Investigation of PAM-4/6/8 Signaling and FEC for 100 Gb/s Serial Transmission

IEEE 802.3bm Task Force

Ali Ghiasi, Zhongfeng Wang, and Vivek Telang - Broadcom

Brian Welch – Luxtera

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Overview

- Investigating unipolar PAM signaling
  - PAM-4 operating at 51.562 GBd requiring BJ FEC with latency of 100 ns
  - PAM-6 operating at 43.7 GBd requiring 8.7 dB FEC with latency of 105 ns
  - PAM-8 operating at 43.6 Gbd requiring 12 dB FEC with latency of 400 ns
- All of the above option are feasible and expect to converge to a single solution by Jan interim meeting
- Since Sept 2012 interim we have added MPI to the simulation as well as equalization
  - Our link model build in Rsoft include all the know impairments
  - Statistical eyes now show BER contour and with 4 T/2FFE+1DFE equalizer
  - After adding MPI link now has startup transient sometimes making it difficult to symbols
- During Sept 2012 meeting our result showed PAM-8 is not feasible so what has changed
  - 12 dB FEC and improving connector RL to -35 could make PAM-8 feasible.
- For PAM-4/6/8 Link budget please see
  - http://www.ieee802.org/3/bm/public/nov12/welch_01_1112_optx.pdf

PAM-n Options

- In addition to PAM-4, PAM-6/DSQ-32, and PAM-8 are the other viable options
  - The required SNR for each of the above signaling with green highlight
- We are open to any modulation scheme that we can close the link with margin considering all the impairments

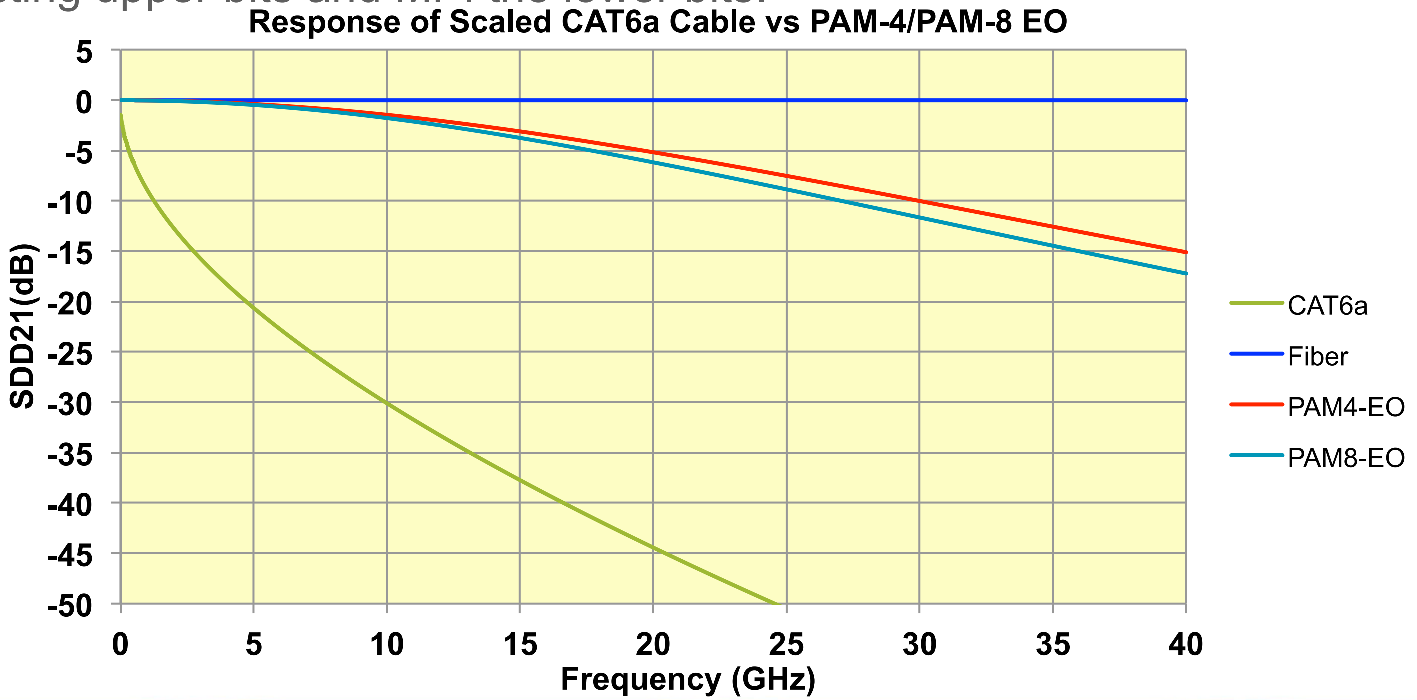
PAM-n	Required SNR (dB) for BER 1E-2	1E-3	1e-4	1e-5	Baudrate (GBd)	Bit/ Symbol
PAM-2	12.6 dB	9.80 dB	11.41 dB	12.6 dB	103.125	1
PAM-4	14.86 dB	17.12 dB	18.63 dB	19.77 dB	51.562	2
PAM-6/ DSQ-32	18.67 dB	20.87 dB	22.37 dB	23.49 dB	41.512	2.5*
PAM-8	21.28 dB	23.47 dB	24.95 dB	26.65 dB	34.375	3
PAM-12/ DSQ-128	24.90 dB	27.06 dB	28.54 dB	29.65 dB	29.652	3.5**
PAM-16	27.44 dB	29.59 dB	31.06 dB	32.17 dB	25.781	4

* PAM-6 uses 32 of 36 symbols

** PAM-12 uses 128 of 144 symbols

10Gbase-T vs PAM-n Optical

- 10Gbase-T CAT-6a channel was scaled to have equivalent loss at 25.78 GHz
  - CAT-6a was only characterized up to 500 MHz as specified per ISO/IEC 11801 Class E with extension in TIA/EIA TSB-155
  - DSQ-128 was a reasonable choice given 500 MHz channel
- In case of optical PAM-n cable frequency dependent loss~0
  - E/O and electronics determine channel BW
  - On optical link error mechanism are more complex due to non-linarites, with RIN impacting upper bits and MPI the lower bits.

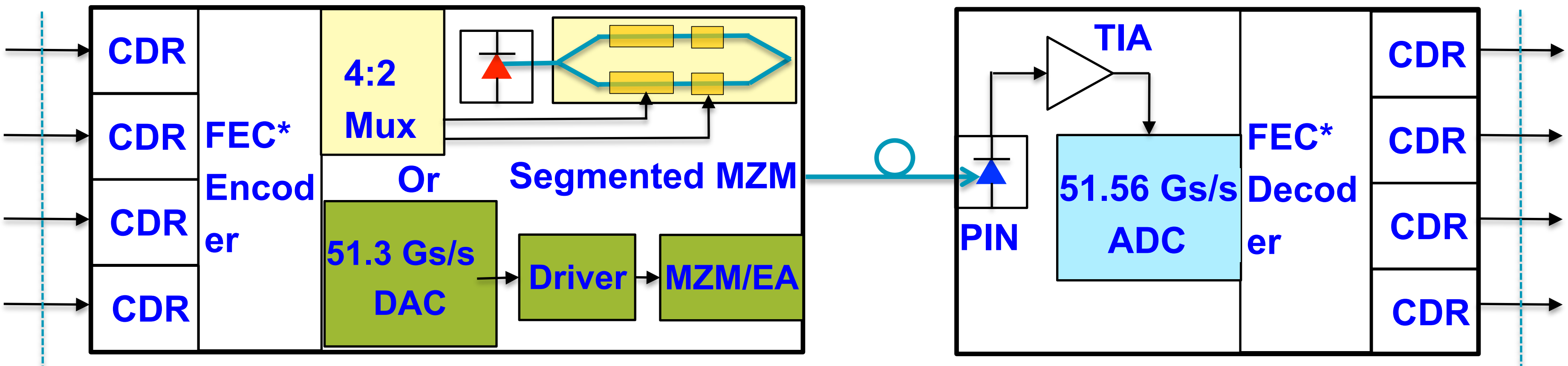


PAM-n Investigation

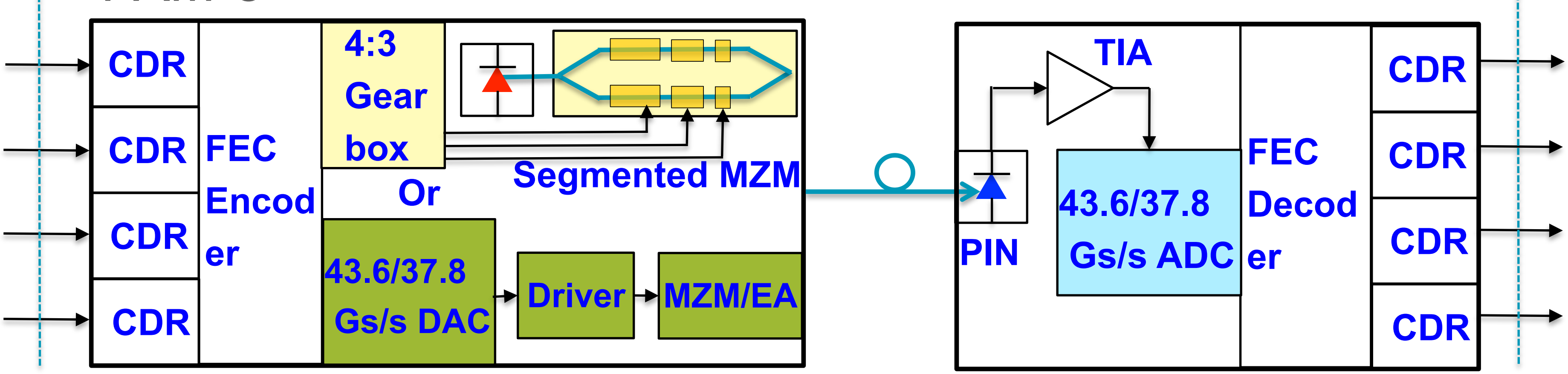
- This presentation compares various PAM-n modulation schemes for 100G optics in some aspects
- Starting with PAM-4 modulation as baseline link budget allow adopting 802.3bj FEC (coding gain ~ 5.8dB at 1e-15)
- Investigation of PAM-8 modulation even with hot transmitter require BER of 1E-5 which is not achievable and require stronger than BJ FEC
- PAM-6/DSQ-32 modulation operating at about 40GBd is more efficient signaling compare to PAM-8 but operating slower than PAM-4
- As we move to higher PAM to compensate for the penalties require more complex FEC where latency (and possibly power) will increase
  - Propose to limit PAM-n FEC latency 2.5x the bj FEC (250 ns).

