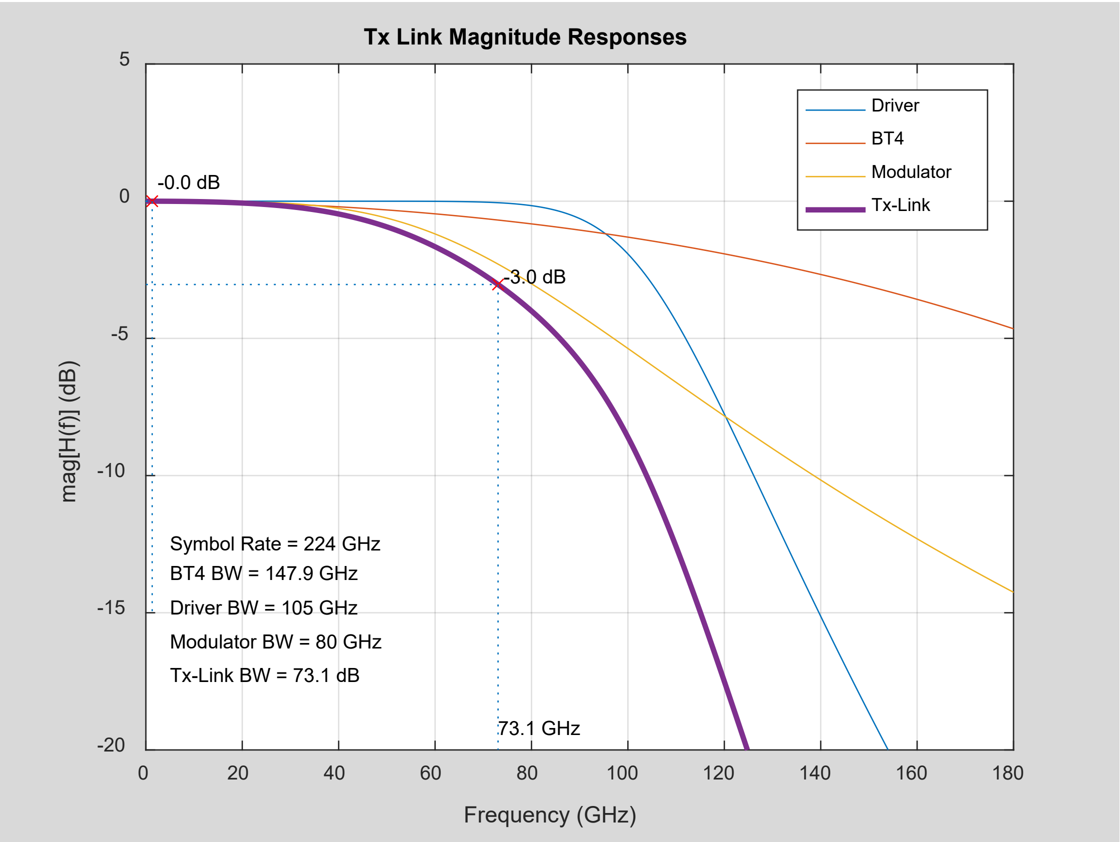
$$P_e = SER = 2 \cdot \frac{L-1}{L} \cdot \mathrm{Q}\left(\sqrt{\frac{3}{L^2 - 1} \cdot SNR}\right)$$

Transmit Link Definition



- Tx Link = BT4 + Driver + Modulator
  - BT4 smoothing filter has BW = 0.66 * Symbol Rate
  - Driver: 6th Order Butterworth Filter
  - Modulator: 2nd order Butterworth Filter
- Test Procedure
  - Vary BWs of Driver and Modulator
  - Record Tx Link BW
  - Plot ref. receiver noise enhancement vs. Tx Link BW
- Note: receiver noise enhance is sensitive to the resultant roll-off shape of the Tx link

