Update on technical feasibility for PAM modulation

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IEEE 802.3 NG100GE PMD Study Group

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Overview

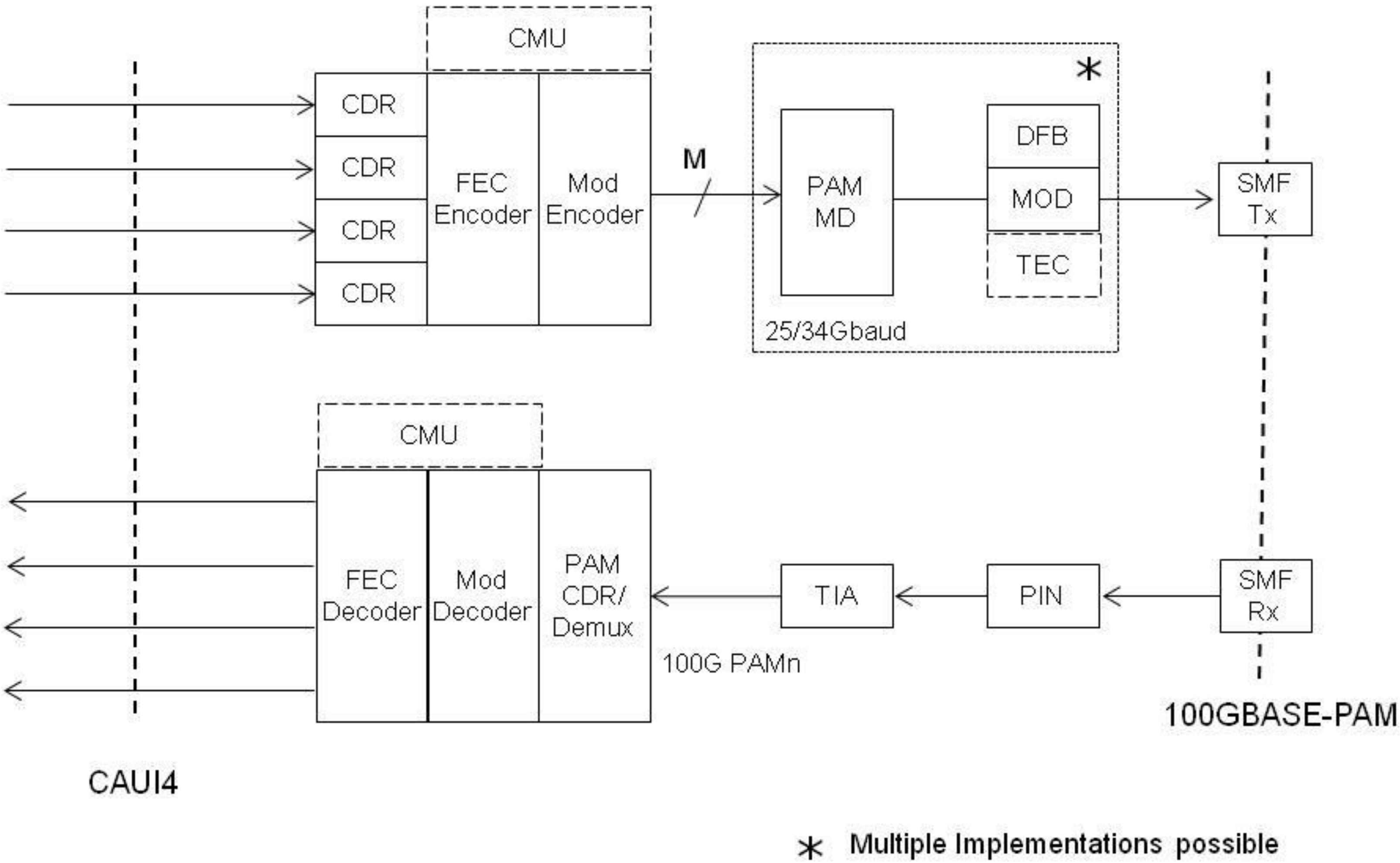
- PAM Architecture Overview [Gary Nicholl]
- PAM Link Modeling Analysis [Chris Fludger]
  - Strategy and Assumptions
  - Analysis (RX Sensitivity, RX BW, RIN, ER, CD, DGD, etc …)
  - Summary
- PAM MPI (Multi-Path Interference) Analysis [Chris Fludger]
  - Approach
  - Results for single reflected path
  - Extension to multiple reflected paths
  - Implications on connector requirements for different system configurations

PAM Architecture Overview

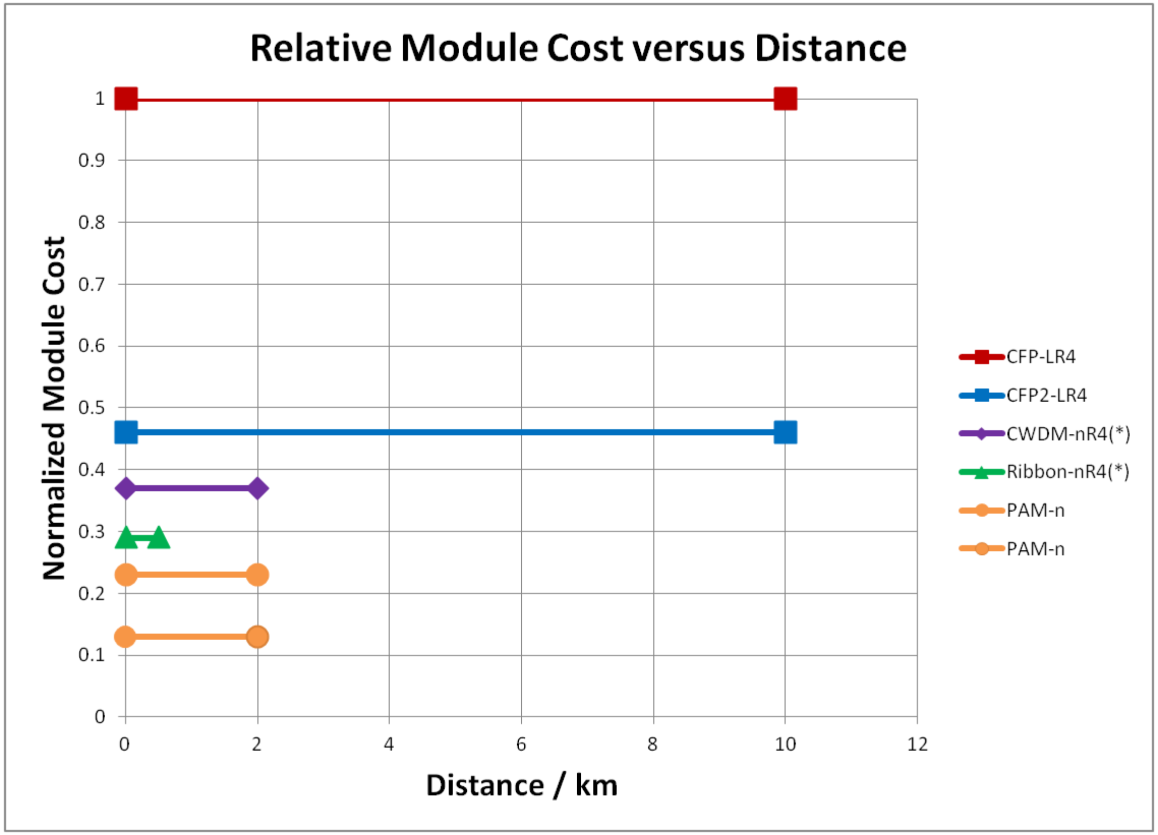
Introduction

- This work investigates the technical feasibility of PAM modulation schemes for a single laser 100G SMF PMD
- PAM8 and PAM16 are investigated
- nicholl_01_0112 showed that PAM potentially provides substantial cost savings over current 100G-LR4, primarily due to reduction on optics component count / mfg complexity
- Goals:
  - A substantial lower cost solution for 100G (that is potentially scalable to 400G)
  - Single laser. Uncooled operation is desirable.
  - Wavelength: 1310nm
  - Loss Budget: 4dB
  - Link Length: 500m to 2 km

PAM Architecture



PAM Cost Analysis



- Presented in nicholl_01_0112
- Substantial cost savings (in range of 0.5x to 0.25x), compared to mature 100GBASE-LR4 (blue line above)

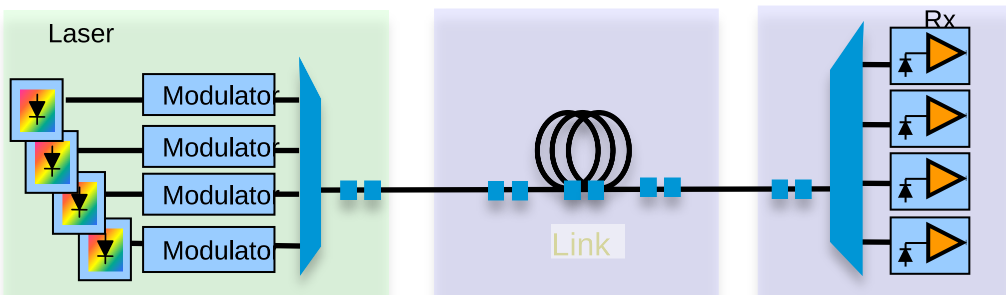
PAM Link Budget Analysis

Strategy

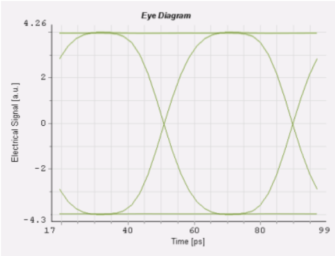
- Numerical simulations using VPI simulator
  - More complex scenarios
- Analytical calculations
  - Deeper understanding
- Effects examined and short summary
  - Chromatic dispersion : All formats > 2km ☺
  - DGD : All formats > 2km ☺
  - RIN : Stringent requirements for higher order PAM ☹
  - Thermal noise / Sensitivity : M-PAM is worse than simply faster ASK 😐
  - Electrical bandwidth : Higher requirements for M-PAM 😐
  - Extinction ratio : Impairment same for M-PAM ☺

Scenarios

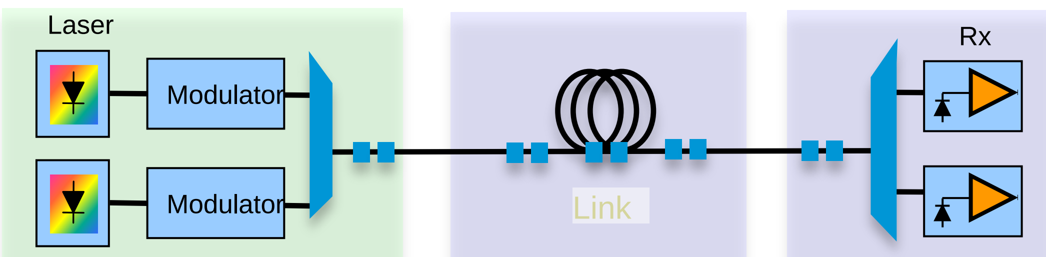
4 Lasers



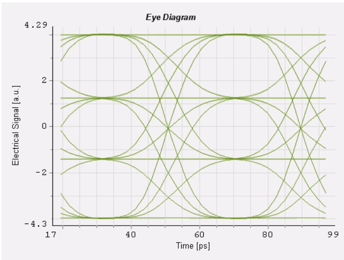
2 levels @ 28Gbaud



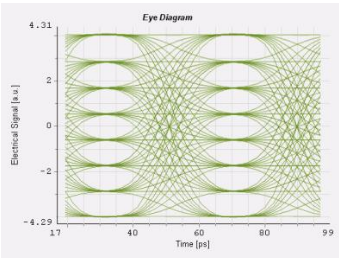
2 Lasers



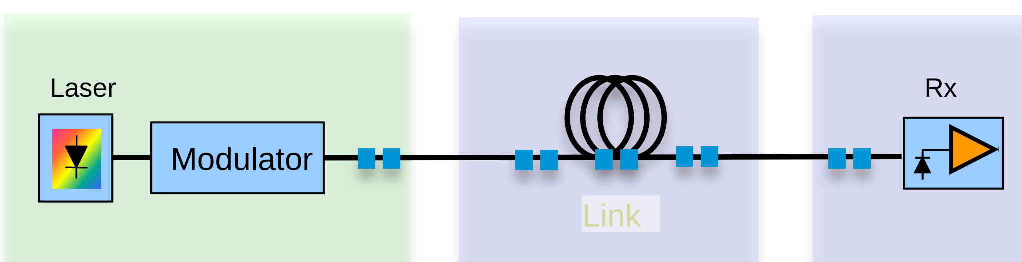
4 levels @ 28Gbaud



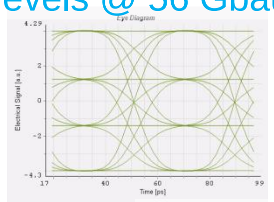
8 levels @ 18.6Gbaud



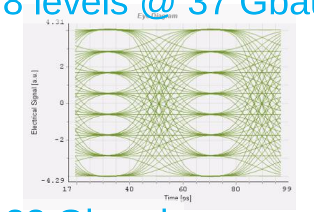
1 Laser



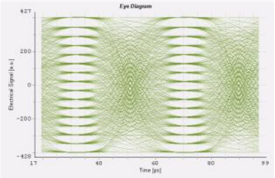
4 levels @ 56 Gbaud



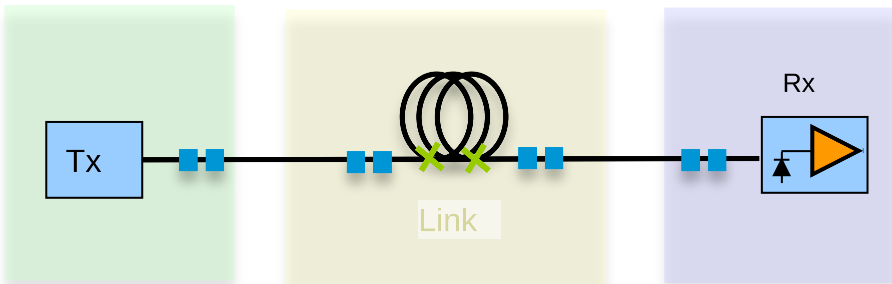
8 levels @ 37 Gbaud



16 levels @ 28 Gbaud



Link Assumptions



- Wavelength available : 1295.56, 1300.05, 1304.58, 1309.14 nm
- Dispersion : -2.85 to +0.95 ps/nm/km
  - For 2km, there is no CD penalty
- Loss ~0.43 dB/km
- Connectors/Splices : 1.5dB (2 dB in IEEE spec. for 10km)
- Total loss for 2km fibre = 2.4 dB