PAM-4 vs PAM-8 Implementation

- PAM-4



- PAM-8

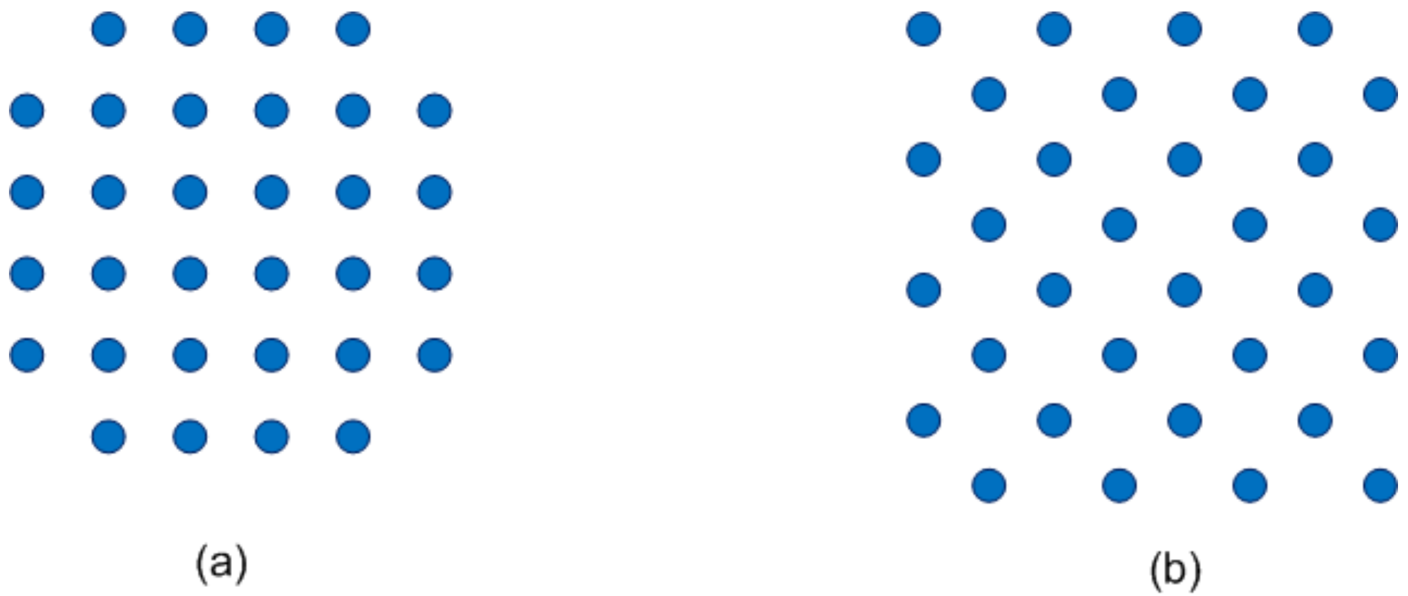


CAUI-4 **CAUI-4**

* BJ FEC maybe sufficient for PAM-4

PAM-8 Based DSQ32

- The following figure (a) shows PAM6 based diamond32 constellation. It transmit 2.5 bits per symbol on average
  - Compared to PAM4, it has a SNR loss of 3.7 dB
- The following figure (b) shows PAM8 based DSQ32 constellation. This is about 0.5dB better than (a) [1].



[1] G. Ungerboeck, "10GBASE-T Coding and Modulation: 128-DSQ +LDPC", IEEE P802.3an, Sep. 2004.

FEC Options for DSQ-32

- DSQ-32 has a SNR loss of about 3.2dB compared to PAM-4
- Multi-level coding can be considered for DSQ-32.
- Set partition into two groups is a good tradeoff.
- Baud rate: 41.25GS/s (0% OC) ~ 43.7GS/s (6% OC)
- Option-I:
  - Use set partition with 12dB gain, 1 bit with weak coding (e.g., t=1 block code) plus 4 coded bits per 2 symbols. For the 4 coded bits, a FEC code with about 8.5dB gain may be considered.
  - BCH(3456, 3084, t=31), CG=8.7dB, latency ~105ns, OC~=6%
  - RS(578, 514, t=32,m=10), CG~8.4dB, latency ~140ns, OC~=7%
  - Compared to PAM-4, FEC compensates the SNR loss. But it has 15% lower baud rate, though other kinds of noise/loss is not considered yet.
- Option-II:
  - Use set partition with 9.5dB gain, 2 bits with weak coding (e.g., t=2 RS code) and the rest 3 bits with strong FEC coding, e.g., CG=8.7dB BCH code.
  - OC~=4.7% latency ~= 115ns.

FEC Options for DSQ-32 (cont'd)

- DSQ-32 has a SNR loss of about 3.2dB compared to PAM-4
- Option-III:
  - Use set partition with 6dB gain, 3 bits with bj FEC coding, the rest 2 bits with very strong FEC coding.
  - Ex-1: BCH(154, 130)xBCH(152, 128), CG ~= 12.2dB

    Baud rate = 1.16*103.125/2.5=47.85GB

    Latency ~= 490+120 =610ns

- **Option-IV:**
  - Use set partition with 9.5dB gain for lower 2 bits with bj FEC coding, the rest 3 bits with very strong FEC coding.
  - Ex-1: BCH(154, 130)xBCH(152, 128), CG ~= 12.2dB

    Baud rate = 1.24*103.125/2.5=51.15GB

    Latency ~= 305+120 =425ns

- Either Option-III or option-IV has about 3dB gain over PAM4+bj FEC case from modulation and FEC perspective.,

PAM-8 Modulation

- PAM-8 with set partition of 12dB (for msb)
- Transmit 3bits per symbol
- SNR loss compared to PAM4 is about 6.3 dB
- The msb is protected with weak FEC code, e.g., RS(t=1)code.
- Use strong FEC to protect the 2 other bits.
  - If using 40% OH product code, CG ~12.2 dB, latency ~ 400ns,
    - OC=27%, Baud rate: 43.6 GS/s,
  - If using 20% OH FEC code, e.g., BCH(2464, 2056, t=34),
    - CG~9.25 dB, latency ~ 105 ns
    - OC ~ 13.3%, Baud rate:38.9GS/s
    - It has 10% lower baud rate than DSQ32 while having about 2.5dB SNR loss.

FECs with Embedded Tradeoffs

- In [1], it was mentioned that it is preferable to define a FEC code with embedded tradeoffs between coding gain and latency.
- For a true-product code (**trPC**) BCH(154, 130) x BCH(150, 128), one variant is a pseudo-product code (**psPC**) defined as **BCH(314, 260, t=6) x BCH(152, 128),** where one row code covers two rows in the code matrix [2].
- When this code is decoded as a ps**PC** at RX side, it has almost the same coding gain as the original product code.
- If we only perform row decoding for row codes BCH(314, 260, t=6), we have CG~=7.64dB. Latency ~= 80ns.

[1] Z. Wang and A. Ghiasi , "FEC Tradeoffs and Analyses for 100G Optical networking," IEEE P802.3abj Sep. 2012.
[2] Z. Wang, "Super-FEC Codes for 40/100 Gbps Networking," available at http://arxiv.org/ftp/arxiv/papers/1202/1202.4664.pdf

FEC Compensation for PAM-n (n>4) vs. PAM-4

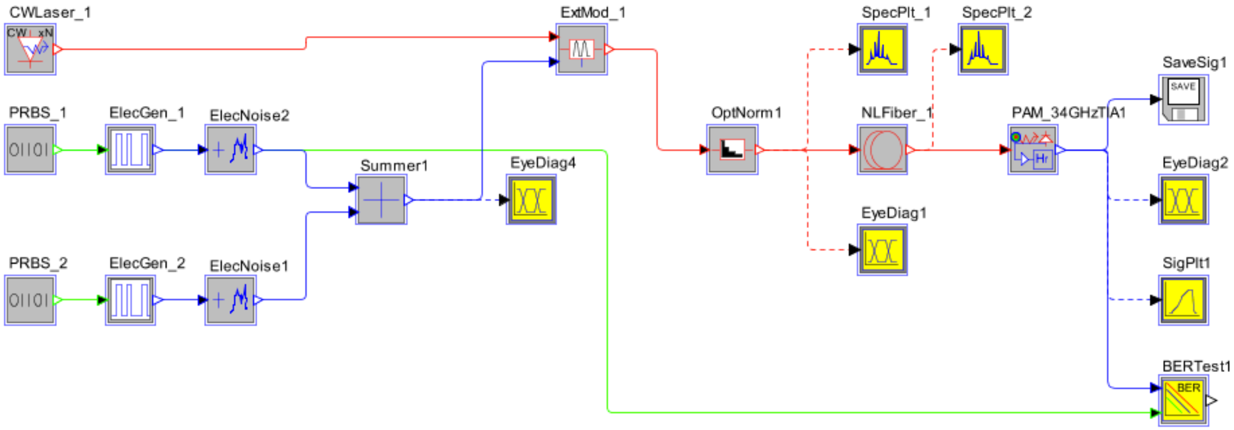
PAM-n	SNR gain compared to PAM-4+bj FEC	Baud rate (GBd)	FEC latency (ns)
PAM-4+bj FEC	0	51.6	~100
DSQ32+ MLC with 8.7dB FEC	~ 0	43.7	~ 105
PAM-8 + MLC with 12dB FEC	~ 0	43.6	~ 400
DSQ32+ MLC1 With 12dB FEC	+3.0 or -1.3 dB	51.25 or ~51.6	~ 425 or ~80
DSQ32 + MLC2 with 12dB FEC	+3.0	47.85	~ 610

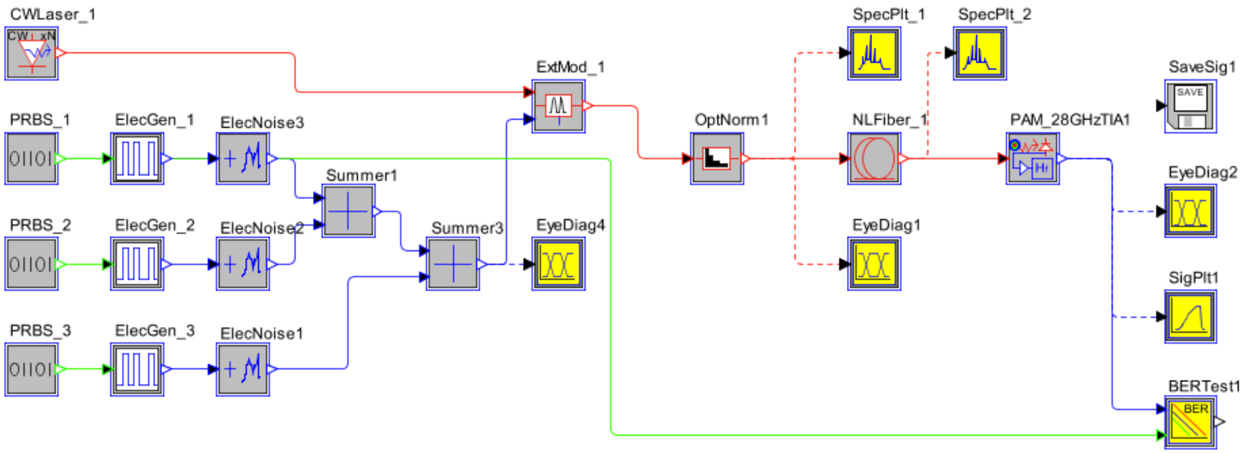
Basic Simulation Assumptions

- 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=-144 dBm/Hz for PAM-8 and -144 for PAM-4
  - RIN based on Q=2 for PAM8 could be reduced to 141.5 dB/Hz see http://www.ieee802.org/3/bm/public/nov12/welch_01_1112_optx.pdf
  - 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=PN9 by 8x
- Extinction Ratio= 6.5 dB
- Receiver BW=28 GHz 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

