Study of PAM modulation for 100GE over a single laser

Sudeep Bhoja, Broadcom

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Contributors

- Howard Frazier, Broadcom
- Ali Ghiasi, Broadcom
- Hari Shankar, Inphi
- Francis Ho, Inphi
- Beck Mason, JDSU
- Kevin Zhang, JDSU
- Arlon Martin, Kotura
- Vipul Bhatt, Lightwire
- Chris Bergey, Luxtera
- Brian Welch - Luxtera

Supporters

- Mark Nowell, Cisco
- Gary Nicholl, Cisco
- Matt Traverso, Cisco
- Harold Kamisugi, Sumitomo Electric (SEI)
- Scott Kipp, Brocade
- Ted Sprague, Infinera
- Matt Brown, APM

Outline

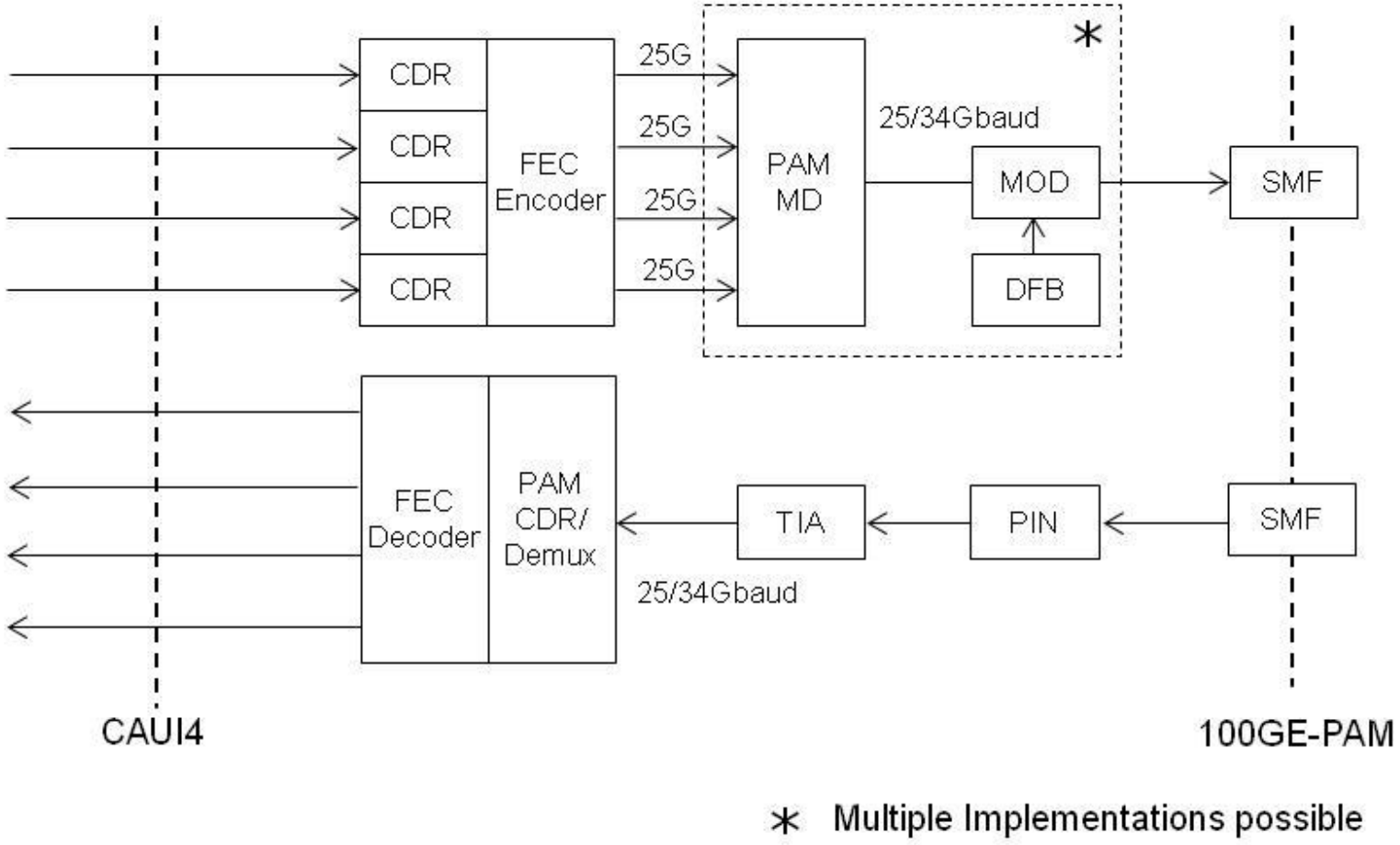
- Introduction
- PAM8 System Model
- Building Blocks
  - 2 Examples of PAM Transmitters
  - 2 Examples of Multilevel CDR/Rx
  - FEC
- PAM8 Link Budget
- PAM16 System Model & Link Budget
- Summary
- Next Steps

Introduction

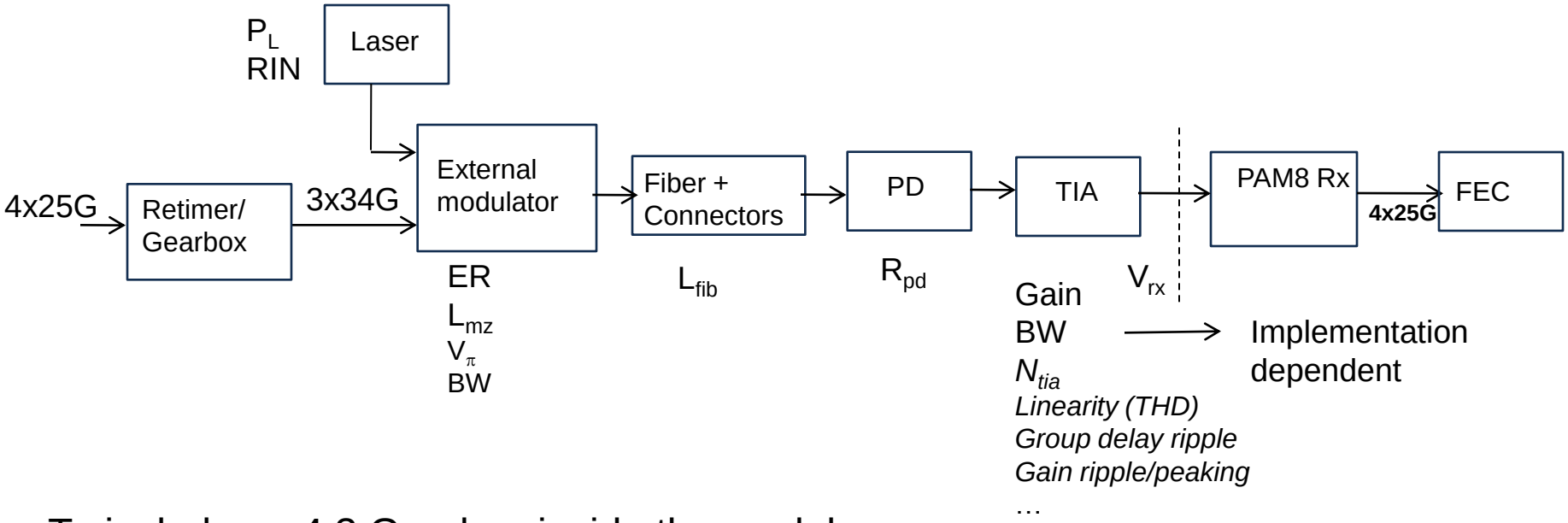
- Nowell_01_1111 suggested that alternate schemes might help deliver step function reduction in cost over 100GBASE-LR4
  - The number of lasers has direct impact on cost
- This work investigates feasibility of PAM modulation over a single laser
- PAM8 and PAM16 modulation are investigated
  - Wavelength: 1310nm
  - Optical Loss Budget: 4dB
  - Link length: 500m to 2km
  - Externally modulated laser

➢ PAM8 and PAM16 modulation are investigated

PAM Block Diagram



PAM8 System Model



- Tx includes a 4:3 Gearbox inside the module
  - ➢Converts 4x25.78125 Gb/s to PAM8 at 34.375 Gbaud
  - ➢Single Laser externally modulated to 8 PAM
  - ➢Baud Rate 34.375 Gbaud, 3 bits/baud
- A single PAM8 Rx CDR recovers the data and de-multiplexes to 4x25G
  - ➢Host based FEC targets input BER of 1E-5, output BER 1E-15