Rx Sensitivity Analysis

Assumptions

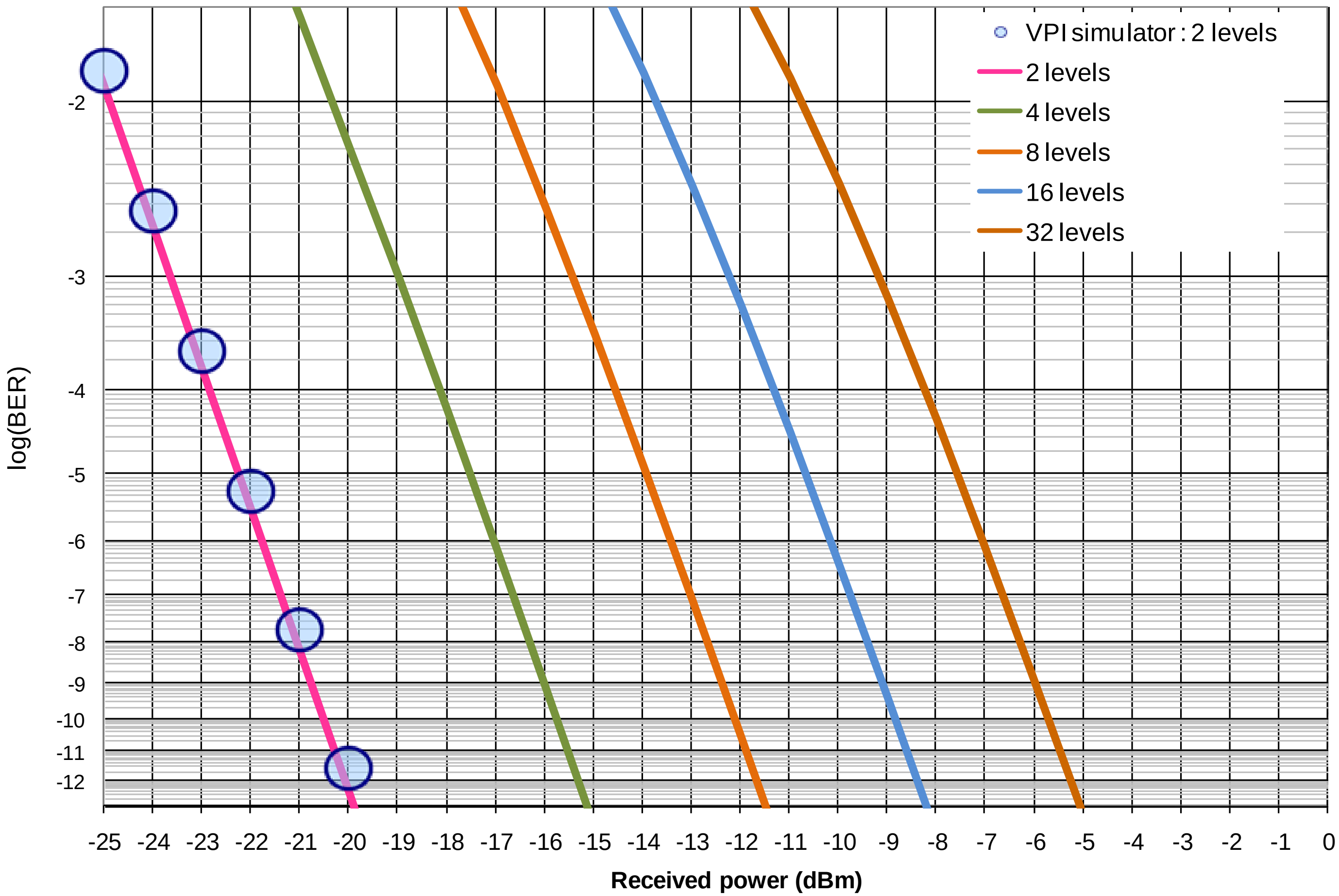
- Channel dominated by thermal noise
  - No RIN included

$$\sigma_N^2 = \sigma_T^2 = \frac{4k_B T}{R_L} = N_{th}{}^2 \Delta f$$

e.g. 10pA/√Hz

- Extinction ratio can be included as power penalty later
- M-ASK levels are linear after square-law optical detector
  - Noise is evenly distributed on rails
- Baud-rate is constant at 25Gbaud
  - More levels means more overall capacity (per wavelength)

Constant Baud-rate : 25Gbaud (10pA/√Hz)



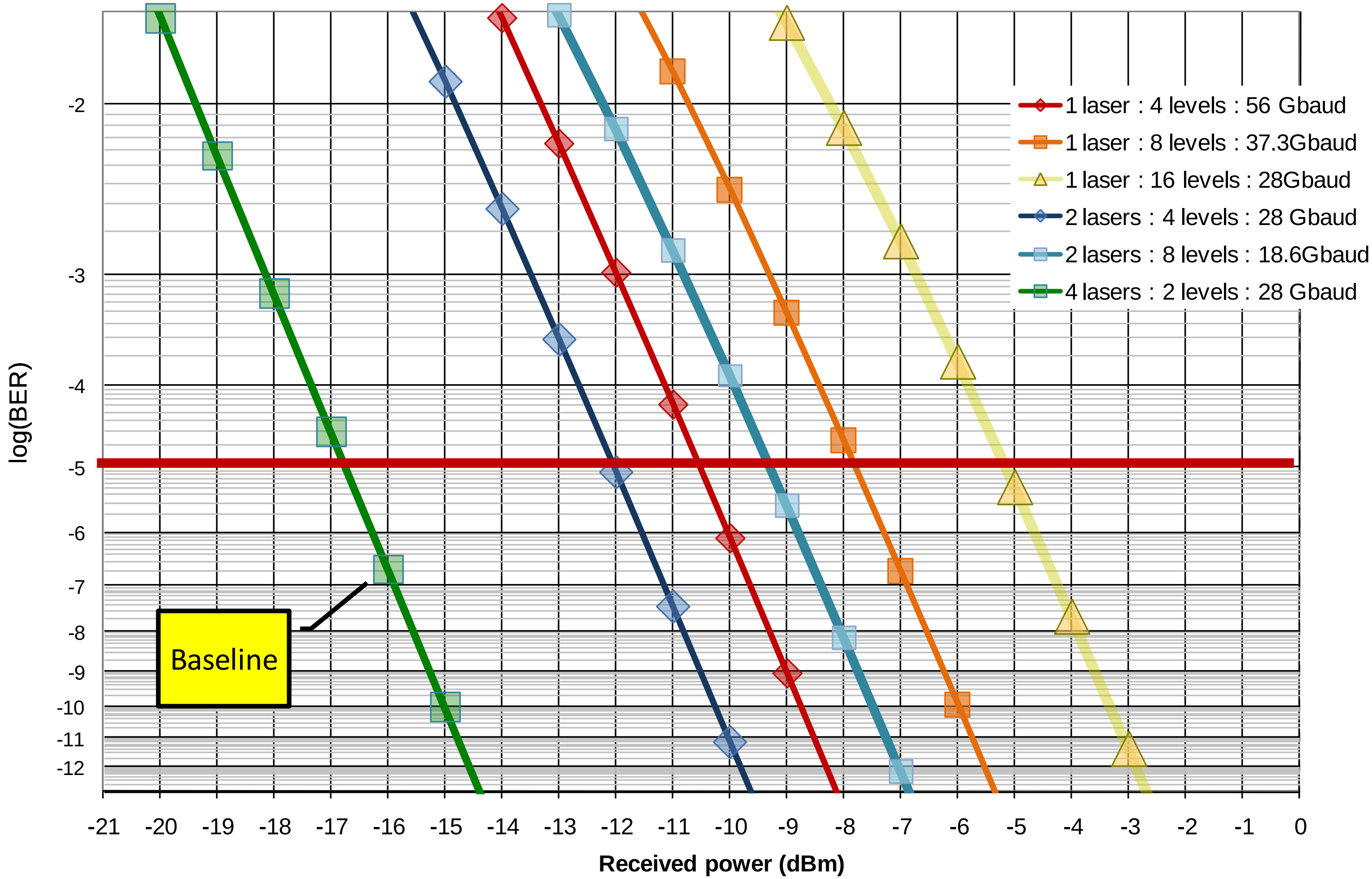
- Agreement between analytical and VPI model for M=2

Levels (M)	2	4	8	16	32
Penalty (dB)	0	-4.8	-8.5	-11.8	-14.9

$$Penalty[dB] \approx -10\log_{10}(M-1)$$

at low BER

Scenarios at 112Gbit/s (25pA/√Hz)



- All scenarios carry 112Gbit/s data
- Received power is 'at the photo-detector' (demux etc not included)

RIN Analysis

RIN Analysis

- Thermal noise

$$\sigma_N^2 = \sigma_T^2 = \frac{4k_B T}{R_L} = N_{th}{}^2 \Delta f$$

e.g. 25pA/√Hz

- Noise from RIN depends upon the level (m=0....M-1)
  - In a binary signal, the 1's have RIN, 0's have no RIN (for infinite extinction)
  - Extinction ratio is ignored in this analysis (optimistic)

$$\sigma_{RIN}^2 = I_m^2 \cdot RIN \cdot \Delta f$$

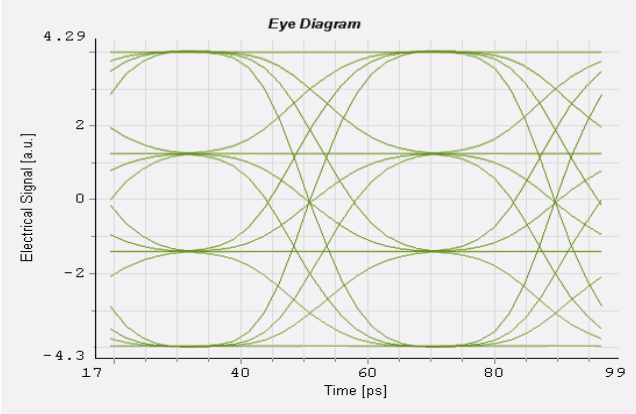
e.g. -130 dB/Hz

m=3

m=2

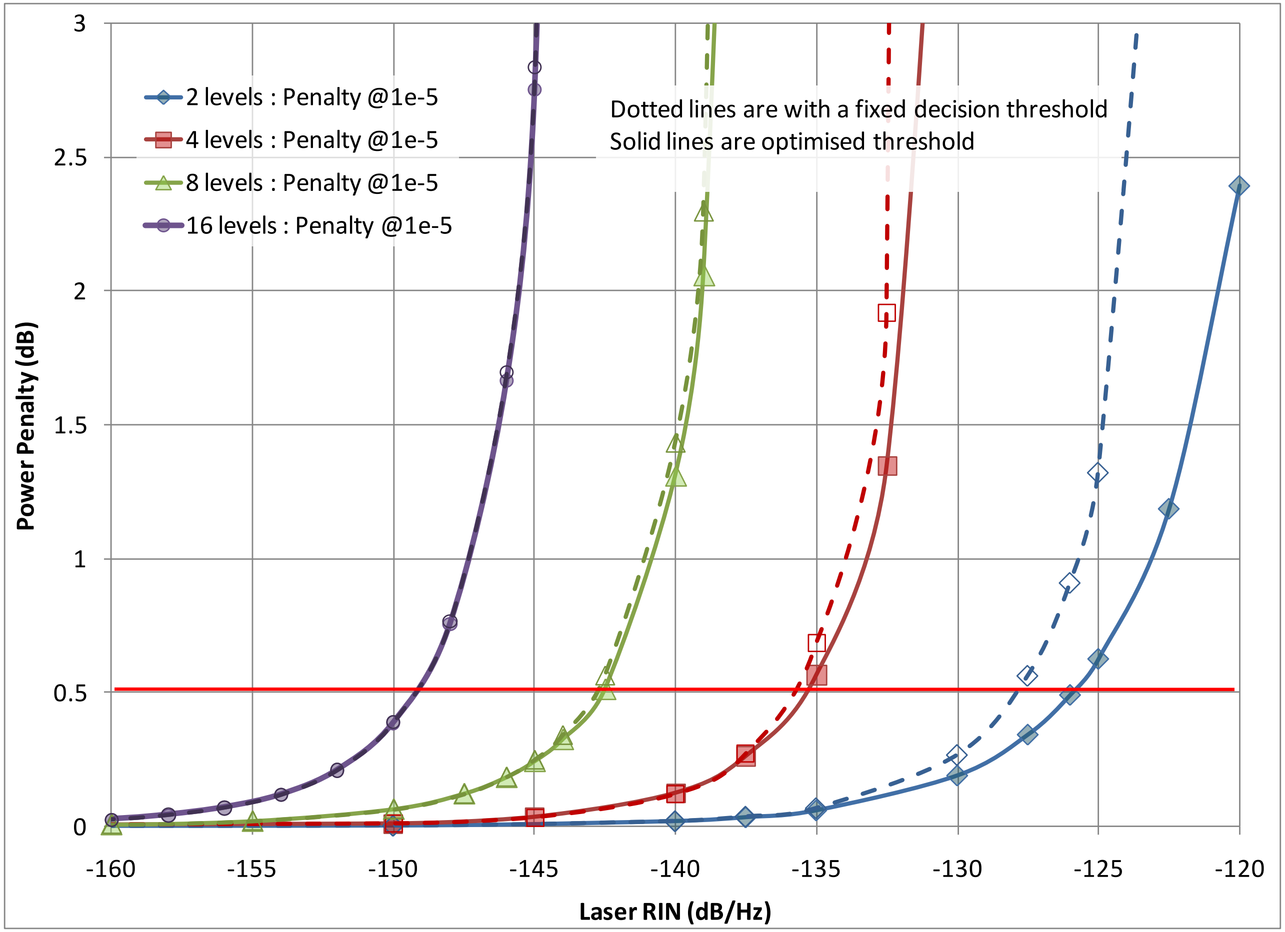
m=1

m=0



- Decision thresholds at receiver should ideally be optimised.