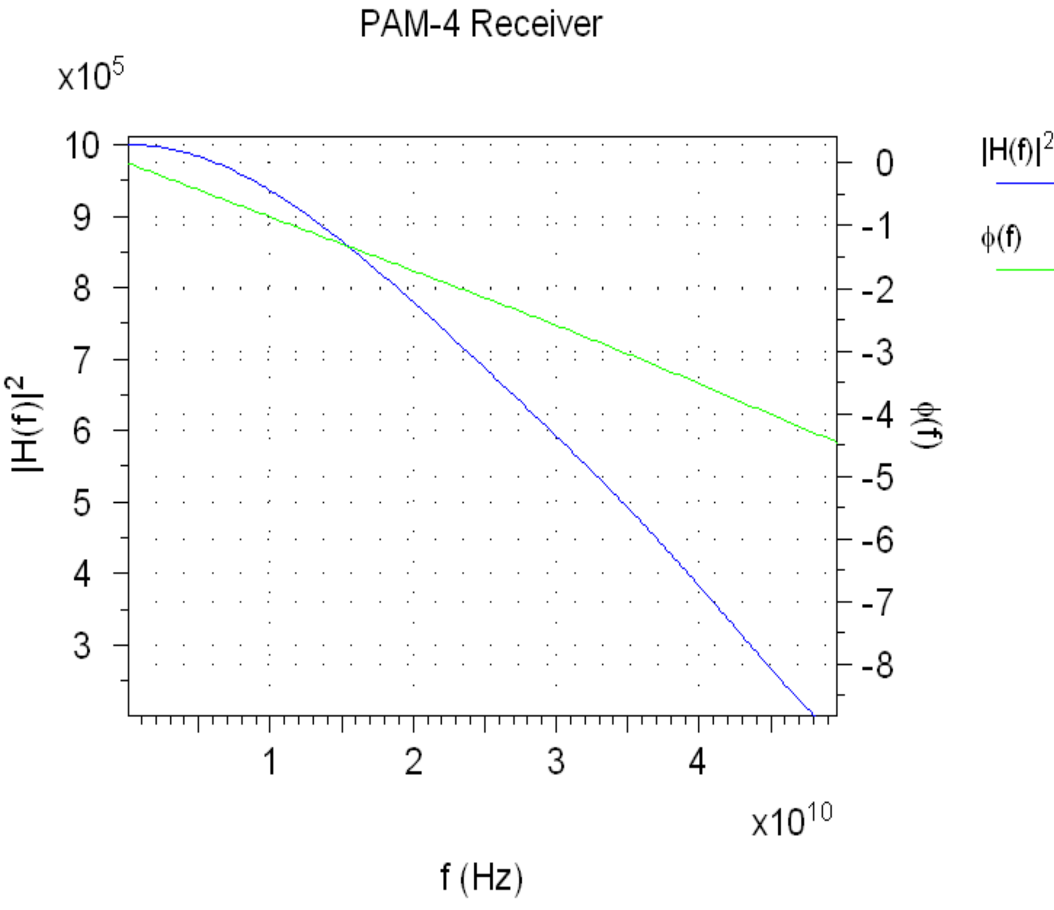
- Rsoft Schematic

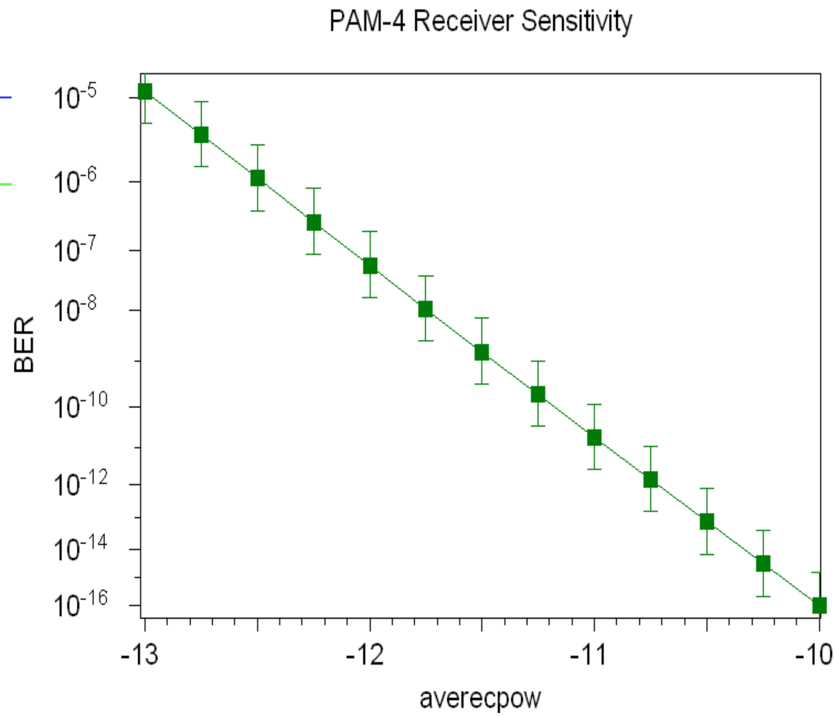




PAM-4 Optical Receiver Response

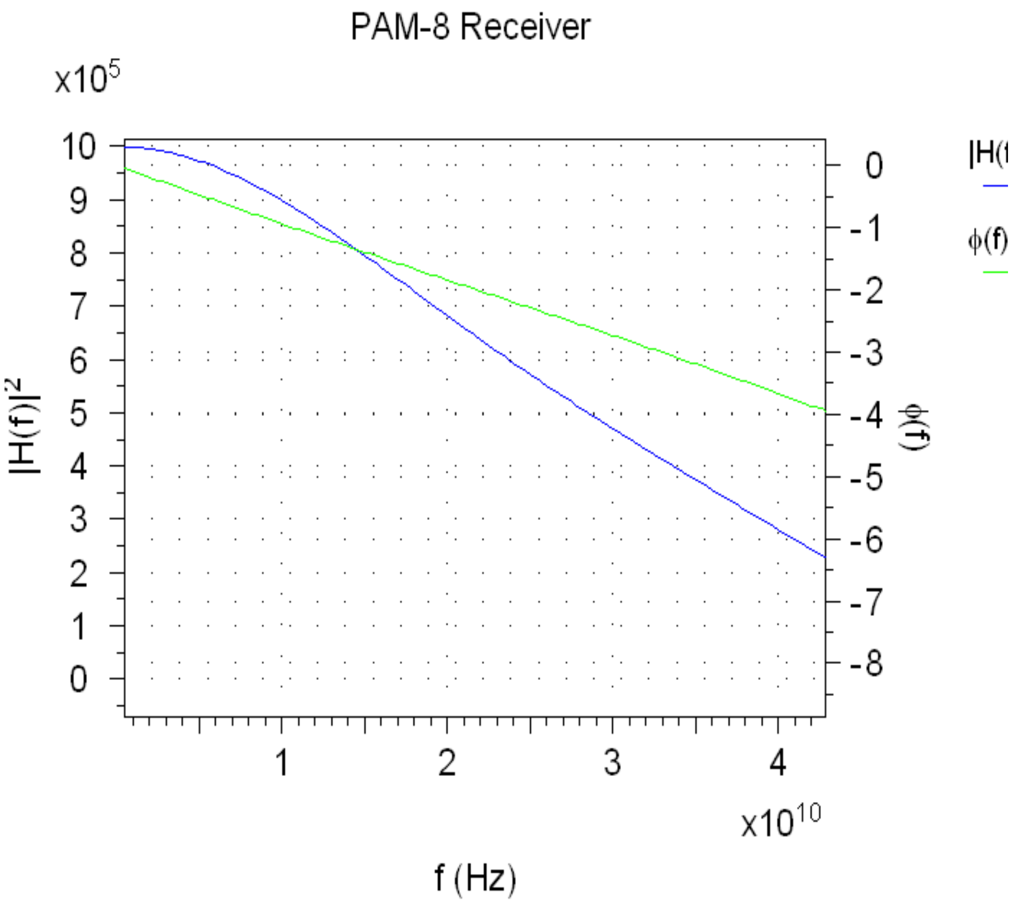
- Response of a realistic PD+TZ AMP with 34 GHz BW and sensitivity of 1e-5 at -13 dBm AOP or -12 dBm OMA at ER=6.5 dB

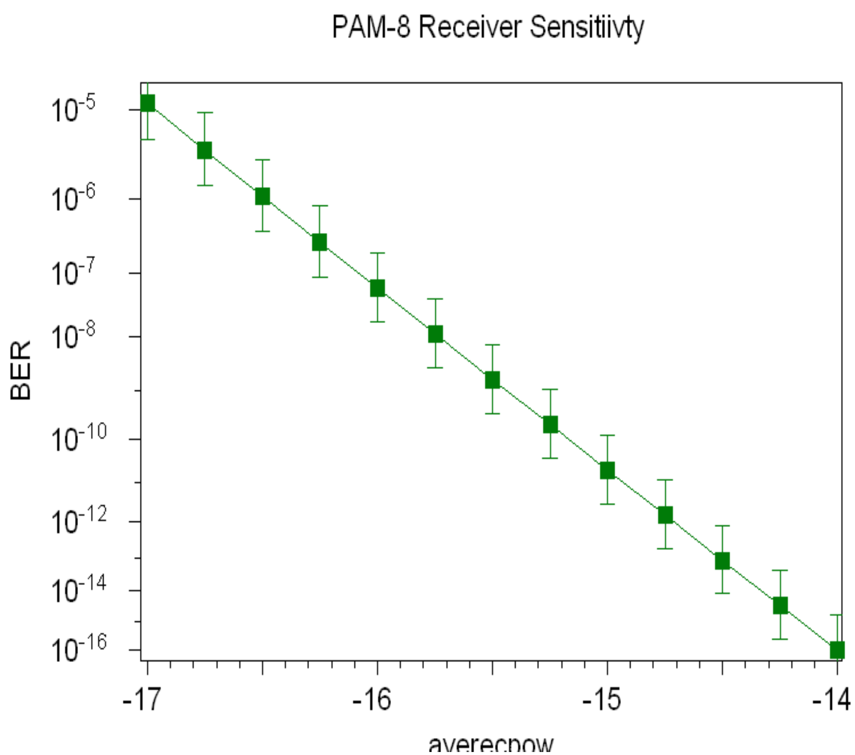




PAM-8 Optical Receiver Response

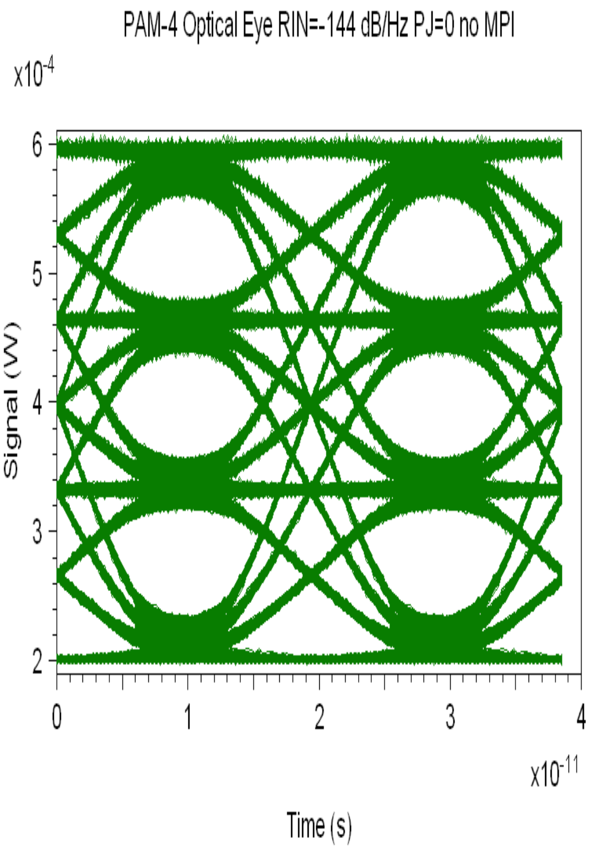
- Response of a realistic PD+TZ AMP with 28GHz BW and sensitivity of 1e-5 at -17 dBm AOP or -16 dBm OMA at ER=6.5 dB