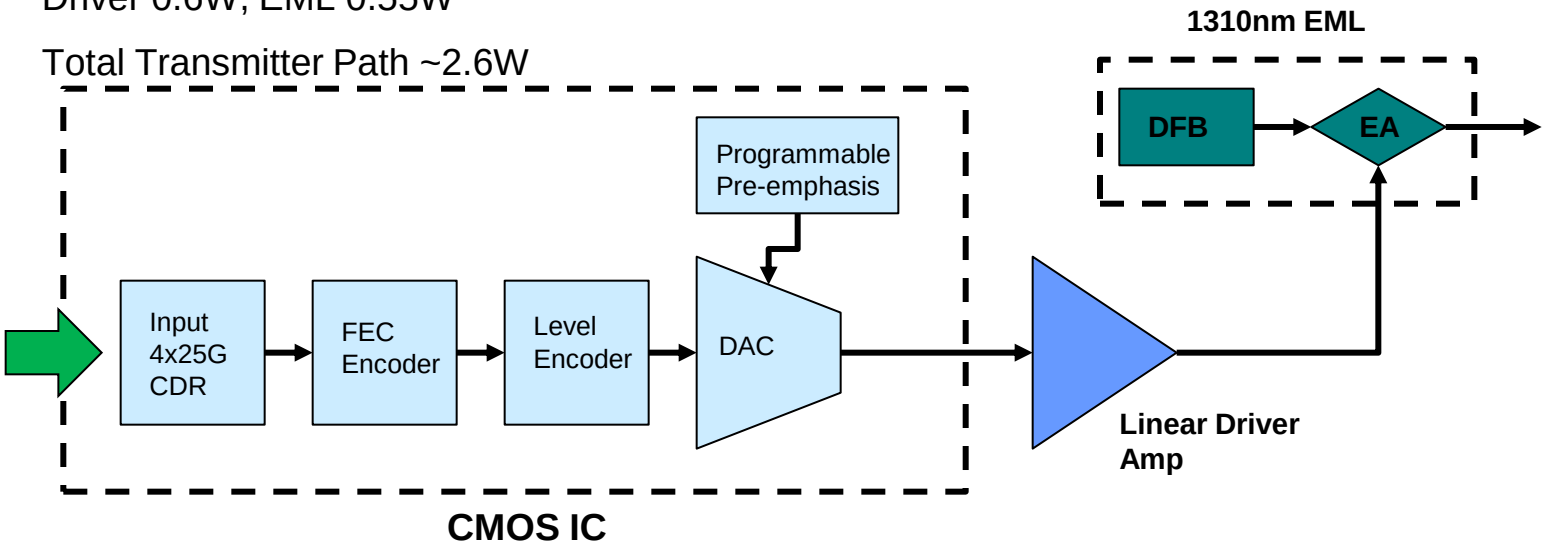
Example Multilevel Modulator - I

- Example of digital generation architecture for multilevel modulation
  - ➢Simple single 1310nm EML laser source
  - ➢CMOS IC with quad CDR, FEC encoder, level encoder, and DAC
    - ➢Level encoder and higher resolution DAC enables
      - ➢Digital linearization of modulator transfer function
      - ➢Multilevel coding with non-equal level spacing for optimum SNR performance
- Estimated power dissipation

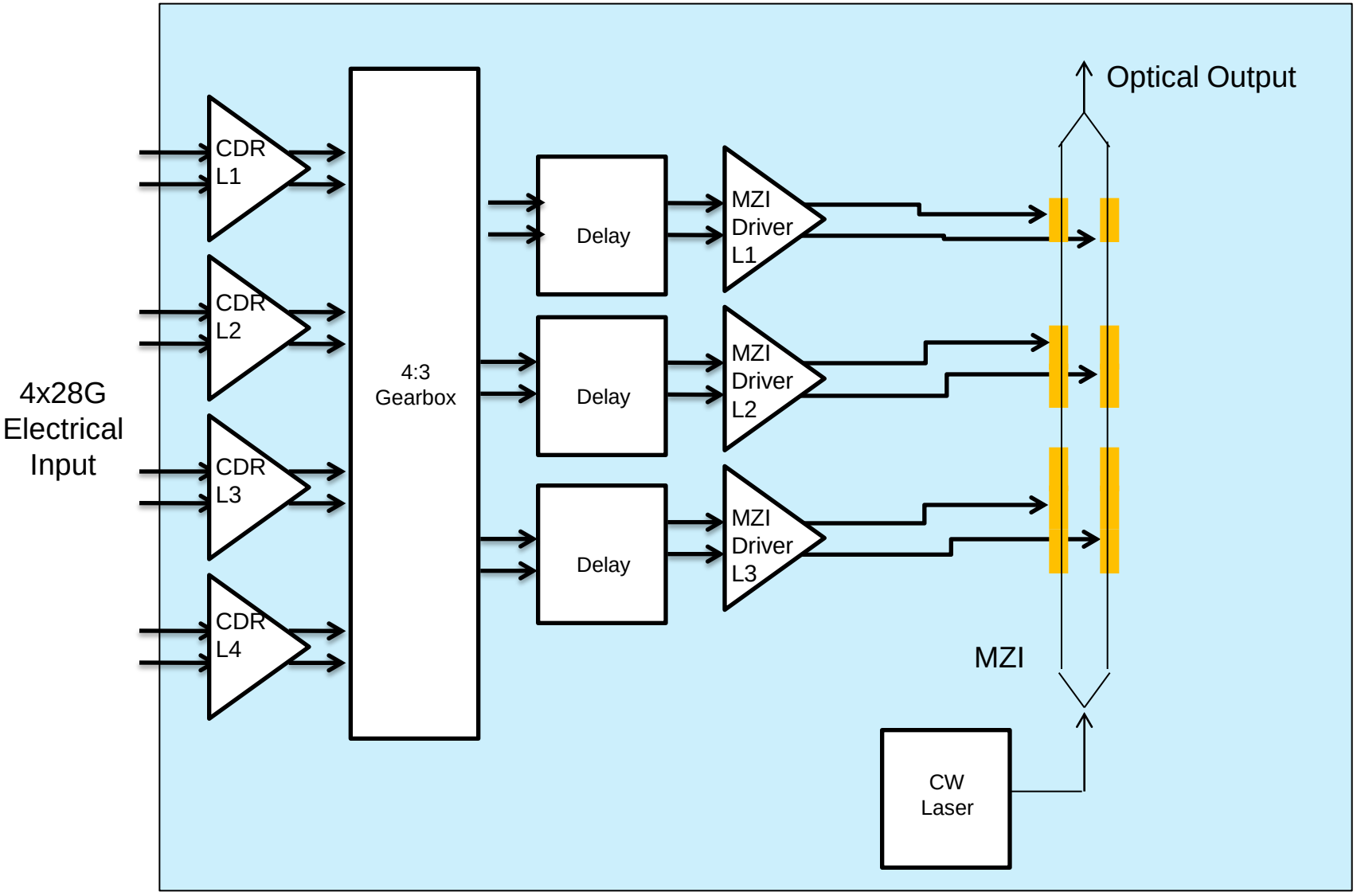
  DAC 0.4W, Quad CDR 0.8W, FEC and Encoder 0.25W – 1.45W

  Driver 0.6W, EML 0.55W

  Total Transmitter Path ~2.6W

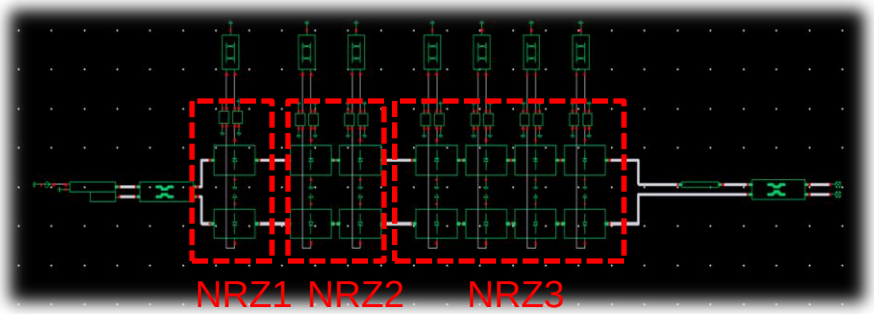


Example PAM8 Tx II – Multi-segmented MZI

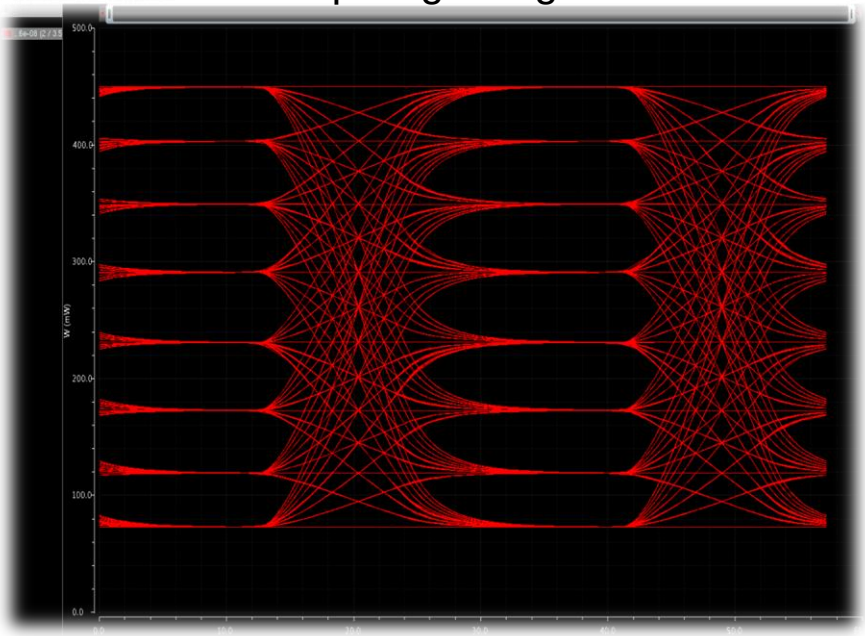


PAM-8 Transmitter in Silicon Photonics

Opto-electronic Schematic



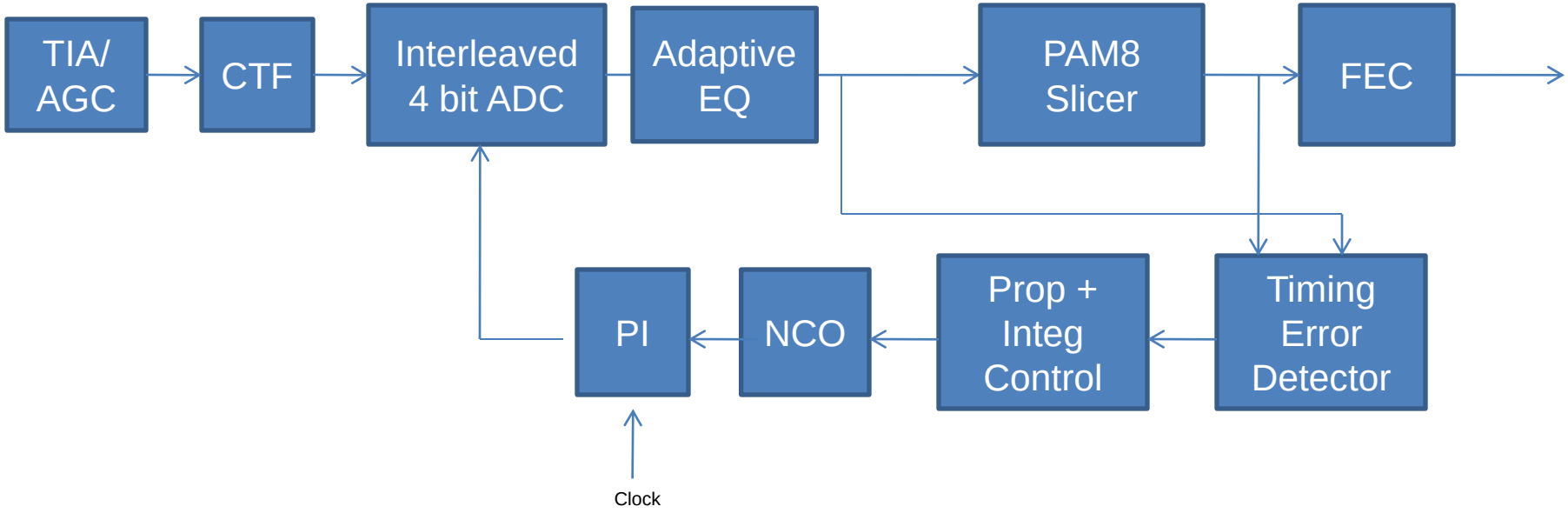
PAM-8 at 35 Gbps signaling rate



Multi-segmented MZI:

- Accepts direct NRZ encoding
- Allows for non-linear modulator drivers
  - Low Power (CMOS drivers)
  - Low Headroom
- Enables low parasitic interconnects between electronic and photonic building blocks
- Allows for better electro-optical phase matching

Example Digital Multilevel CDR/RX



- PAM8 requires a 7 level slicer to recover data
- 1 sample/bit baud rate timing recovery is commonly used for multilevel Clock Data Recovery
- 4 bit ADC sampling at 34.375 Gsamples/s

Digital Multilevel Rx feasibility

- A 34GS/s parallelized baud rate timing error detector [5] and CDR implementation is feasible
- A 5.1 ENOB low power ADC at 10 Gbps KR line rate in 65 nm has been demonstrated in literature[6]
- For coherent receivers in optical communications, a 8 bit ADC at 56 Gbps has been demonstrated showing that higher ENOB, higher speed ADC's are feasible[7]
- Technology changes from 65 nm to 20 nm allow further increases in speed
- ADC POWER: <300 mW (extrapolation from reference 6&7)

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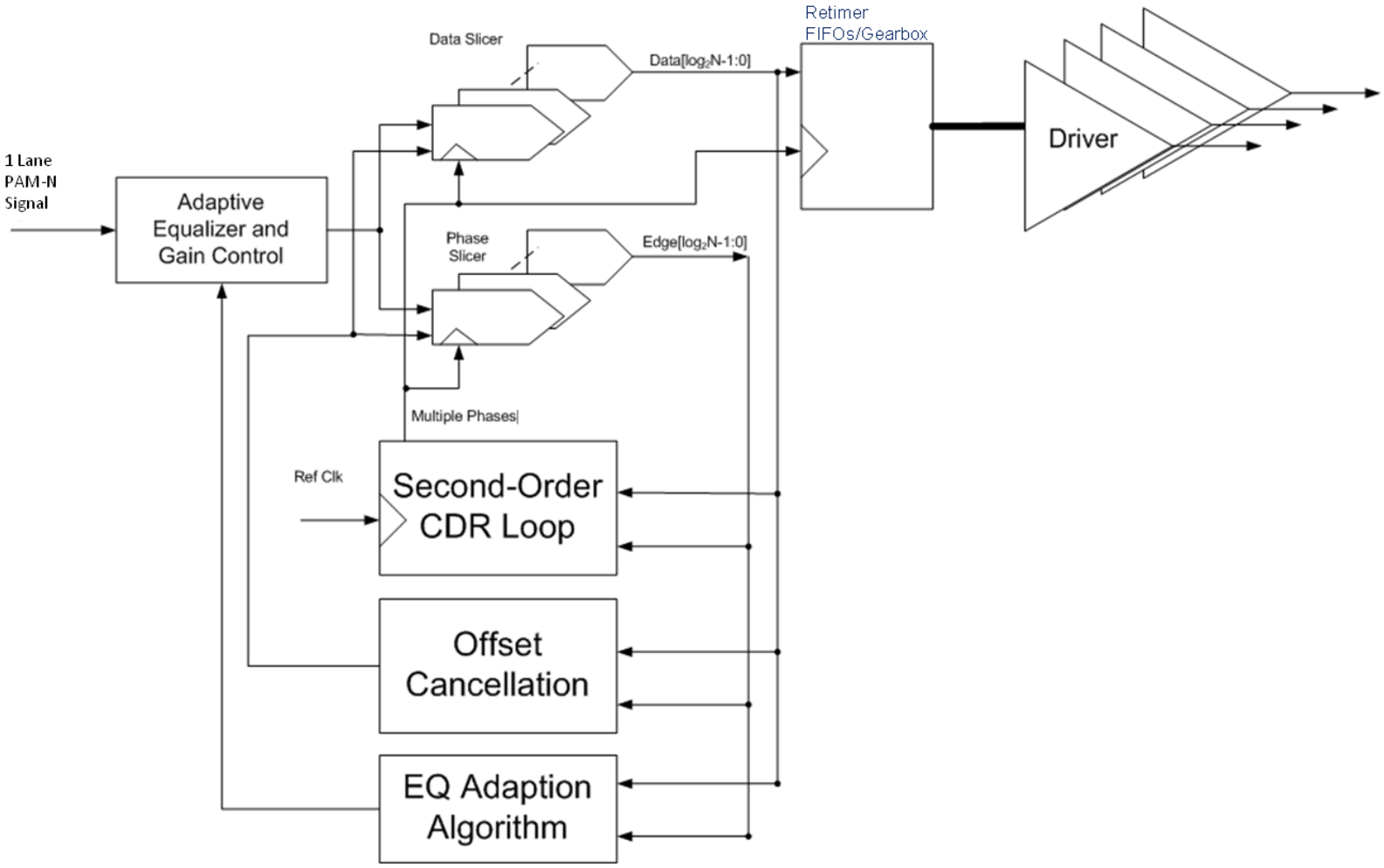
[5] K. H. Mueller and M. S. Muller, "Timing Recovery in Digital Synchronous Data Receivers", *IEEE Transactions on Communications*, vol. COM-24, pp. 516-531, May 1976

[6] J.Cao et. al., A 500 mW ADC-Based CMOS AFE With Digital Calibration for 10 Gb/s Serial Links Over KR-Backplane and Multimode Fiber", *IEEE Journal on Solid State Circuits*, June 2010

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

Example Of An Analog Multilevel CDR/RX



- Analog and digital PAM CDR/Rx architectures are possible

FEC feasibility

- Block codes which provide 5 dB coding gain are readily available and have been presented at IEEE [9,10]
- G.975 RS(255,239) already implements a FEC with 6dB gain at ~10.5 Gbps
- Example 100G FEC – 0% overhead
  - ➢512b/514b transcoding to extract overhead information
  - ➢RS(528, 514, t = 7) over GF(2^10), supports 1E-5 input BER
  - ➢Possibly reuses 100G FEC designed to support front panel DAC, SR4 and backplanes
  - ➢Metrics from synthesis in 40nm (gustlin_01_0112)
    - ➢Latency: 99.4ns
    - ➢Total Area (40nm gates): 275K gates
    - ➢Power: 101mW

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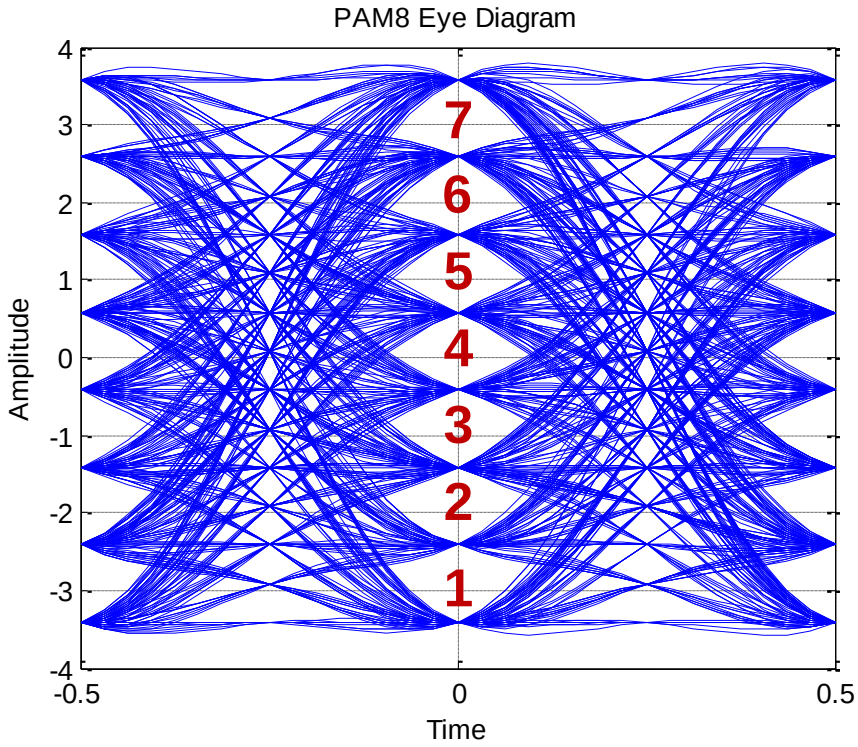
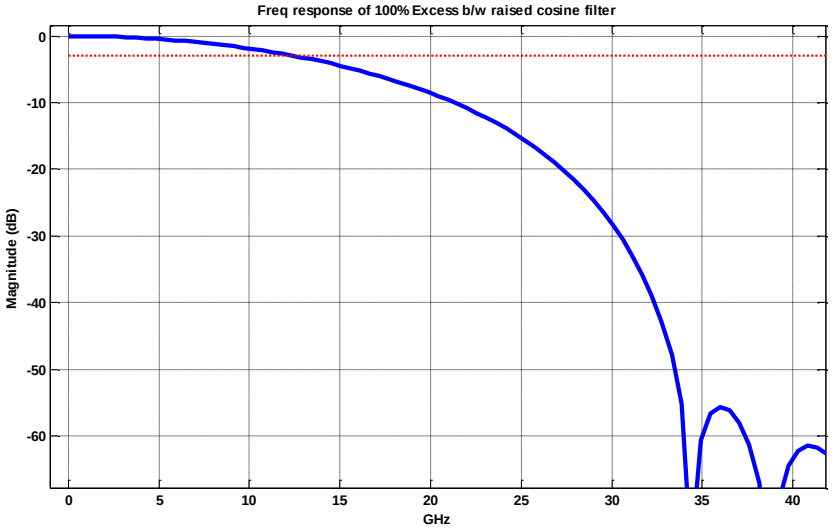
[10] http://www.ieee802.org/3/bj/public/nov11/cideciyan_01a_1111.pdf, R. Cideciyan and J. Ewen, IEEE Nov 2011