Results: Penalties at 1e-5 BER

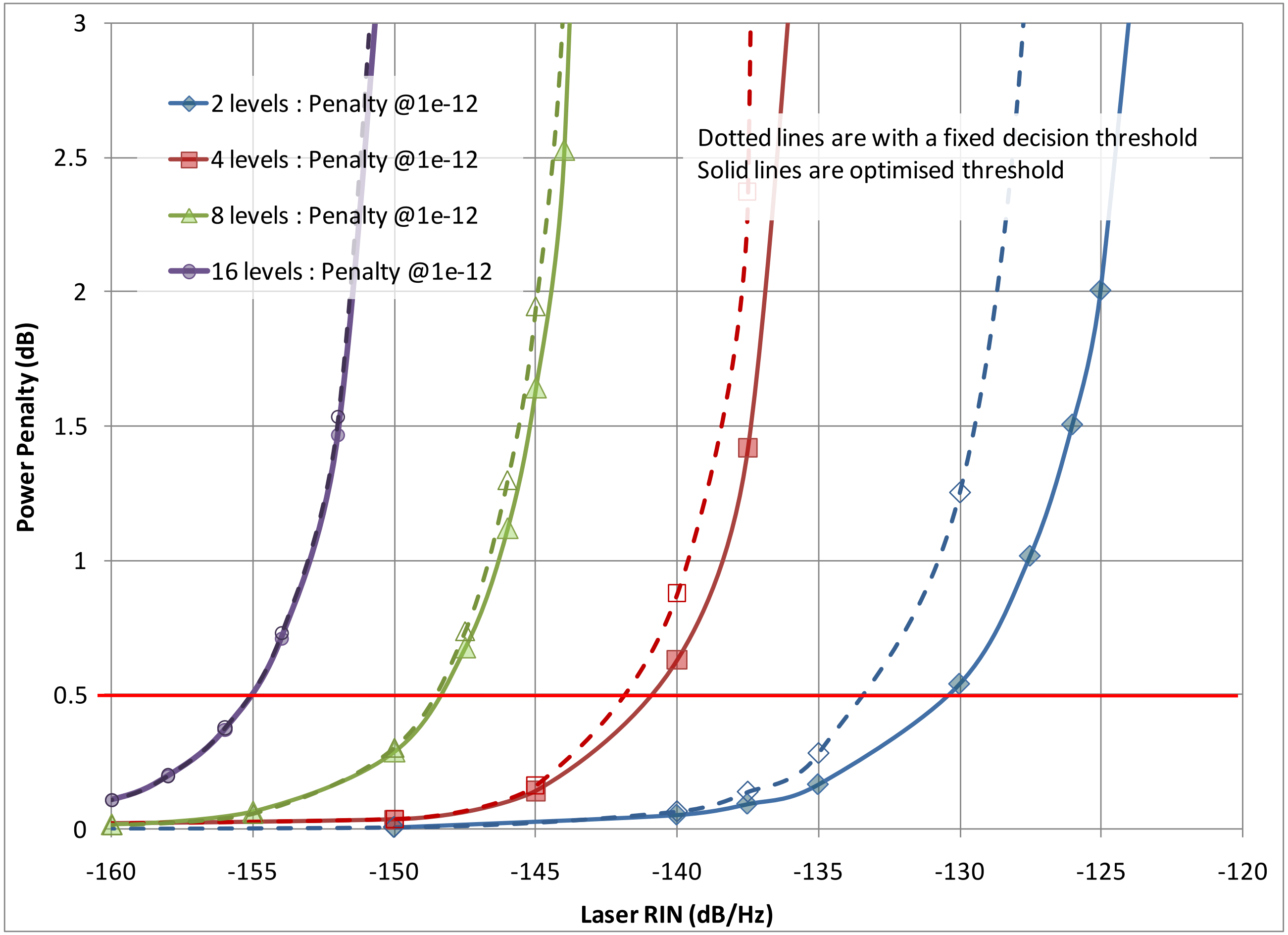


25 Gbaud

- 1e-5 BER assumes FEC

Levels	2	4	8	16
For 1e-5	-126	-135	-143	-149

Results: Penalties at 1e-12 BER



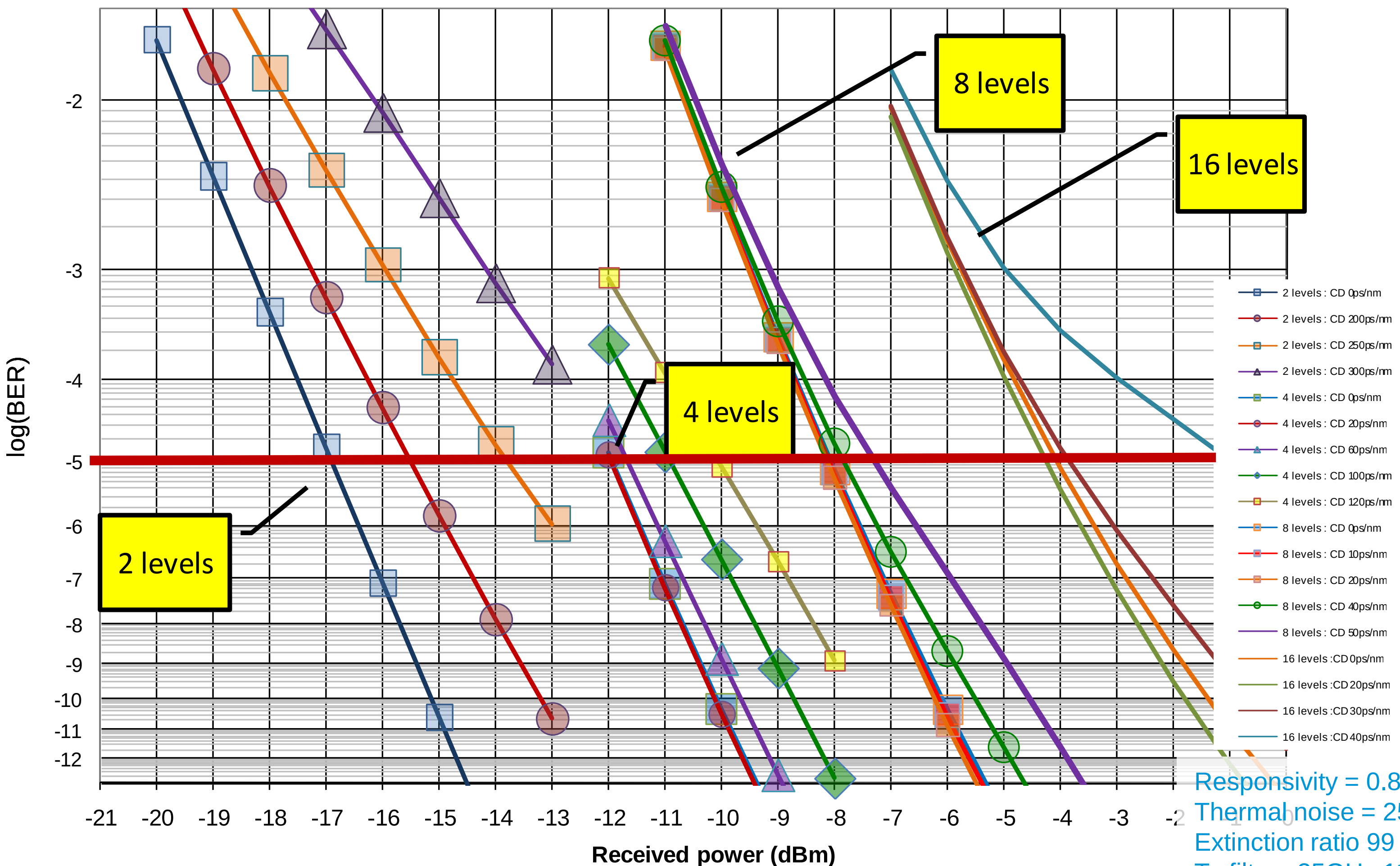
25 Gbaud

- For 1e-12 BER

Levels	2	4	8	16
For 1e-12	-130	-141	-148	-155

Chromatic dispersion analysis

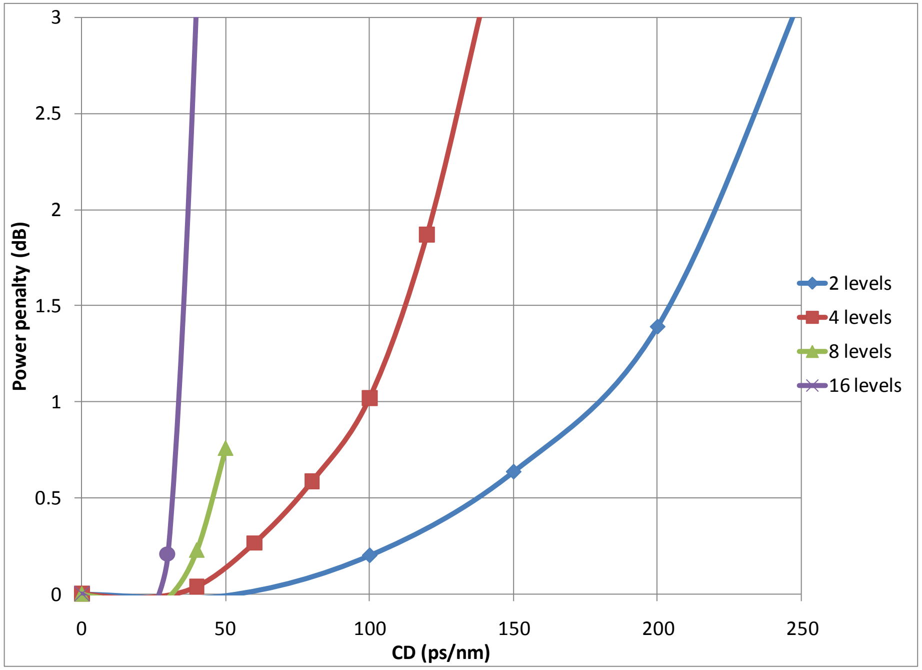
Sensitivity to CD



Responsivity = 0.8 A/W
Thermal noise = 25pA/√Hz
Extinction ratio 99 dB
Tx filter : 25GHz 1st order Bessel
Rx Filter : 22GHz 4th order Bessel

- Higher order formats are significantly more sensitive to CD

Sensitivity to CD @25.8Gbaud



25.8 Gbaud	
Levels	CD (1 dB penalty @1e-5 BER)
2	180
4	100
8	50
16	30

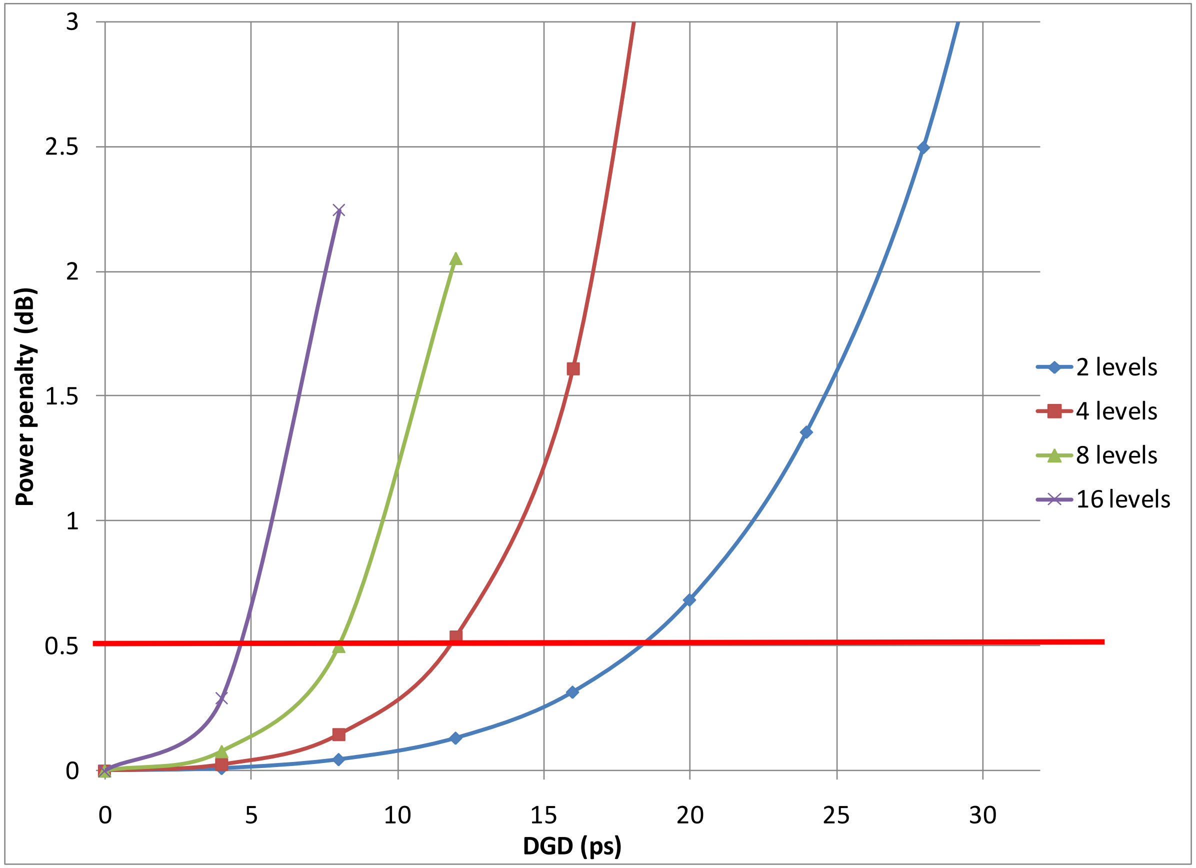
- Higher order formats are significantly more sensitive to CD
- Not an issue for links in the 500m to 2km range