Example for 448 Gb/s PAM4:
Driver BW = 105 GHz, Modulator BW = 80 GHz



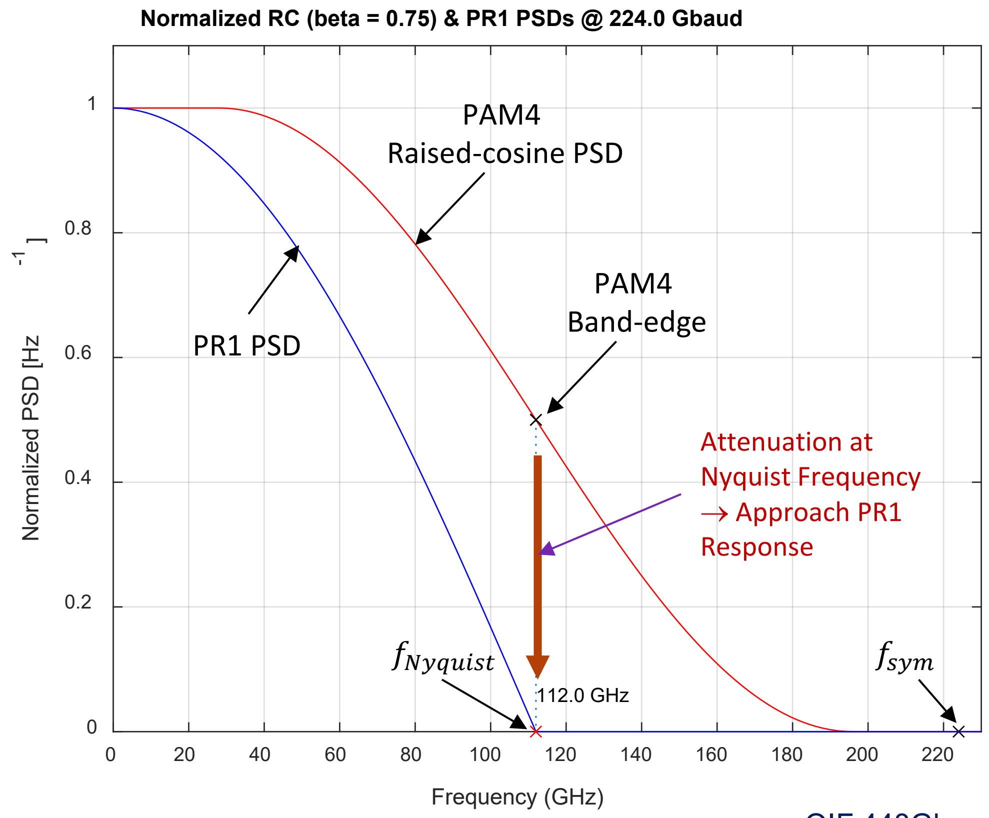
Symbol Rates & Corresponding Line Codes at 448 Gb/s

PAM4		
Bit rate =	448.0	Gb/s
bits/sym =	2.0	bit/sym
f_sym =	224.0	Gbaud
f_Nyquist =	112.0	GHz

PAM6		
Bit rate =	448.0	Gb/s
bits/sym =	2.5	bits/sym
f_sym =	179.2	Gbaud
f_Nyquist =	89.6	GHz

PAM8		
Bit rate =	448.0	Gb/s
bits/sym =	3.0	bit/sym
f_sym =	149.3	Gbaud
f_Nyquist =	74.7	GHz

Link BW impacts the received PSD and corresponding detection method in receiver



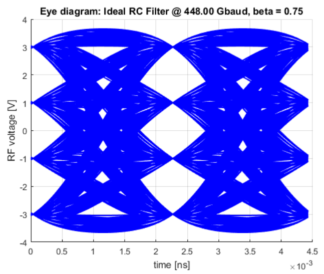
PAM-L PSD Characteristics:

- Symbol rate: $f_{sym} = f_{bit}/(\#\text{bits per symbol})$
- Band-edge (Nyquist) frequency: $f_{Nyquist} = \frac{f_{sym}}{2}$
- PSD energy = 0 at f_{sym}

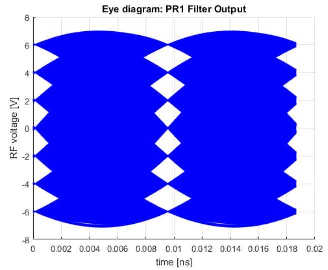
Partial-response PSD

- Zero energy at Nyquist
- Two adjacent PAM-L symbols interfere (controlled ISI)
- Maximum likelihood sequence detection (MLSD) required in receiver in addition to equalization