9 http://www.ieee802.org/3/100GCU/public/mar11/gustlin_02a_0311.pdf, S. Bhoja and M. Gustlin, IEEE March 2011

PAM8 Rx Eye

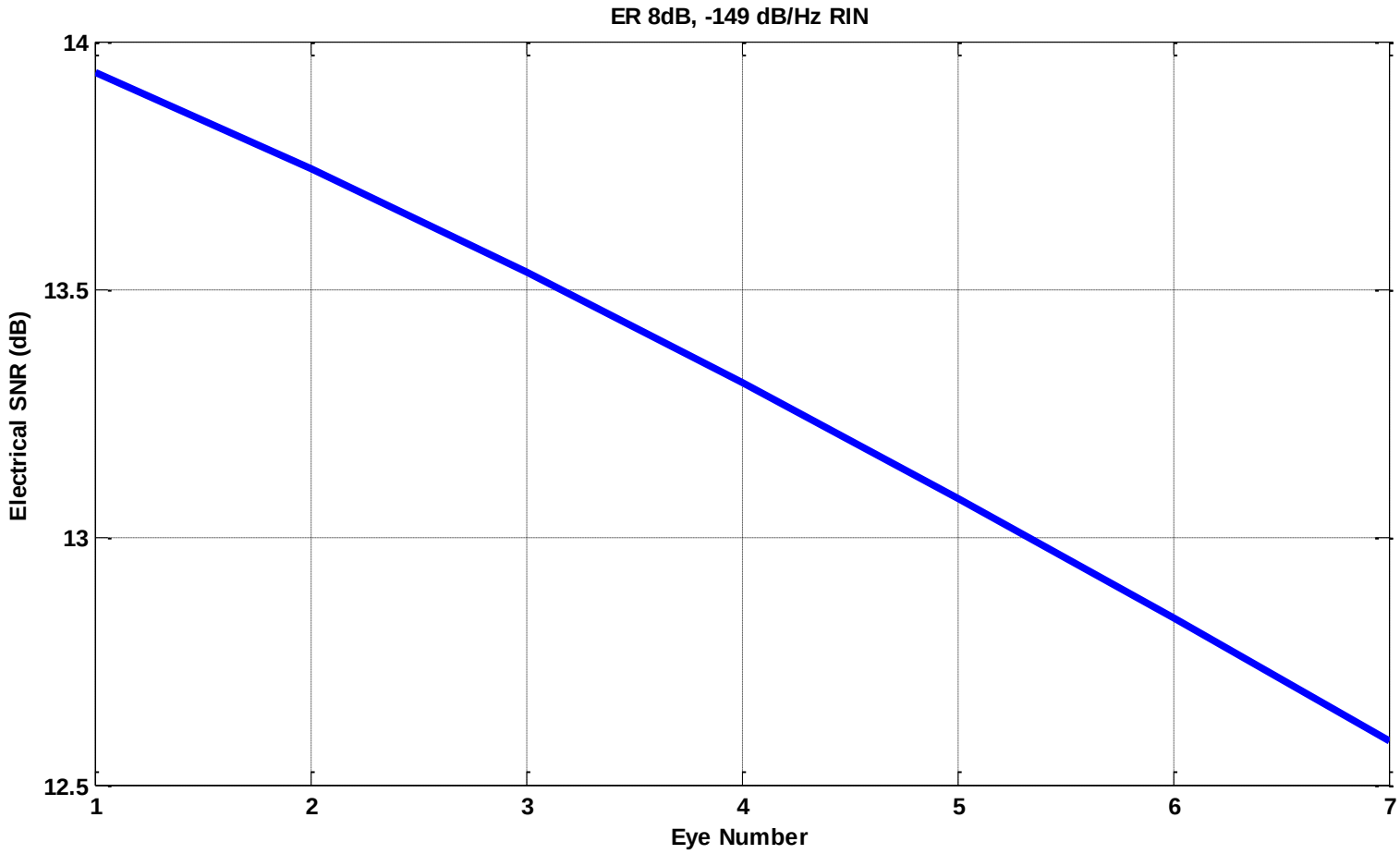




- 100% Excess Bandwidth – Ideal Raised cosine
  - ➢3dB BW 12.5GHz, 0.4UI Horizontal Eye Opening (Qualitative Metric. See bliss_01a_1111 in 802.3bj for detailed discussion)
- 8.4dB Optical penalty, 7 “inner eyes”
- SNR is computed for each individual eye

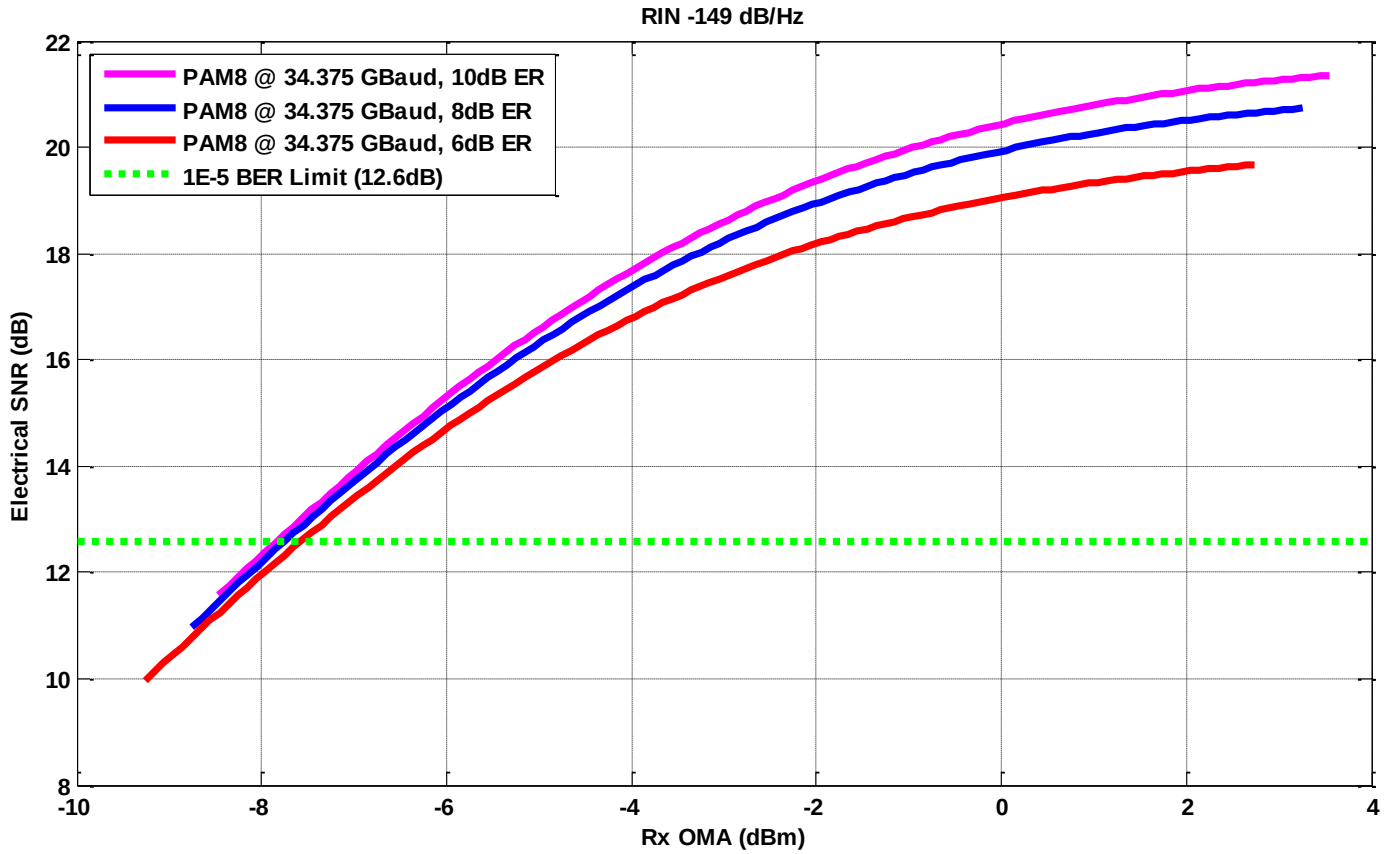
SNR_l (dB) = 20 * log10((V_l – V_{l-1}) / ($Sigma_l$ + $Sigma_{l-1}$))