DGD Analysis

DGD

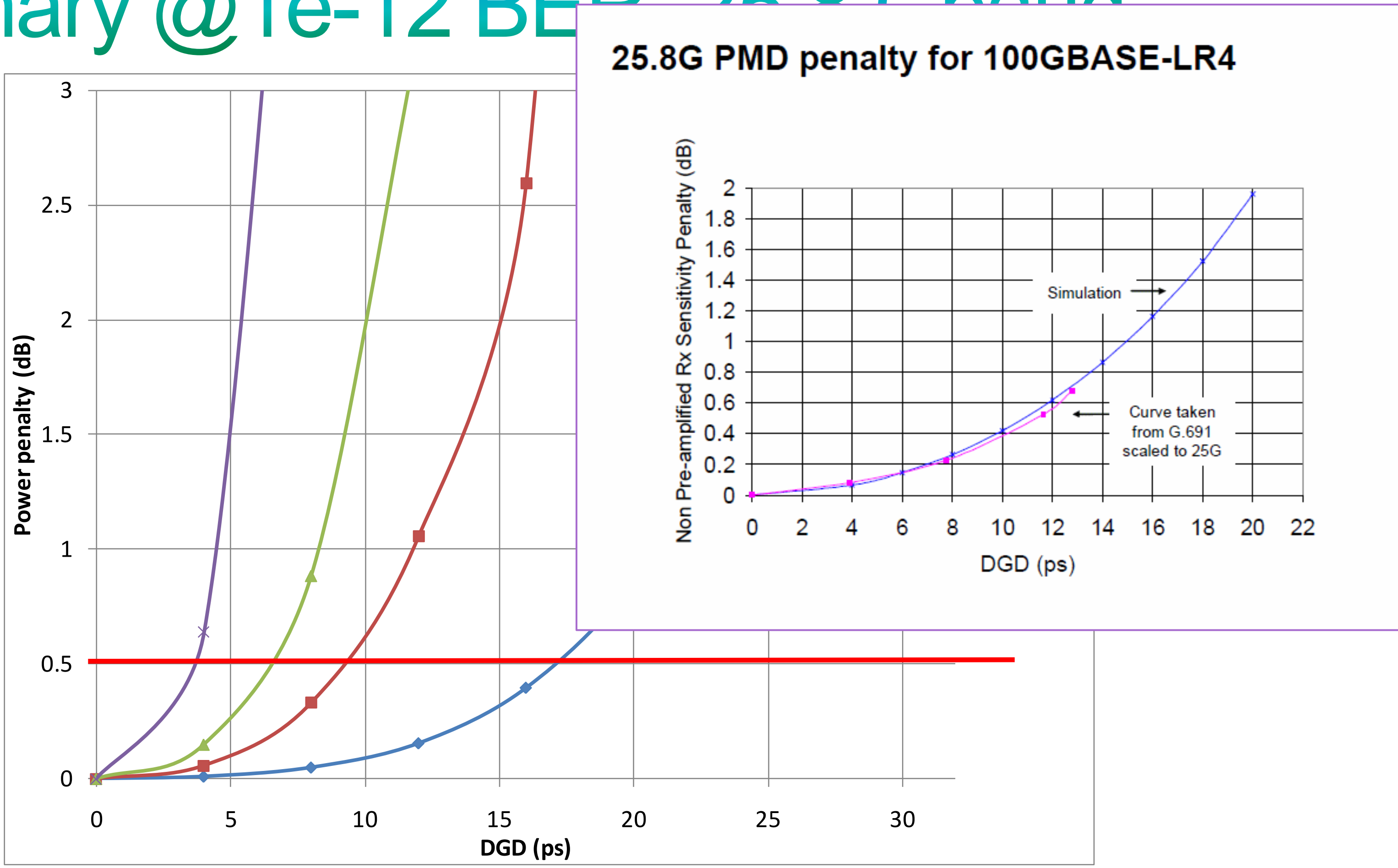
- Single DGD element at 45 degrees to signal
- Ideal waveforms
  - Infinite extinction ratio
  - 25 pA/√Hz thermal noise
  - No RIN
  - Optimised receiver bandwidth

Summary @1e-5 BER, 25.8 Gbaud



	2	4	8	16
DGD (ps)	18	12	8	4

Summary @1e-12 BER, 25.8 Gbaud



- Pete Anslow's data show 0.5 dB penalty at 11ps rather than 17p

	2	4	8	16
DGD (ps)	17	9	6	3

Comparison

Lasers	Levels	Baud rate	Required BW (GHz)	Sensitivity @1e-5 BER	RIN for 0.5dB penalty @1e-5	CD limited distance (km)	Max DGD (ps) @1e-5	DGD limited distance (km)
1	4	56	44	-10.5	-135	7.3	5.5	8.7
1	8	37.3	32	-7.8	-143	8.4	5.5	8.7
1	16	28	25	-5.2	-149	9.1	3.7	3.9
2	4	28	22	-12	-135	29.8	11.0	34.7
2	8	18.6	16	-9.4	-143	33.3	11.1	35.0
4	2	28	20	-16.8	-126	53.7	16.6	78.1

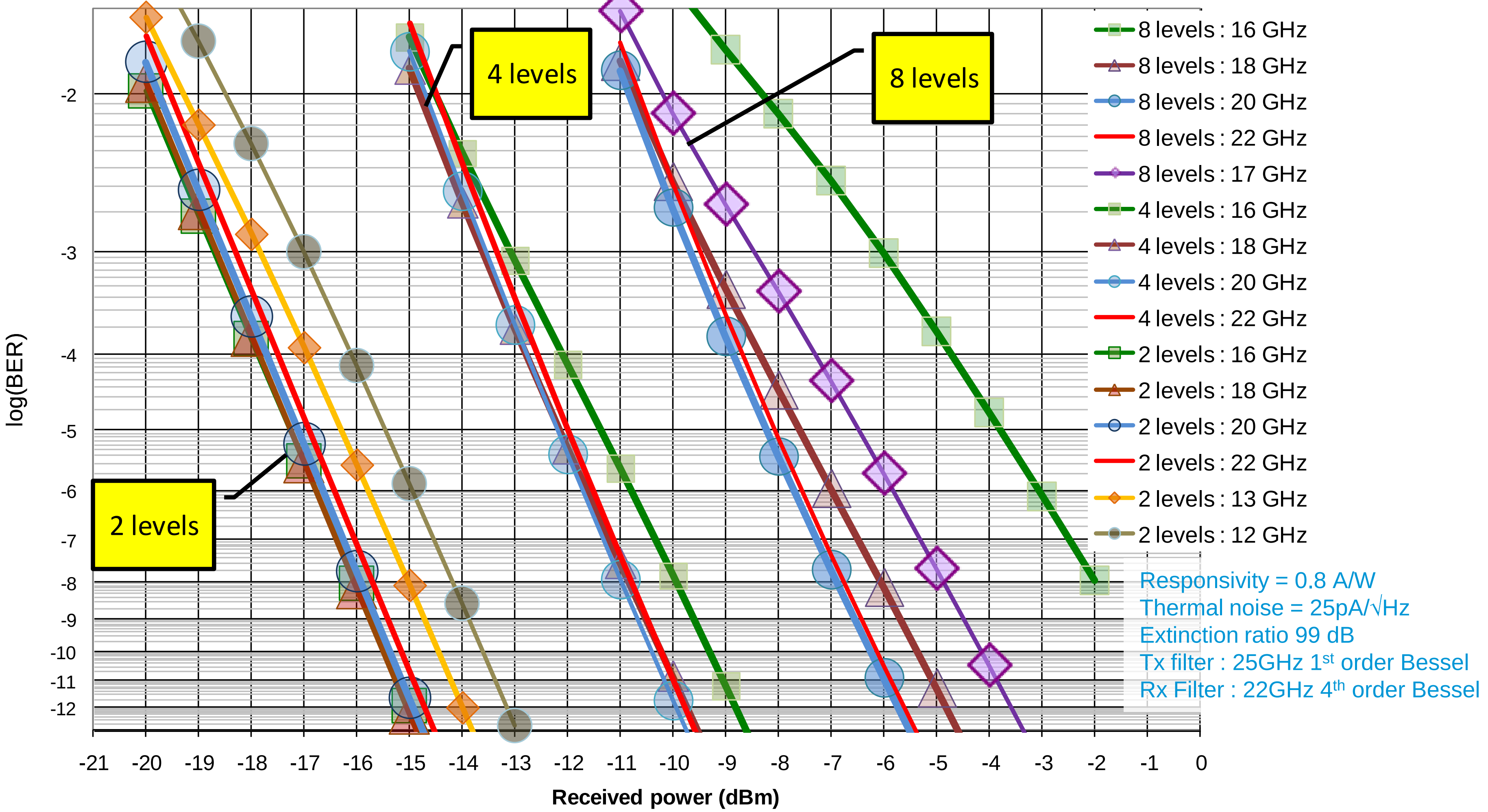
$$DGD_{max} = S \times \sqrt{L} \times PMD$$

3.75 (conservative) 0.5ps/√km (v.bad fibre)

- All 1 laser solutions have ~5 ps peak DGD tolerance
- All 2 laser solutions have ~10 ps peak DGD tolerance
- 2km (~2.5ps DGD) seems possible with all formats

Receiver bandwidth Analysis

Sensitivity to Receiver bandwidth



- Higher order modulation schemes are more sensitive to receiver bandwidth
  - The same ISI causes a more significant closure in the sub-level eyes

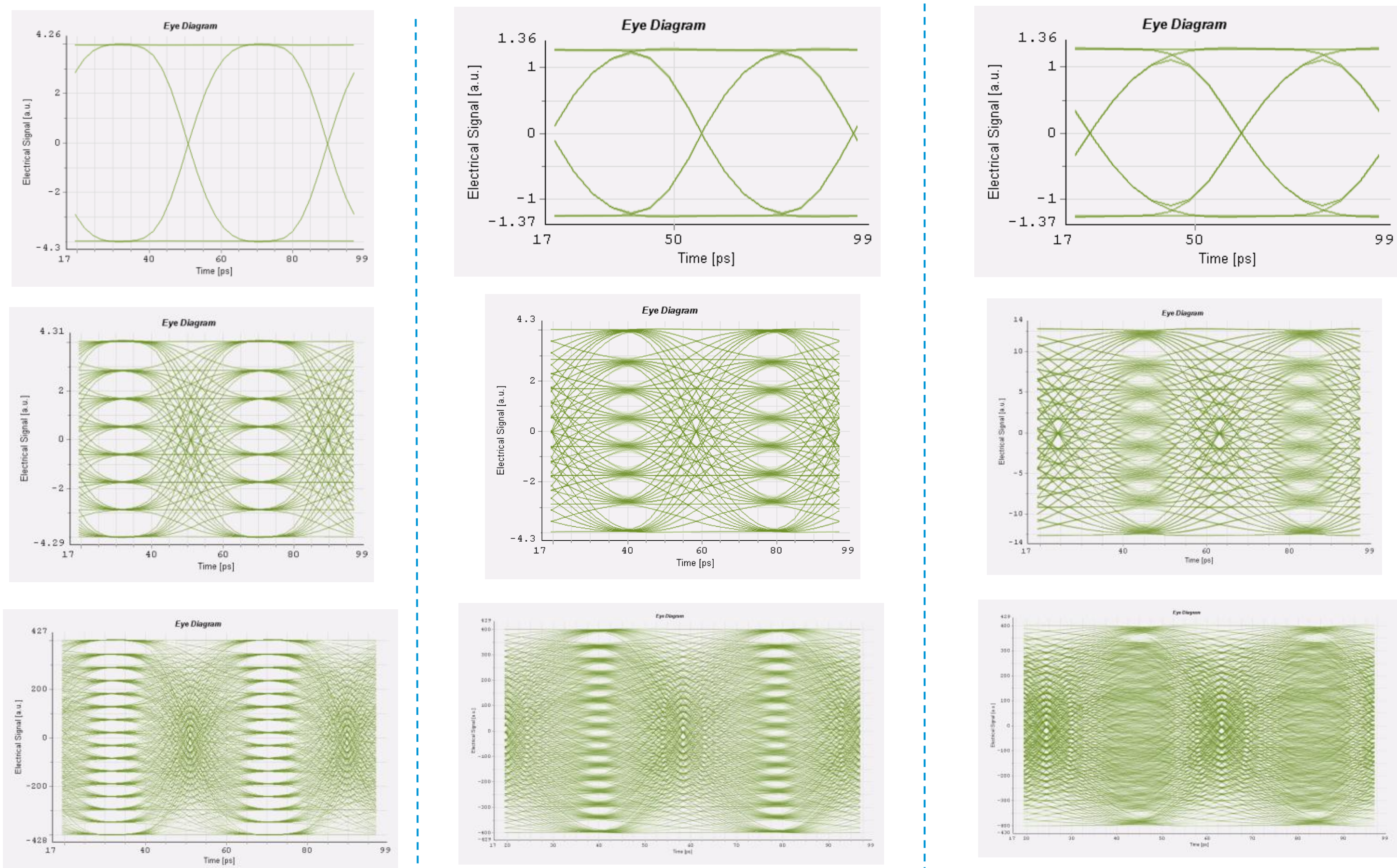
RX Bandwidth Results (Constant 25.8Gbaud)

Optimum Rx BW

PAM2 — 17.5 GHz (0.7x baudrate)

PAM8 — 22 GHz (0.85x baudrate)

PAM16 — 23.2 GHz (0.9x baudrate)



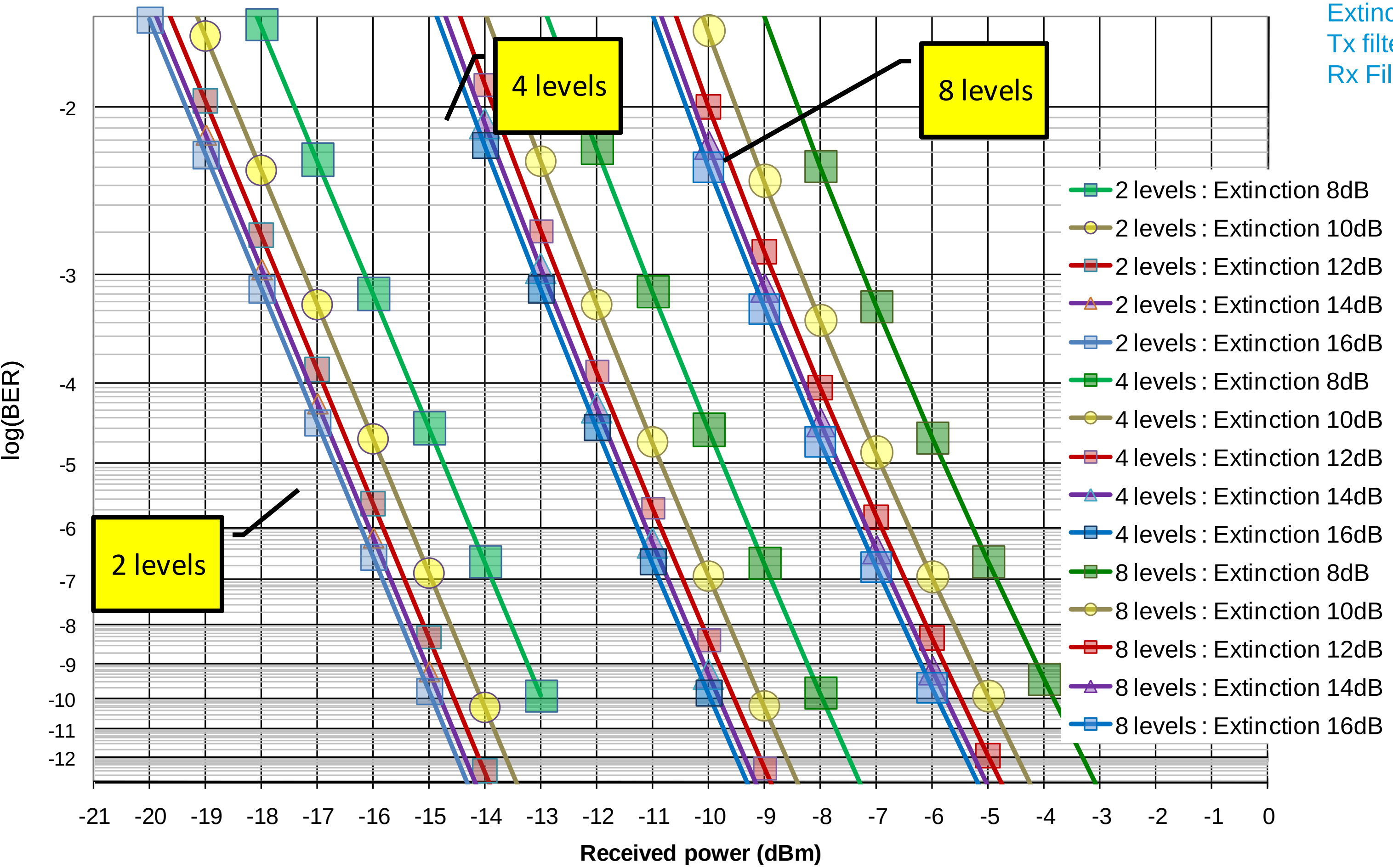
25 GHz | 16 GHz | 13 GHz

← Electrical Bandwidth (4th order Bessel Filter) →

Extinction ratio analysis

Sensitivity to Extinction ratio

Responsivity = 0.8 A/W
Thermal noise = 25pA/√Hz
Extinction ratio 99 dB
Tx filter : 25GHz 1st order Bessel
Rx Filter : 22GHz 4th order Bessel