PAM4 Eye



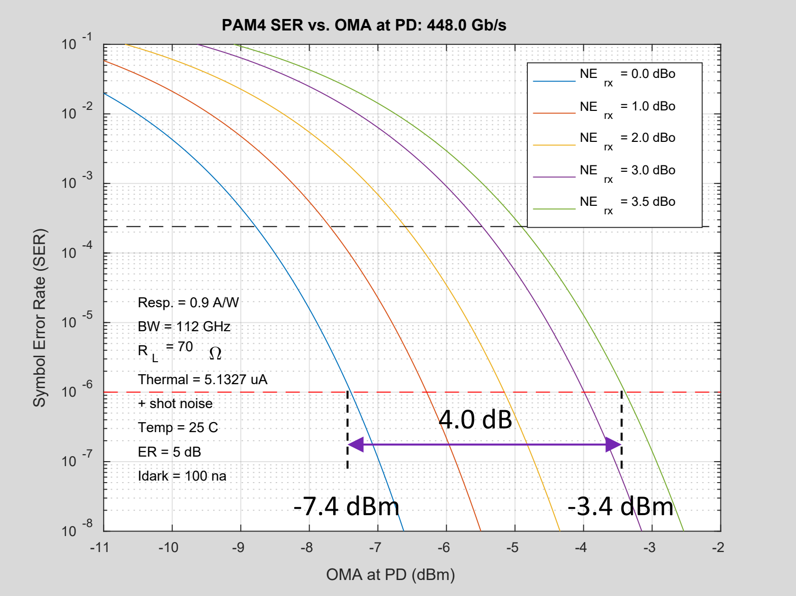
PAM4 → PR1 Eye

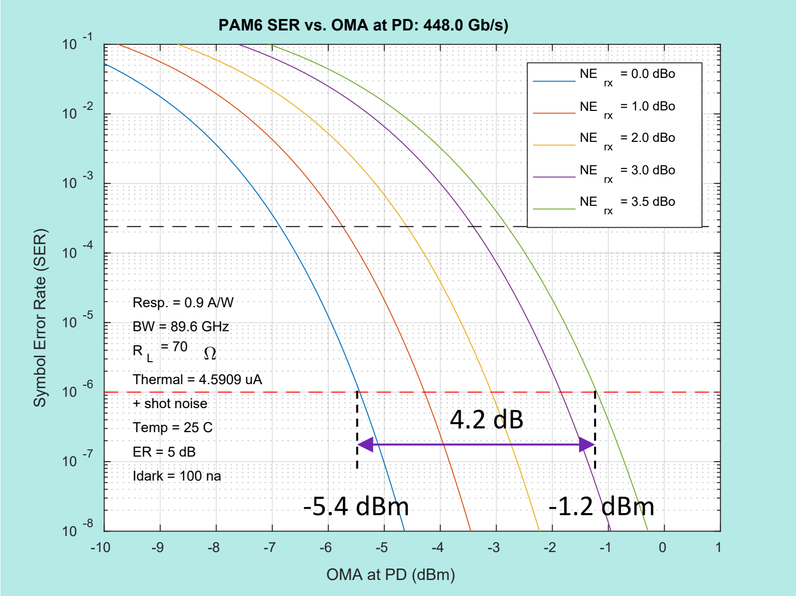


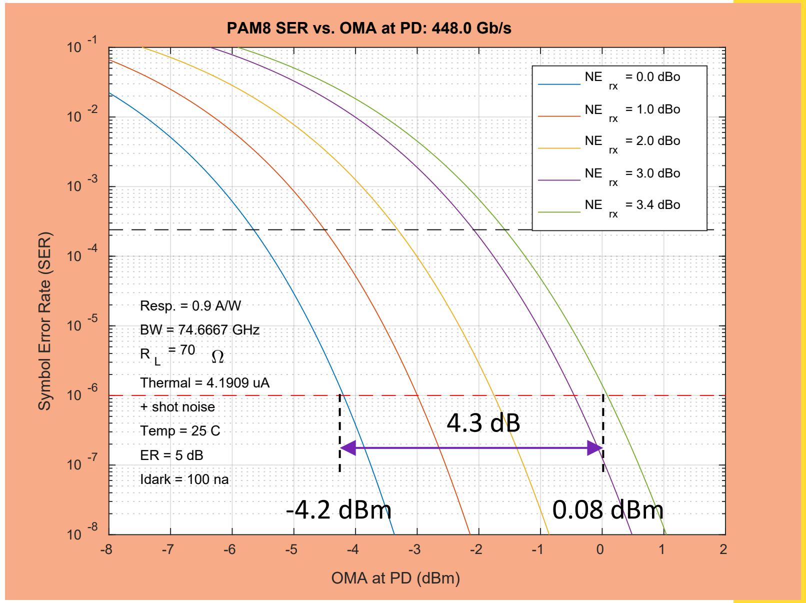
Total link BW impacts received PSD energy at $f \geq f_{Nyquist}$ and corresponding detection type:

- Direct PAM-L: PSD energy at $f > f_{Nyquist}$
- Partial-response: or no
  - (1+αD) MLSD: minimal energy $f > f_{Nyquist}$
  - (1+D) MLSD: no energy at $f \geq f_{Nyquist}$

Impact of Receiver Noise Enhancement on SER vs OMA







PAM4:

$$SER = \frac{3}{2} \cdot Q\left(\sqrt{\frac{SNR}{5}}\right) = \frac{3}{2} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 3 \cdot i_{rms} \cdot NE_{rx}}\right)$$

PAM6:

$$SER = \frac{5}{3} \cdot Q\left(\sqrt{\frac{3 \cdot SNR}{35}}\right) = \frac{5}{3} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 5 \cdot i_{rms} \cdot NE_{rx}}\right)$$

PAM8:

$$SER = \frac{7}{4} \cdot Q\left(\sqrt{\frac{SNR}{21}}\right) = \frac{7}{4} \cdot Q\left(\frac{\rho \cdot OMA}{2 \cdot 7 \cdot i_{rms} \cdot NE_{rx}}\right)$$

OMA ranges for $SER \leq 10^{-6}$ and NE_{rx} in 0 to 3.5 dBo

- PAM4: -7.4 to -3.4 dBm
- PAM6: -5.4 to -1.2 dBm
- PAM8: -4.2 to +0.1 dBm

OMA penalties w.r.t. PAM4 for $SER \leq 10^{-6}$ and NE_{rx} in 0 to 3.5 dBo range