PAM8 Rx SNR



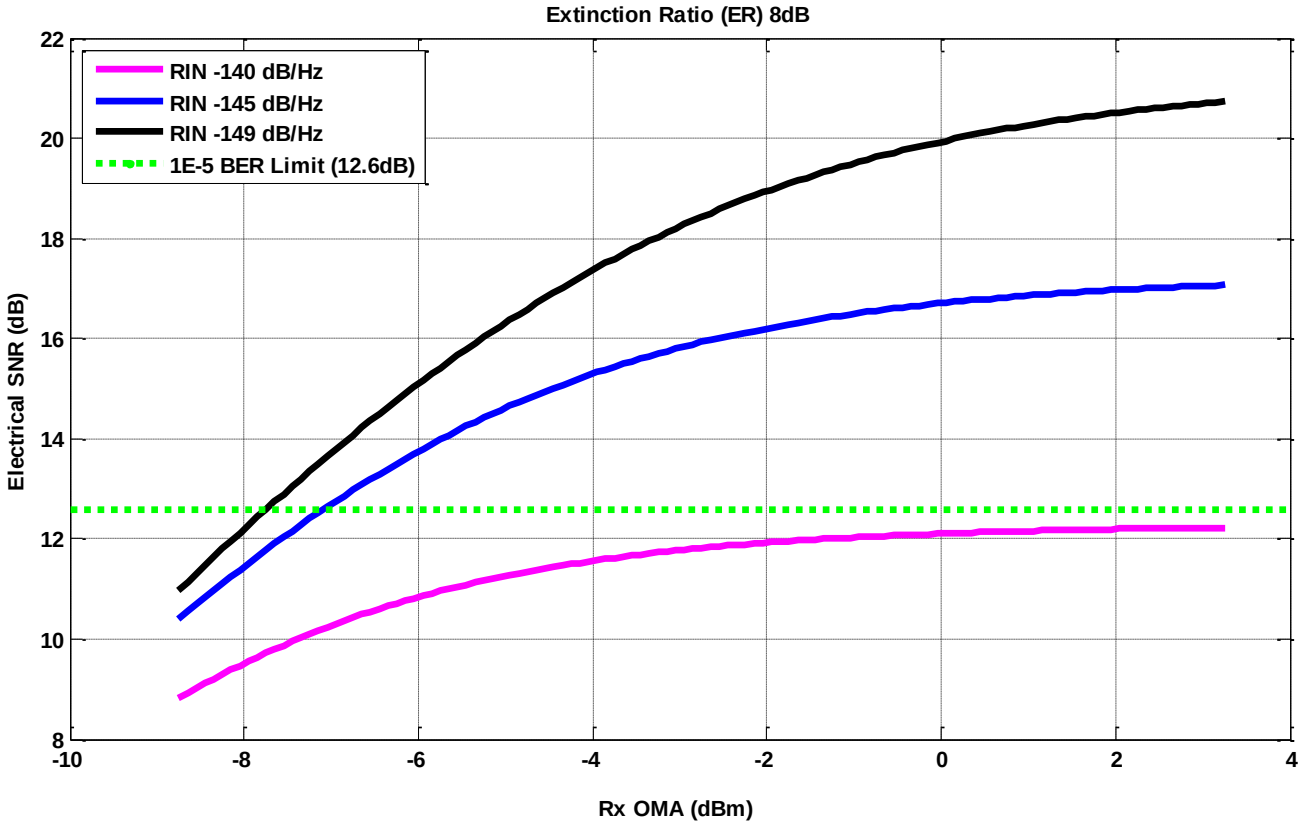
- Noise is signal dependent resulting in variation of SNR
- Equal spacing at Tx results in 2dB SNR variation among 7 “sub-eye” diagrams
- Worst case SNR assumed in subsequent link budget

PAM8 Rx performance (ER)



- Extinction Ratio varied from 6-10dB
  - ER defined as ratio of 7th level (P7) to 0th level (P0)
- -7.75dBm Rx Sensitivity with RIN, Shot and thermal noise for ER = 8dB

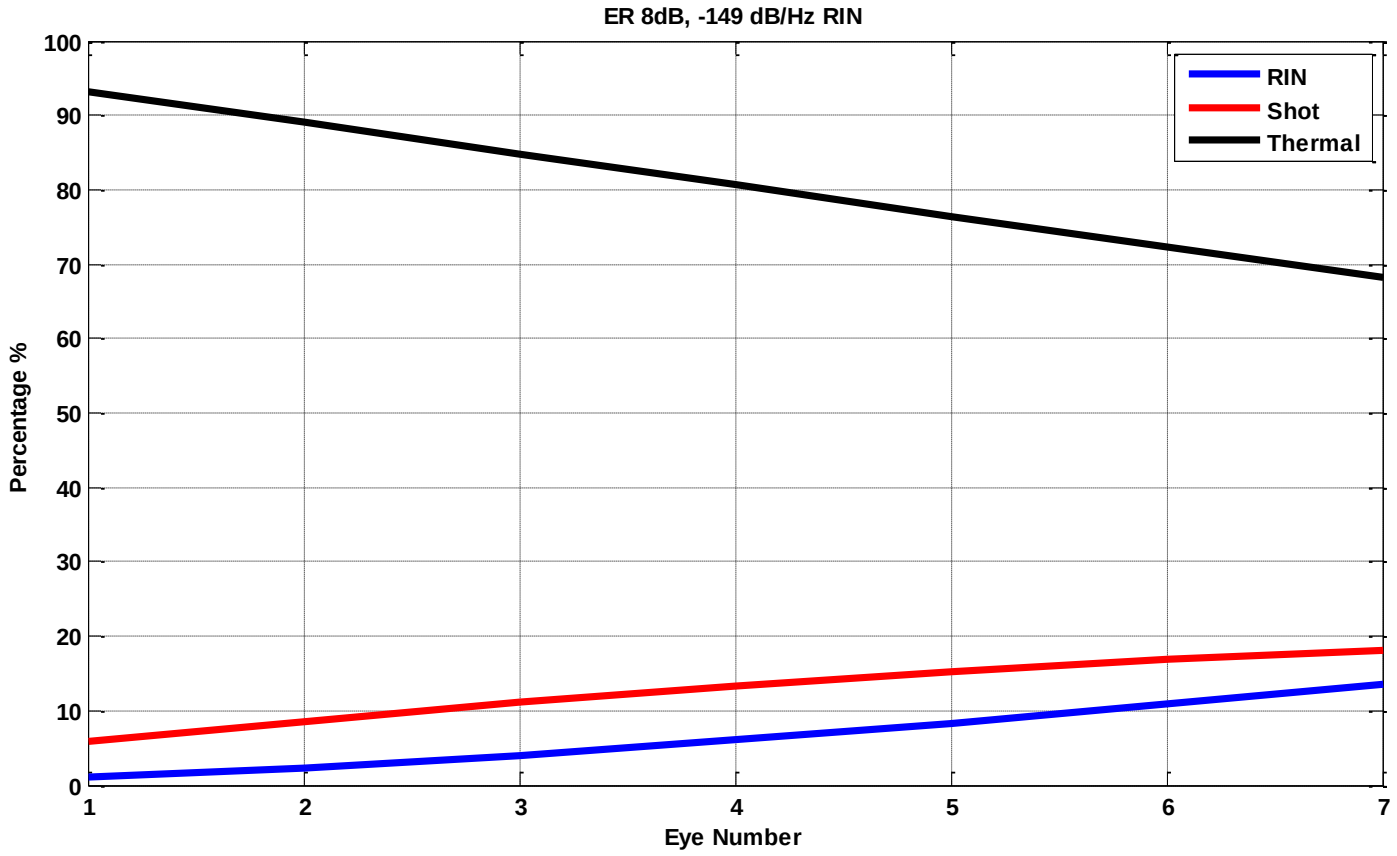
PAM8 Rx Performance (RIN)



- -140 dB/Hz RIN results in error floors
- -149 dB/Hz RIN provides very good performance.
- RIN can be low when laser operates at high power and CW

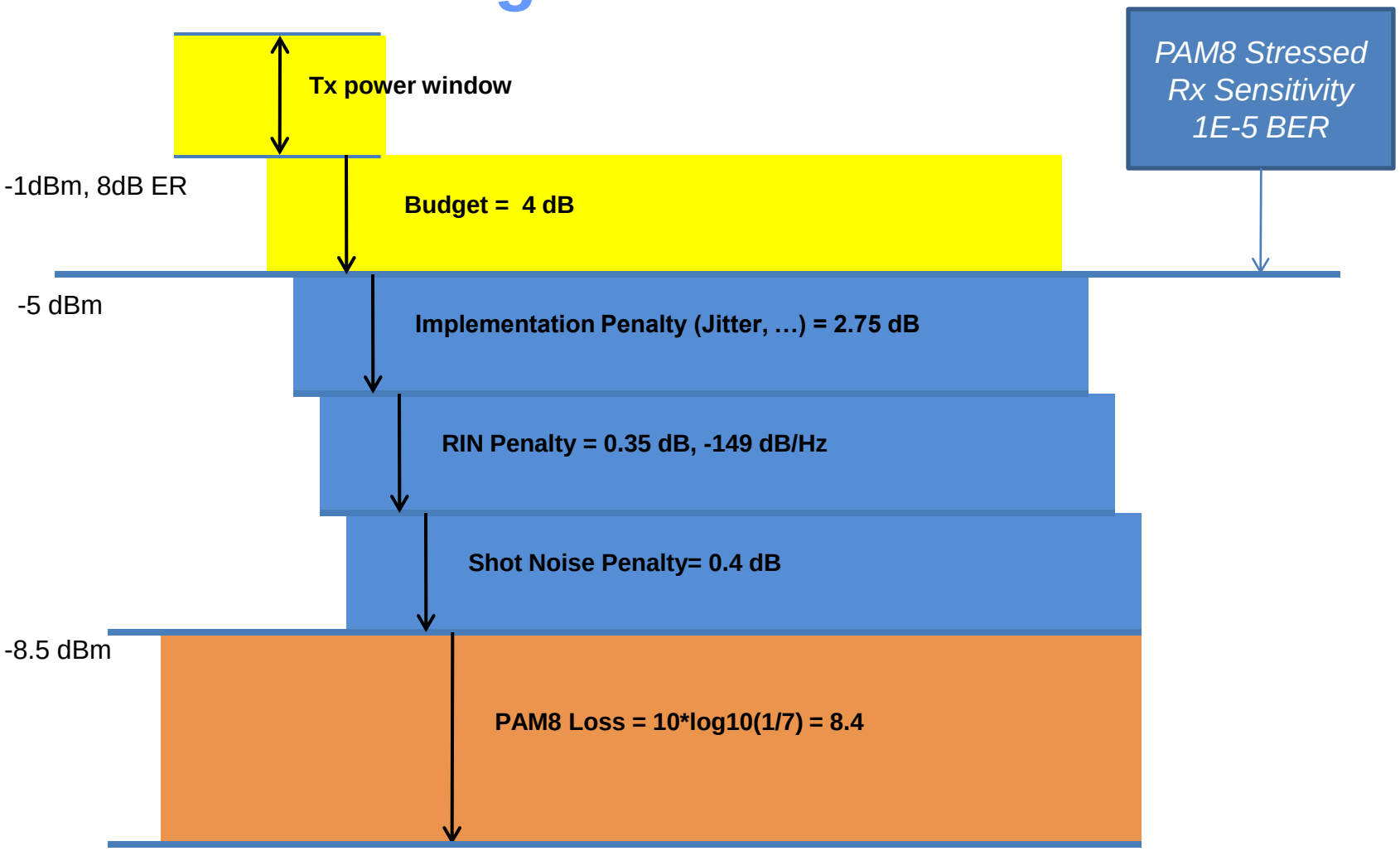
[1] Huang, Jia-Sheng; Su, Hui; He, Xiaoguang; Lei, Chun; Zendejaz, Ruby; Agarwal, Rajiv; Lomeli, Matt; Ye, Jinlin; Chin, Heng; Kim, Harqkyun; , "Ultra-high power, low RIN and narrow linewidth lasers for C-band DWDM +100km fiber optic link," Photonics Conference , 2011 IEEE , vol., no., pp.212-213, 9-13 Oct. 2011