- Higher order formats have same sensitivity to extinction ratio
- Relatively small penalties for extinction ratios of 12-14 dB

Link Modeling Summary

Lasers	Levels	Baud rate	Required BW (GHz)	Sensitivity @1e-5 BER	RIN for 0.5dB penalty @1e-5	CD limited distance (km)	Max DGD (ps) @1e-5	DGD limited distance (km)
1	4	56	44	-10.5	-135	7.3	5.5	8.7
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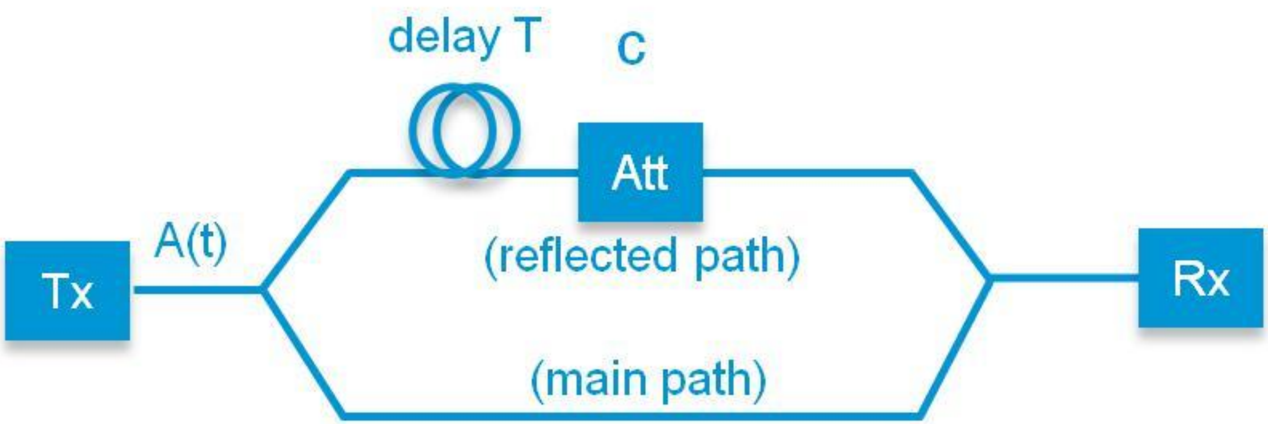
2	4	28	22	-12	-135	29.8	11.0	34.7
2	8	18.6	16	-9.4	-143	33.3	11.1	35.0
4	2	28	20	-16.8	-126	53.7	16.6	78.1

- All M-PAM options are feasible for <2km transmission
- RIN is a critical parameter
- Higher receiver bandwidths are required for higher order modulations (~0.7x for PAM2, ~0.86x for PAM8 and ~ 0.9x for PAM16)
- FEC is required

PAM MPI Analysis

MPI Analysis Approach



$$\left|A(t) + cA(t-T)e^{j(\phi+\omega_c T)}\right|^2 =$$

$$\left|A(t)\right|^2 + c^2\left|A(t-T)\right|^2 + 2cA(t)A(t-T)\cos(\phi+\omega_c T)$$

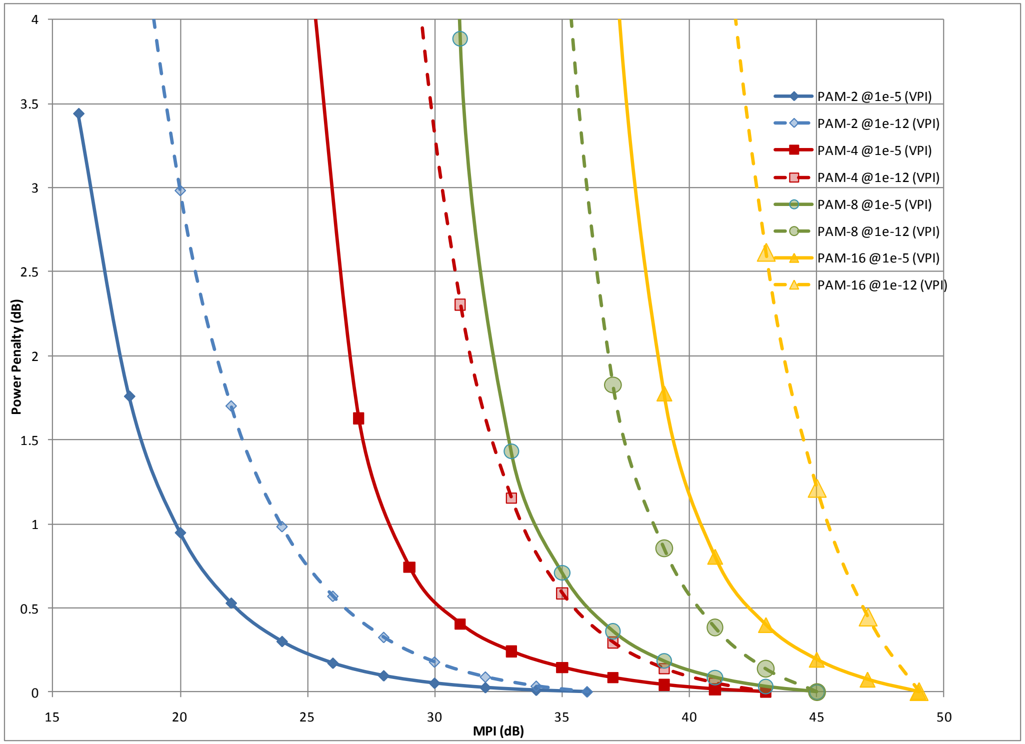
What we want

small

coherent interference

- Beat product of each rail with a delayed version
- Depends upon
  - polarisation alignment
  - phase alignment of reflection
- In general we will have to budget for the worst case

VPI simulations for single reflection

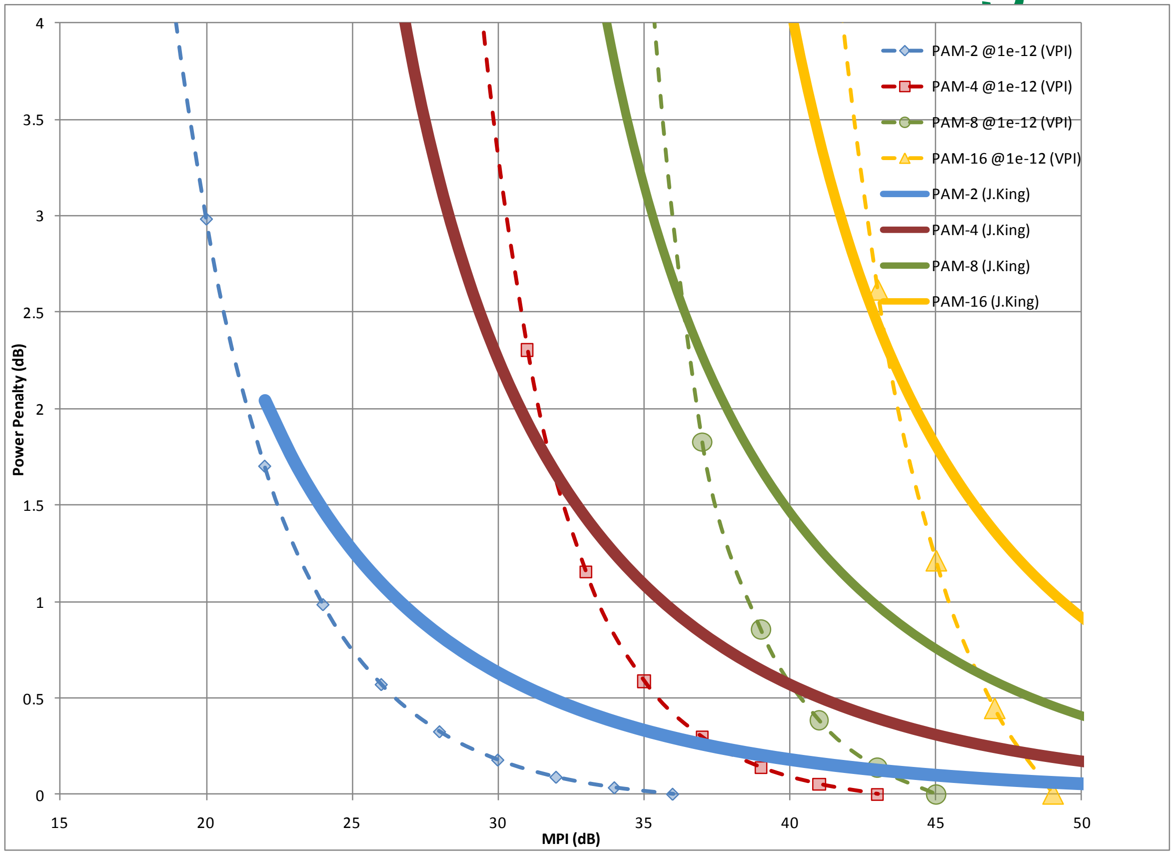


- Simulations assume interferometric noise looks Gaussian rather than eye closure
- Correct statistics for a single reflection will be 'top-hat' shaped.
- Multiple refelections will tend to a Gaussian.

  See differences between models in "Effects of Phase-to-Intensity Noise Conversion by Multiple Reflections on Gigabit-per-second DFB Laser Transmission Systems", J.L. Gimlett et al., JLT Vol.7, No.6, June 1989 and

  "Performance Implications of Component Crosstalk in Transparent Lightwave Networks", E.L. Goldstein et al., PTL Vol.6, No.5, May 1994.

VPI simulations – comparison with estimates from Jonathan King



- Estimates seem more conservative

  Based on eye closure penalty : $P=-10\log10(1-4\cdot10^{EdB/20})$

- **It is difficult to say which is correct without measurements**

Multiple reflections/crosstalk sources

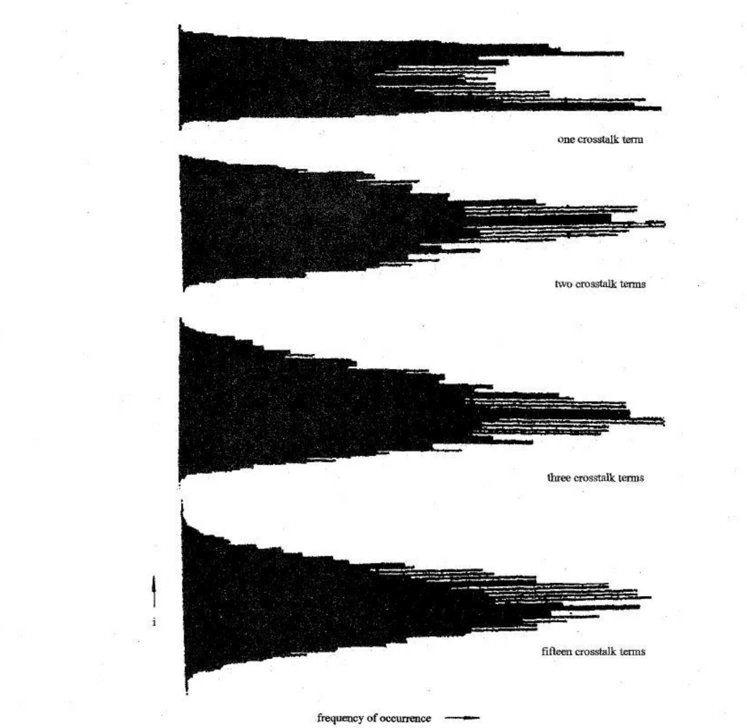


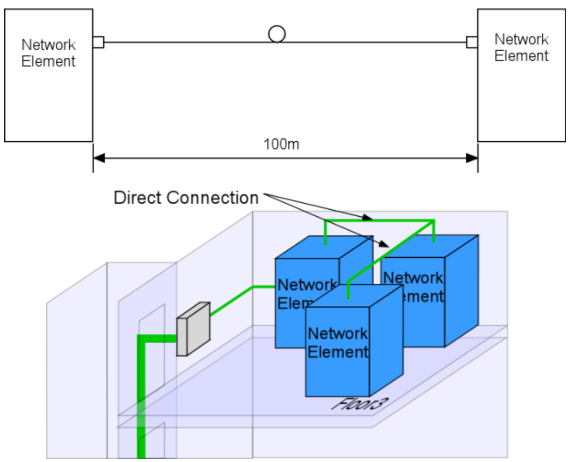
Fig. 9. Histograms of interferometric noise for words 2, 3, 4, and 16.

