100Gb/s SMF PMD Alternatives Analysis

40Gb/s and 100Gb/s Fiber Optic Task Force

IEEE 802.3 Plenary Session

San Antonio, TX

13-15 November 2012

Chris Bergey, Luxtera
Sudeep Bhoja, InPhi
Chris Cole, Finisar
Ali Ghiasi, Broadcom
Jonathan King, Finisar
Ilya Lyubomirsky, Finisar
Hari Shankar, InPhi
Brian Welch, Luxtera

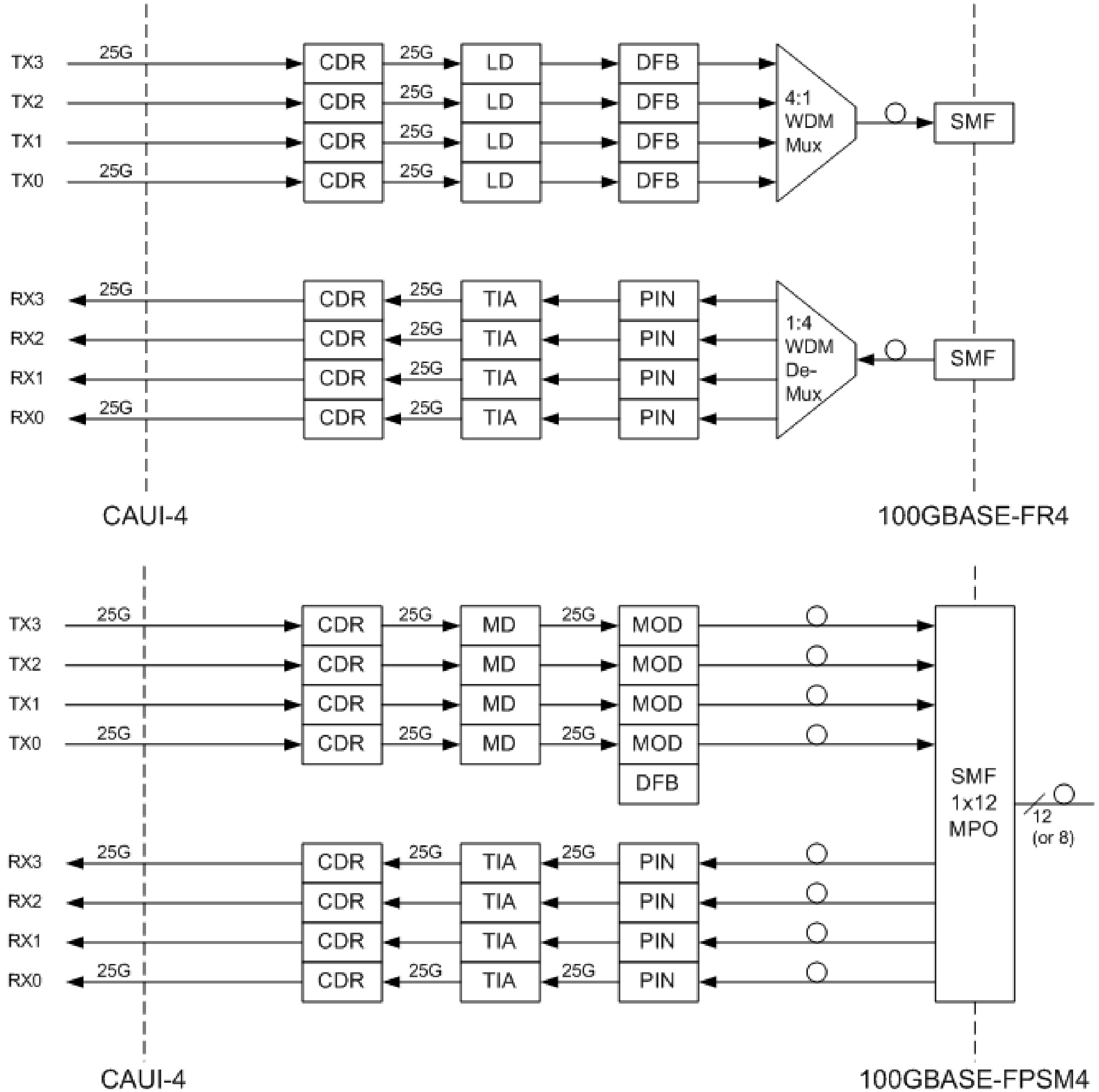
Outline

- Objectives
- 25GBaud Alternatives
- 50GBuad Alternatives
- Ideal Case Thermal Noise Limited SNR
- SNR Gain with FEC
- General Case SNR
- RIN Requirements
- Summary
- Future Work