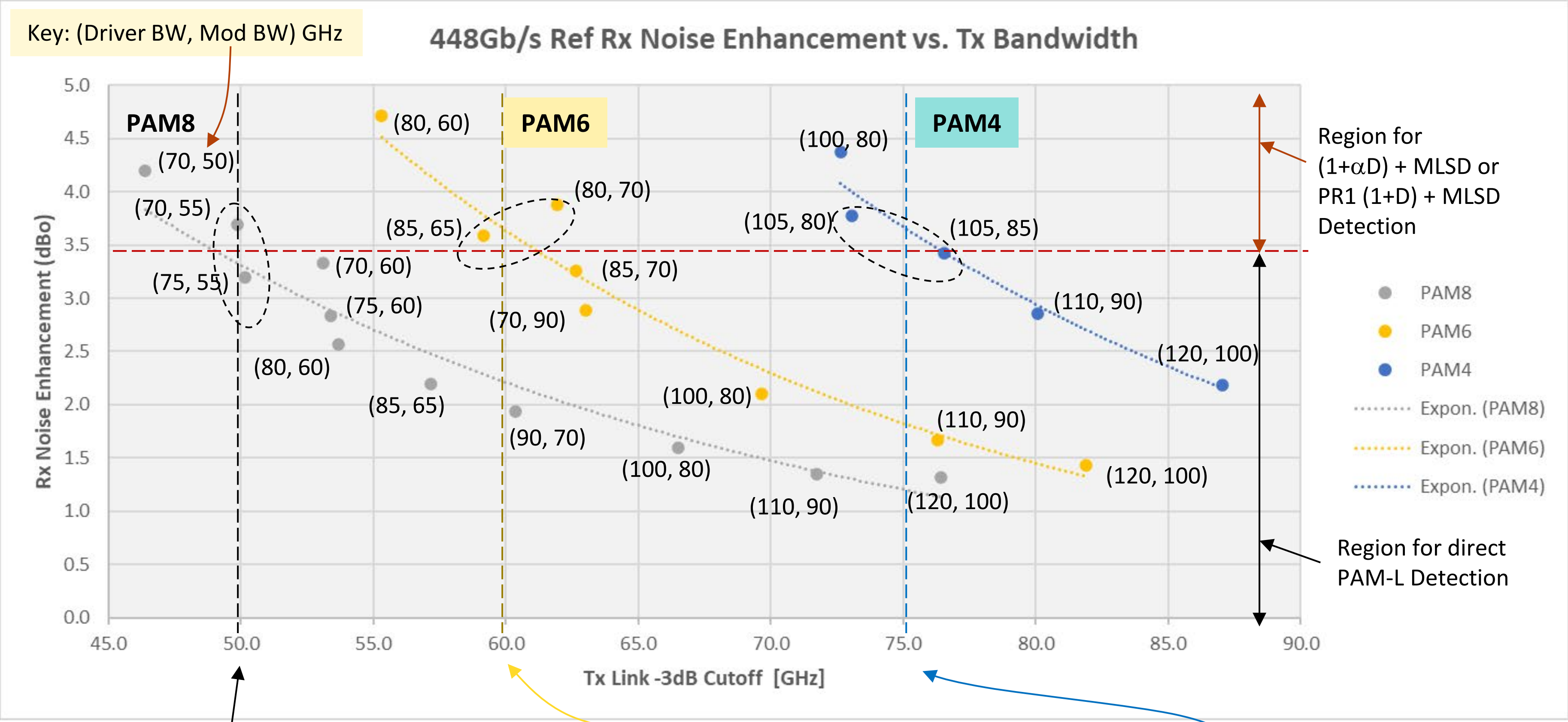
- PAM4: ---
- PAM6: ≈ 2.0 dB
- PAM8: ≈ 3.2 dB

Link Modulation Loss (IL, ER) must be added to the OMA at PD to determine corresponding minimum required laser power.

AC Link Analysis Exercise:
For a given Tx Link Bandwidth (Driver and Modulator) determine the following:

- NE_{rx} in reference receiver for PAM4, PAM6, and PAM8
- Corresponding OMA at PD in reference noise environment for $SER \leq 10^{-6}$
- For reported NE_{rx}, extract OMA for target BER from above graphs
- See next slide for NE_{rx} vs. Tx-link BW

Rx Noise Enhancement vs. Tx Link Bandwidth

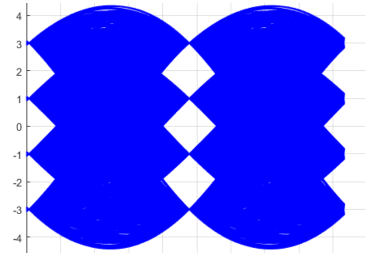


As Tx-Link full BW decreases → ($f_{sym}/2$),

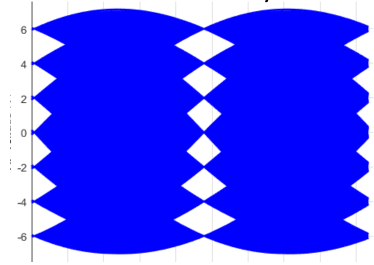
- Ref Rx NE_{rx} increases
- PAM4 eye approaches 7-level partial response class 1 (PR1) eye

- $NE_{rx} > 3.5$ dB will likely require advanced equalization, e.g.
  - ≥ 15-taps FFE
  - DFE
  - MLSE (1 + αD)

