Investigation of 100GbE Based on PAM-4 and PAM-8

IEEE 802.3bm Task Force

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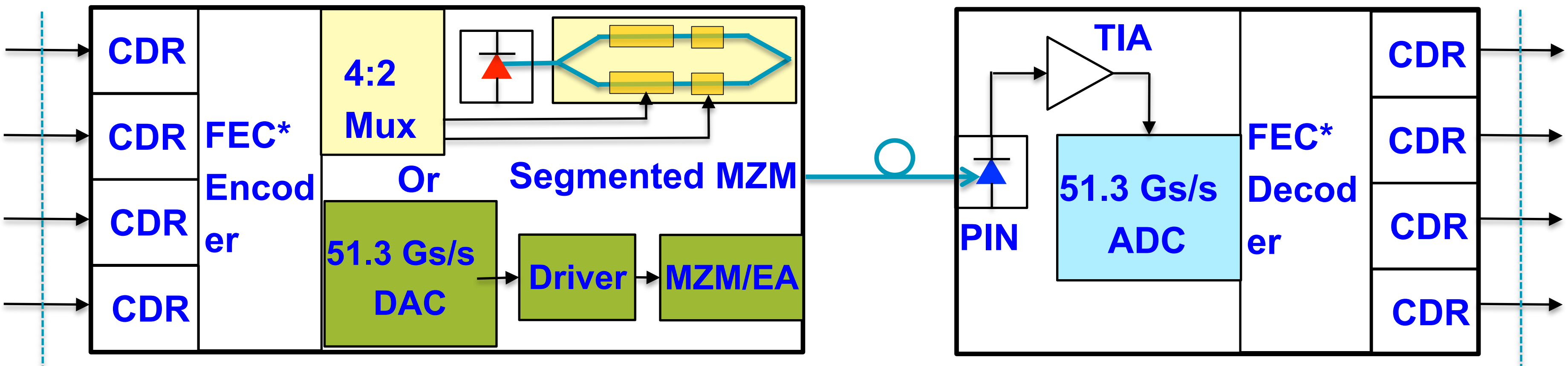
Agenda

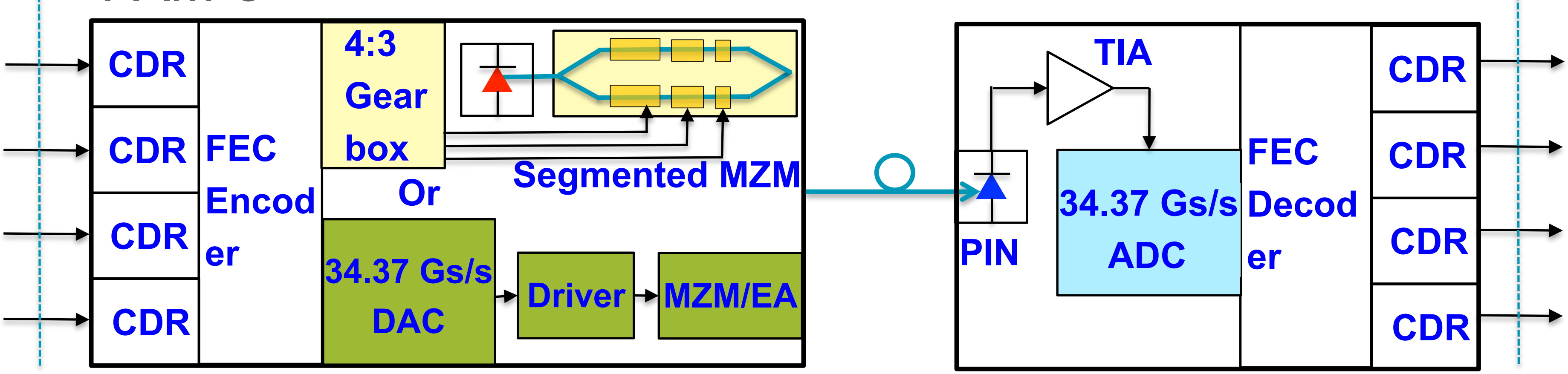
- System Overview
- Electronics Front End
  - Retimer and FEC
- Electro-Optical Subsystems
  - PAM-N Transmitter/DAC
  - PAM-N Receiver
- Optical Link Budgets Implications
  - PAM-4 operate with more relax link parameters (lower RIN and less power) but require faster electronics but less ENOB, and BJ FEC likely sufficient
  - PAM-8 link must operate with very strengthen link parameters (higher RIN and and more power) but require more moderate speed electronics but with higher ENOB, and would require stronger FEC than BJ FEC
- Electronics Back End
- ADC/Decoder

PAM-4 vs PAM-8 Implementation

- PAM-4



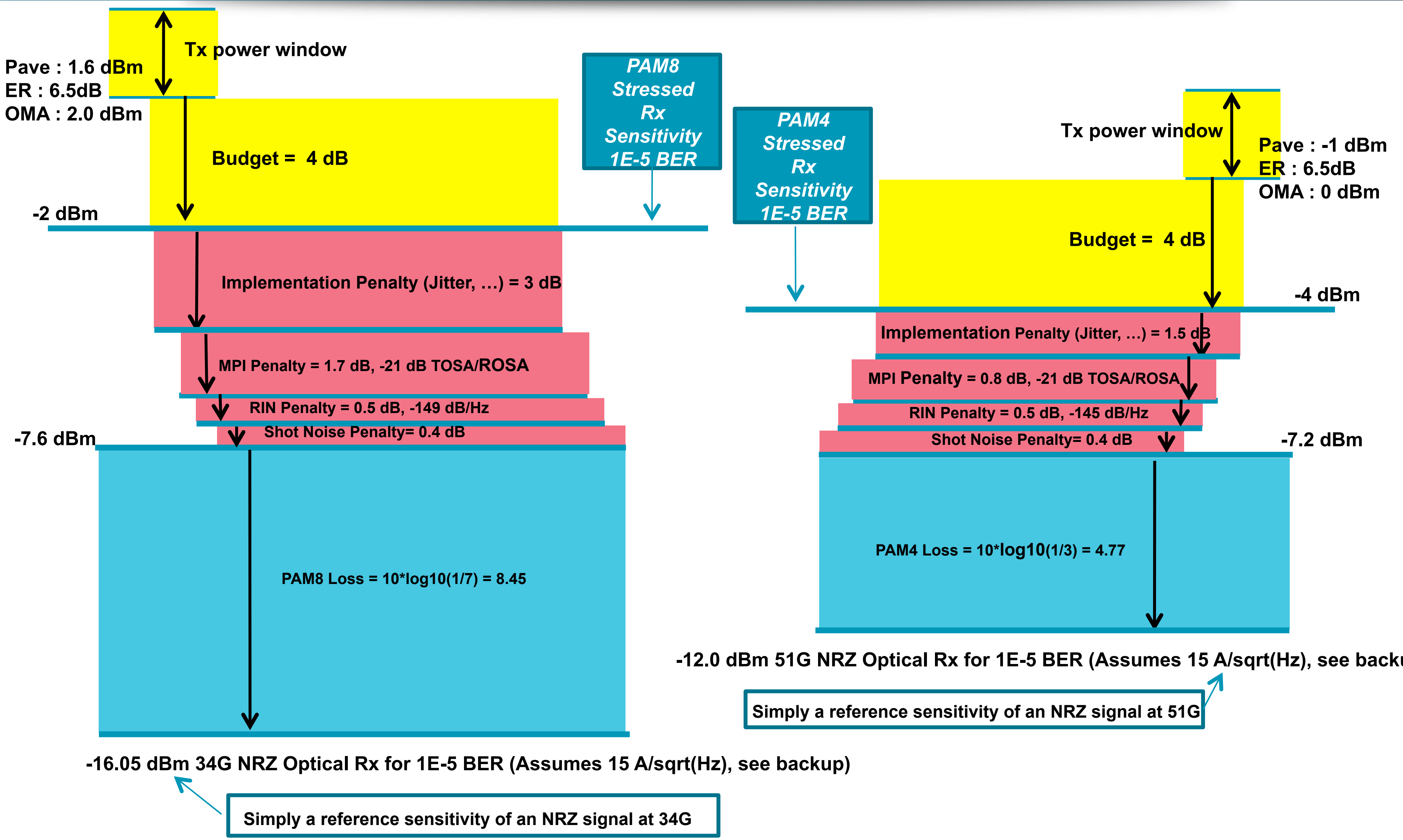
- PAM-8



CAUI-4 **CAUI-4**

* BJ FEC maybe sufficient for PAM-4

PAM-8 vs PAM-4 Link Budget



PAM-N Electro-Optical Subsystems

Transmitters

- PAM8 and PAM4 transmitters @ 34.375G and 51.5625G
  - Three and Two segment electro-optical DACs
- Segmented Mach Zender Interferometer type
  - CMOS Inverter diode drive Mild inductive pre-emphasis
  - High Bandwidth MZI
    - PN BW > 100 GHz
- 40 nm CMOS

Receivers

- PAM8 and PAM4 receivers @ 34.375G and 51.5625G
  - Linear front end to drive electrical ADC
  - Mild linear equalization
- Integrated Photodetector
  - Germanium on waveguide
  - 3dB BW ~ 50 GHz
- Receiver BW (TIA+PD)
  - PAM8 ~ 22 GHz
  - PAM4 ~ 26 GHz
- 40 nm CMOS