PAM8 Rx SNR breakdown



- Rx thermal noise dominates RIN & Shot noise

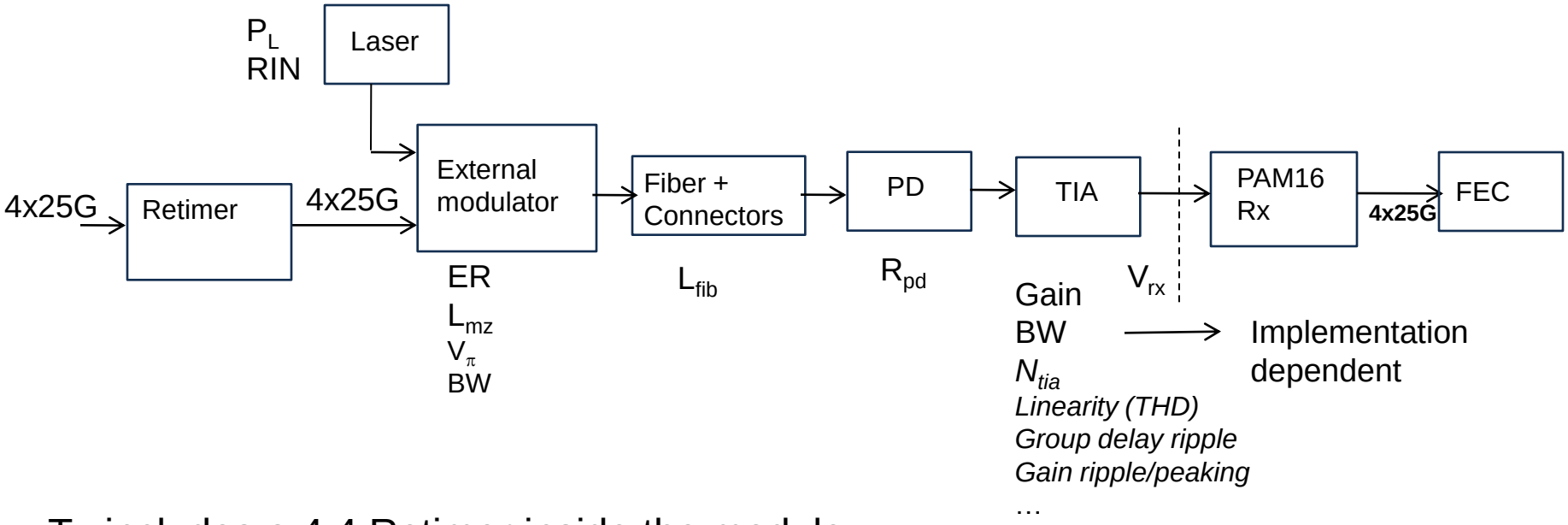
PAM8 Link Budget



-16.9 dBm 34G NRZ Optical Rx for 1E-5 BER (Assumes 15pA/sqrt(Hz), see backup)

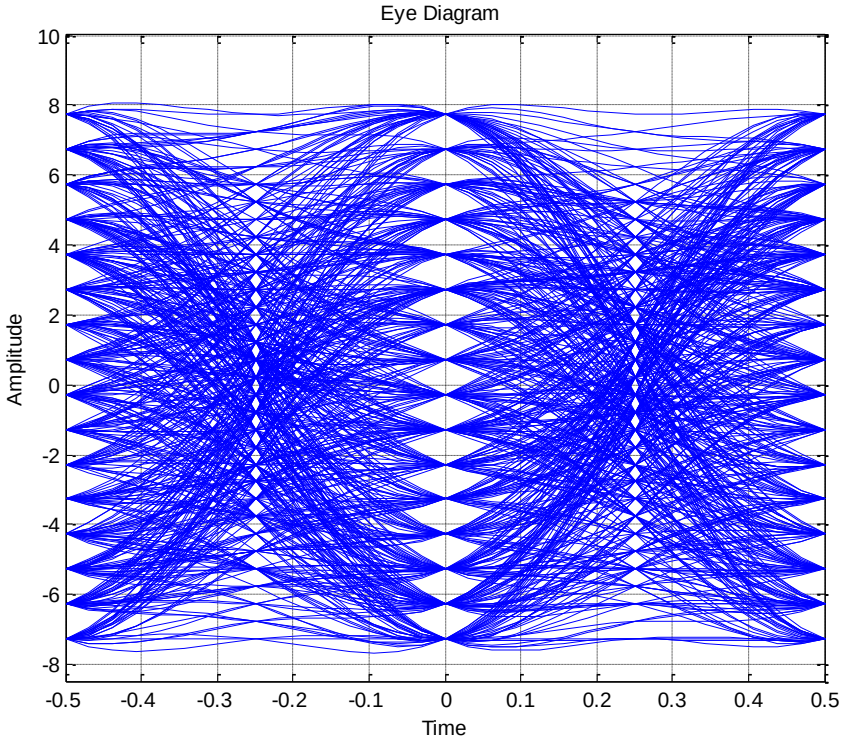
Simply a reference sensitivity of an NRZ signal at 34G

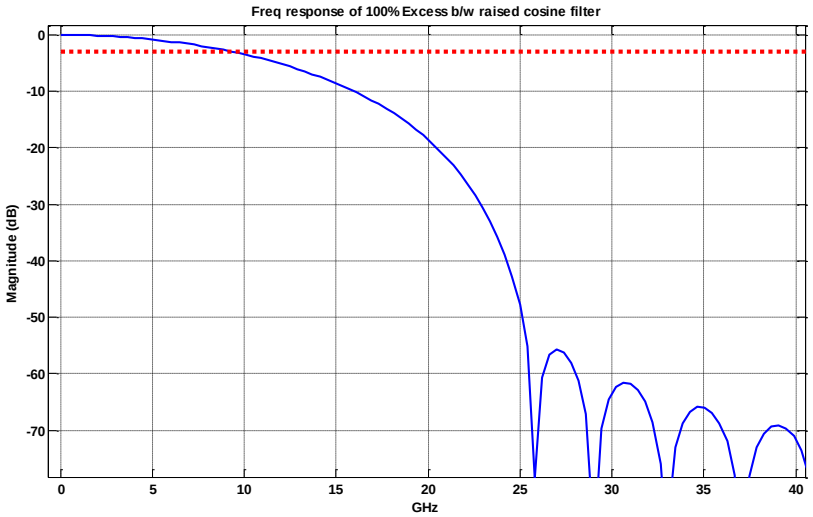
PAM16 System Model



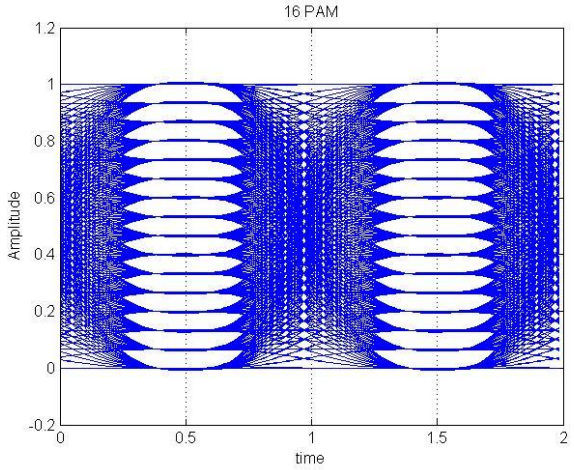
- Tx includes a 4:4 Retimer inside the module
  - ➢Converts 4x25.78125 Gb/s to PAM16 at 25.78125 Gbaud
  - ➢Single Laser externally modulated to 16 PAM
  - ➢Baud Rate 25.78125 Gbaud, 4 bits/baud
  - ➢Optionally a 28Gbaud provides for higher FEC coding gain
- A single PAM16 Rx CDR recovers the data and de-multiplexes to 4x25G
  - ➢Host based FEC targets input BER of 1E-5, output BER 1E-15