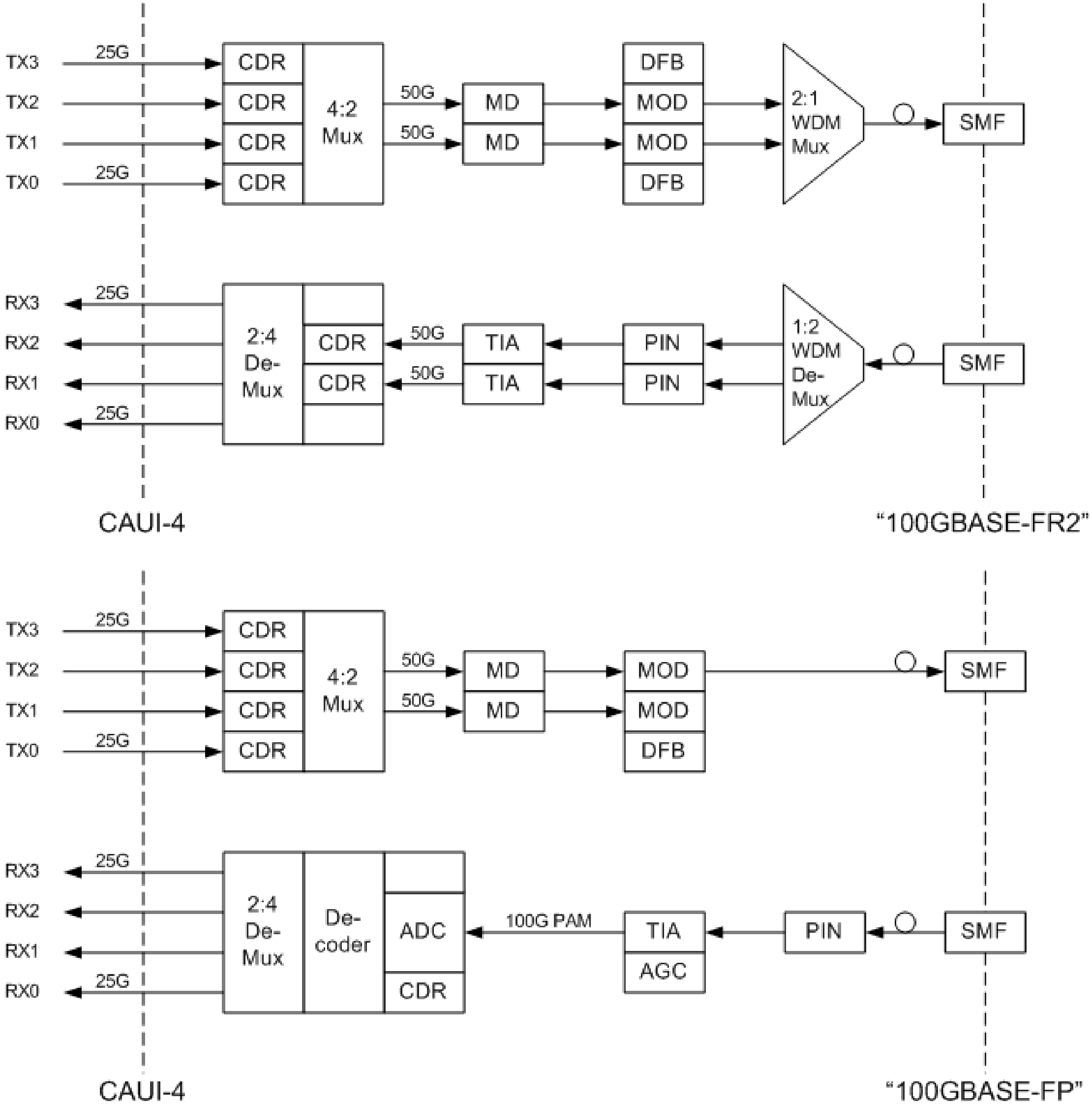
Objectives

- Continue higher order modulation analysis development from ghiasi_01a_0912 and nicholl_01b_0312
- Compare performance of 802.3bm SMF PMD higher order modulation alternatives