PAM-N Electro-Optical Subsystems

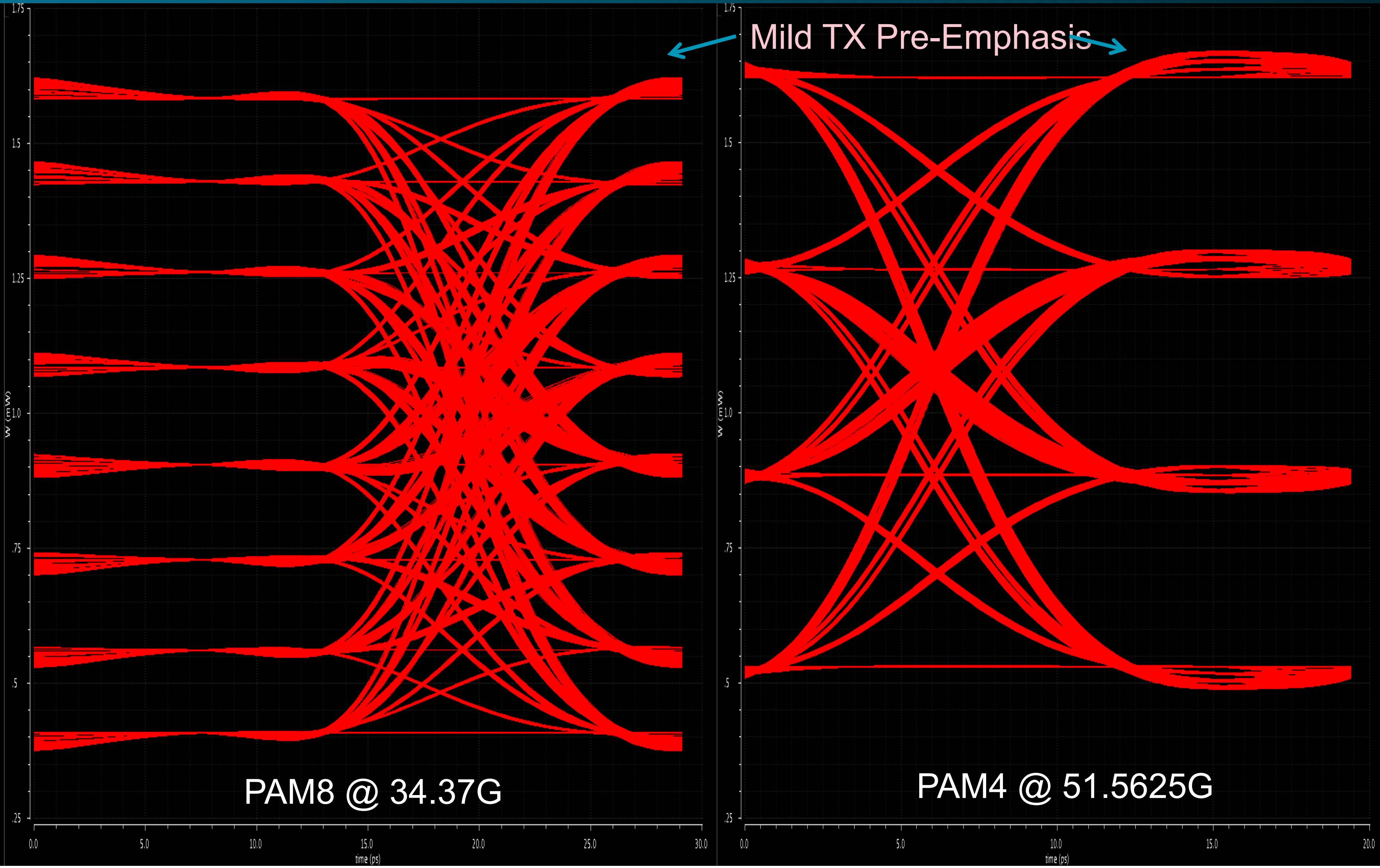
Conditions

- Electro-Optical Link Deterministic Simulations
  - Captures deterministic performance only, not Gaussian noise effects
  - Excludes source jitter
    - Assumes ideal input NRZ streams
  - Excludes laser RIN

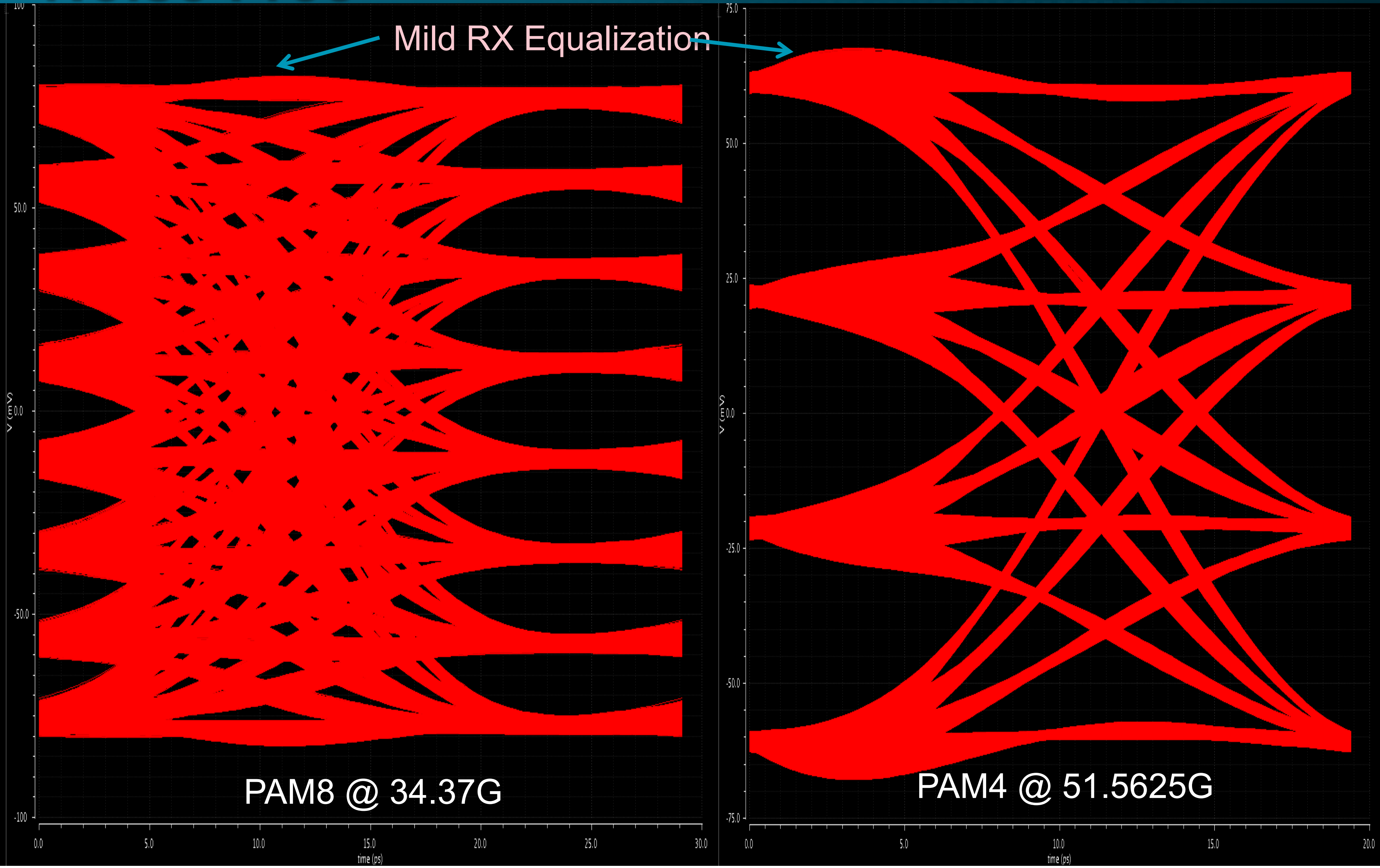
Results

1. Transmitter Performance
2. Receiver Performance I
   - Driven by optical transmitter
   - Noiseless
3. Receiver Performance II
   - Driven by optical transmitter
   - PD and TIA noise
   - No laser RIN

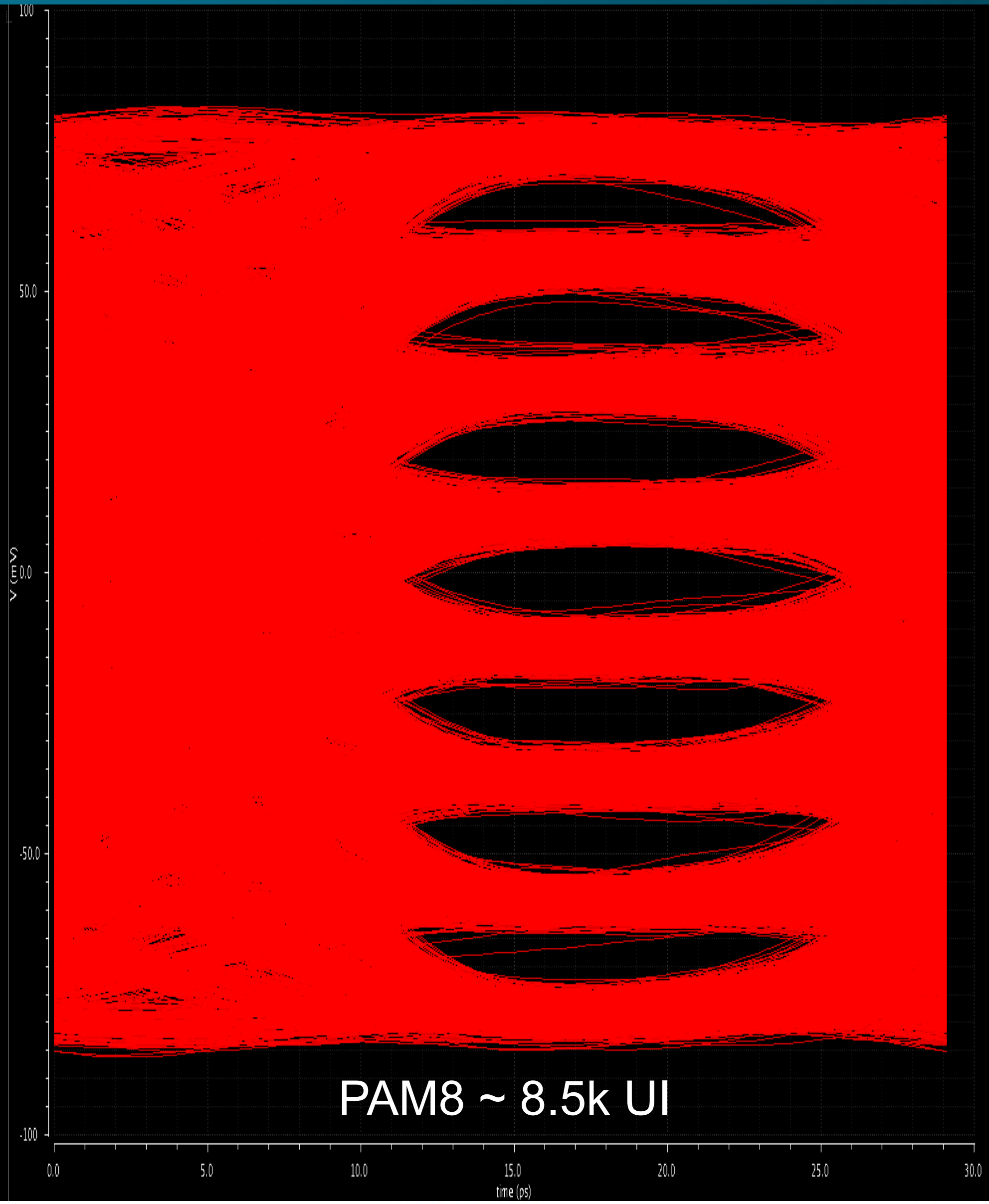
Actual Circuit Simulation of the Transmitter