PAM4 Eye



PAM4→PR1 Eye



PAM8

fcLD_GHz	fcMZM_GHz	fcTx_GHz	NErx_dBo
75	55	50.2	3.2
70	55	49.9	3.7

PAM6

fcLD_GHz	fcMZM_GHz	fcTx_GHz	NErx_dBo
85	65	59.2	3.6
80	70	62.0	3.9

PAM4

fcLD_GHz	fcMZM_GHz	fcTx_GHz	NErx_dBo
105	85	76.6	3.4
105	80	73.1	3.8

Note: Tx Link BW includes $H_{BT4} * H_{driver} * H_{modulator}$

Tradeoff Summary: BW with OMA and Line Code

Driver BW =	105 GHz			
Mod. BW =	85 GHz			
Line Code	**OMA_pd (dBm)**	**NE_rx (dB)**	**SNRo (dB)**	**SER (dB)**
PAM4	-3.3	3.5	20.9	5.5E-07
PAM6	-3.3	1.8	24.4	1.1E-06
PAM8	-3.3	1.37	25.72	2.2E-05

Driver BW = 105 GHz, and Modulator BW = 85 GHz

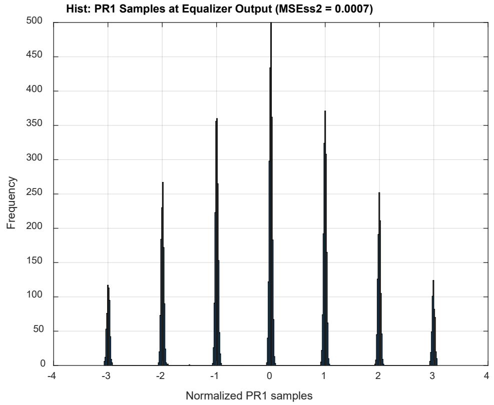
- Direct detect PAM4 has highest NE_{rx} but SER<10^-6 obtained w/ OMA = -3.3 dBm
- PAM6 and PAM8 each have lower NE_{rx} but higher OMA

Driver BW =	85 GHz			
Mod. BW =	70 GHz			
Line Code	**OMA_pd (dBm)**	**NE_rx (dB)**	**SNRo (dB)**	**SER (dB)**
PAM4	--	> 10	Closed Eye	
PAM6	-1.4	3.3	24.5	6.6E-07
PAM8	-1.4	2.1	27.3	3.7E-07

Driver BW = 85 GHz, and Modulator BW = 70 GHz

- PAM4 direct detect: Closed eye out of equalizer, requires either
  - $\rightarrow$ (1 + αD) detection plus MLSD, or
  - $\rightarrow$ (1 + D) PR1 detection plus MLSD
- PAM6 direct detect: SER < 1e-6 with OMA = -1.4 dBm
  - $\rightarrow$ can directly detect PAM6 w/o MLSD
  - $\rightarrow$ may include (1 + αD) + MLSD for lower BWs

Example
PAM4 w/ PR1 Detection
(Driver 85 GHz; Mod 70 GHz)



Driver BW =	70 GHz			
Mod. BW =	55 GHz			
Line Code	**OMA_pd (dBm)**	**NE_rx (dB)**	**SNRo (dB)**	**SER (dB)**
PAM4	--	> 10	Closed Eye	
PAM6	--	> 10	Closed Eye	
PAM8	1	3.8	27.5	2.3E-07

Driver BW = 70 GHz, and Modulator BW = 55 GHz

- PAM4 and PAM6 each have closed eyes at equalizer output
- May use PAM6 with partial response detection and MLSD
- PAM8 achieves SER < 1e-6 with OMA = 1.0 dBm

Industry View of Optical Modulators & Photodetectors

- 200GBaud transmission demonstrations are in early stages

- OFC 2025 reported wide range of optical modulators and GePD's:
  - Modulator reported bandwidths or symbol rates:
    - Silicon Modulators: 55 to 80 GHz (trade-offs of extinction ratios and modulation losses with bandwidth)
    - TFLN and III-V (e.g., InP, GaAs, etc.) Modulators (including EMLs): 67 to greater than 110 GHz bandwidths
    - Electro-Absorption Modulator with BWs > 67 GHz
    - Barium Titinate (BTO) or organic electro optic materials demonstrated 250 GBaud transmission
    - Plasmonics: 100GBaud NRZ
  - Photodetectors:
    - GePD with BWs from 60 GHz to 100+ GHz
    - APDs with BW > 45 GHz
    - Plasmonics / 2D materials (Graphene) with BW > 70 GHz (tradeoff of responsivity with bandwidth)
  - Numerous demonstrations of PAM4, PAM6, and PAM8