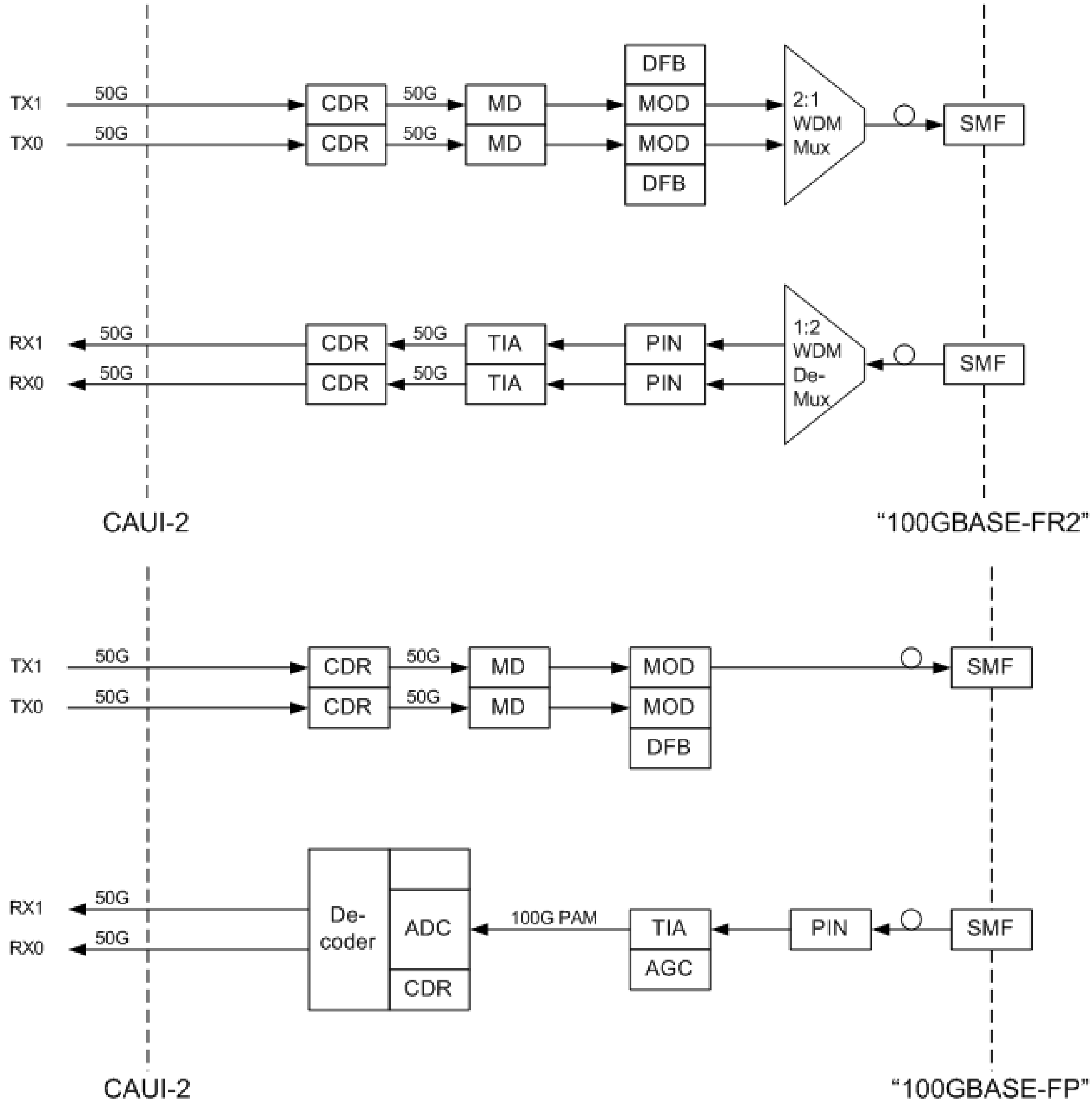
25GBaud CAUI-4 PMD Alternatives



50GBaud CAUI-4 PMD Alternatives

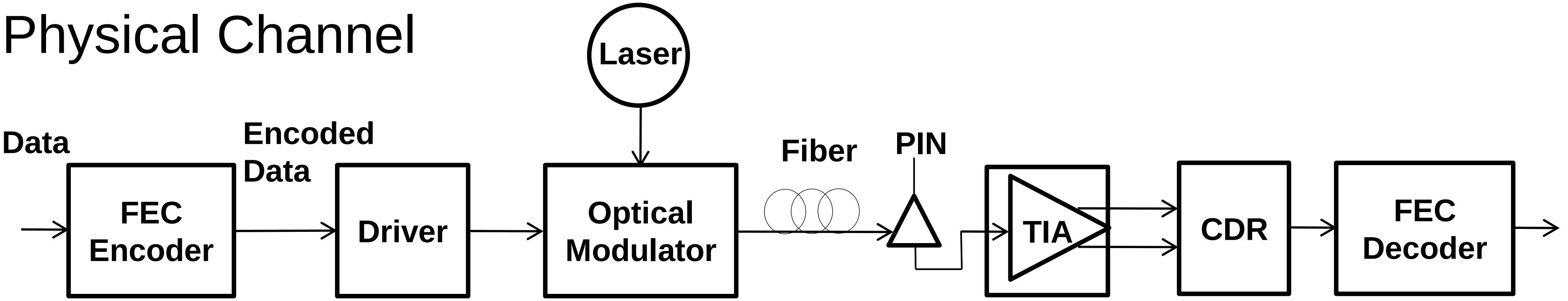


50GBaud CAUI-2 PMD Alternatives

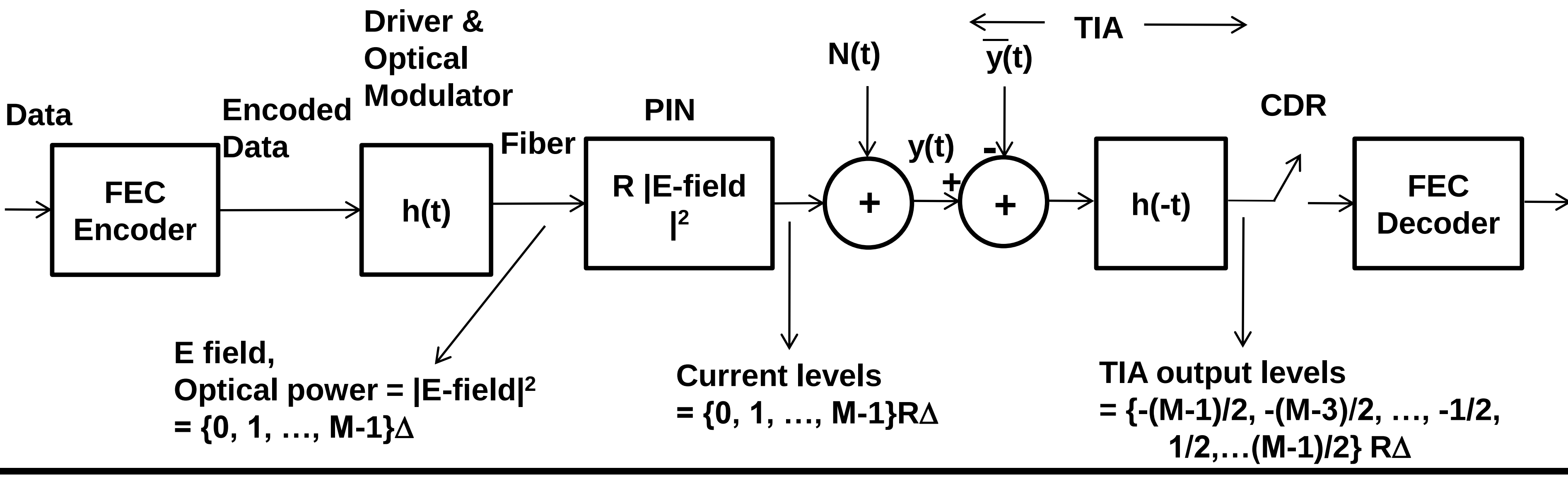


SNR Channel Model

Physical Channel



Equivalent AWGN Channel Model



Ideal Case Thermal Noise Limited SNR

- Laser RIN not included
- MPI not included