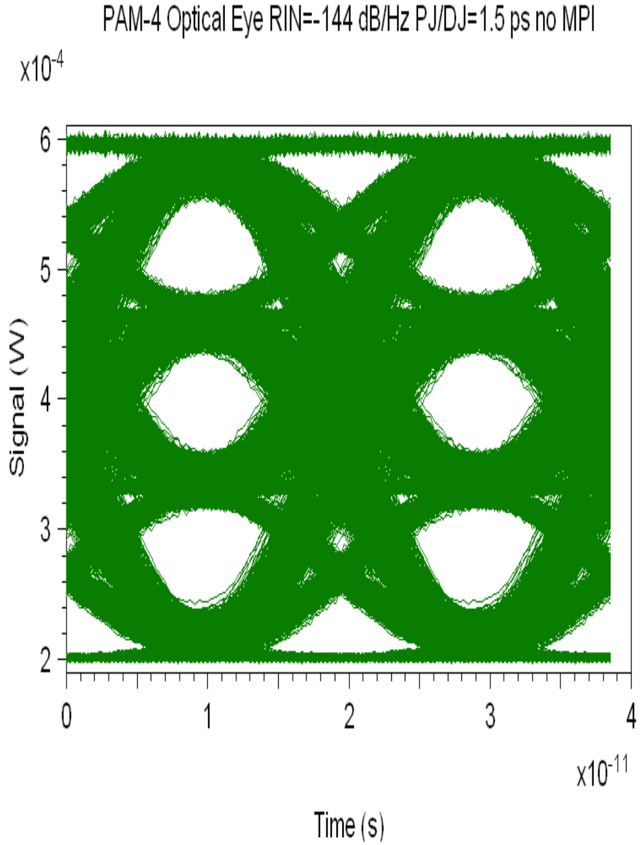


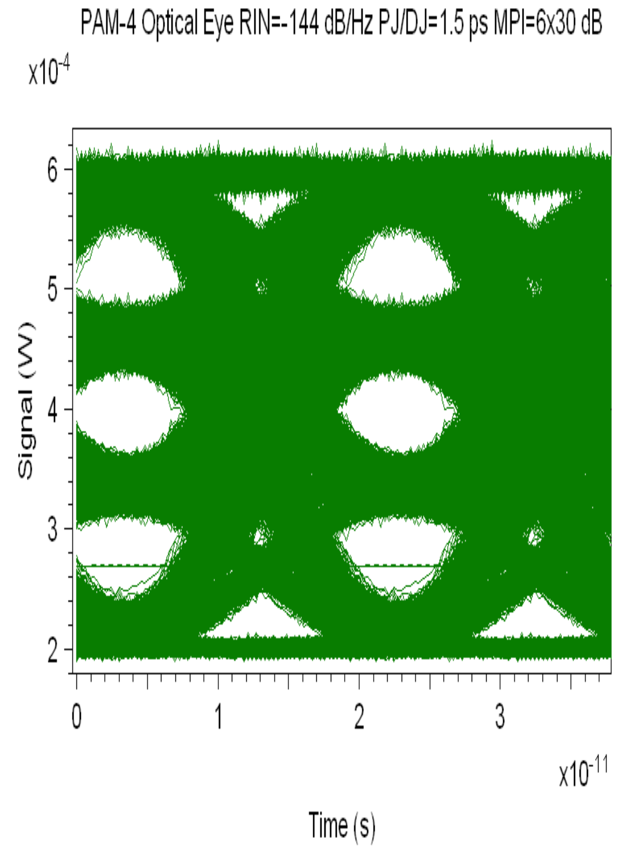


PAM-4 Optical Eyes at 51.6 GBd

- Without PJ and MPI, with 1.5 ps PJ/DJ, and with 1.5 ps PJ and MPI
  - Link with MPI assumed to have 4 connectors + TOSA/ROSA @30 dB and some startup transient are visible in the eye

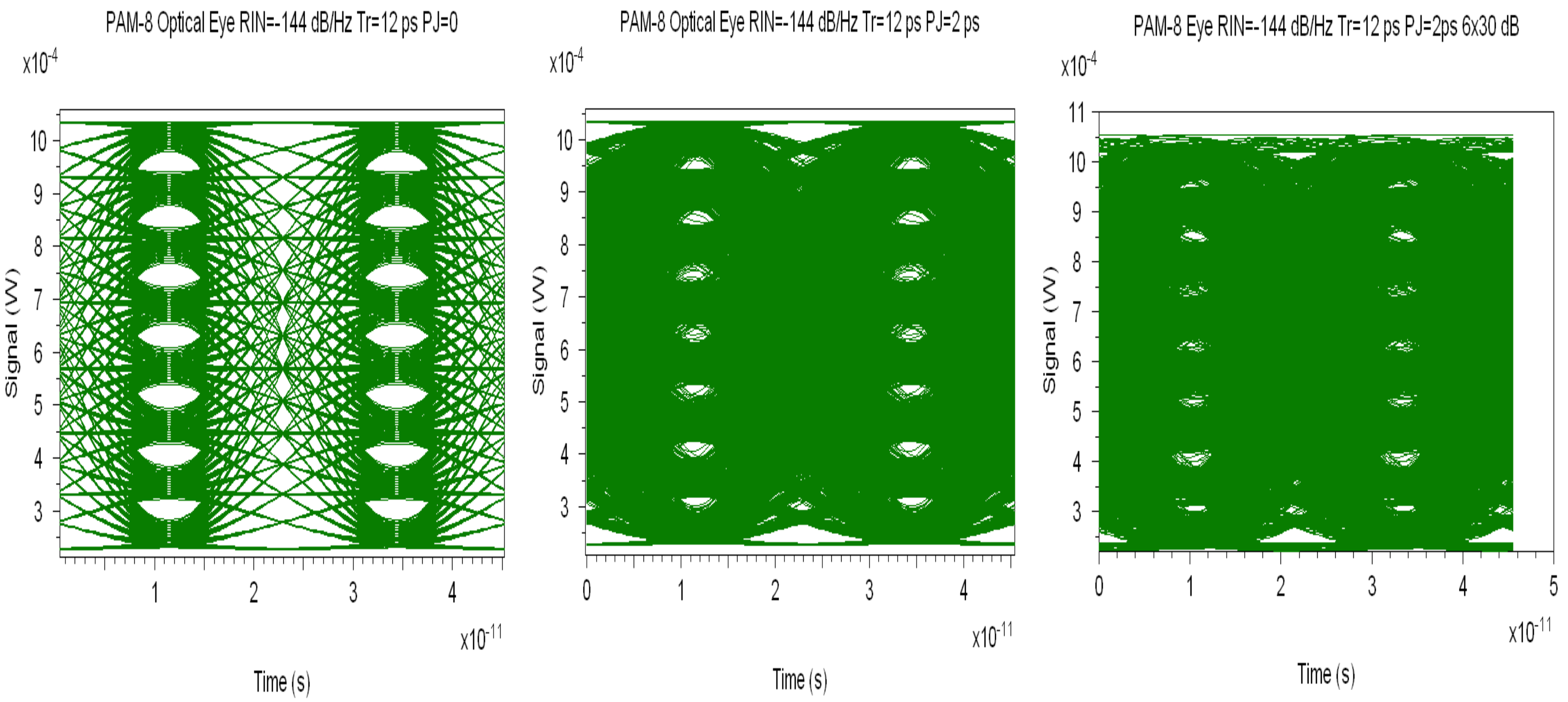






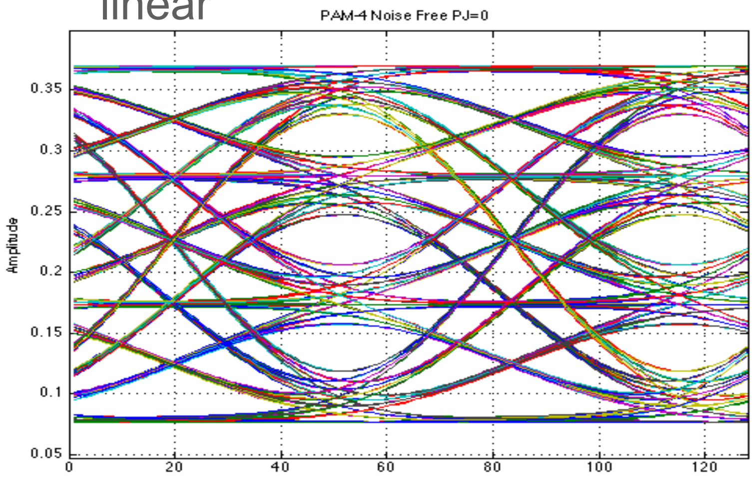
PAM-8 Optical Eyes at 43.6 GBd

- Without PJ and MPI, with 2 ps PJ/DJ, and with 2 ps PJ and MPI
  - Link with MPI assumed to have 4 connectors + TOSA/ROSA @35 dB

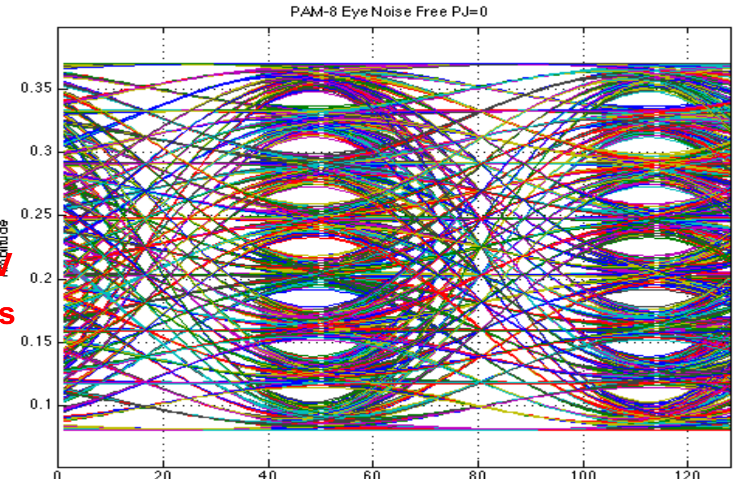


Noise Free PAM-4/PAM-8 Eyes – without and with PJ/DJ

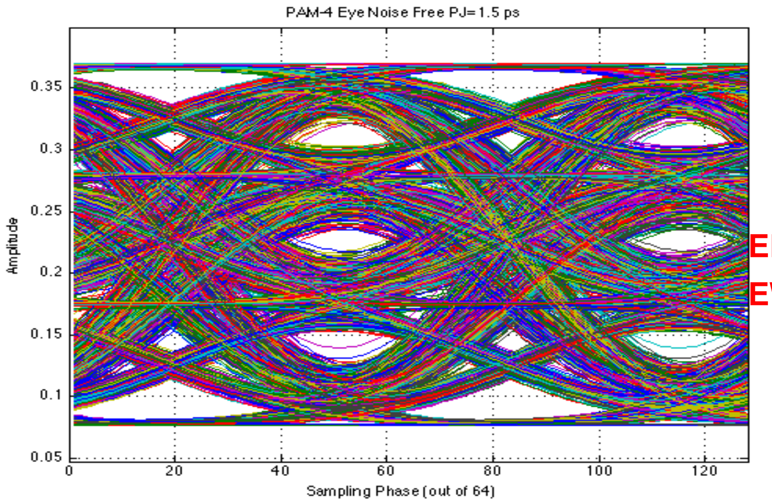
- BER estimate may be to optimistic due to non-linear distortions and jitter
  - Equalization may help open the eye when link is not noise limited and distortion is linear