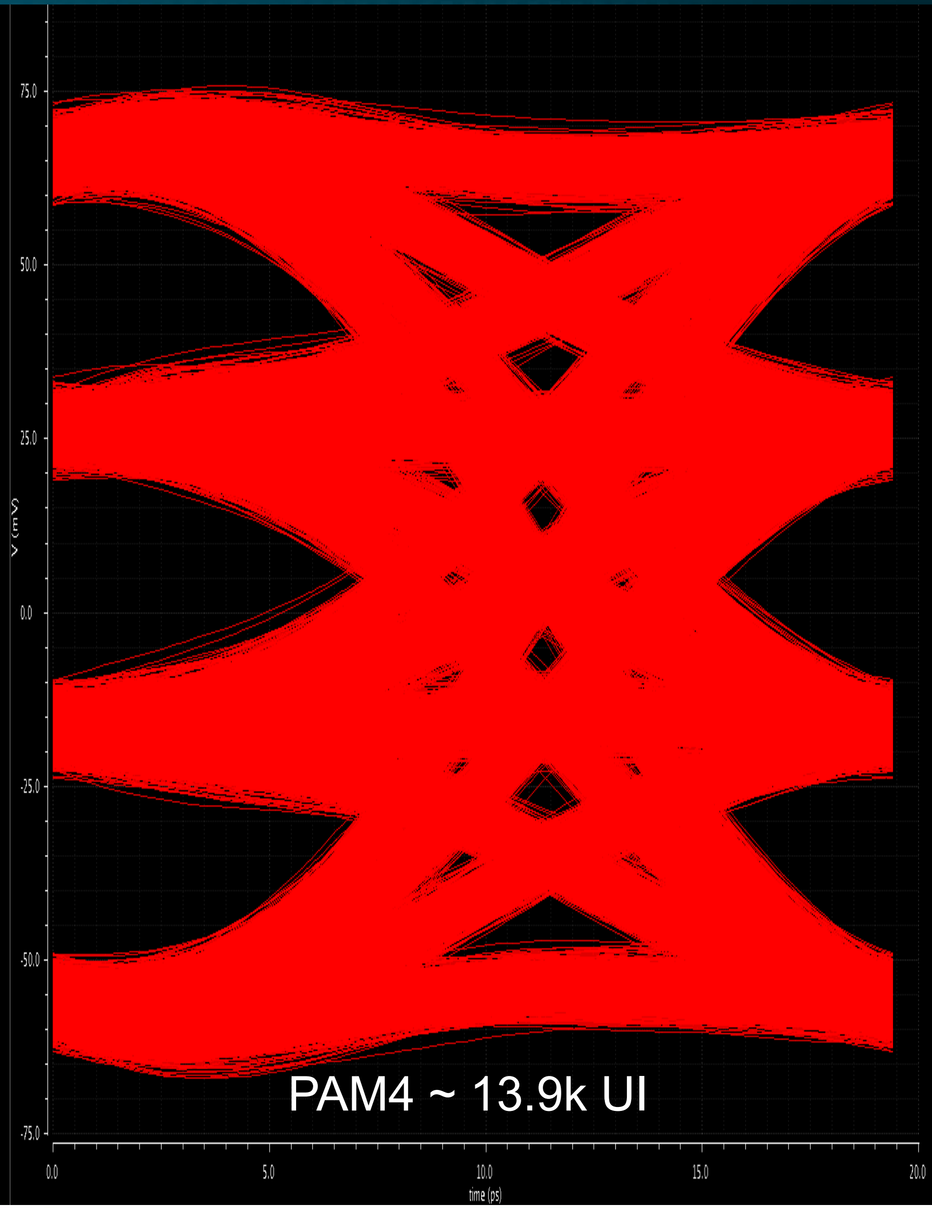


Actual Receiver Circuit Performance I – Noise Free



Actual Receiver Receiver Performance II – With Noise





PAM-N Link Penalties

PAM 8

- Vertical Eye Closure ~ 8.8 dB
  - PAM8 Loss = 8.4 dB
  - Linearity Penalty ~ 0.4 dB
- Horizontal Eye Closure
  - Noise Less ~ 0.47 UI
  - With Noise ~ 0.56 UI

PAM 4

- Vertical Eye Closure ~ 4.87 dB
  - PAM8 Loss = 4.77 dB
  - Linearity Penalty ~ 0.1 dB
- Horizontal Eye Closure
  - Noise Less ~ 0.36 UI
  - With Noise ~ 0.46 UI

Jitter Budget

PAM8

Module CDR
DJ = 2 ps
RJ (RMS) = 0.1 ps

Optical TX
DJ = 8.5 ps
RJ (RMS) = 0.1 ps

Optical RX
DJ = 5.17 ps
RJ (RMS) = 0.31 ps

ADC Input
DJ-Out = 15.67 ps
RJ (RMS) = 0.34 ps
TJ (BER5) = 18.58 ps

PAM4

Module CDR
DJ = 1.5 ps
RJ (RMS) = 0.1 ps

Optical TX
DJ = 5.0 ps
RJ (RMS) = 0.03 ps

Optical RX
DJ = 1.98 ps
RJ (RMS) = 0.21 ps

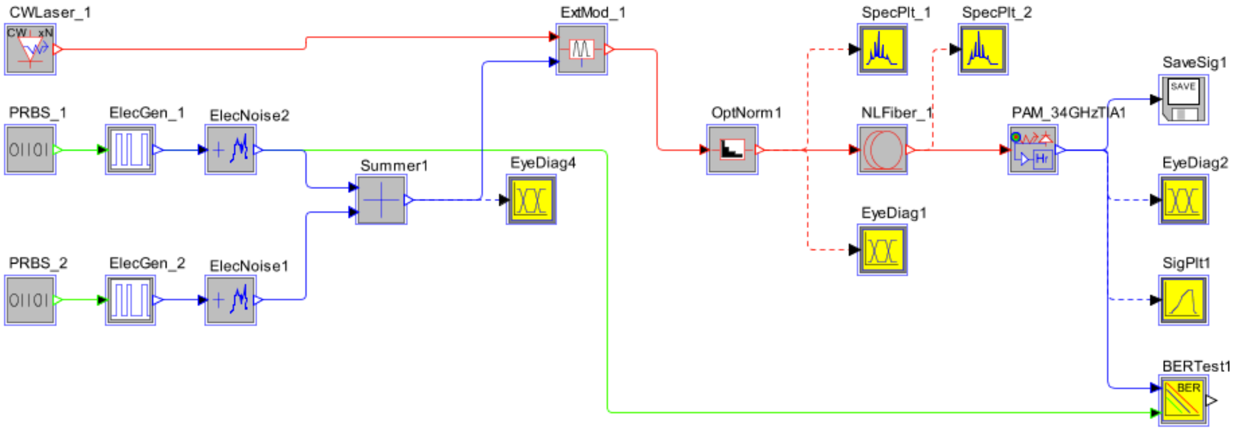
ADC Input
DJ-Out = 8.48 ps
RJ (RMS) = 0.26 ps
TJ (BER5) = 10.48 ps

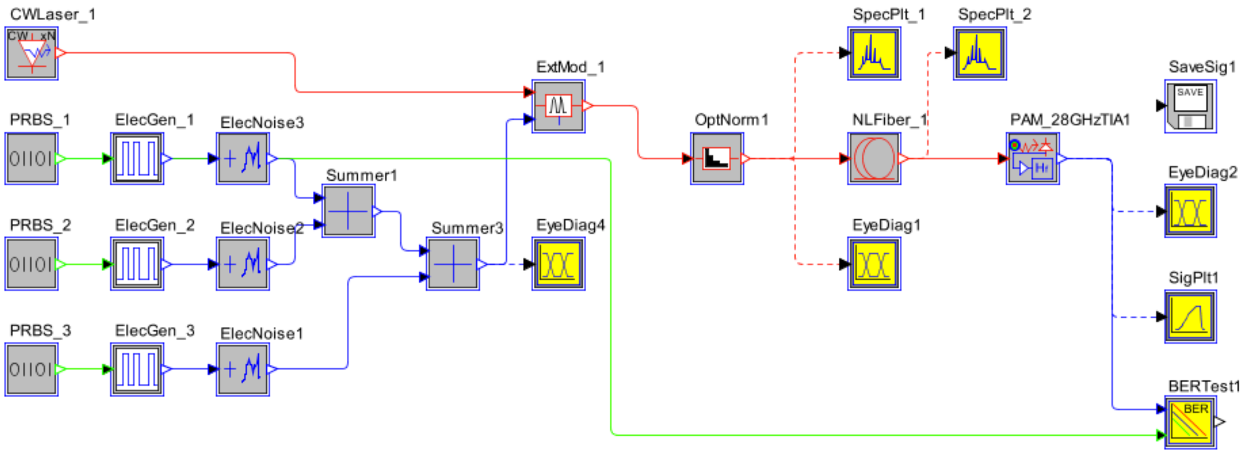
Basic Simulation Assumptions

- Modulator is MZ type
  - In case of PAM-8, 3 input signals with amplitude 1/7, 2/7, and 4/7 are linearly summed into MZ modulator
  - In case of PAM-4, 2 input signals with amplitude 1/3, 2/3 are linearly summed into MZ modulator
- Modulator Type MZ RC BW of 34 GHz zero chirp for both PAM-4 and PAM-8
  - Input electrical signal $V\pi/2$ to limit the compression
- RIN=-149 dBm/Hz for PAM-8 and -145 for PAM-4
- TX Wavelength=1280 nm and linewidth 100 MHz
- TX DJ = 2 ps for PAM-8 and 1.5 ps for PAM-4
- TX Output Power = - 2 dBm OMA for PAM-8 and -4 dBm for PAM-4
- Optical transmitter 20-80% rise/fall 12 ps for PAM-8 and 8 ps for PAM-4
- Data pattern=PN12
- Extinction Ratio= 6.5 dB
- Receiver BW=28 for PAM-8 and 34 GHz for PAM-4
- Receiver sensitivity PAM-8 -16 dBm OMA at 1e-5 and PAM-4 -12 dBm OMA at 1e-5