PAM16 Rx Eye



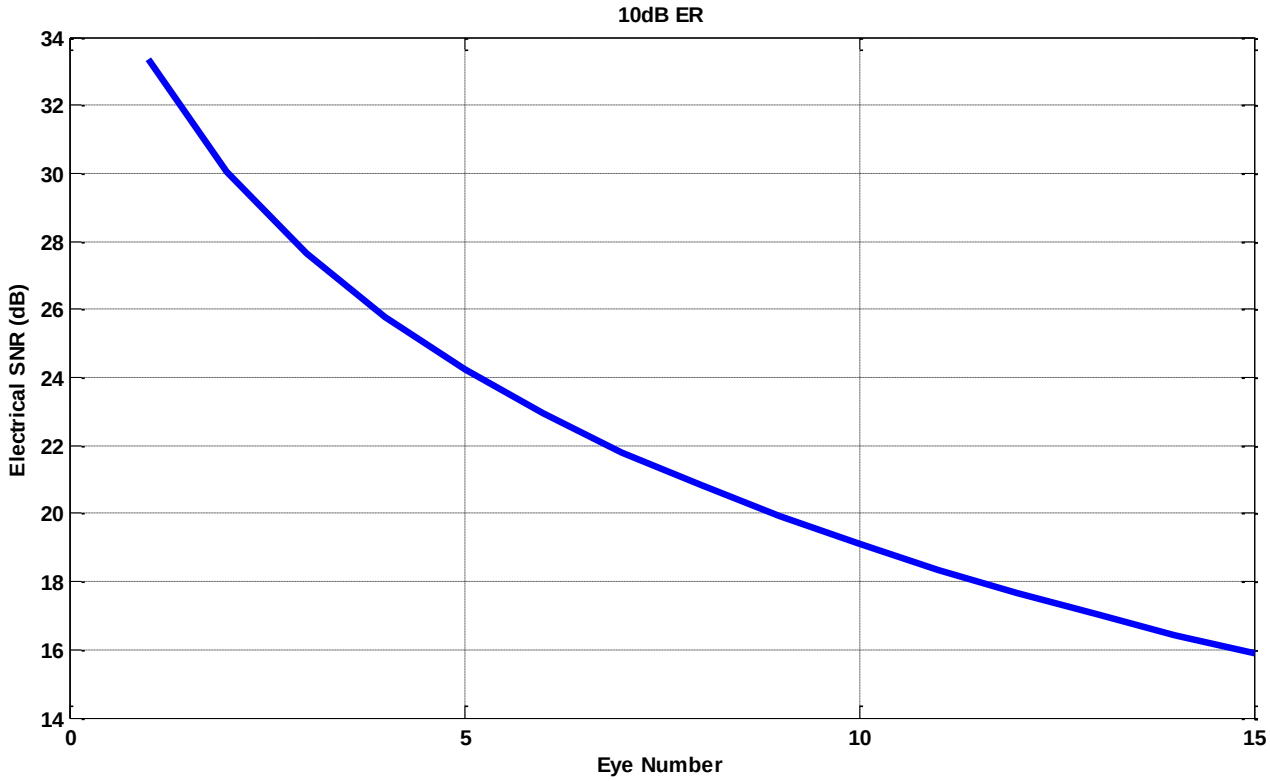


- 100% Excess Bandwidth – Ideal Raised cosine (3dB BW 9.4GHz)
- 11.76dB Optical penalty
- 0.2UI Horizontal Eye Opening. Wider bandwidth can tradeoff horizontal eye opening for reduced noise filtering. Example =>



Example: 0.4 UI, Bessel Filter (5th Order), BW = 20GHz

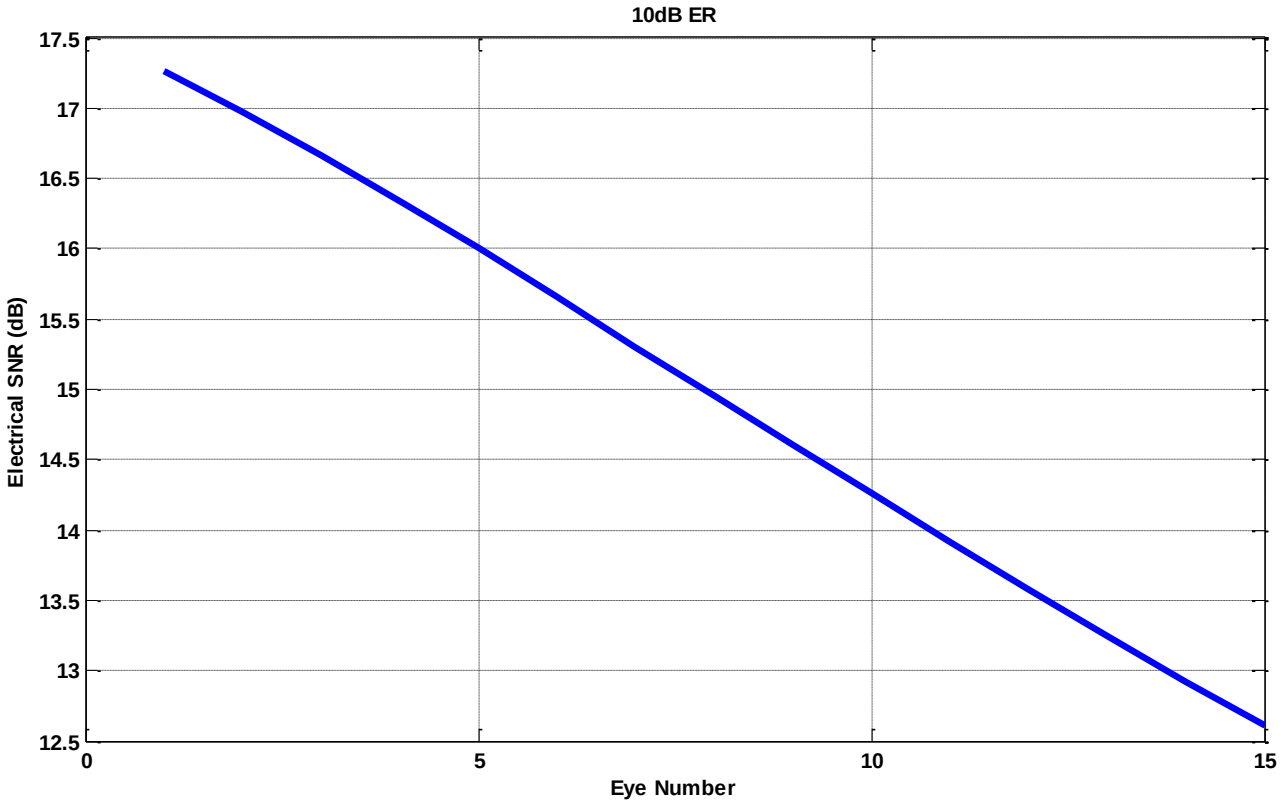
Laser RIN



- RIN @ -149 dB / Hz
- Noise is signal dependent. Wide variation of SNR
- Tx limited Electrical SNR varies from 33dB to 16dB