- Noise variance independent of signal amplitude
- Thermal noise >> shot noise
- BER specified by a simple formula
- SNR specified by a single number

SNR Definitions

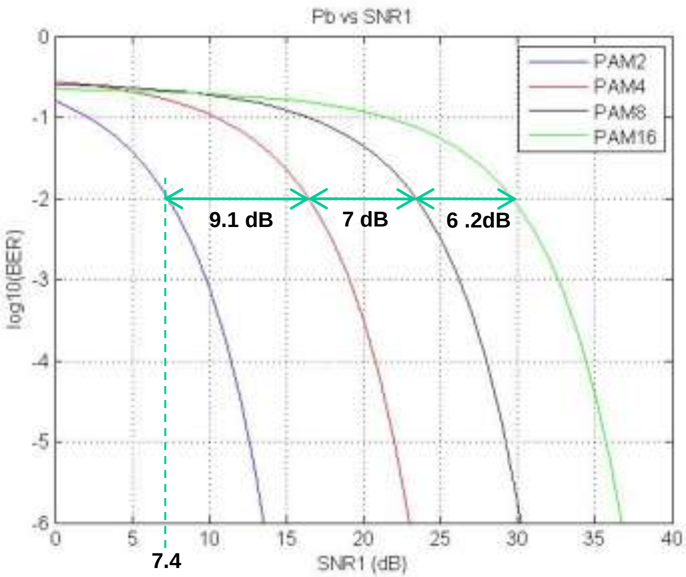
$$P_{avg,optical} = \frac{(M-1)\Delta}{2}, \quad P_{avg,electrical@TIAinput} = \frac{(M-1)(2M-1)(R\Delta)^2}{6}, \quad P_{avg,electrical@TIAoutput} = \frac{(M^2-1)(R\Delta)^2}{12}$$