- Heterogeneous Integration on silicon photonics is required for 448 Gbps/λ for TROSA implementations
  - Electro-absorption Modulators EAM (QCSE for O-band)
  - Electro-absorption Modulated Laser (EML - InP)
  - Thin-film Lithium Niobate (TFLN)
  - Barium Titanate (BTO)

Silicon Processes for 448 Gb/s Optical Transmission

- Technology choices for TIA & Driver need to optimize bandwidth, gain, noise & voltage swing
- Options include Fully Depleted SOI, SiGe BiCMOS, and Integrated Silicon Photonics on SOI
- System integration can be done within module, 2.5D/3D hybrid packaging or all on chip

Technology	22FDSOI	9HP+	130CBIC	40nm SiGe**	HBT-3DI**	45SPCLO	CLO-HBT***
Technology Type	SOI	SiGe BiCMOS	SiGe BiCMOS	SiGe BiCMOS	SiGe Bipolar	SOI	SOI + SiGe
Transistor Type	nFET	npn	npn	npn	npn	nFET	npn
CMOS Node	22nm	90nm	130nm	45nm	NA	45nm	45nm
Ft	350 GHz	340 GHz	420 GHz	450 GHz	600 GHz	325 GHz	600 GHz
Supply V	0.8V	1.8V	1.8V	1.8V	1.8V	1.0V	1.8V
Integration	Flip Chip	Flip Chip	Flip Chip	Flip Chip	Wafer bond	Monolithic	Monolithic
Ext ESD Diode	Yes	Yes	Yes	Yes	Yes	No	No
Input Cap	70fF	70fF	70fF	70fF	25fF	10fF	10fF
1st Stage TIA BW*	85 GHz	88 GHz	98GHz	101GHz	195GHz	227 GHz	309 GHz

*Assumes Rt = 100 Ohms

$$BW \leq \sqrt{\frac{ft}{2\pi Rt Ct}}$$

**In Development ***In Planning

Summary

- For direct PAM4 detection at 448 Gbps/λ
  - The Tx-link bandwidth needs to be > 75 GHz assuming Rx front-end OE BW = ½*symbol rate = 112 GHz
  - DSP likely to need implementation of (1 + αD) detection with MLSD to accommodate link BW variations.
- For direct PAM6 detection at 448 Gbps/λ
  - The Tx-link bandwidth needs to be > 60 GHz assuming Rx front-end OE BW = ½*symbol rate = 89.6 GHz
  - DSP likely to need implementation of (1 + αD) detection with MLSD to accommodate link BW variations.
- Feasibility of Driver and TIA BWs > 100 GHz;
  - FETs with f_T > 325 GHz are available
  - HBT with f_T ~ 600GHz are expected
- Hybrid and monolithic TIA designs with target BW > 80 GHz
  - Capacitive loading for hybrid integration (bond wires, bumps) on input reduces BW performance
  - Monolithic SiPh process greatly reduces capacitive loading on 1st stage of TIA increasing the 1st stage BW
  - Additional monolithic gain stages reduce overall BW to approximately 1.2x that of hybrid topologies
- Photonic Modulators (e.g. MZM, MRM, RAMZI, etc.) with BW > 65 GHz are feasible
  - Alternative modulation options should be further explored (EAM, SISCAP, etc)
  - Hybrid/Heterogeneous Integration: TFLN, BTO, InP
  - Organic (polymer) materials, Plasmonics (e.g., Cu), and 2D materials (e.g. Graphene)
- Photonic GePD with BW > 75 GHz have been demonstrated with monolithic photonic processes
- Reasonable 200+ Gbaud system performance is within the reach of present SiGe and Silicon Photonics Technologies

References

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