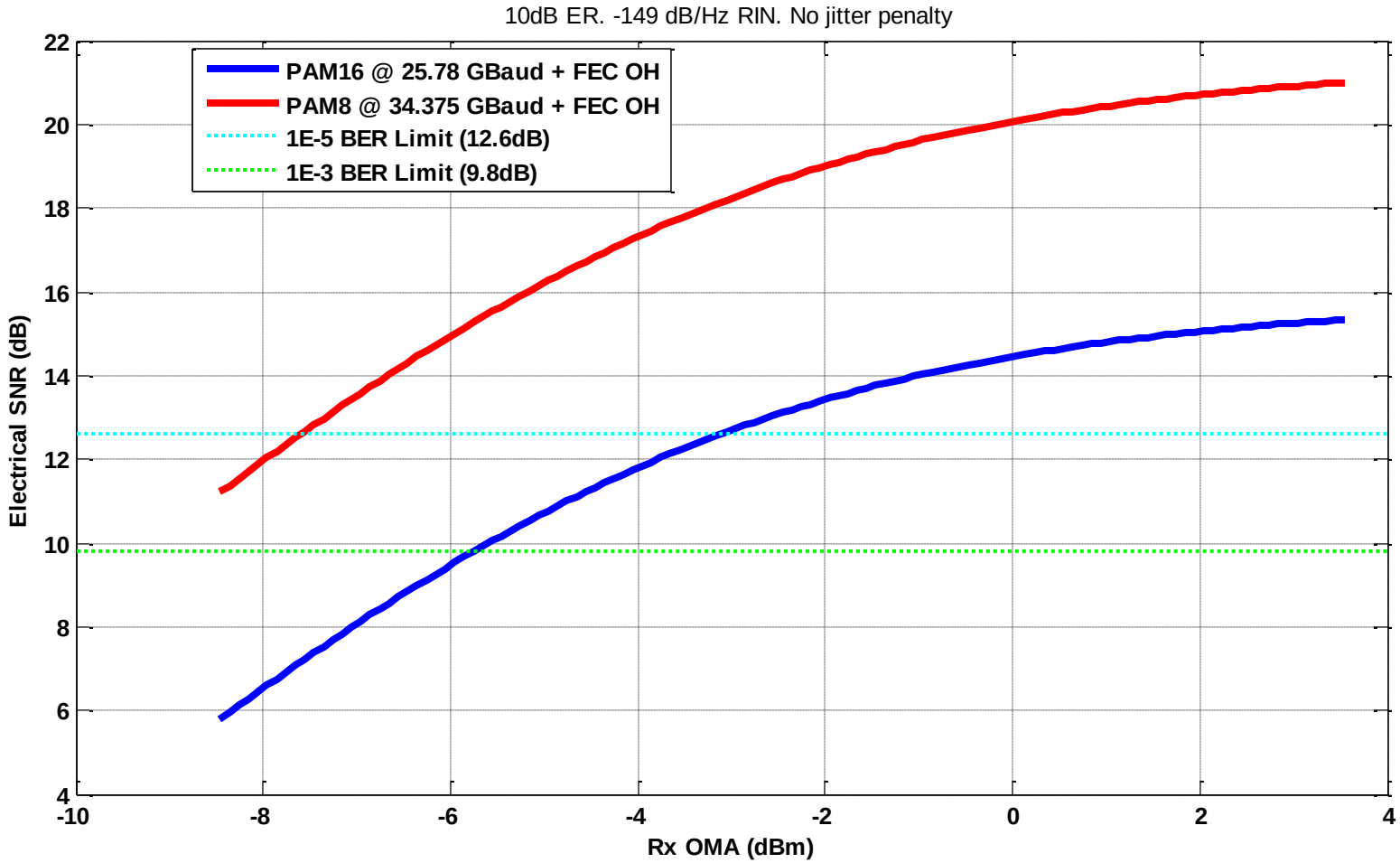
  Minimum SNR 16dB for outermost level

PAM16 Rx SNR



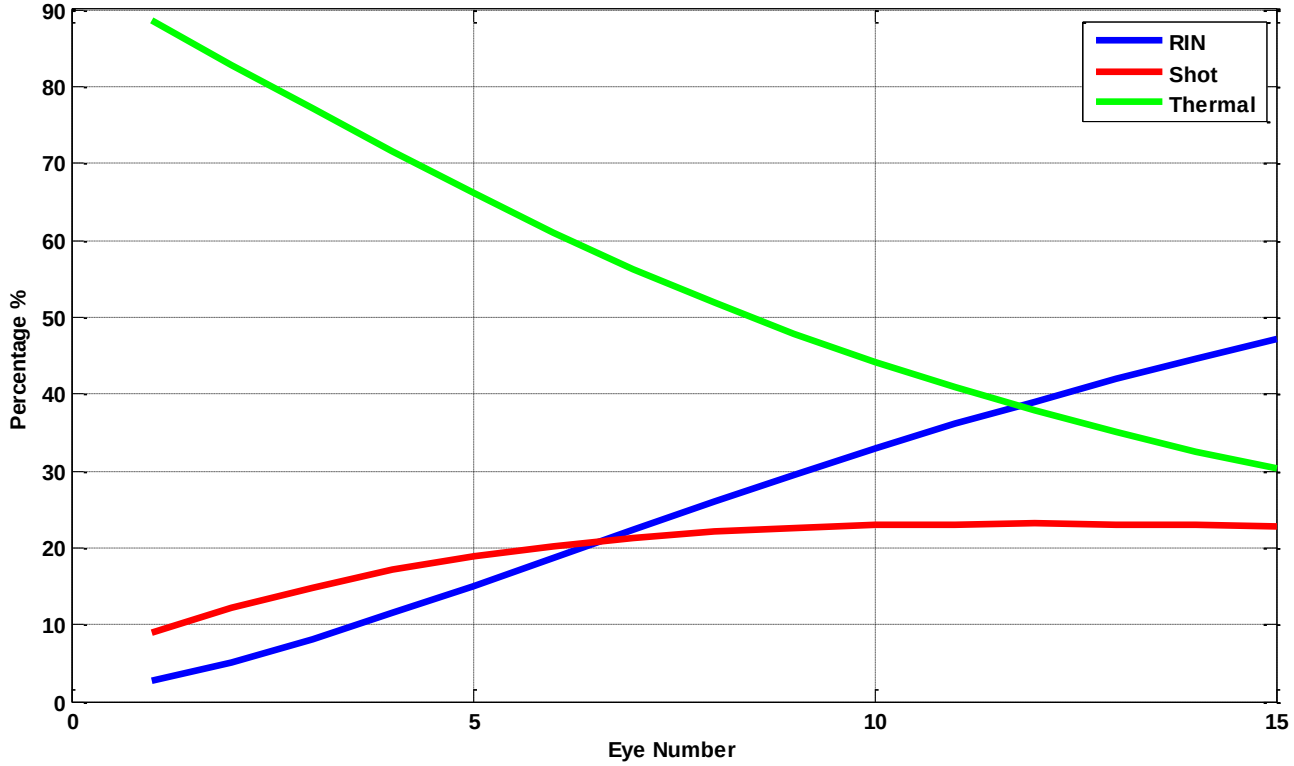
- Equal spacing at Tx results in 4.5dB SNR variation
- Can we improve PAM16 SNR with unequal spacing at the Tx?

PAM8 vs. PAM16



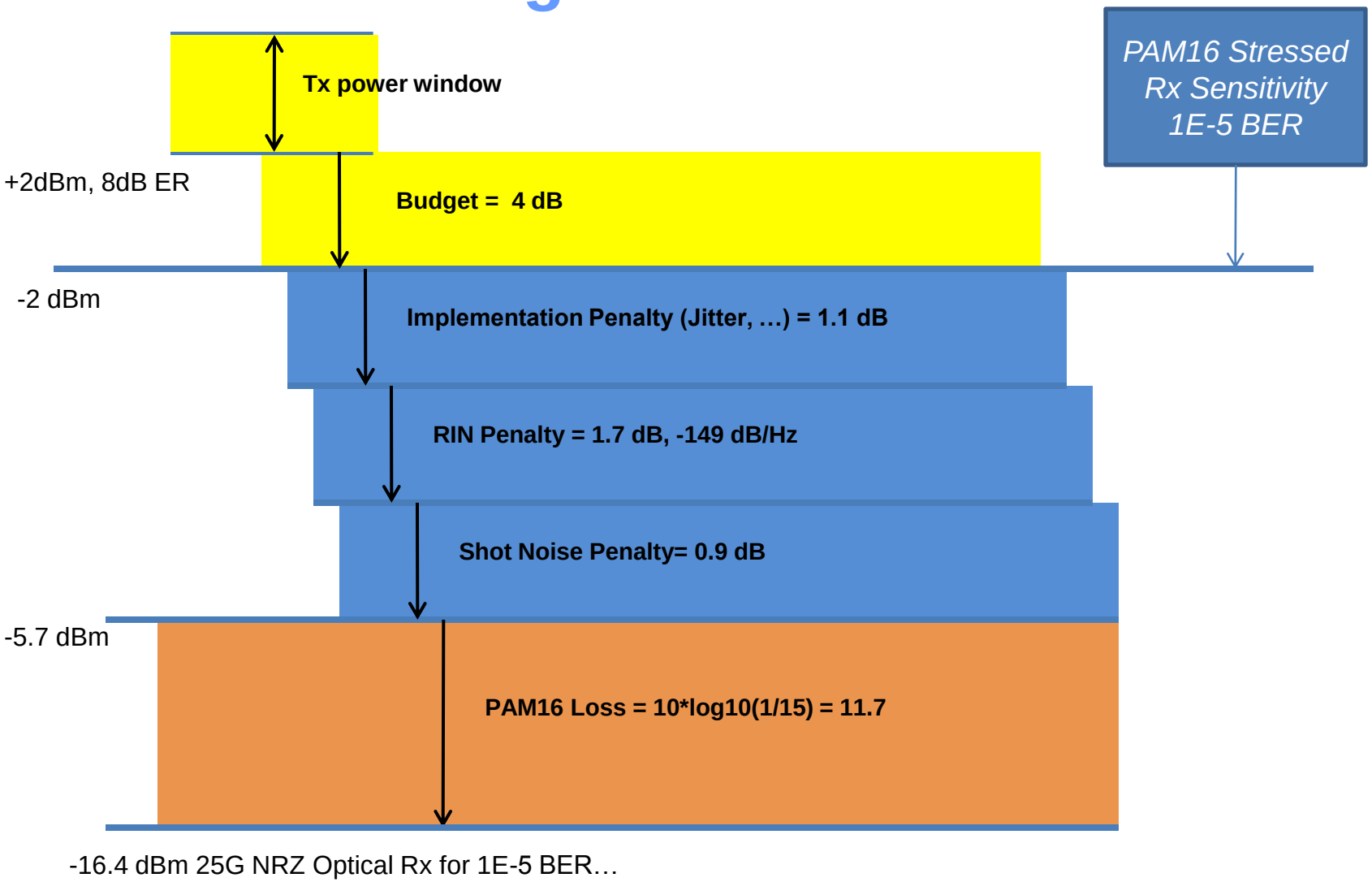
- PAM8 provides 4dB+ margin compared to PAM16
- Assumes equal spacing at PAM16 transmitter

PAM16 Rx SNR breakdown



- RIN contributes more noise than shot or thermal effects at high levels

PAM16 Link Budget



Summary

- PAM solution for 100GE using a single laser was explored and is feasible
- Multiple example implementations of external modulators and multilevel CDR were shown
- Link budgets for PAM8 and PAM16 were investigated
- Link budgets look promising, requires further investigation

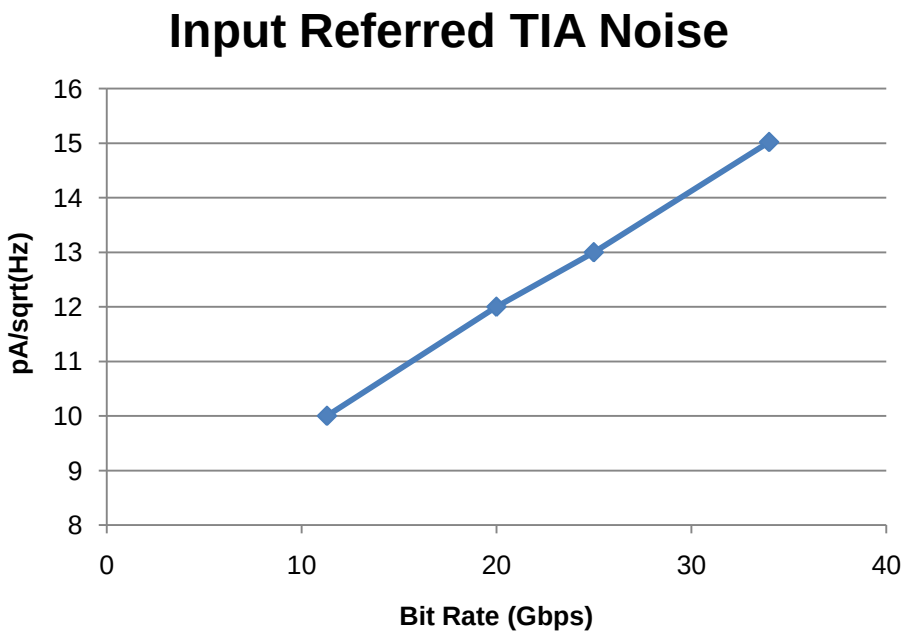
Next steps

- Investigate unequal transmit level spacing for SNR improvement
- Bandwidth tradeoffs and Jitter
- Higher FEC coding gain via coded modulation for multilevel PAM
- Linearity
- Timing Error/Jitter sensitivity to FEC output BER

Backup

34 GSymbol/sec TIA Noise

•TIA noise numbers are process and node dependent.



Gbps	pA/sqrt(Hz)	Reference
11.3	10	TI part http://www.ti.com/lit/ds/symlink/onet8511t.pdf
20	12	Schmid R., et al, "20 Gbit/s Transimpedance preamplifier and modulator driver in SiGe bipolar technology", Electronic Letters, June 1997
25	13	Chris Cole, "Technical & Economic Feasibility of 40km SMF 100GE Transceivers", IEEE 802.3 Higher Speed Study Group, May 2007, http://ieee802.org/3/hssg/public/may07/cole_01_0507.pdf
34	15.0	Extrapolated value