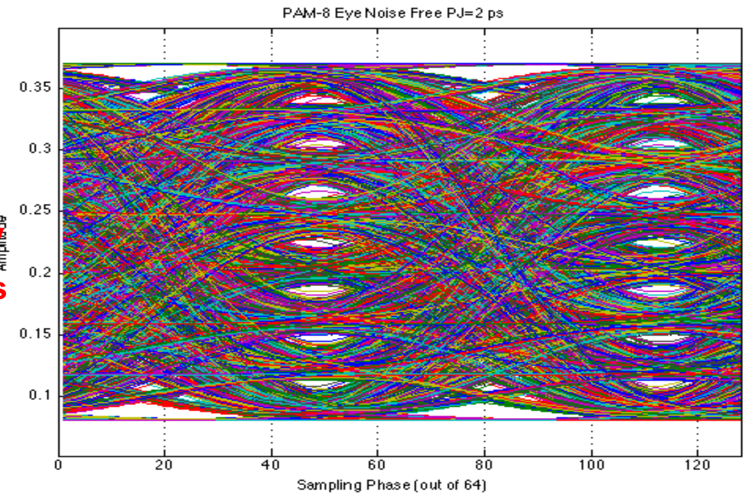
EH=40 mV
EW=9.2 ps



EH=14 mV
EW=8.2 ps



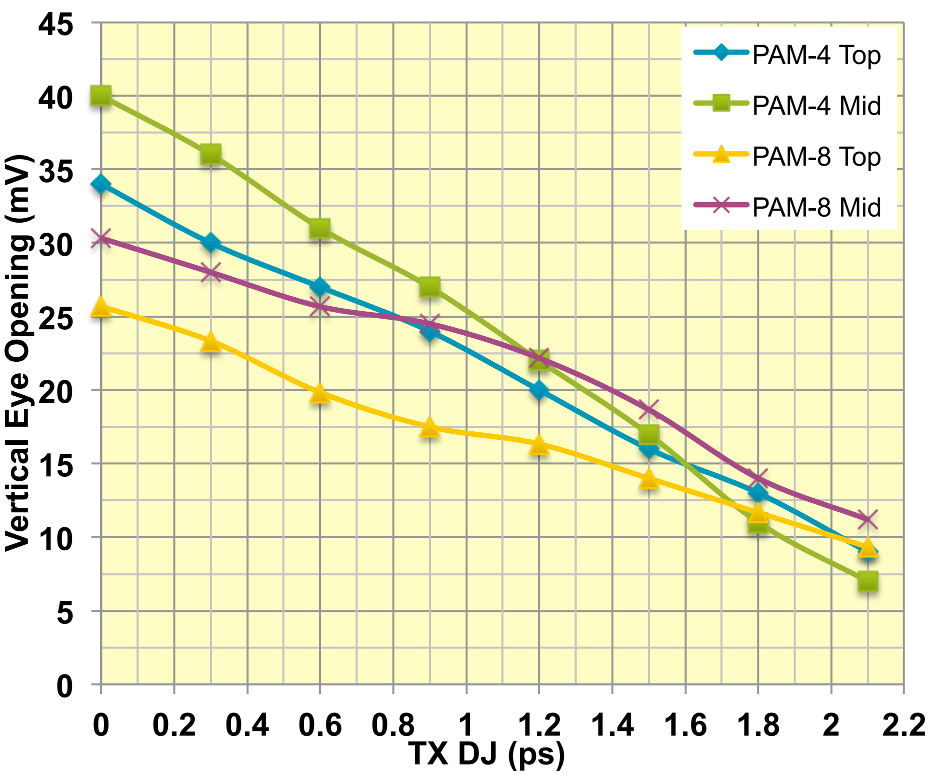
EH=18 mV
EW=4.8 ps

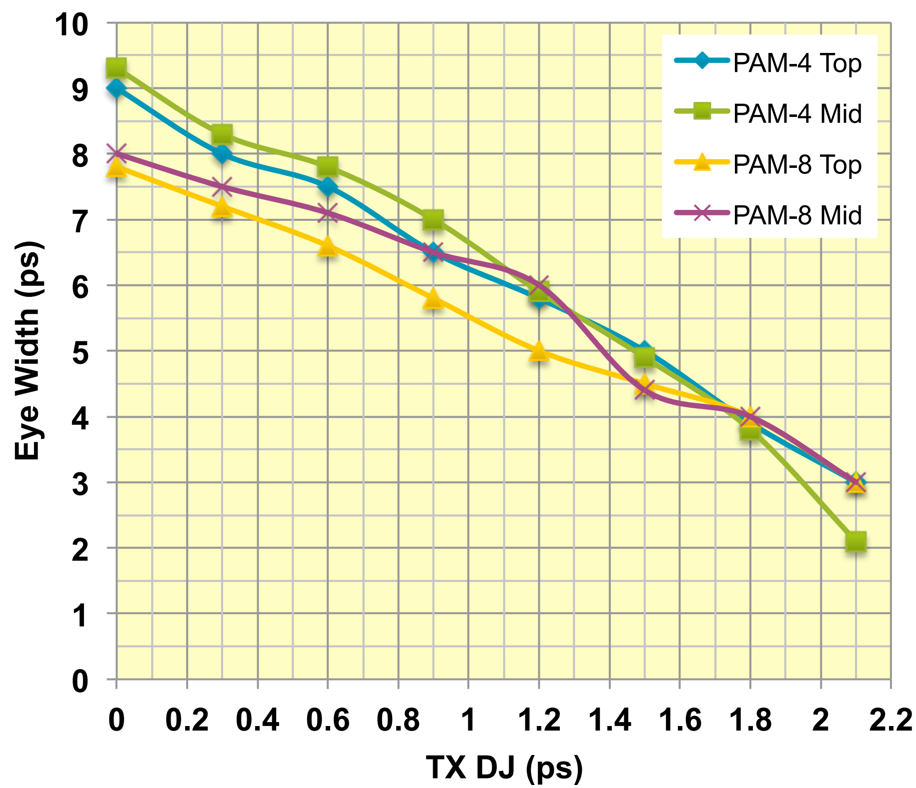


EH=5 mV
EW=3.8 ps

Noise Free PAM-4/PAM-8 as Function of Input PJ

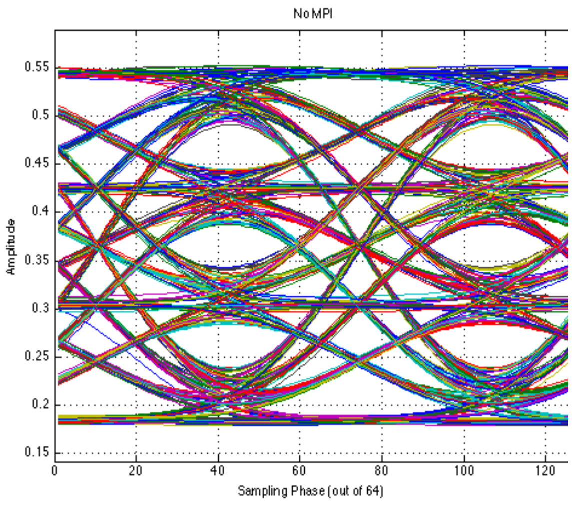
- Transmitter PJ/DJ penalty can be very significant
  - PAM-8 vertical eye are adjusted by ratio of 7/3 to normalize the signal
  - In case of PAM-4 at 1.5 ps PJ top penalty is 3.7 dBo and for middle eye 3.3 dBo but penalty at 1E-5 with 4-T/2FFE + 1 DFE is only 1.4 dBe (slide 26)
  - In case of PAM-8 at 2 ps PJ top penalty is 3.4 dBo dBo and for middle eye 5.2 dBo

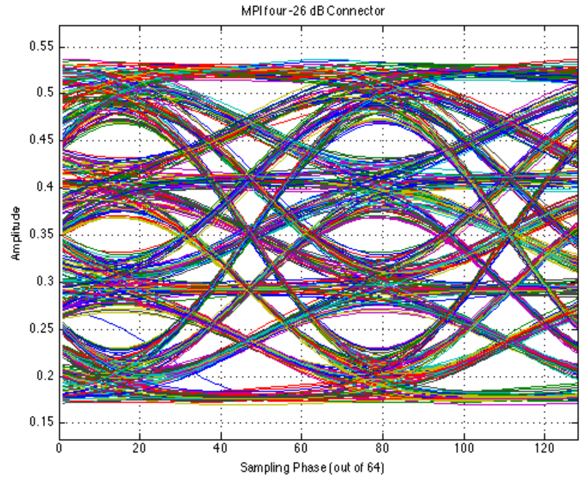


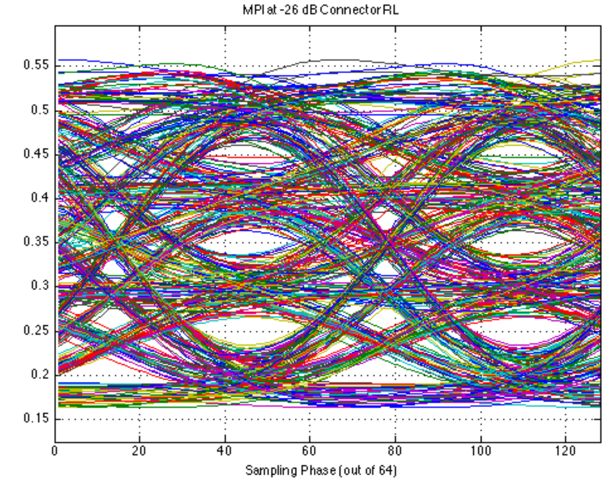


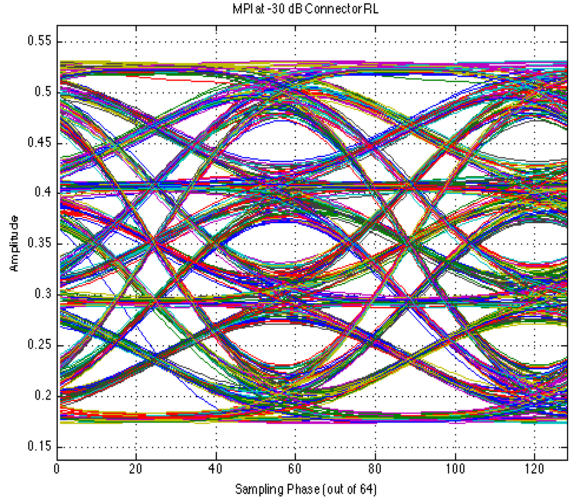
MPI Simulation-Jitter and Noise Free

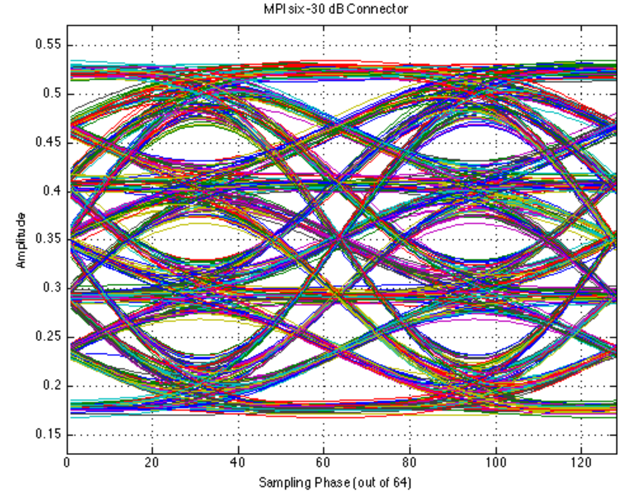
- MPI with no connector and 4 and 6 connectors at -26 dB and -30 dB