Block Diagram of PAM-4 and PAM-8

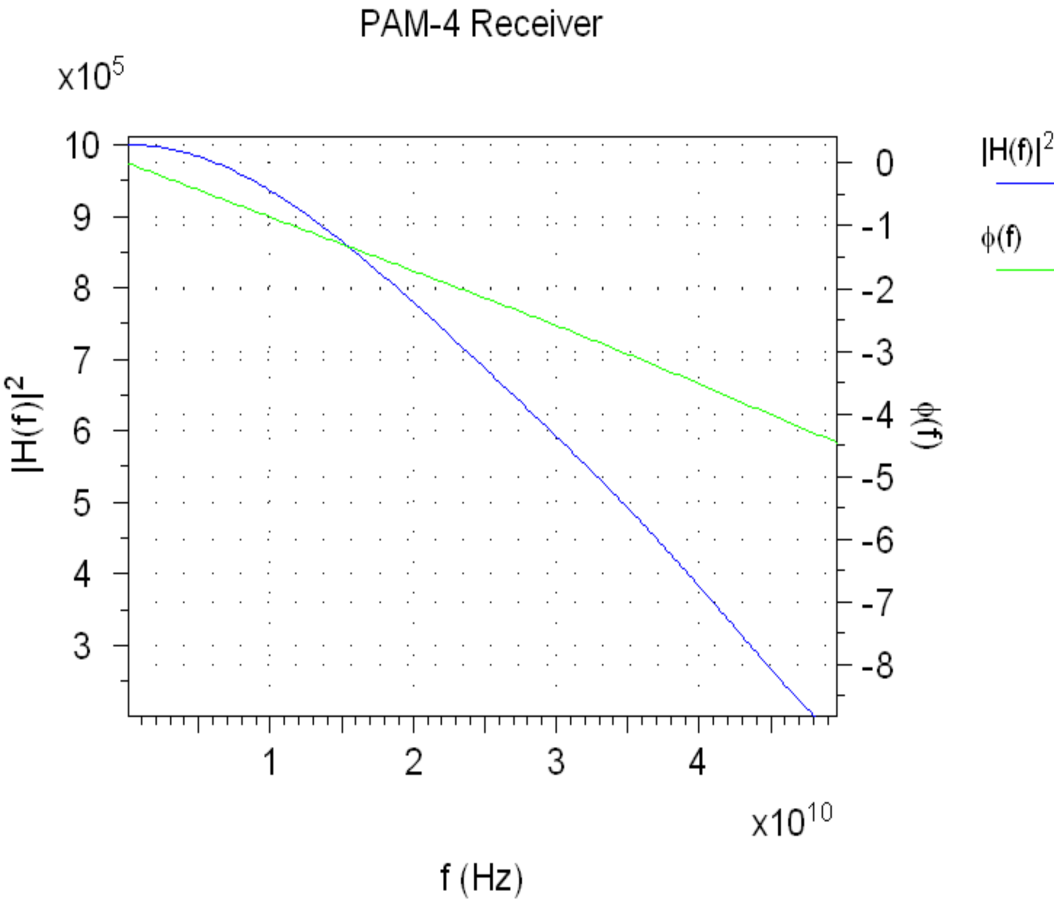
- Rsoft Schematic

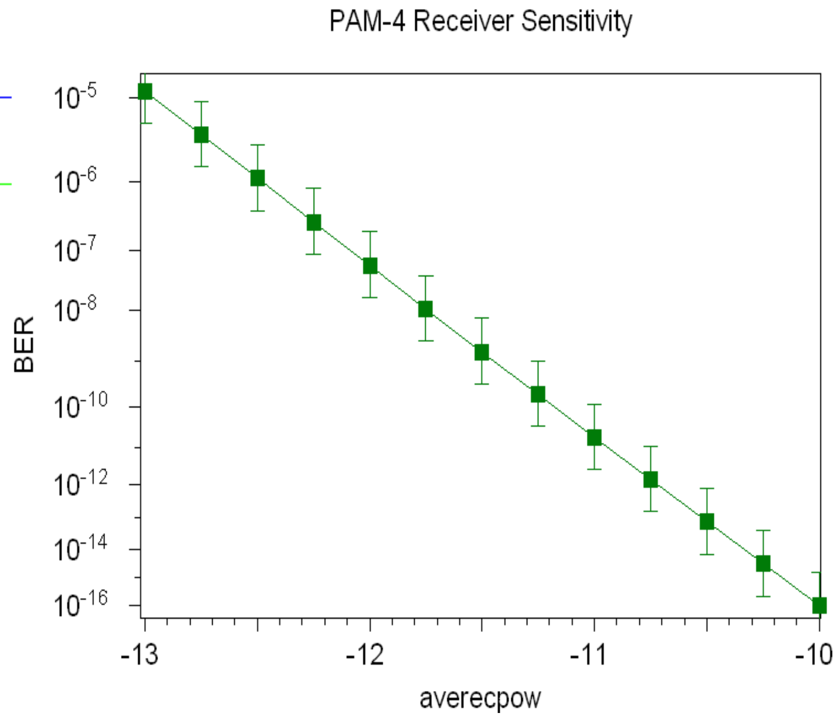




PAM-4 Optical Receiver Response

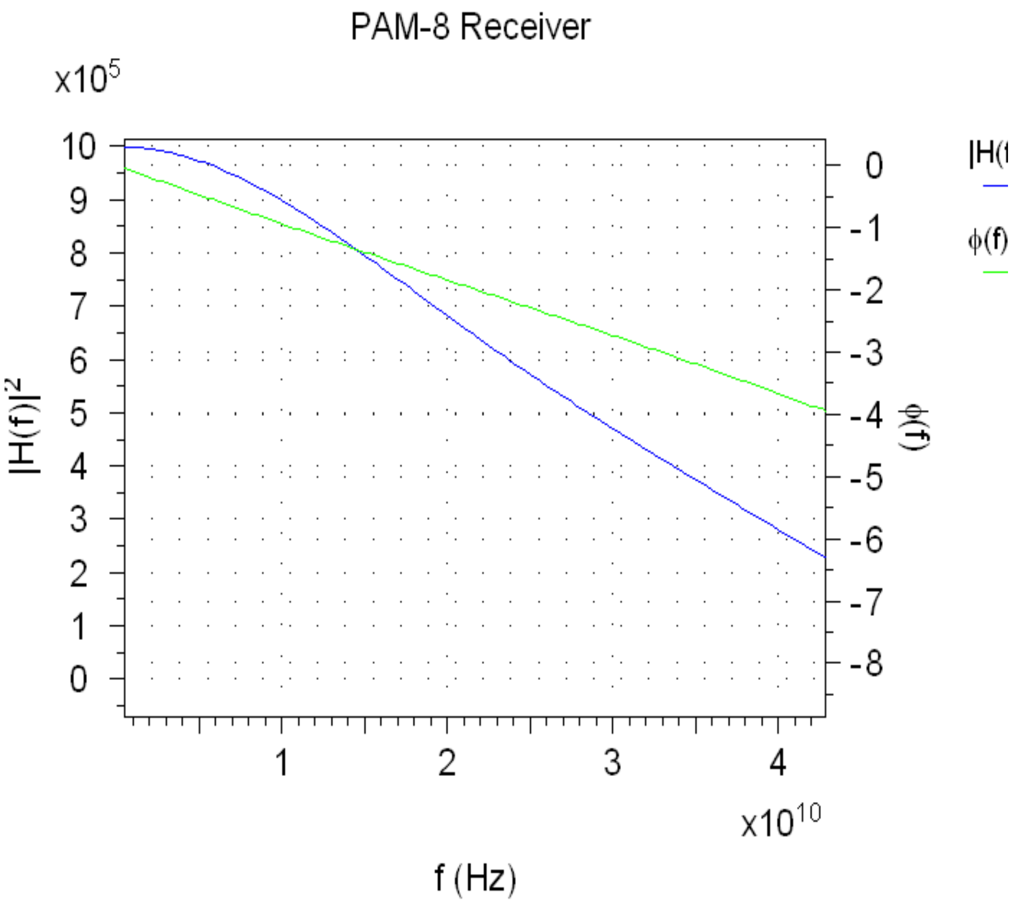
- Response of a realistic PD+TZ AMP with 34 GHz BW and sensitivity of 1e-5 at -13 dBm AOP or -12 dBm OMA at ER=6.5 dB