- With multiple reflection sources, the statistics tend towards a Gaussian distribution (Central limit theorem)
- “Solution Paths to Limit Interferometric Noise Induced Performance Degradation in ASK/Direct Detection Lightwave Networks”, P.J. Legg et al., JLT Vol.14, No.9, Sept 1996

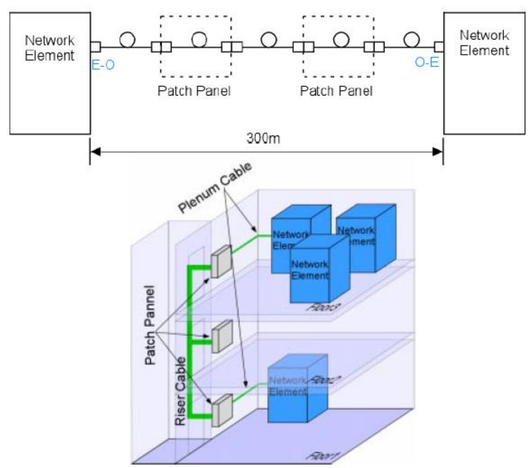
Application Scenarios

Potential Application Scenarios (taken from OIF2000.263):

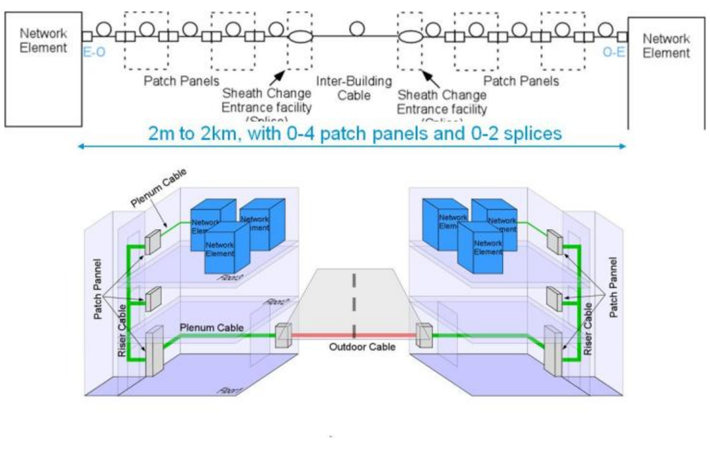
1. B2B w/ no intermediate connectors
2. B2B w/ 2 intermediate connectors (one patch panel)
3. B2B w/ 4 intermediate connectors (two patch panels)
4. B2B w/10 intermediate connectors (inter-building, 2 x patch panel / building)



Tx/Rx + 0 connectors



Tx/Rx + 4 connectors

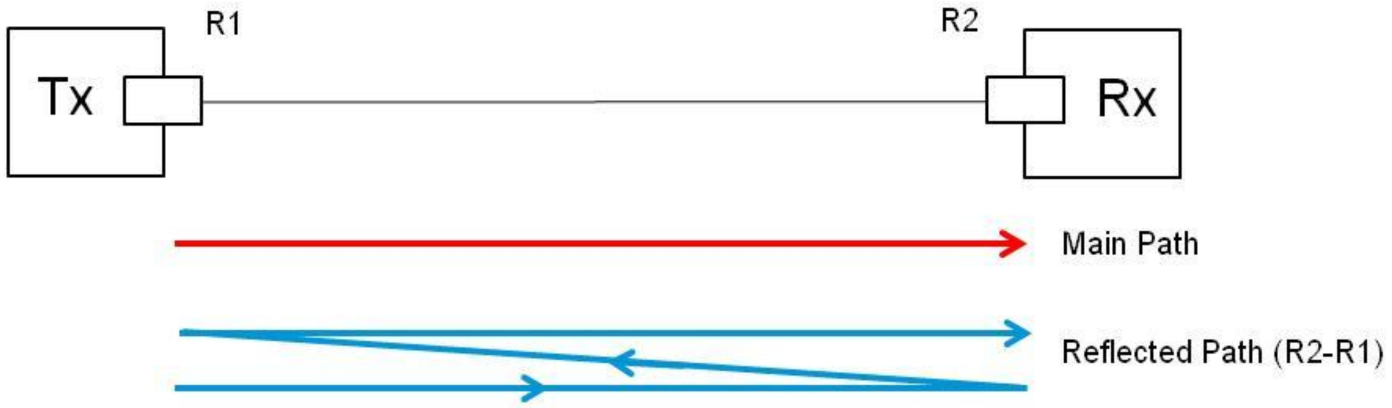


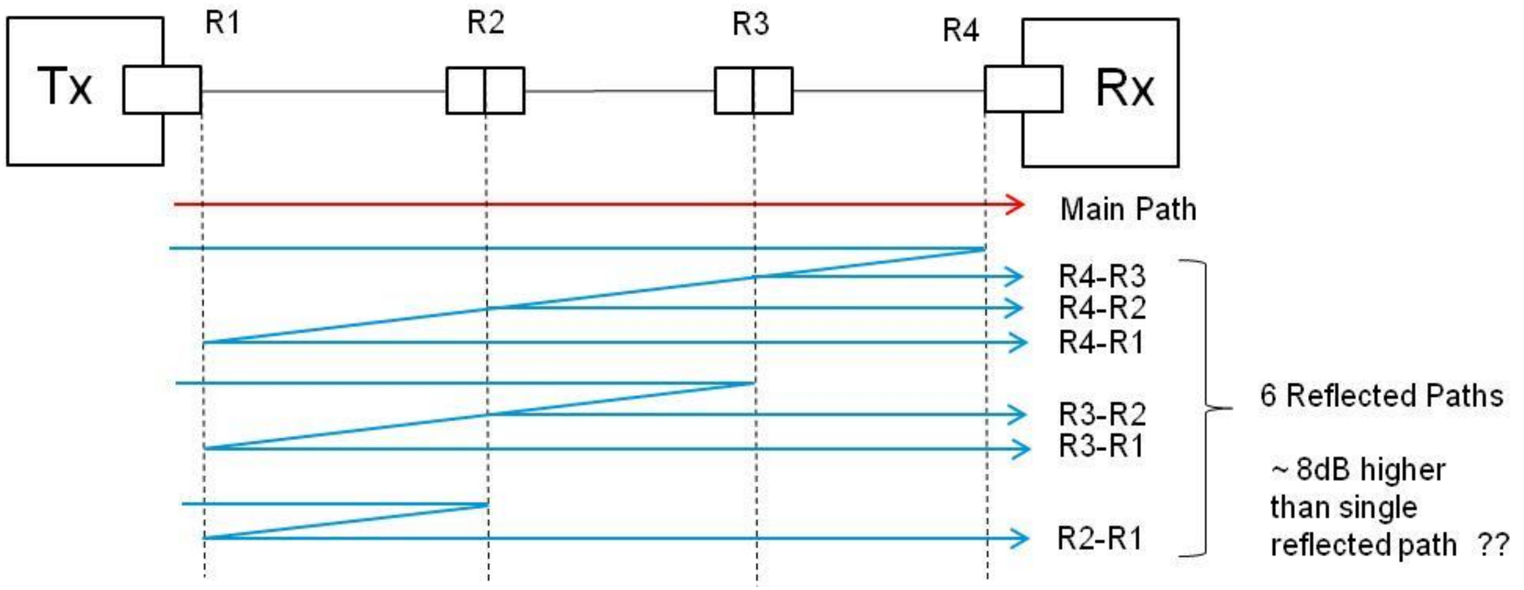
Tx/Rx + 10 connectors

(Note: Not a likely NG 100G PMD application)

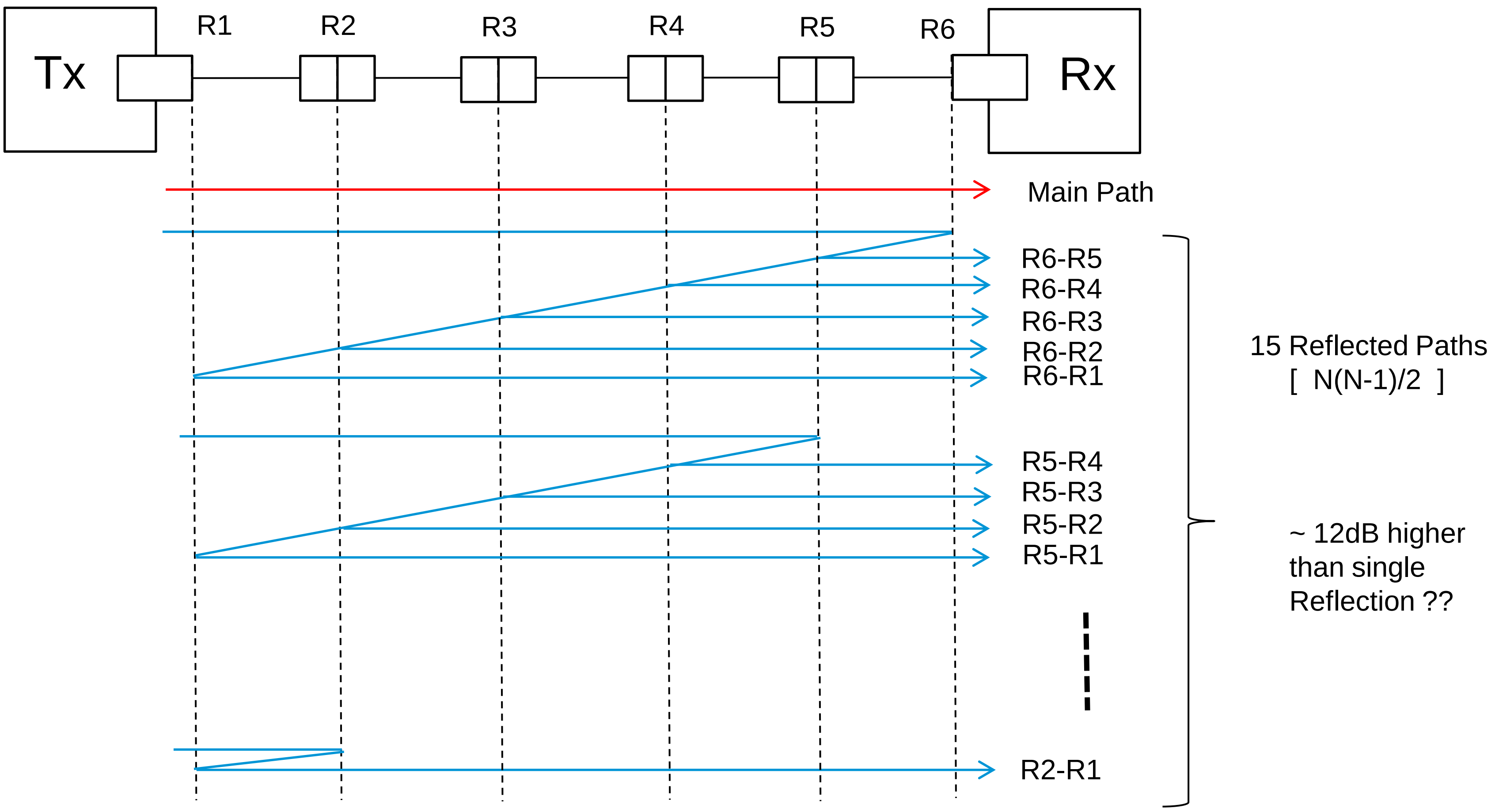
Source:OIF2000.263

Multiple Reflections

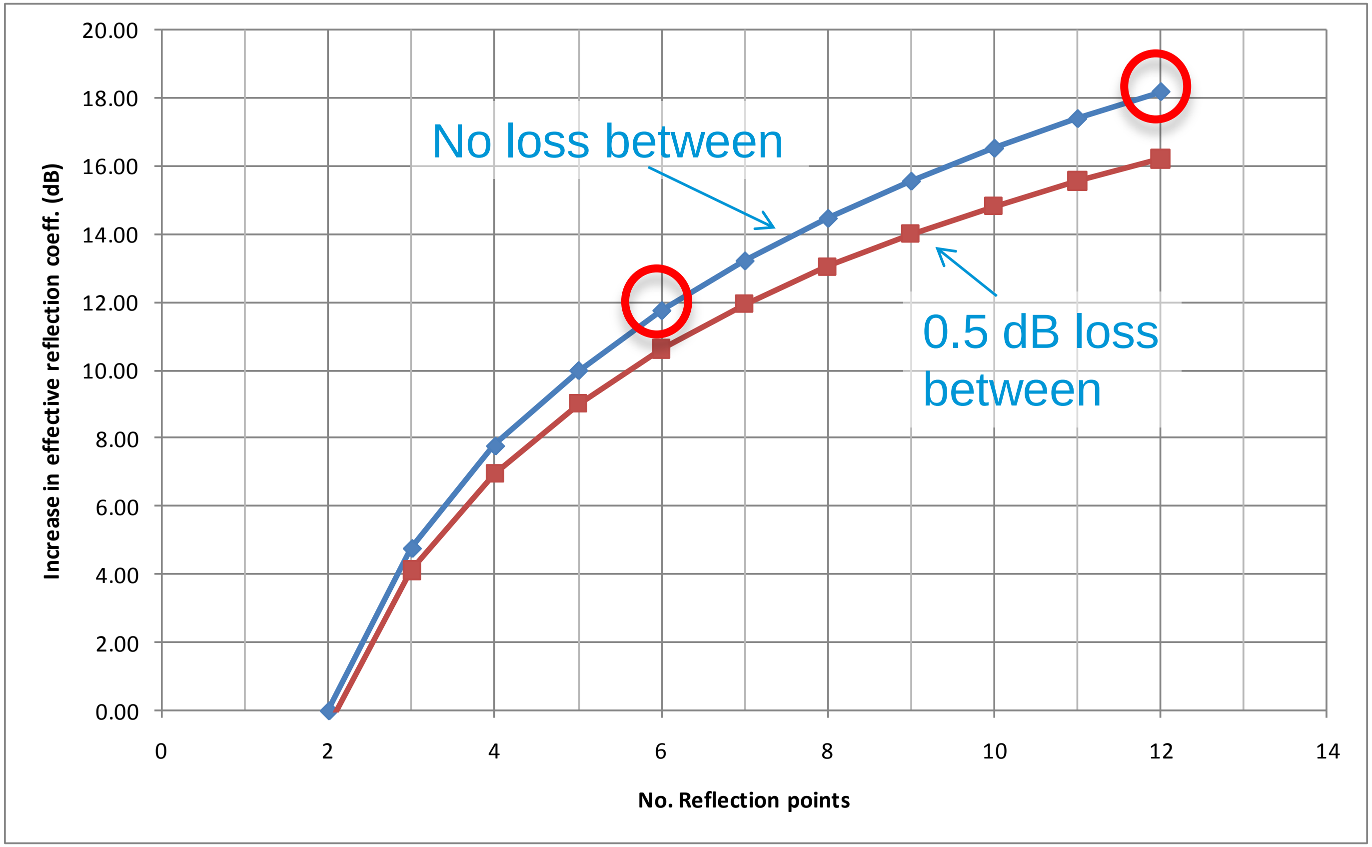




Multiple Reflections



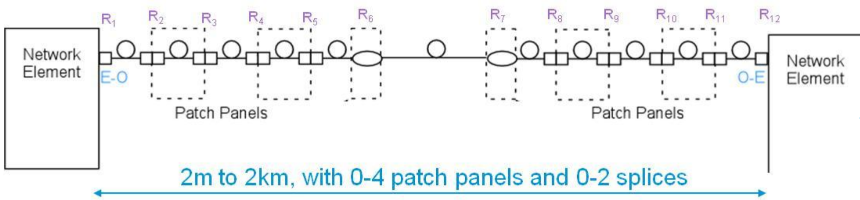
Multiple Reflections

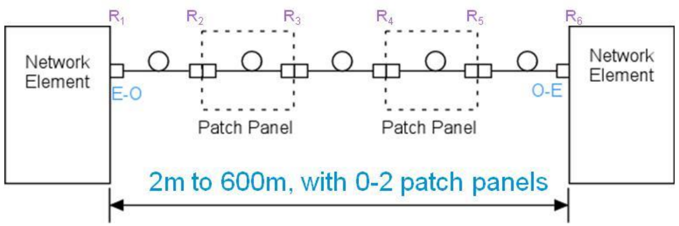


Graph for when all reflections are equal

- All reflections equal, then eff reflection = single reflection + 10log ((N(N-1)/2)
- One reflection dominates, then eff reflection = single reflection + 10log(N-1)