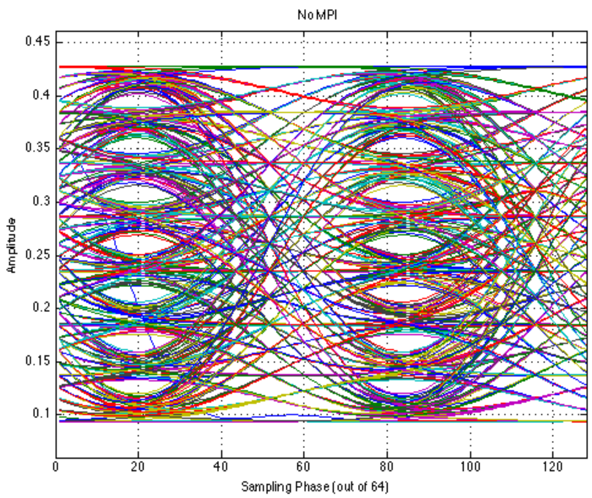


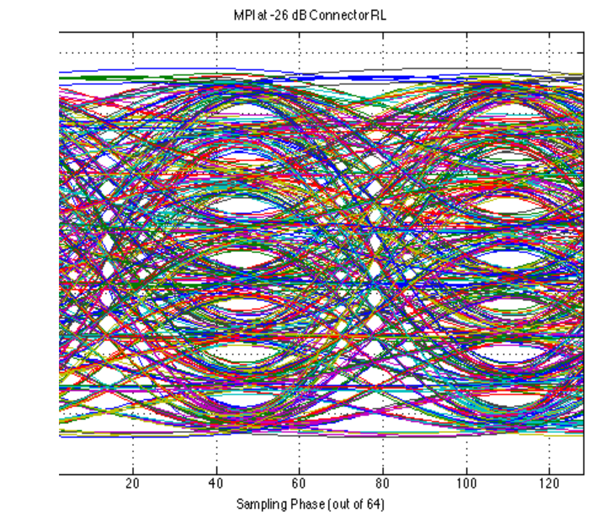


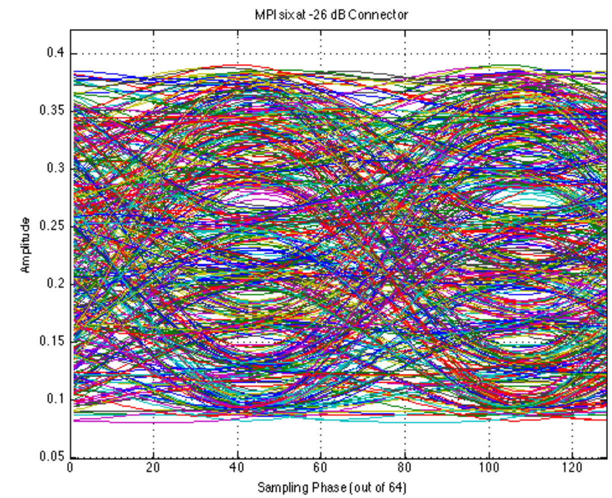


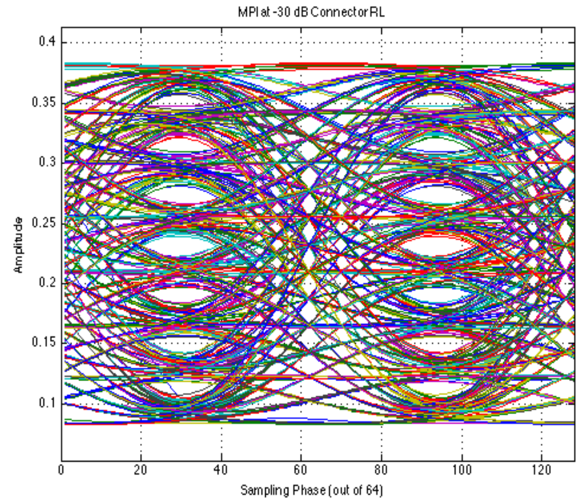
MPI Simulation-Jitter and Noise Free

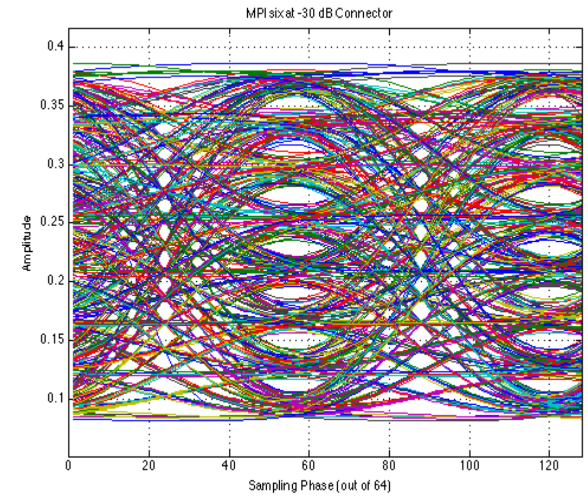
- MPI with no connector and 4 and 6 connectors at -26 dB and -30 dB











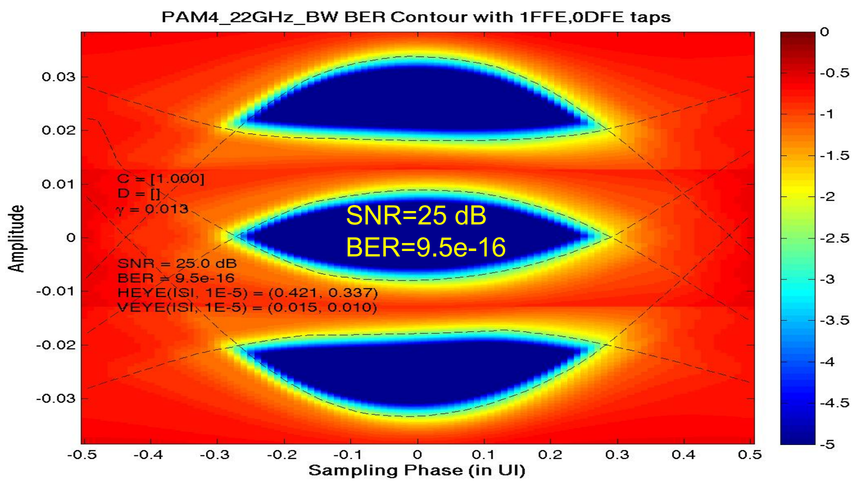
MPI Penalty Summary

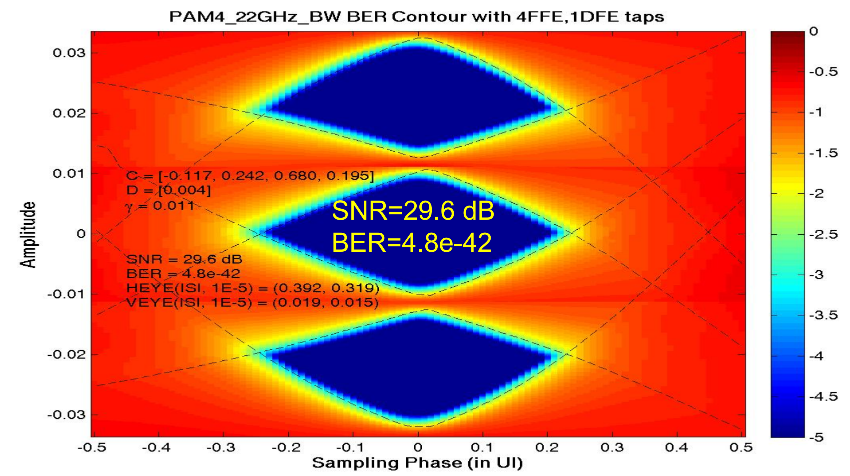
- Result based on time domain simulation
  - As the penalty increased > 5dBo it becomes difficult to measure the eye opening
  - Also cases with very small penalty ~0.1 dB then step size could limit the accuracy
  - For the upper bound analysis see http://www.ieee802.org/3/100GNGOPTX/public/mar12/plenary/ghiasi_03_0312_NG100GOPTX.pdf and http://www.ieee802.org/3/bm/public/nov12/index.html Welch

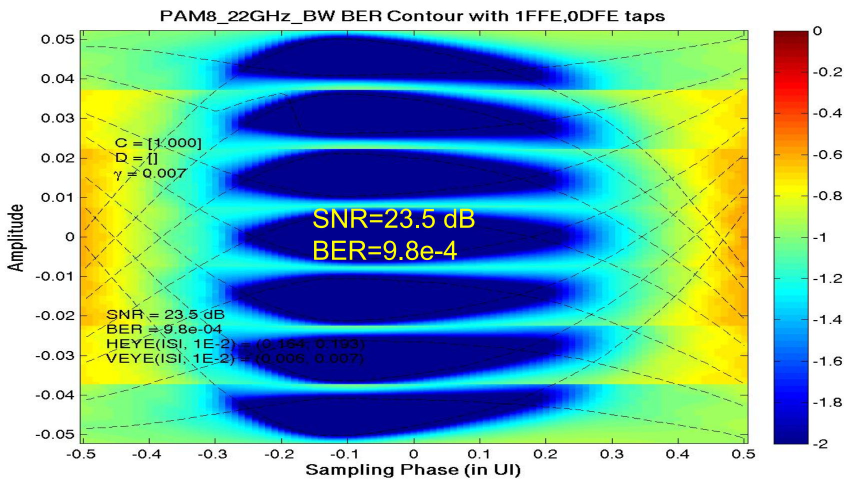
RL	4 Connectors			6 Connectors		
	PAM-2	PAM-4 min/max	PAM-8 Min/max	PAM-2	PAM-4 Min/max	PAM-8 min/max
-26 dB	0.34	0.6/1.0 dB	3.5/7.0 dB	0.86	4.4/5.4 dB	NA
-30 dB	0.2	0.23/0.47 dB	0.42/1.0 dB	0.34	0.6/1.3 dB	1.3/4.0dB
-35 dB	0.15	0.07/0.12 dB	0.09/0.13 dB	0.19	0.17/0.34	0.46/0.81 dB

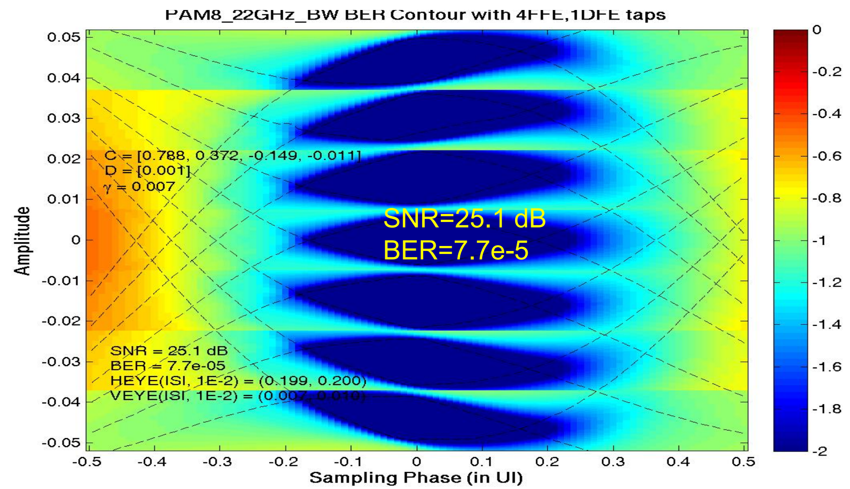
PAM-4/PAM-8 (51.56/37.81 GBd) Eyes Based on Luxtera Segmented Modulator with 22 GHz Receiver

- Qualitative eyes without added TX jitter, noise, MPI, RIN
  - Add 0.85 mV AWGN to at (-4 dBm) with no excess penalty included for above impairments, see link budget http://www.ieee802.org/3/bm/public/nov12/welch_01_1112_optx.pdf