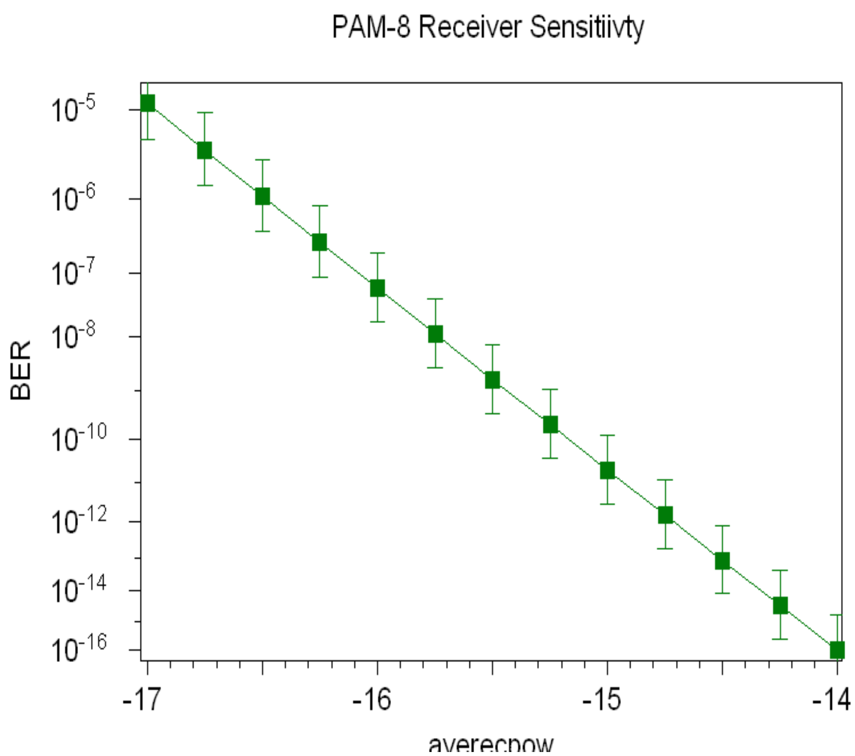




PAM-8 Optical Receiver Response

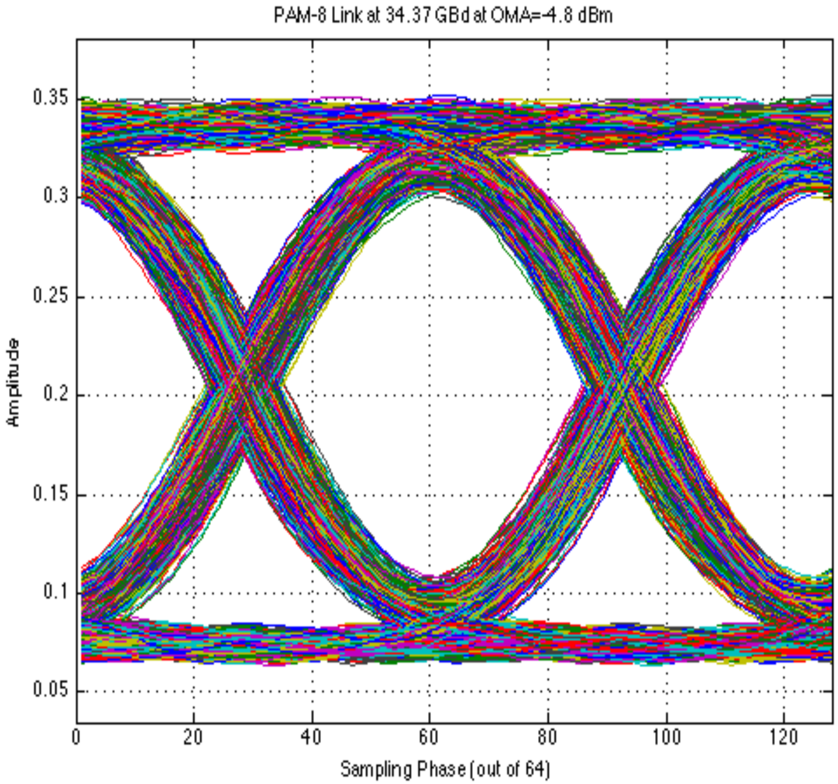
- Response of a realistic PD+TZ AMP with 28GHz BW and sensitivity of 1e-5 at -17 dBm AOP or -16 dBm OMA at ER=6.5 dB

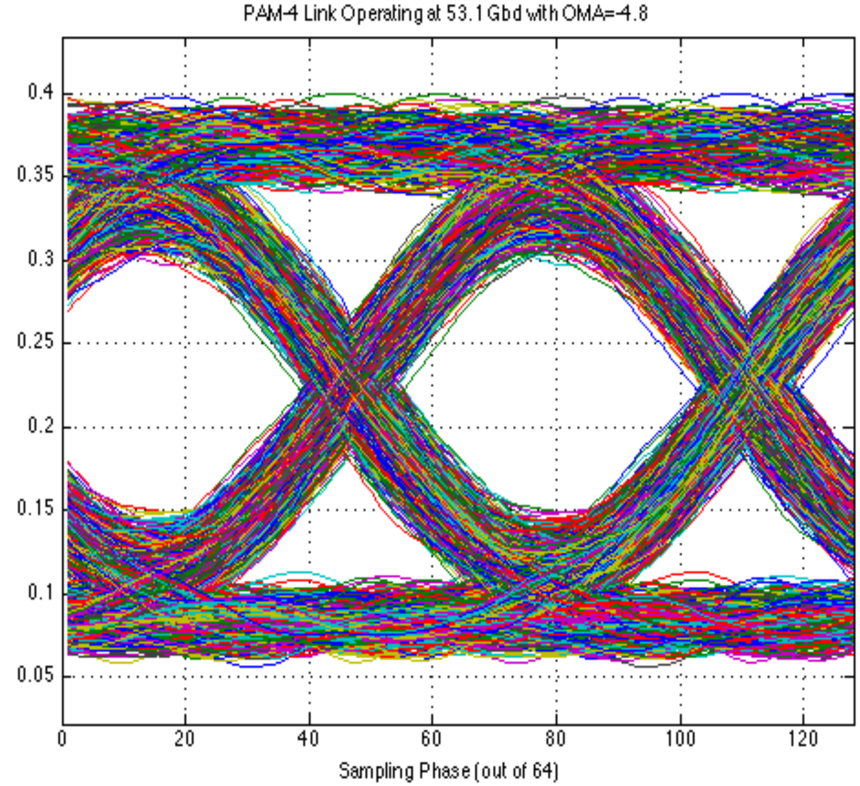




Optical Transmitter PAM-2 Response

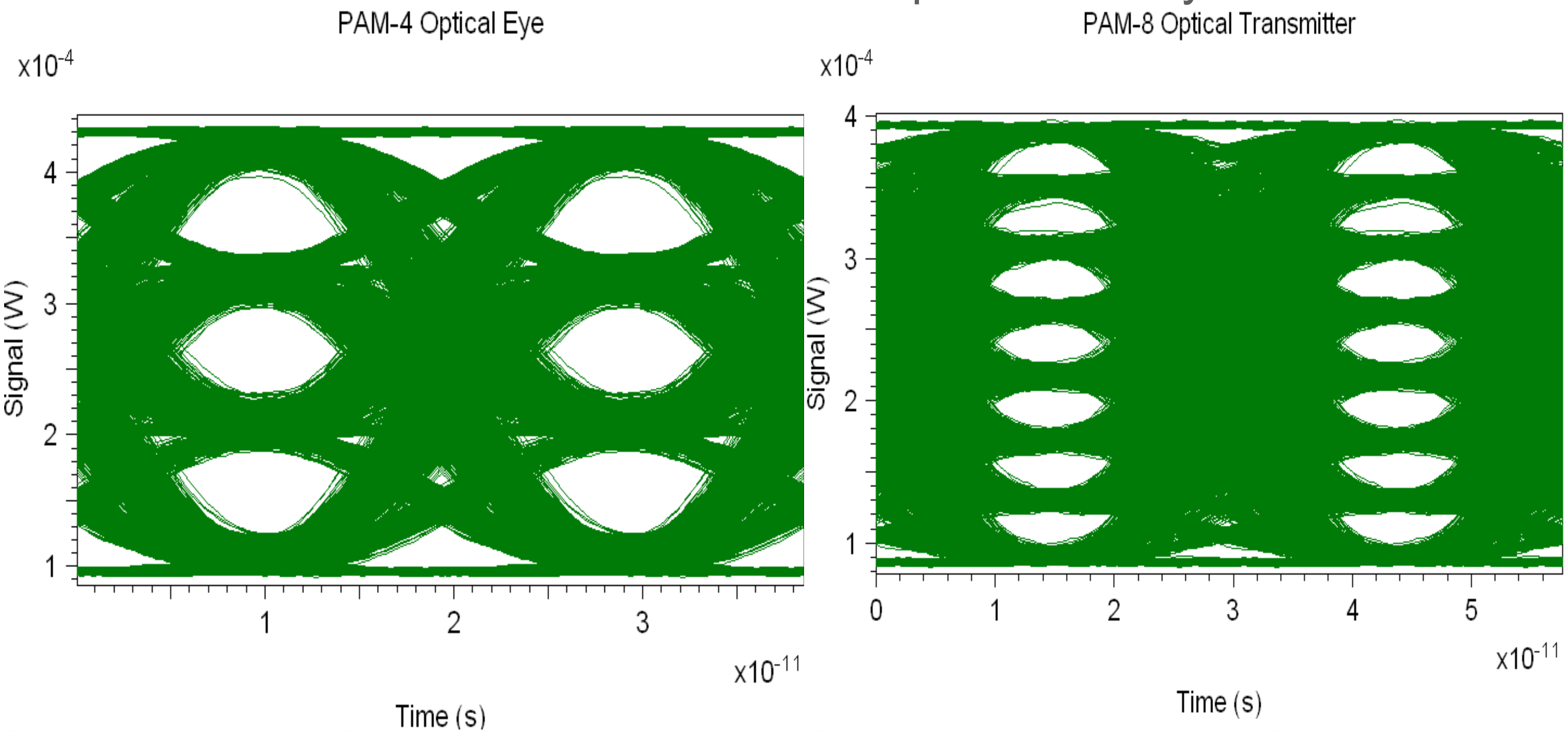
- At 34.37GBd and 51.5625 GBd
  - The components are limiting the 51.56 GBd operation but still PAM-4 link perform better than PAM-8