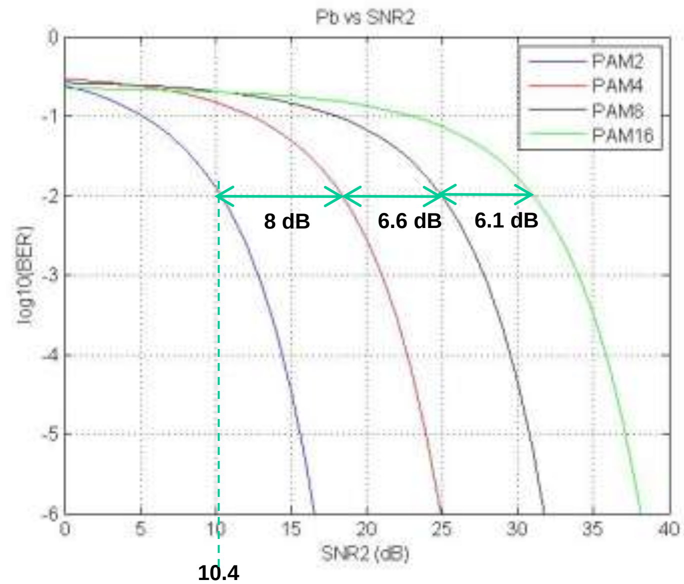
$$P_b = \frac{(M-1)}{M\log 2(M)} erfc\left(\frac{R\Delta/2}{\sqrt{2}\sigma}\right), \quad \text{where} \quad \frac{R\Delta}{2} = \begin{cases} \dfrac{RP_{avg,optical}}{M-1} \\ \sqrt{\dfrac{3P_{avg,electrical@TIAinput}}{2(M-1)(2M-1)}} \\ \sqrt{\dfrac{3P_{avg,electrical@TIAoutput}}{(M^2-1)}} \end{cases}$$