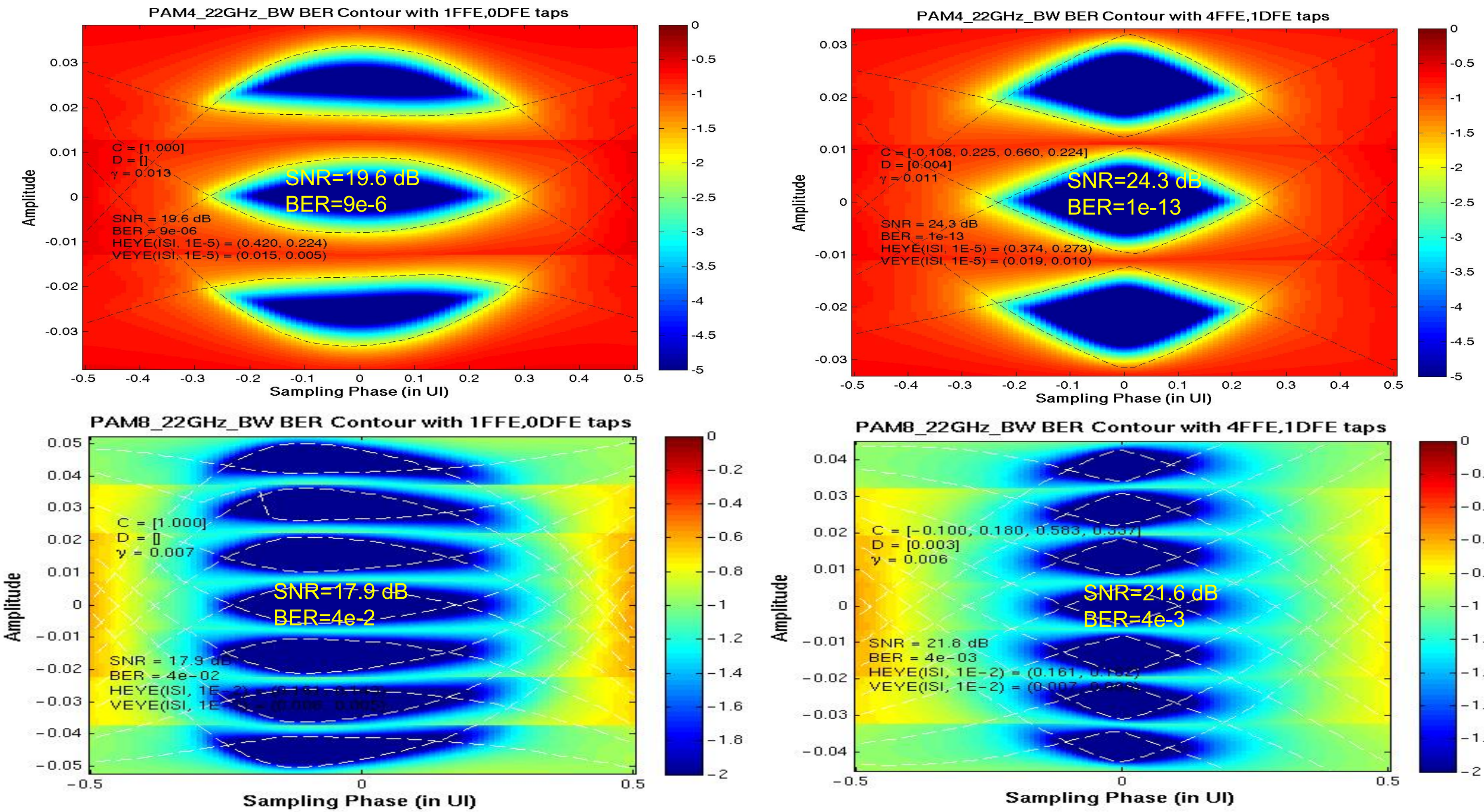






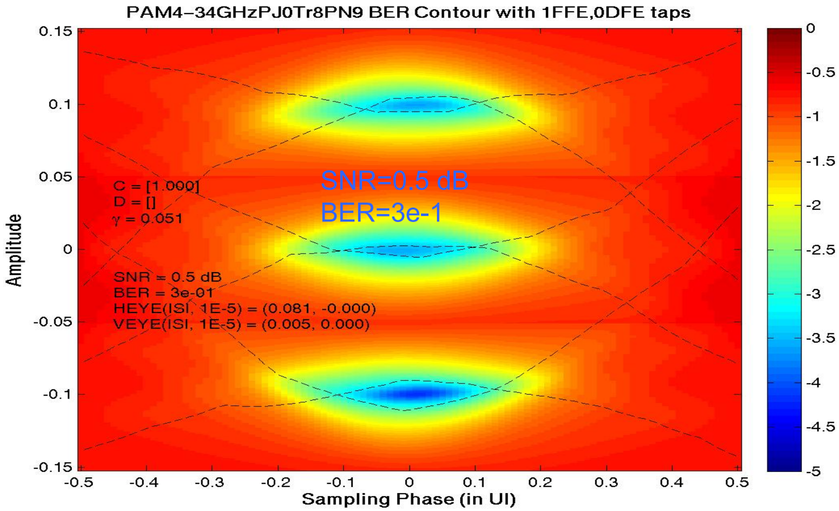
PAM-4/PAM-8 (51.56/37.81 GBd) Eyes Based on Luxtera Segmented Modulator with 22 GHz Receiver

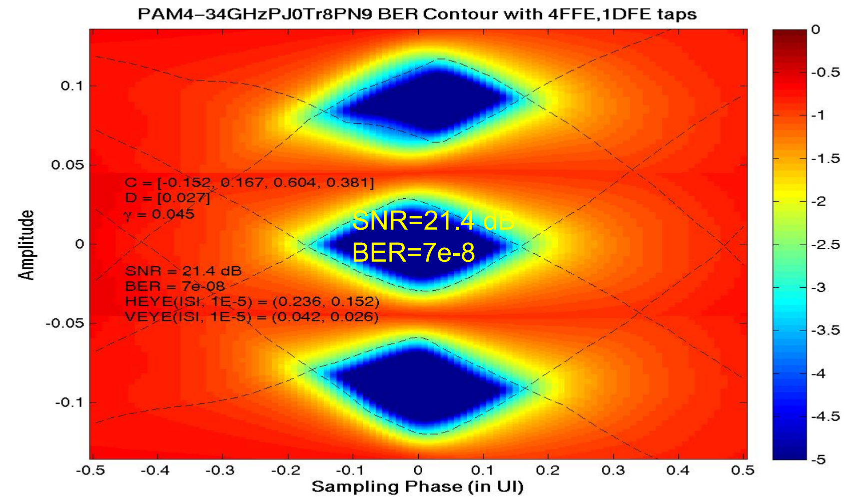
- Qualitative eyes without added TX jitter, noise, MPI, RIN
  - Add 1.7 mV AWGN to at (-7 dBm) 3 dB excess penalty included for above impairments, see link budget http://www.ieee802.org/3/bm/public/nov12/welch_01_1112_optx.pdf

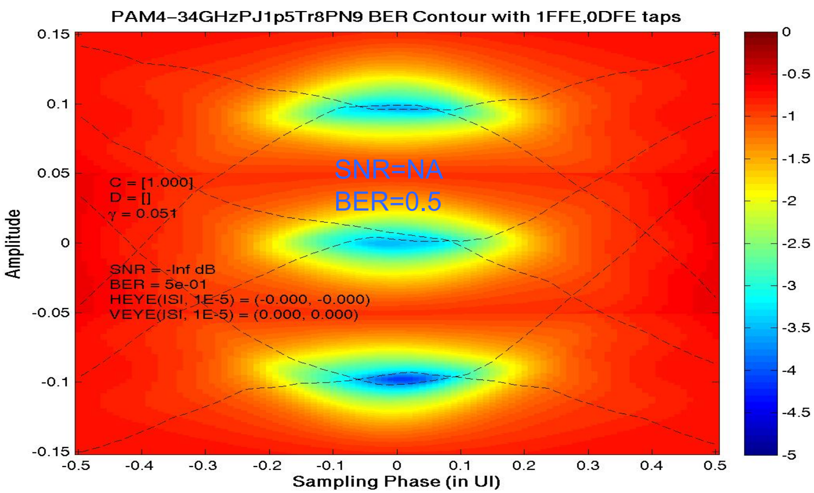


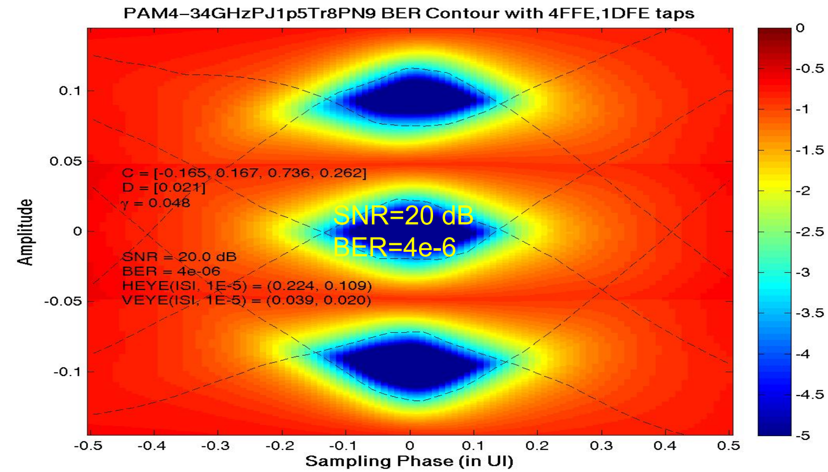
PAM-4 Simulation with All Impairments Except MPI at 51.56 GBd

- Without /with1.5 ps PJ/DJ and equalization



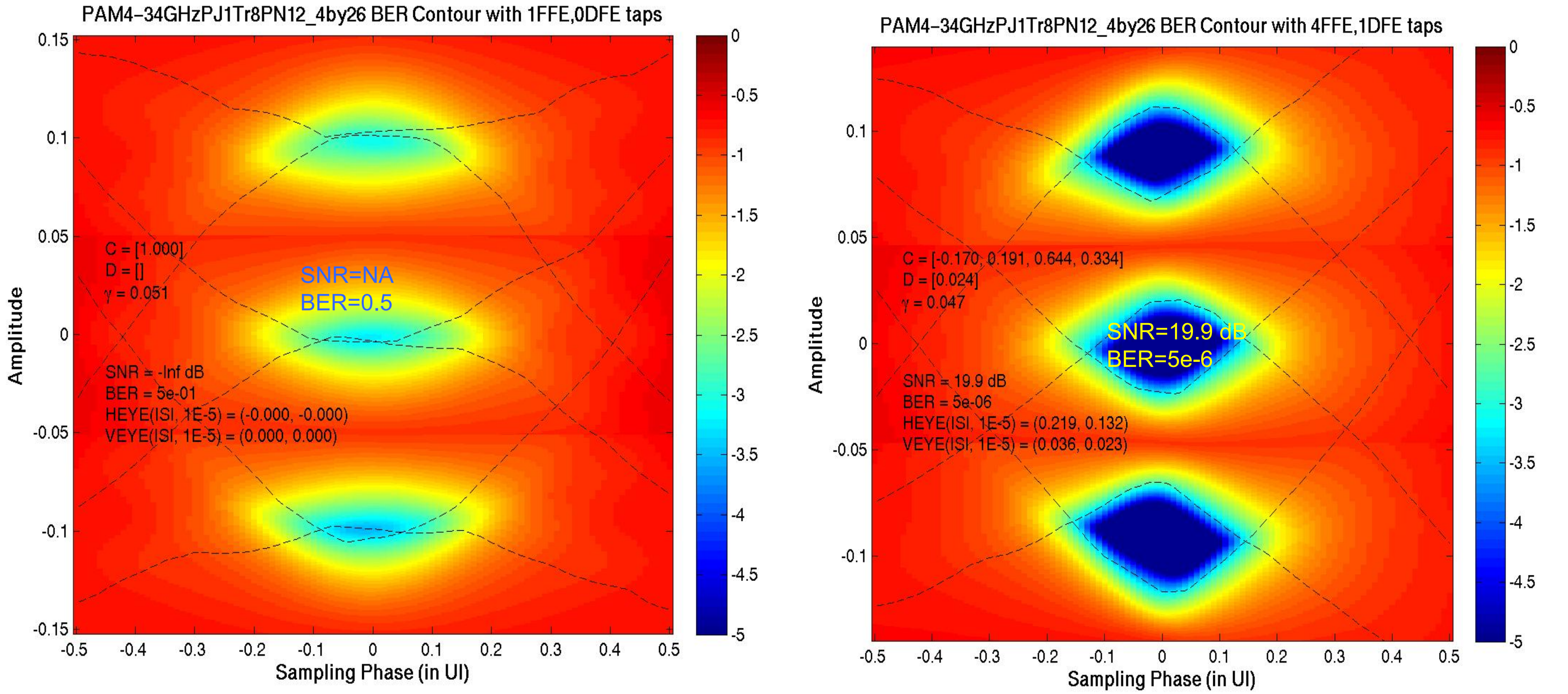






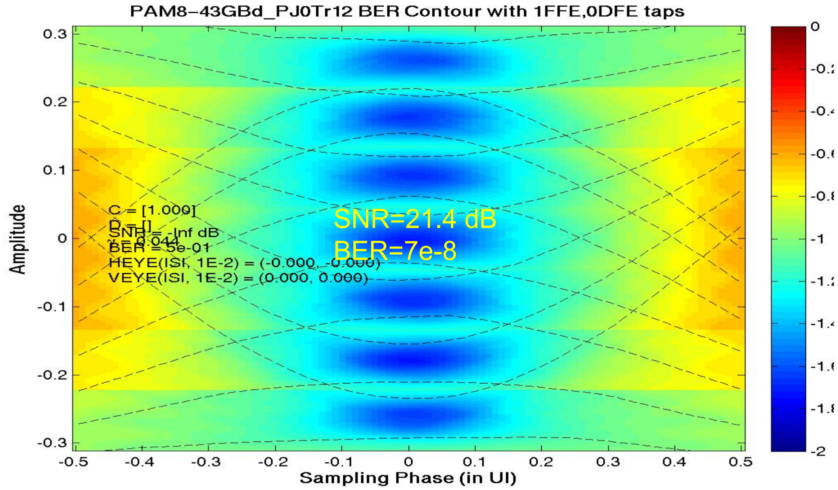
PAM-4 Simulation Eyes at 51.56 GBd with All Impairments

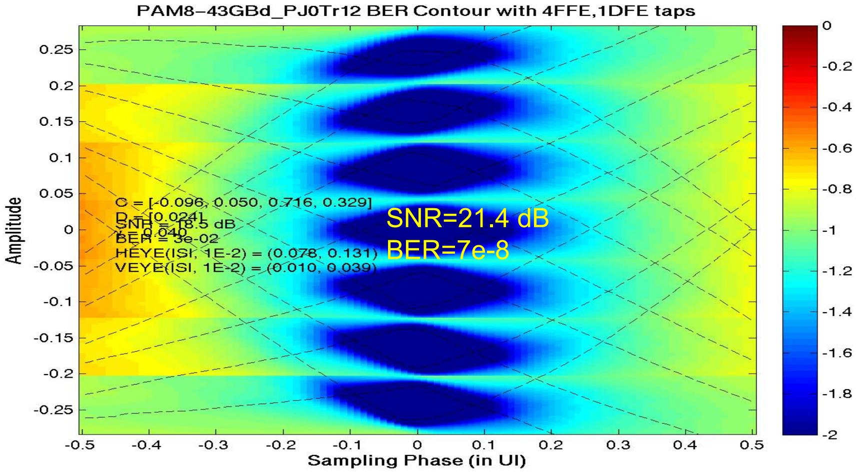
- Include MPI assuming 4 mid span connectors + TOSA/ ROSA all with RL of -30 dB
  - With post EQ SNR=19.9 dB and BER of 5e-6