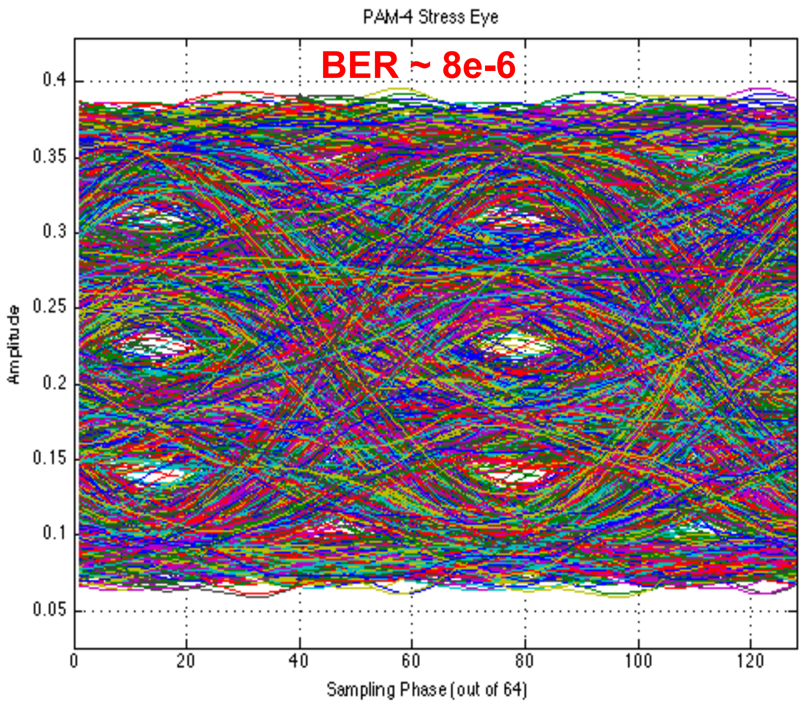
PAM-4 and PAM-8 Transmit Optical Eye

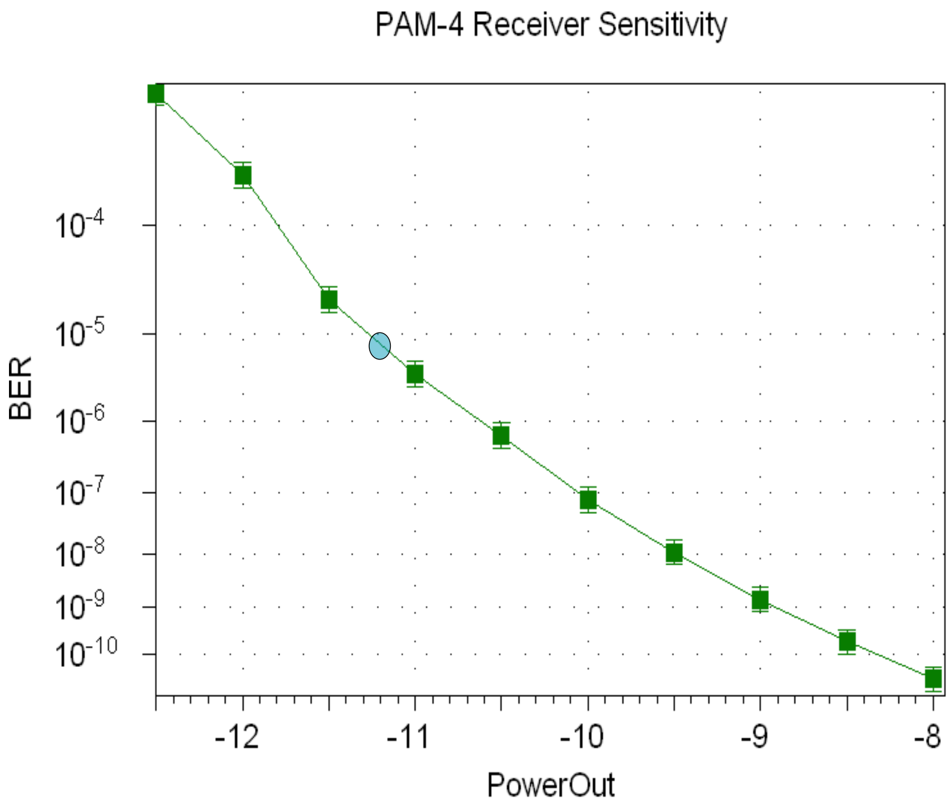
- PAM-4 Tr=8 ps, σ=0.14 ps, PJ=1.5 ps
- PAM-8 Tr=12 ps, σ=0.1 ps, PJ=2 ps
- Segmented balance modulator will improve both eyes



PAM-4 Receiver

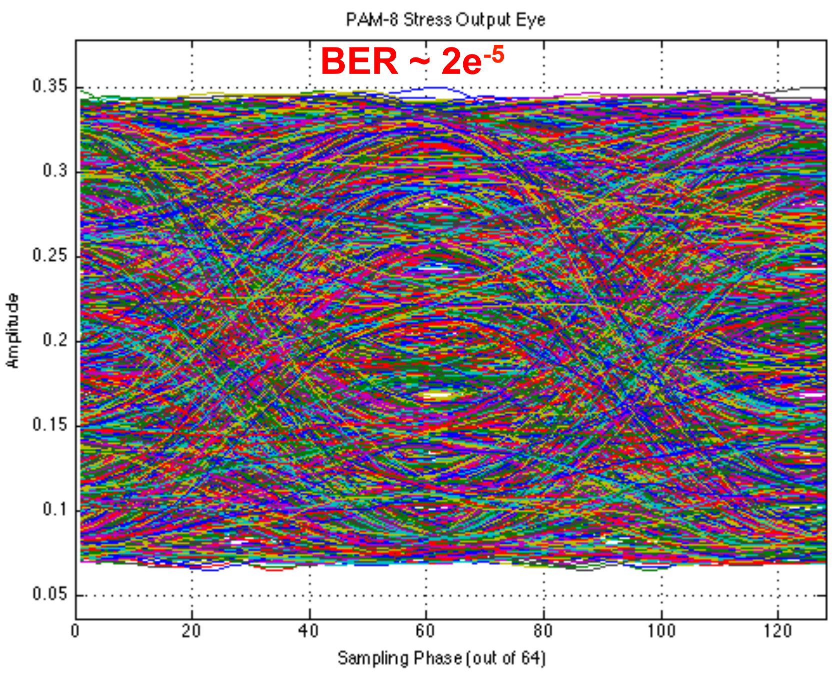
- PAM-4 eye Diagram at OMA=-4.7 dBm and link sensitivity for PAM-2
  - PAM-8 sensitivity subtract 0.8 dB for MPI and ~ 0.4 dB for other penalty sensitivity at AOP=-11.8 dBm (at ER=6.5 OMA=AOP-1)
  - Estimated BER is 8e-6 but actual BER may be worse due to non-linear distortion and jitter interaction
  - The link does have some modest amount of ISI that can be equalized

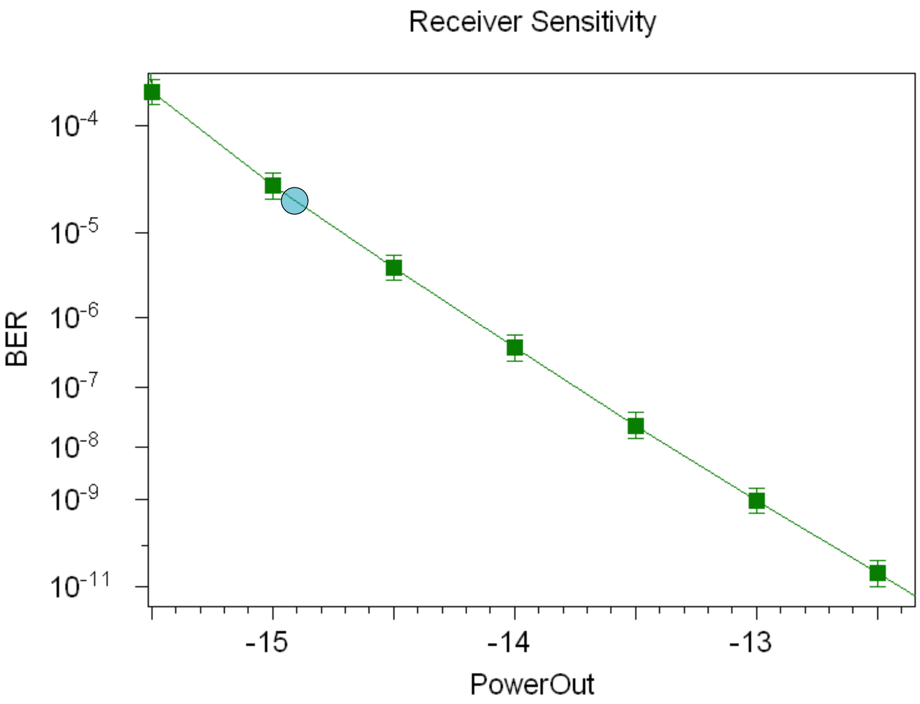




PAM-8 Receiver

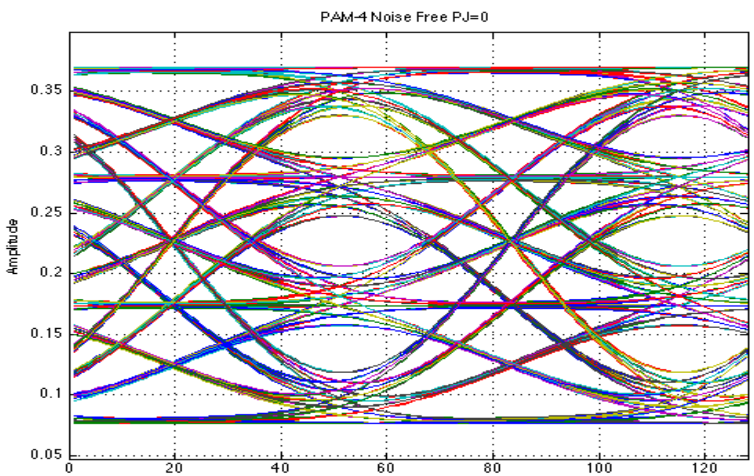
- PAM-8 eye Diagram at OMA=-4.7 dBm and link sensitivity for PAM-2
  - PAM-8 sensitivity subtract 1.8 dB for MPI and ~ 0.4 dB for other penalty from AOP of -17 dBm (at ER=6.5 OMA=AOP-1)
  - Estimated BER is 2e-5 but actual BER may be worse due to non-linear distortion and jitter interaction
  - Due to high BW component link has very little ISI and is noise limited





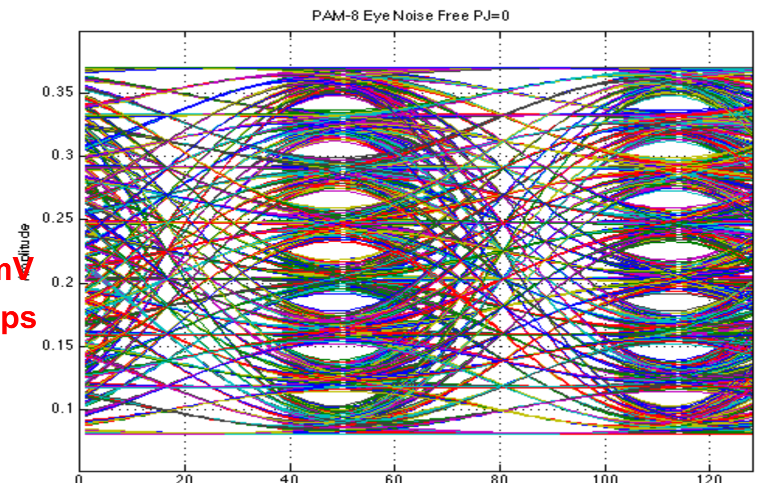
Noise Free PAM-4/PAM-8 Eyes – without and with PJ