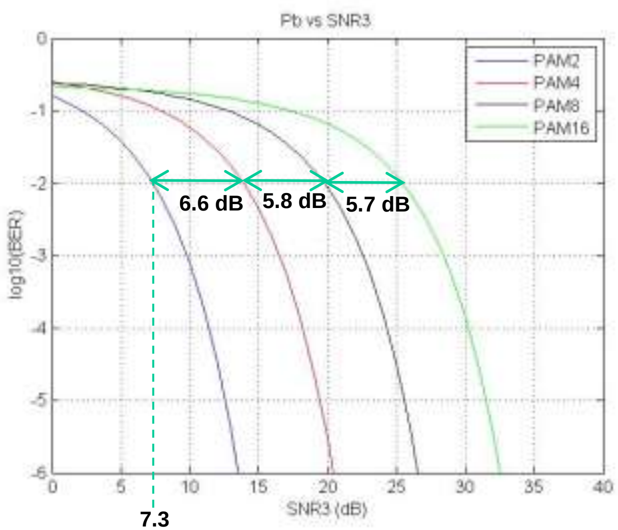
$$SNR_1 = \frac{\left(RP_{avg,optical}\right)^2}{\sigma^2}, \quad SNR_2 = \frac{P_{avg,electrical@TIAinput}}{\sigma^2}, \quad SNR_3 = \frac{P_{avg,electrical@TIAoutput}}{\sigma^2}$$

$$P_b = \begin{cases} \dfrac{(M-1)}{M\log 2(M)} erfc\left(\sqrt{\dfrac{SNR_1}{2(M-1)^2}}\right) \\ \dfrac{(M-1)}{M\log 2(M)} erfc\left(\sqrt{\dfrac{3\ SNR_2}{4(M-1)(2M-1)}}\right) \\ \dfrac{(M-1)}{M\log 2(M)} erfc\left(\sqrt{\dfrac{3\ SNR_3}{2(M^2-1)}}\right) \end{cases}$$

SNR Penalties: PAM-M vs. NRZ (PAM-2)







Penalty depends on SNR definition

PAM-M SNR Gain with FEC

PAM-4 SNRs	SNR1 (dB)	SNR2 (dB)	SNR3 (dB)
BER=1.e-2	16.4	18.4	13.9
BER=1.e-12	26.4	28.4	23.9
FEC Gain (dB)	10	10	10

PAM-M order	FEC Gain for SNR1 (dB)
M=2	9.6
M=4	10
M=16	10.8

FEC gain for PAM-4 assuming FEC threshold at BER=1.e-2

General Case SNR

Noise is white Gaussian random process with both signal independent thermal noise and signal dependent components due to laser RIN and shot noise. For optimum receiver thresholds, the symbol error probability is:

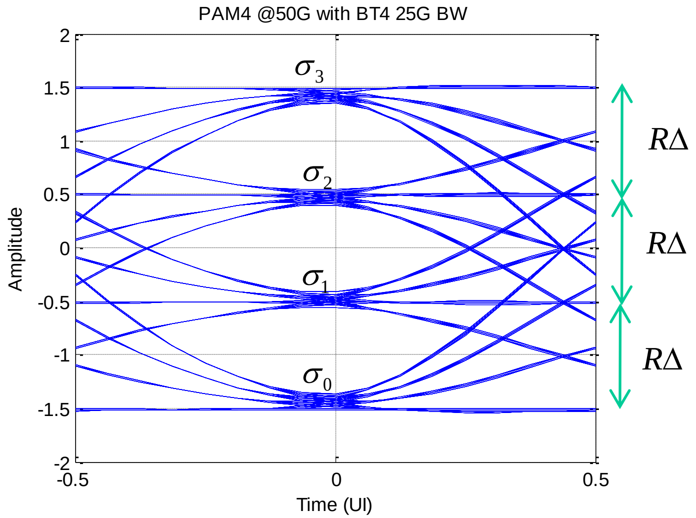
$$Q(k) = R\Delta / (\sigma_{k+1} + \sigma_k),\ k = 0,\ldots,M-2$$