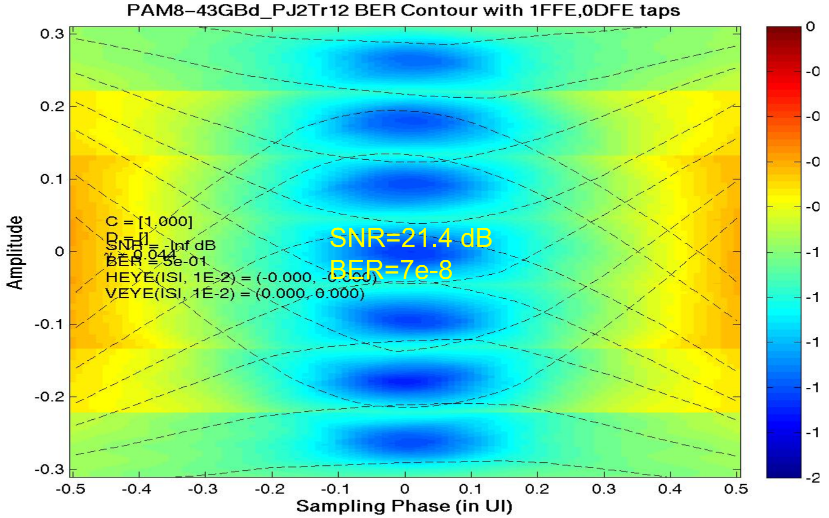


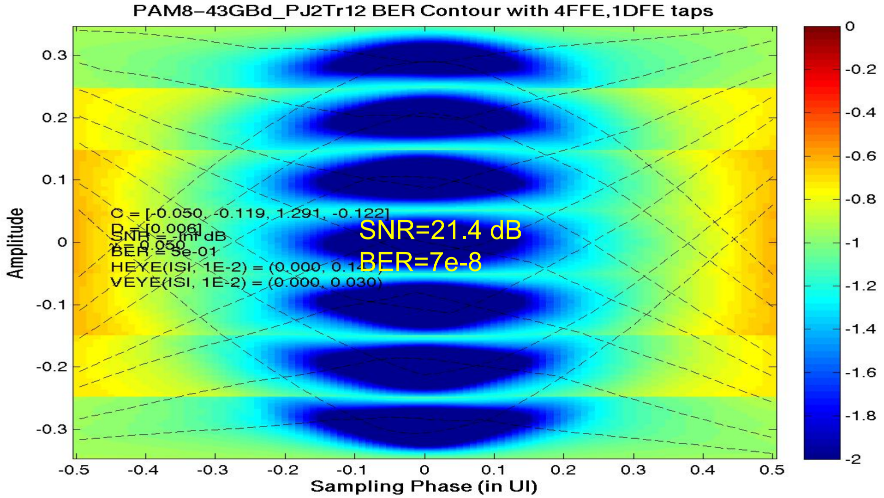
PAM-8 Eyes at 43.6 GBd with All Impairments Except MPI

- Without /with 2 ps PJ/DJ and equalization



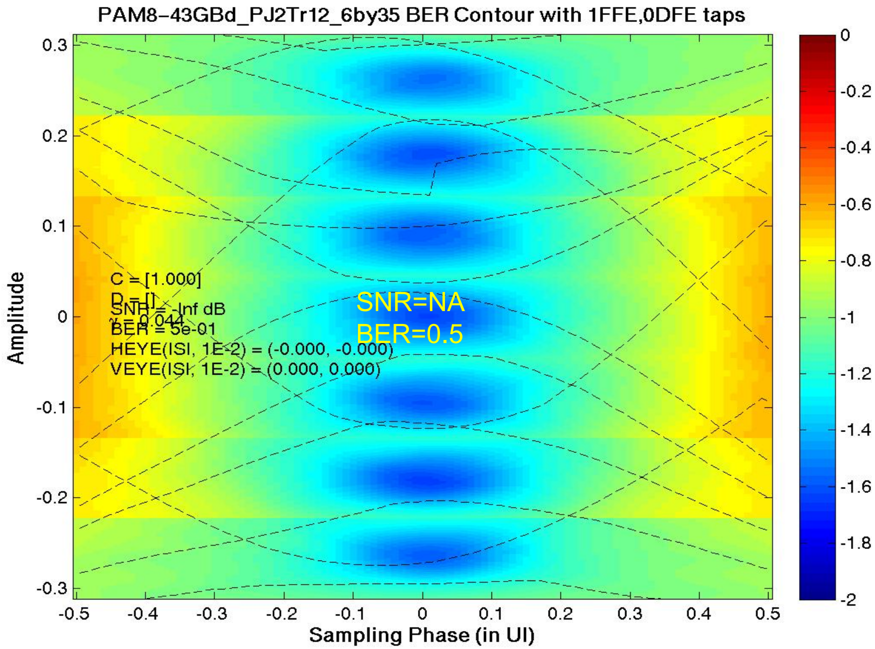


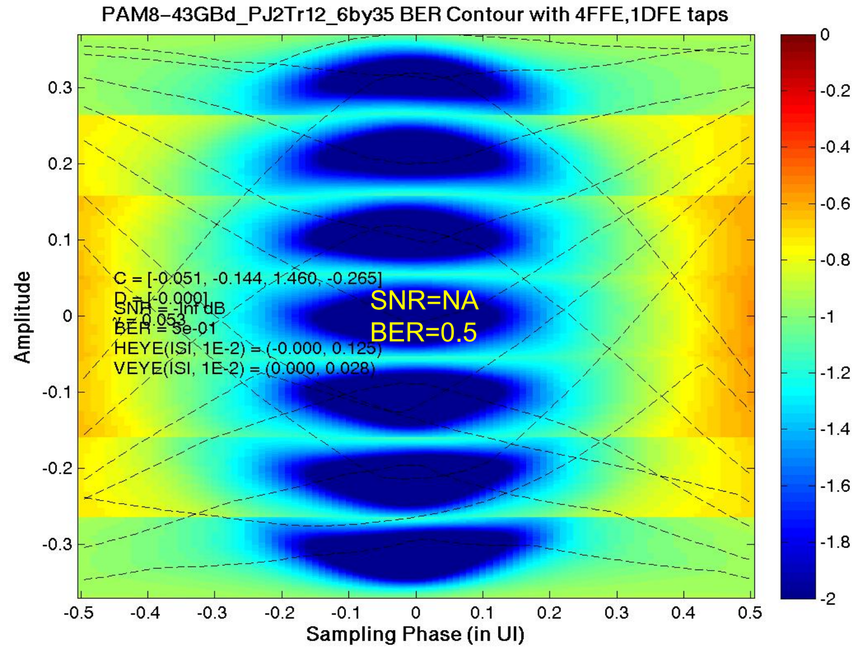




PAM-8 Simulation Eyes at 43.6 GBd with All Impairments

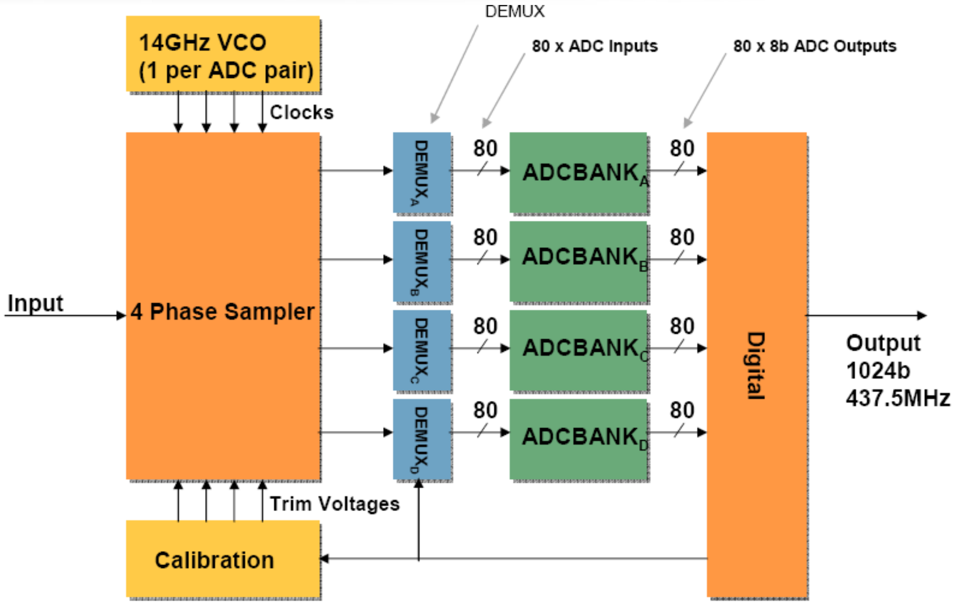
- Include MPI assuming 4 mid span connectors + TOSA/ROSA all with RL of -35 dB
  - We were not able to recover PAM-8 with MPI due to limited time and require further investigation/debug
  - Proposed PAM-8 operate at 38.16 GBd instead of 43.
    - http://www.ieee802.org/3/bm/public/nov12/bhoja_01a_1112_optx.pdf





Existing 63GS/s 8 bit ADC (SAR Architecture)

- 63GS/s ADC
- 320X time interleaving
- 8 bit ADC ➔ ENOB ≈ 6bi
- 40nm CMOS process
- Power = 1250mW
- OFC 2010



- At least 1 bit saving in ENOB ~ 50% power saving
- 20nm provides ~ 50% power saving
- 34G ADC requires ~ 50% less power

http://www.fujitsu.com/downloads/MICRO/fme/dataconverters/OFC-2010-56Gss-ADC-Enabling-100GbE.pdf

Feasibility of CMOS Operating at 38.16 GBd to 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-6 DAC and ADC have ENOB of 5.5 bits
  - Assuming PAM-8 DAC and ADC have ENOB of 6.4 bits

PAM-4 vs PAM-8	PAM-4		PAM-6		PAM-8	
Loss at 14 GHz /in	Std MZM	Seg MZM	Std MZM	Seg MZM	Std MZM	Seg MZM
CAUI-4 System Interface (W)	0.80	0.80	0.80	0.80	0.80	0.80
Laser (W)	0.13	0.13	0.13	0.13	0.20	0.20
TEC (W)	0.00	0.00	0.00	0.00	0.00	0.00
Mod Driver or Segmented Driver (W)	1.00	0.30	0.80	0.25	0.80	0.25
DAC or Gearbox/Bitmux (W)	0.21	0.21	0.22	0.19	0.30	0.18
FEC (W)	NA	NA	0.25	0.25	0.35	0.35
TIA (W)	0.15	0.15	0.13	0.13	0.13	0.13
ADC (W)	0.32	0.32	0.46	0.46	0.57	0.57
Total PD (W)	2.6157	1.9121	2.7805	2.2005	3.1436	2.4717

Summary

- We have investigated unipolar PAM-n modulation and associated FEC
  - Optical channel having RIN, MPI, and compression results in exponential penalty increases with higher PAM
  - As result of these penalties an optical link should be operate as fast as possible using lower order PAM and/or QAM/CAP
- PAM-8 require stronger FEC to compensate for SNR loss at cost of extra latency and overclocking
- PAM-6/DSQ-32 Baudrate is nearly identical PAM-8 with 40% overclocking Baudrate but the lower penalty allow using lighter FEC with latency very similar to BJ FEC
- PAM-4 does require ~20% faster electronics but can operate with lower gain BJ FEC
- If 4 mid-span connector is required PAM-4/PAM-6/PAM-8 all would require improve connector RL
- Optimal signaling for an optical link need to consider link impairments, latency, cost, and power of the implementation
  - PAM-4 is feasible with BJ FEC, PAM-6/DSQ-32 likely feasible with 8.7 dB BCH code, and PAM-8 at 38.16 GBd require further investigation.

Thank You