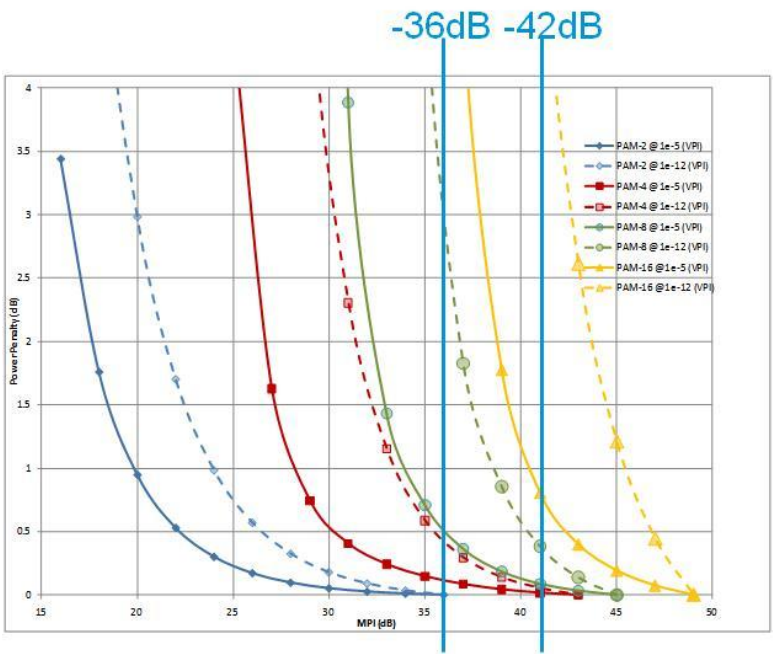
VPI simulations





PAM8 PP ~ 0.5dB

PAM16 PP > 4dB

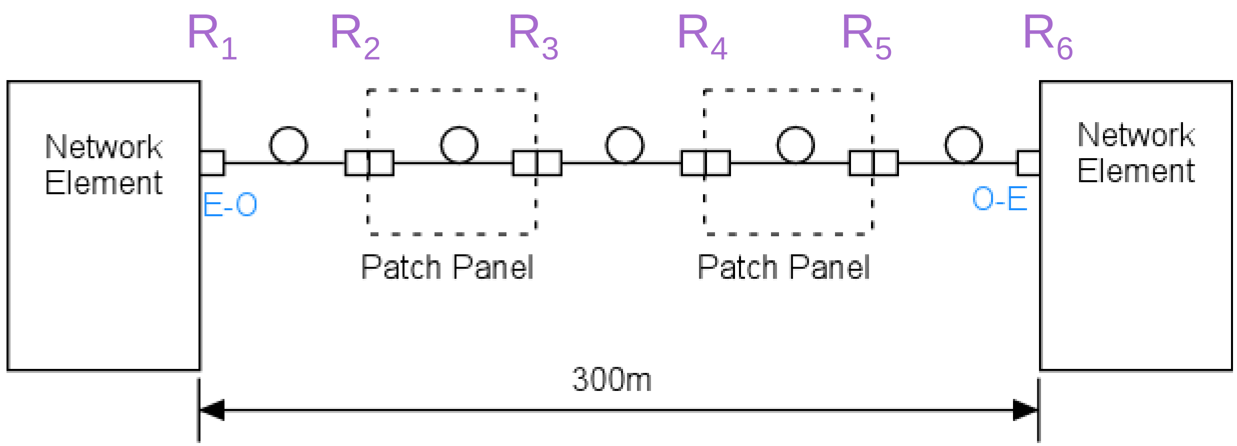


PAM8 PP ~ 0.15dB

PAM16 PP ~ 0.8 dB

- If all reflections are -27dB
- For 2 points we have -27 -27 = -54 dB
- For 6 points we have -54 + 12 = **-42 dB**
- For 12 points we have -54 + 18 = **-36 dB**

Connector Requirement Scenarios



- Fix R1=R6 = -27 dB return loss
- Fix Path Penalty at 0.1dB
- What performance is required from R2-R5, assuming all connectors are equal ?

		Connector Requirement for 0.1 dB penalty @1e-5 BER	
	0.1 dB penalty @1e-5 BER	4 connectors + TX/RX return loss	10 connectors + TX/RX return loss
PAM-2	-28	-18.3	-22.6
PAM-4	-37	-23.4	-27.7
PAM-8	-41	-26.1	-30.3
PAM-16	-47	-31.2	-35.2

Reflectance in Single Mode Connectors

- There are four types of polish used on fiber connectors
  - ➢Physical Contact (PC)*
  - ➢Super Physical Contact (SPC)*
  - ➢Ultra Physical Contact (UPC)*
  - ➢Angled Physical Contact (APC)*

Example: Commercially Available SMF MPO Patch, 55dB RL (UPC)

http://awapps.commscope.com/catalog/systimax/product_details.aspx?id=32396&tab=1

Cable Connectivity per Corning App Note

Table 1 shows different levels of PC polishing that can be achieved with Corning Cable Systems' single-mode termination methods.

Field-Installable Connector Polish Grades & Associated Single-Mode Reflectance	
Physical Contact	≤ -30 dB
Super Physical Contact (SPC)	≤ -40 dB
Ultra Physical Contact (UPC)	≤ -50 or -55 dB
Angled Physical Contact (APC)	≤ - 65 or -70 dB

Table 1- Single-Mode Connector Reflectance Values

*Note: Some references assign the 'P' to mean "polish" rather than "physical"

Corning Source = "Considerations for Optical Fiber Termination, AEN 89, Revision 2 "; http://catalog2.corning.com/CorningCableSystems/media/Resource_Documents/application_engineering_notes_rl/AEN089.pdf

-26 dB appears to be a practical worst case for non APC connector

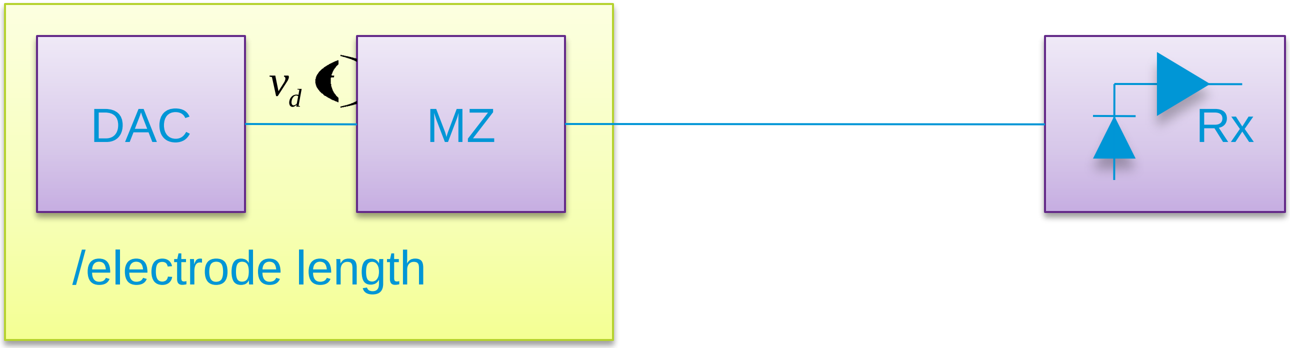
PAM MPI Summary

- Higher order PAM modulations are more sensitive to MPI
- Initial analysis indicates that while this is an effect that needs to be considered, it does not appear to be a show stopper
- Even restricting the MPI penalty to 0.1dB still only requires a fairly practical connector return loss of ~ -26 dB (i.e. non APC) for PAM8. PAM16 is a little more challenging requiring a connector return loss of ~ -31dB.
- This initial analysis is thought to be conservative, and additional work is needed to further refine the results

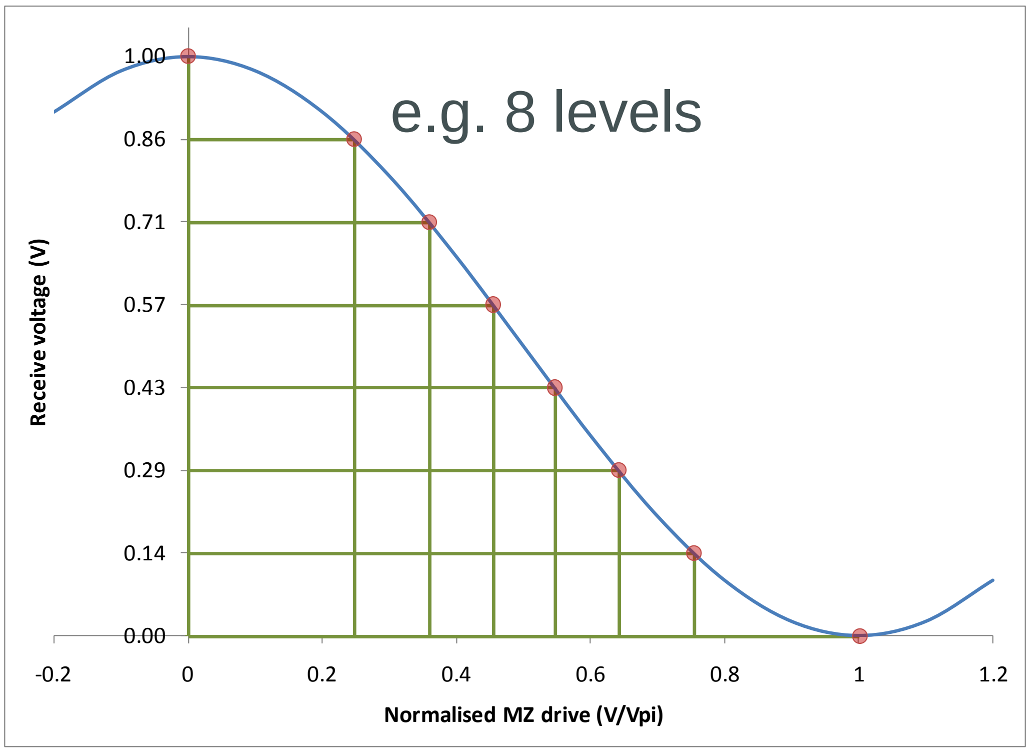
Thank you.

Transmitter

Modulator



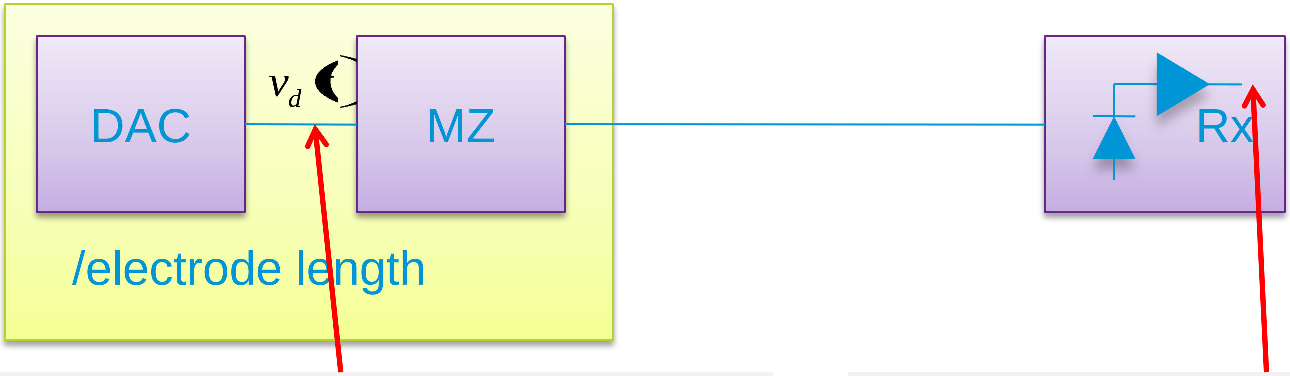
$$v_{rx}(t) = \cos^2\left(\frac{\pi}{2}\frac{v_d(t)}{V_\pi}\right)$$