$$R\Delta = \begin{cases} \dfrac{2RP_{avg,optical}}{M-1} \\ \sqrt{\dfrac{6P_{avg,electrical@TIAinput}}{(M-1)(2M-1)}} \\ \sqrt{\dfrac{12P_{avg,electrical@TIAoutput}}{(M^2-1)}} \end{cases},$$

$$\sigma_k^2 = (N_{Th} + 2qRk\Delta + 10^{\frac{RIN}{10}}(Rk\Delta)^2)W \ \ (W = \text{Rx bandwidth})$$

$$P(k) = erfc\left(\frac{Q(k)}{\sqrt{2}}\right)$$

$$P_s = \frac{1}{M}\sum_{k=0}^{M-2} P(k)$$



- A single noise variance is not valid
- Each individual level k has its own noise variance
- SNR has to be defined for each level k: Q(k)

RIN Q-penalty for PAM-M

Q factor for PAM-M eye between levels P_{k+1} and P_k:

$$Q(k) = \frac{\Re\left(P_{k+1} - P_k\right)}{\sigma_{k+1} + \sigma_k}$$

Noise power for level k with receiver thermal noise and RIN:

$$\sigma_k^2 = \sigma_T^2 + 10^{\frac{RIN}{10}} W\left(\Re P_k\right)^2$$

RIN Q-penalty for PAM-M (cont. 1)

Taylor series expansion:

$$Q(k) = \frac{\Re\left(P_{k+1} - P_k\right)}{2\sigma_T\left[1 + \left(\frac{\Re}{2\sigma_T}\right)^2 10^{\frac{RIN}{10}} W\left(P_{k+1}^2 + P_k^2\right)\right]}$$

Let Q_0 = Q factor without RIN

Let $P_k = k\Delta$

$$Q(k) = \frac{Q_0}{\left[1 + Q_0^2 10^{\frac{RIN}{10}} W\left(\frac{P_{k+1}^2 + P_k^2}{\left(P_{k+1} - P_k\right)^2}\right)\right]} \cong \frac{Q_0}{\left[1 + Q_0^2 10^{\frac{RIN}{10}} W\left(\left(k+1\right)^2 + k^2\right)\right]}$$

RIN Q-penalty for PAM-M (cont. 2)

RIN Q-penalty in dB between levels P_{k+1} and P_k:

$$10Log10\left[1+Q_0^2 10^{\frac{RIN}{10}} W\left((k+1)^2+k^2\right)\right]$$

Worst case Q-penalty occurs for top level or k = M-2:

$$10Log10\left[1+Q_0^2 10^{\frac{RIN}{10}} W\left((M-1)^2+(M-2)^2\right)\right]$$

Required RIN vs. PAM-M Order

At 0.5 dB Q penalty:

$$Q_0^2 10^{\frac{RIN}{10}} W\left((M-1)^2 + (M-2)^2\right) = \frac{1}{8}$$

RIN (dB/Hz) Q_0 = 4.2 (BER = 1.e-5):

M	25GBuad nicholl_01b_0312	25GBaud	50Gbaud
2	-126	-124.5	-127.3
4	-135	-135.5	-138.5
8	-143	-143.8	-146.6
16	-149	-150.7	-153.6

Summary

- The penalty for PAM-M order depends on the SNR definition: the two must always be stated together
- Ideal case of thermal noise limited SNR results in simple BER formula for comparing PAM-M order performance
- Required FEC gain for constant SNR depends on PAM-M order: NRZ results are not extendable
- General case of signal dependent noise SNR requires use of PAM-M level dependent noise variance:
  - define segment Q(k) factor for each PAM-M level k
  - calculate overall SNR by inverse mapping BER
- Required RIN increases with PAM-M order

Future Work

- MPI Penalty
- Jitter Budgets
- Link Budgets
- Extension to higher Data Rates

Thank you