- BER estimate may be to optimistic due to non-linear distortions and jitter
  - Equalization may help open the eye when link is not noise limited and distortion is linear



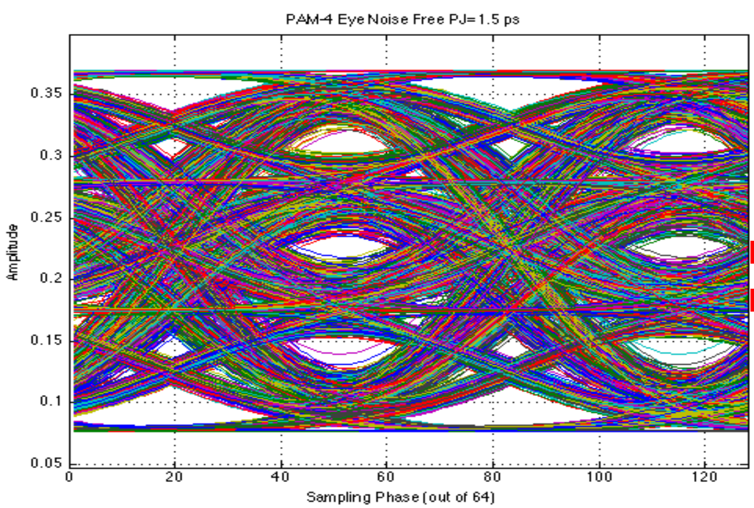
EH=40 mV

EW=9.2 ps



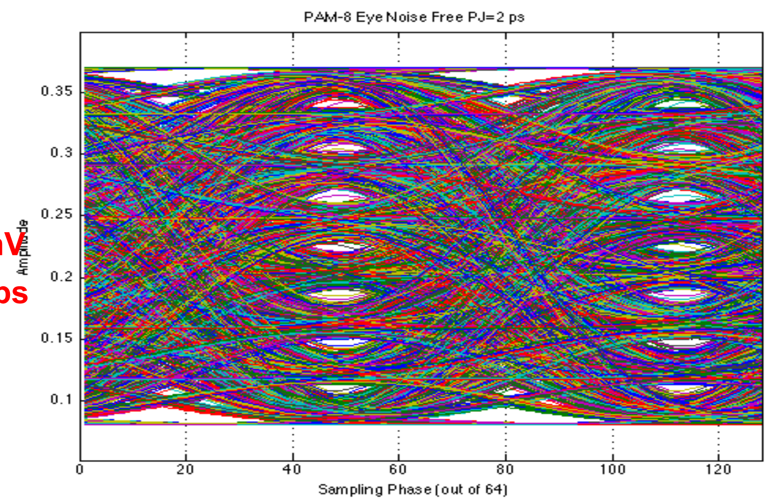
EH=14 mV

EW=8.2 ps



EH=18 mV

EW=4.8 ps

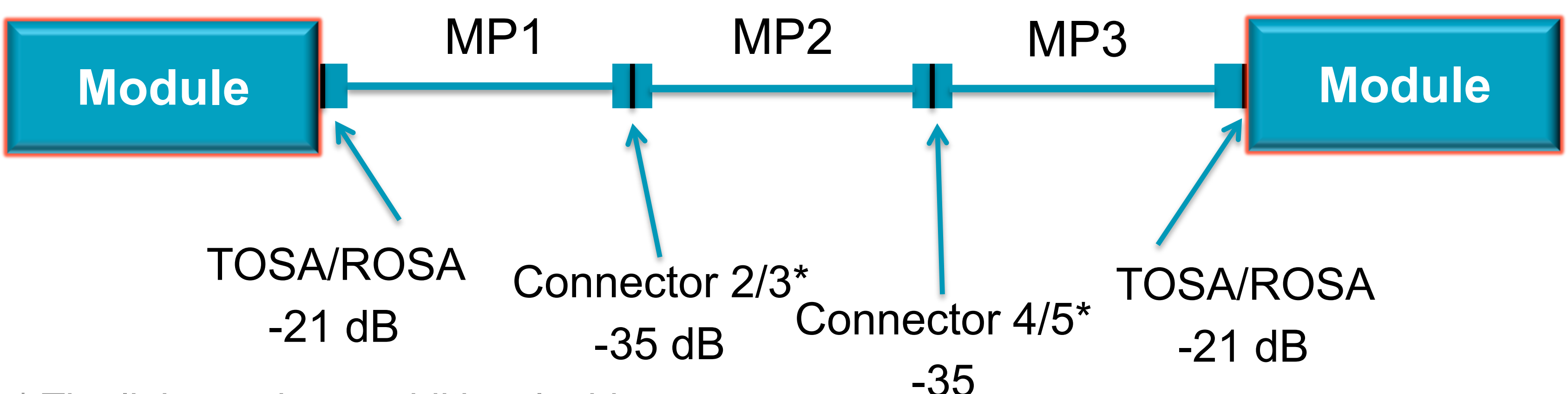


EH=5 mV

EW=3.8 ps

Multiple Patch Cords Reference Model

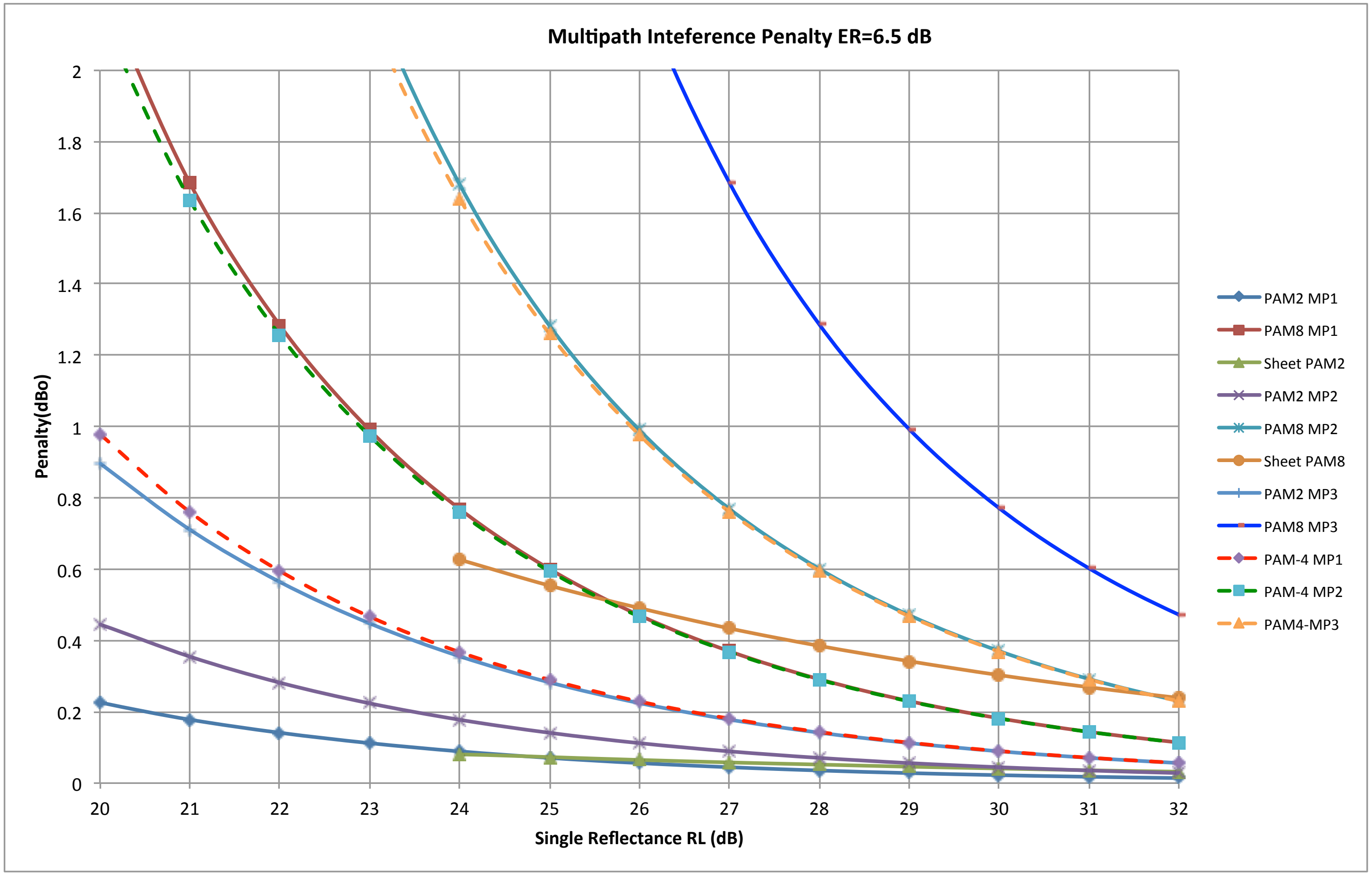
- Multipath Penalty with up to 3 patch cords are analyzed in
  http://www.ieee802.org/3/100GNGOPTX/public/mar12/plenary/ghiasi_03_0312_NG100GOPTX.pdf
- It is reasonable to assume that all mid-span connectors have RL of -35 dB a modest improvement from 1 GbE RL of 26 dB
- Assume both TOSA/ROSA will have RL of -21 dB or better
  - 100Gbase-LR4/ER4 have RL of -12 dB for the TOSA and -26 dB for the ROSA
- Next gen SMF PMD key advantage as stated is low cost and requiring high RL will drive the cost up
  http://www.ieee802.org/3/100GNGOPTX/public/jan12/nicholl_01_0112_NG100GOPTX.pdf