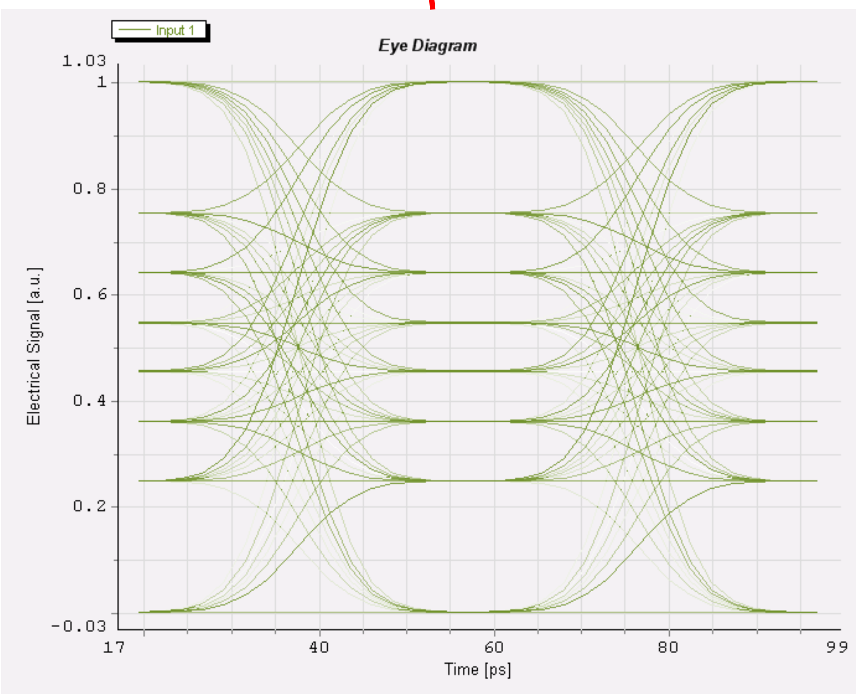
- For M levels and symbol voltage $d_k = \{0 \ldots M-1\}$:

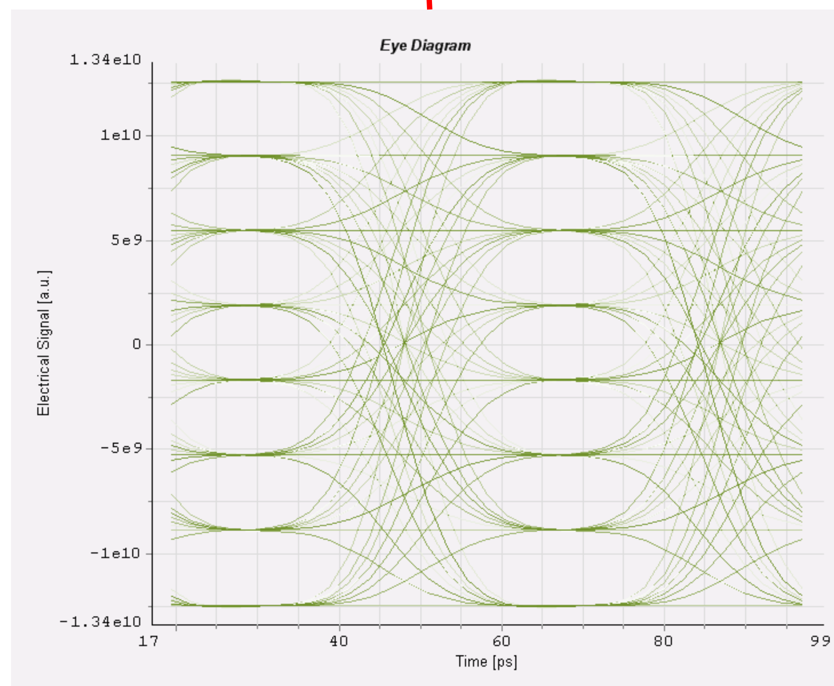
$$\frac{v_d(t)}{V_\pi} = \frac{2}{\pi}\operatorname{acos}\left(\sqrt{\frac{d_k}{M-1}}\right)$$

Modulator



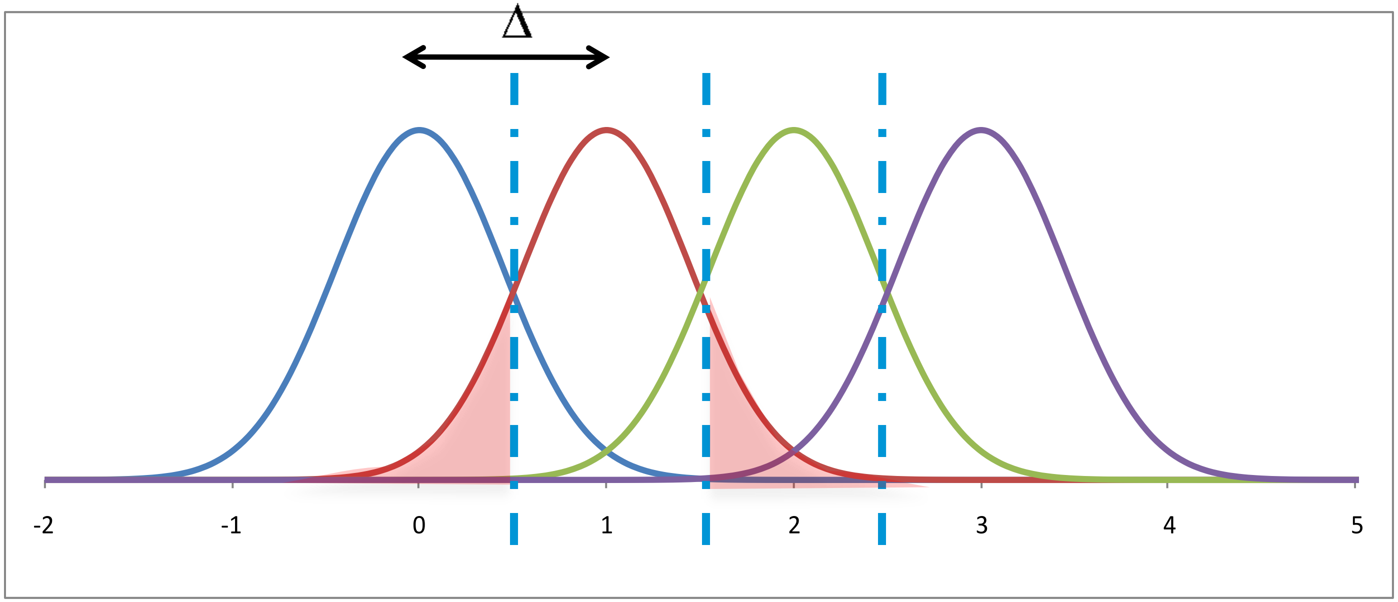
$$v_{rx}(t) = \cos^2\left(\frac{\pi}{2}\frac{v_d(t)}{V_\pi}\right)$$





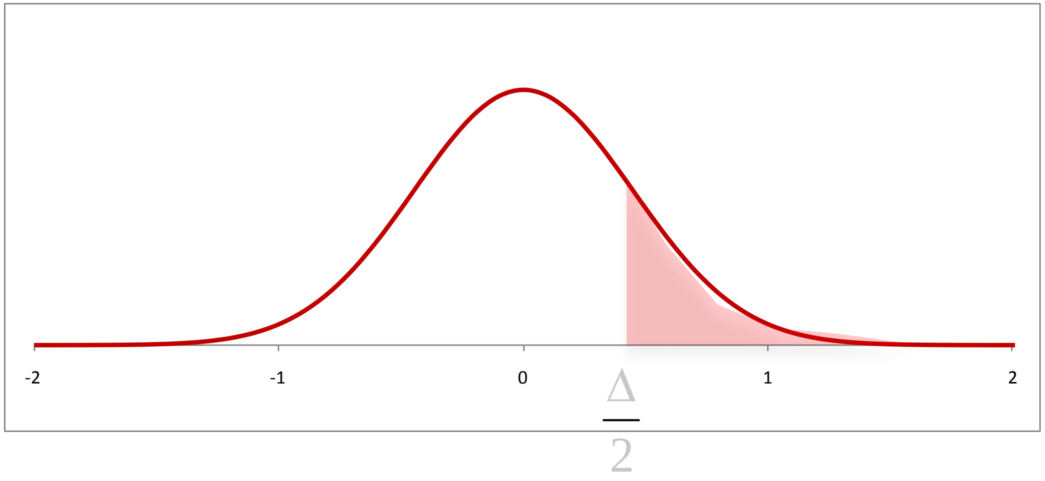
Sensitivity Analysis

Method



- For M levels, the Symbol Error ratio is $P_e = 2\left(\frac{M-1}{M}\right)P^+$

Method



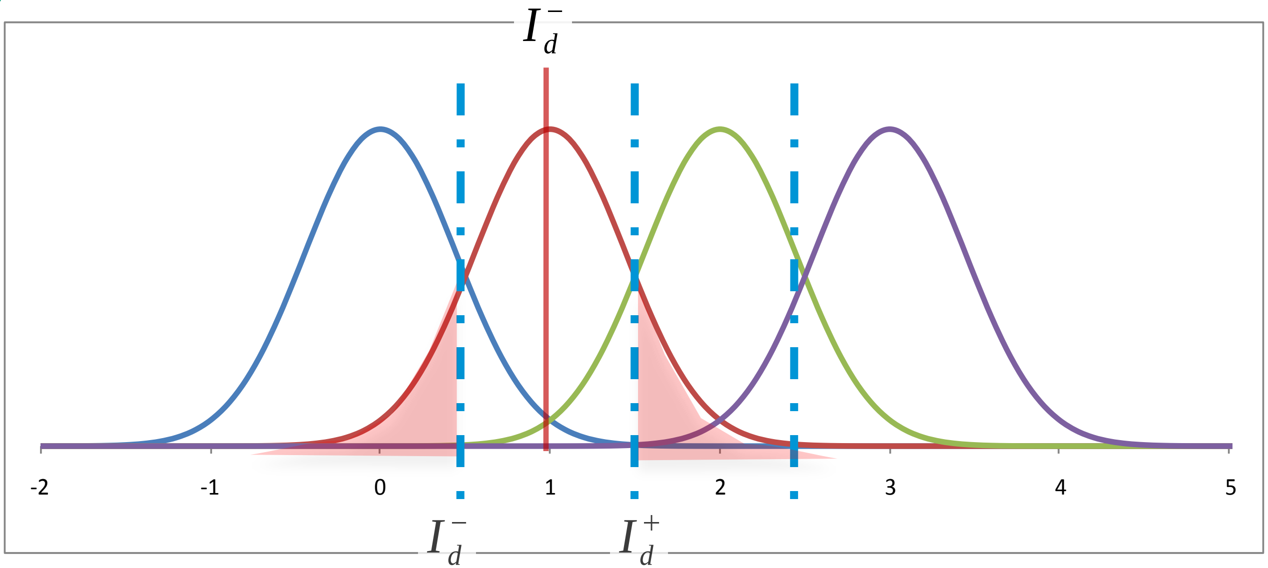
- For a single rail: $$P^{+} = \int_{\frac{\Delta}{2}}^{\infty} \frac{1}{\sqrt{2\pi\sigma_N}} e^{-\frac{x^2}{2\sigma_N}} dx = \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}}\frac{\Delta}{2}\frac{1}{\sigma_N}\right)$$
- Symbol Error ratio : $$P_e = \frac{M-1}{M} erfc\left(\frac{1}{\sqrt{2}}\frac{1}{M-1}\frac{\Re P_{av}}{\sigma_N}\right)$$
- Bit Error ratio $$P_e = \frac{1}{\log_2(M)}\frac{M-1}{M} erfc\left(\frac{1}{\sqrt{2}}\frac{1}{M-1}\frac{\Re P_{av}}{\sigma_N}\right)$$

Responsivity
+ Average power

Noise

RIN Analysis

Analysis I



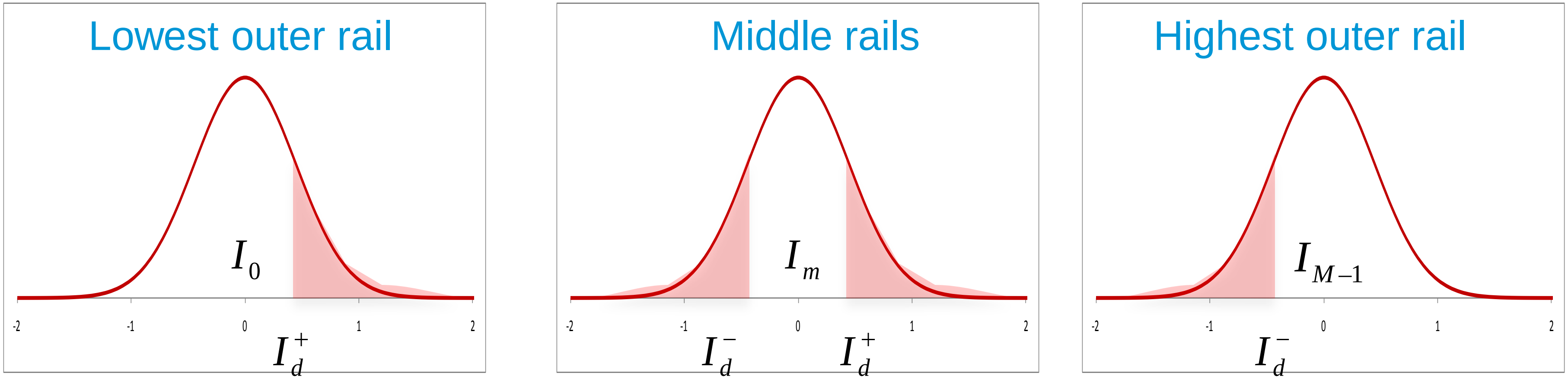
- We can calculate the total noise on each rail

$$\sigma^2_{TOTAL}(m) = \sigma^2_{th} + \sigma^2_{RIN}(m) = N_{th}^2 \Delta f + I_m^2 \cdot RIN \cdot \Delta f$$

$$I_m = 2\Re P_{av} \frac{m}{M-1}$$

- Both thermal noise and RIN noise change at same rate with Δf
  - Penalty will not depend upon baud rate

Analysis II



m=0 m=1...M-2 m=M-1

- Decision threshold depends upon noise of each rail:

$$I_d^-(m) = \frac{\sigma_{m-1} I_m + \sigma_m I_{m-1}}{\sigma_{m-1} + \sigma_m} \qquad I_d^+(m) = \frac{\sigma_m I_{m+1} + \sigma_{m+1} I_m}{\sigma_m + \sigma_{m+1}}$$

- Bit error ratio:

$$P_b = \sum_{m=0}^{M-1} P_b(m)$$

$$P_b(m) = \frac{1}{M \log_2 M} \cdot \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}} \frac{I_m - I_d^-}{\sigma_{TOTAL}(m)} \right)$$

Not on lowest rail

$$+ \frac{1}{M \log_2 M} \cdot \frac{1}{2} erfc\left(\frac{1}{\sqrt{2}} \frac{I_d^+ - I_m}{\sigma_{TOTAL}(m)} \right)$$

Not on highest rail