* The link may have additional mid-span connector

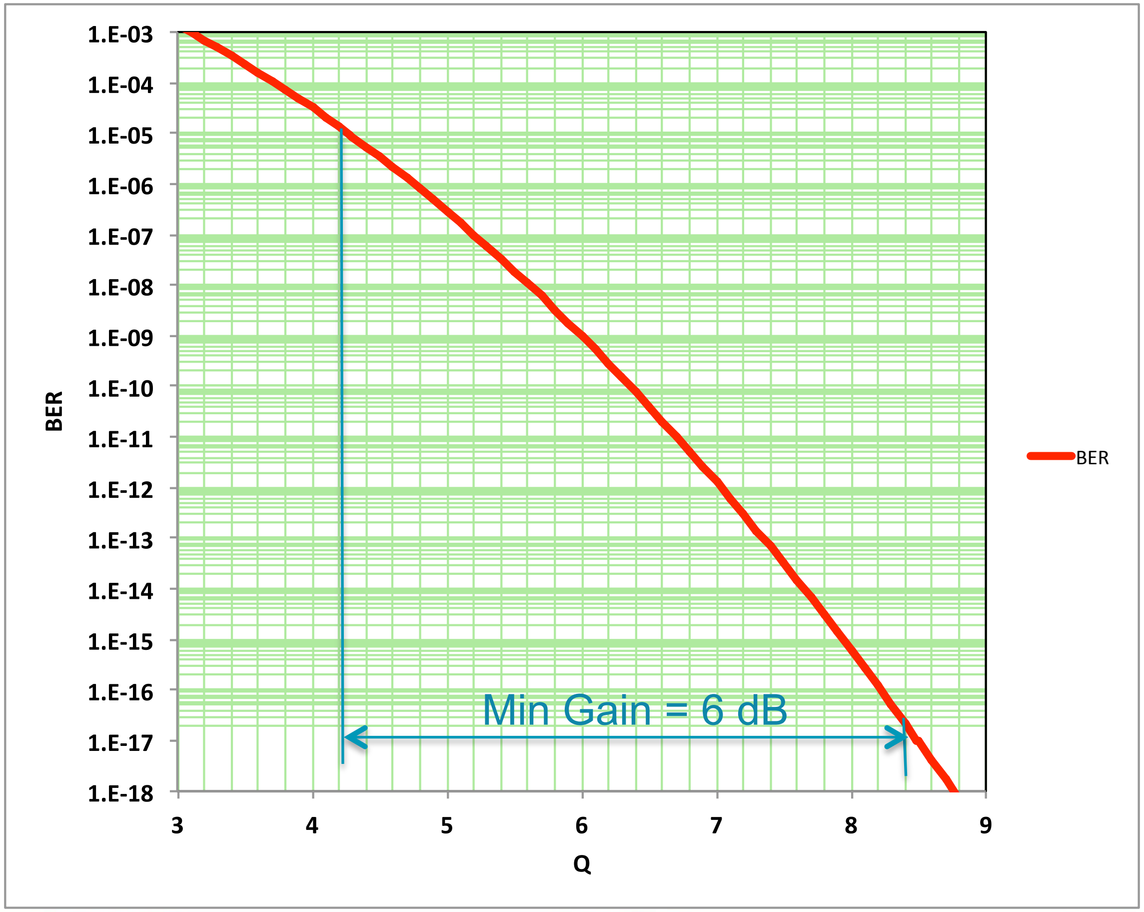
Multipath Interference Penalty

- Assuming TOSA/ROSA dominates MPI at -21 dB
  - MPI penalty for PAM-4=0.8 dBo
  - MPI penalty for PAM-8=1.7 dBo



FEC Requirements

- Raw BER will be 1E-5 (Q=4.27) and minimum BER with FEC 1E-17 (Q=8.49) or better
  - Require min FEC gain of 6 dB, for actual FEC option see http://www.ieee802.org/3/bm/public/sep12/wang_01_0912_optx.pdf



Feasibility of CMOS Operating at 34.37 GBd and 51.56 GBd

- Jun Cao, et al, “A 500 mW ADC-Based CMOS AFE with Digital Calibration for 10 Gb/s Serial Link, ISSCC 2010”,65 nm CMOS 4 way interleaved with with T-spaced FFE with power efficiency of 1.4 pj per conversion step
- Fujitsu announces on Sept 13 2010 65 Gs/s ADC in 65 nm CMOS
- OIF starts OIF-56G-VSR project April 2012
- Broadcom announces on March 5th 2012 OTU-3 Mux/De-mux capable of operation at 44 GBd in 40 nm CMOS
- Altera announces 40 GBd transceivers in 20 nm CMOS date Sept 5 2012

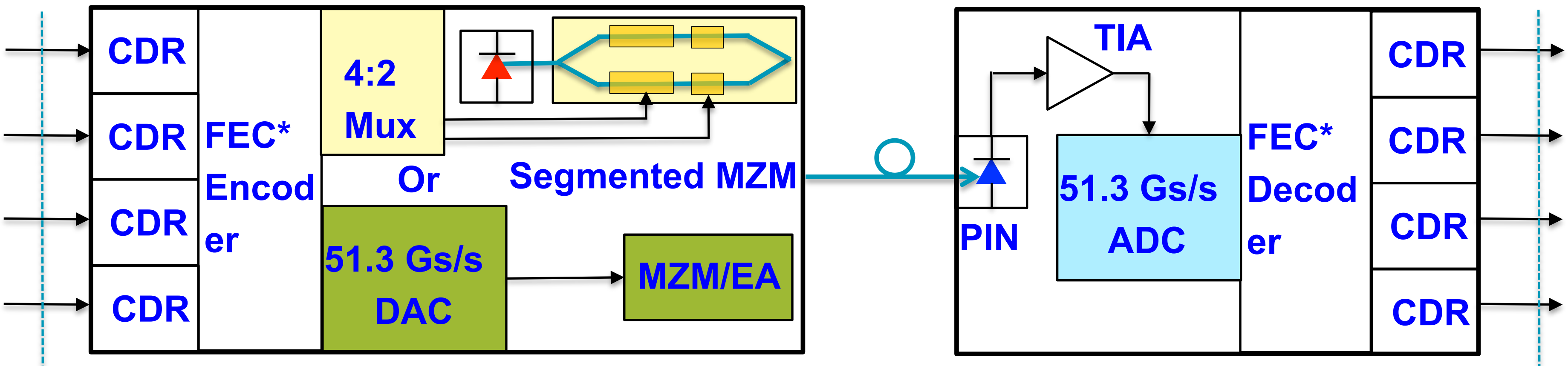
PAM-4 vs PAM-8 PD

- FEC and DAC/ADC will determine the PAM-4 vs PAM-8 PD
  - DAC/ADC PD estimated from http://www.slideshare.net/kennliu/fujitsu-iccad-presentationenable-100g?from=share_email and assuming 28 nm CMOS
  - Assuming PAM-4 DAC and ADC have ENOB of 5 bits
  - Assuming PAM-8 DAC and ADC have ENOB of 6.4 bits

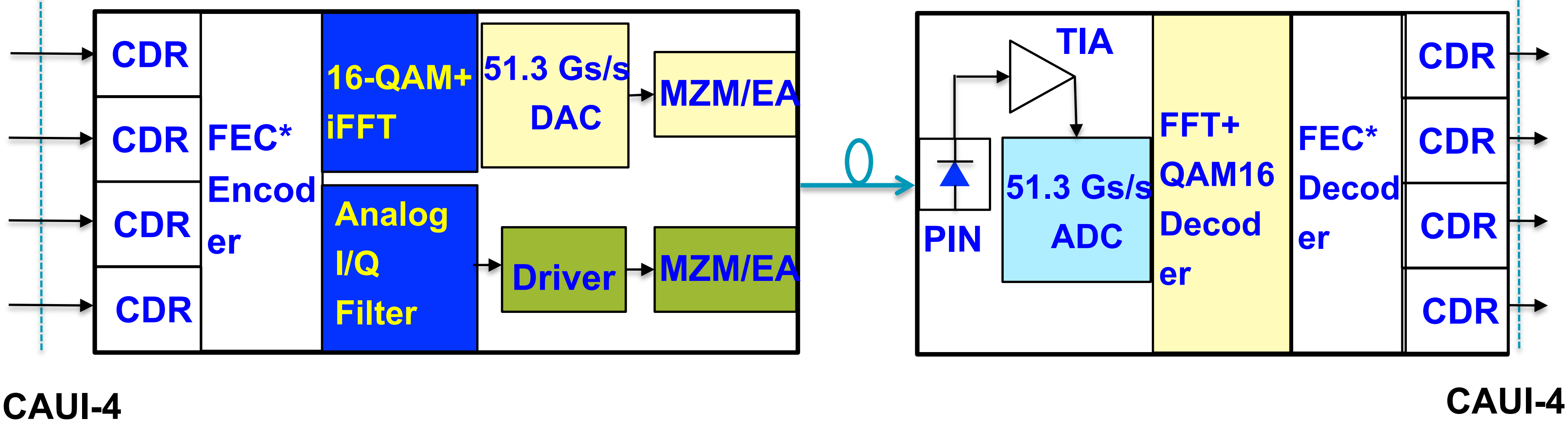
PAM-4 vs PAM-8	PAM-4		PAM-8	
Loss at 14 GHz /in	Std MZM	Seg MZM	Std MZM	Seg MZM
CAUI-4 System Interface (W)	0.80	0.80	0.80	0.80
Laser (W)	0.13	0.13	0.20	0.20
TEC (W)	0.00	0.00	0.00	0.00
Mod Driver or Segmented Driver (W)	1.00	0.30	0.60	0.20
DAC or Gearbox/Bitmux (W)	0.21	0.20	0.24	0.13
FEC (W)	NA	NA	0.35	0.35
TIA (W)	0.15	0.15	0.10	0.10
ADC (W)	0.32	0.43	0.57	0.57
Total PD (W)	2.6157	2.0050	2.8525	2.3467

PAM-4 vs CAP/QAM-16

- PAM-4



- CAP/QAM-16



CAP/QAM-16 due excess BW needed similar front end as PAM-4

Summary

- Next generation SMF PMD targeted for cost sensitive data center application with reach of 500 m
  - These application are latency sensitive and if we require a FEC with double the BJ latency would be non starter!
  - A non BJ FEC would also require the PCS adding ~250 ns of latency
- As we search for lowest cost and power PMD we need to keep an eye on the key cost driver in these serial optical links
  - RIN, TOSA/ROSA RL, connector RL, total link budget/power, and the baudrate
- Actual device implementation show feasibility of PAM-4/PAM-8
  - For nearly identical transmitters and receivers, PAM-4 has greater margin and with more relax link budget
- Link budget simulation indicate BJ FEC is likely sufficient for PAM-4 but even with a hot transmitter BJ FEC is not sufficient to close the PAM-8 link budget
- Development in the 100G coherent and 56G VSR are/will make higher speed components more available.

Thank You