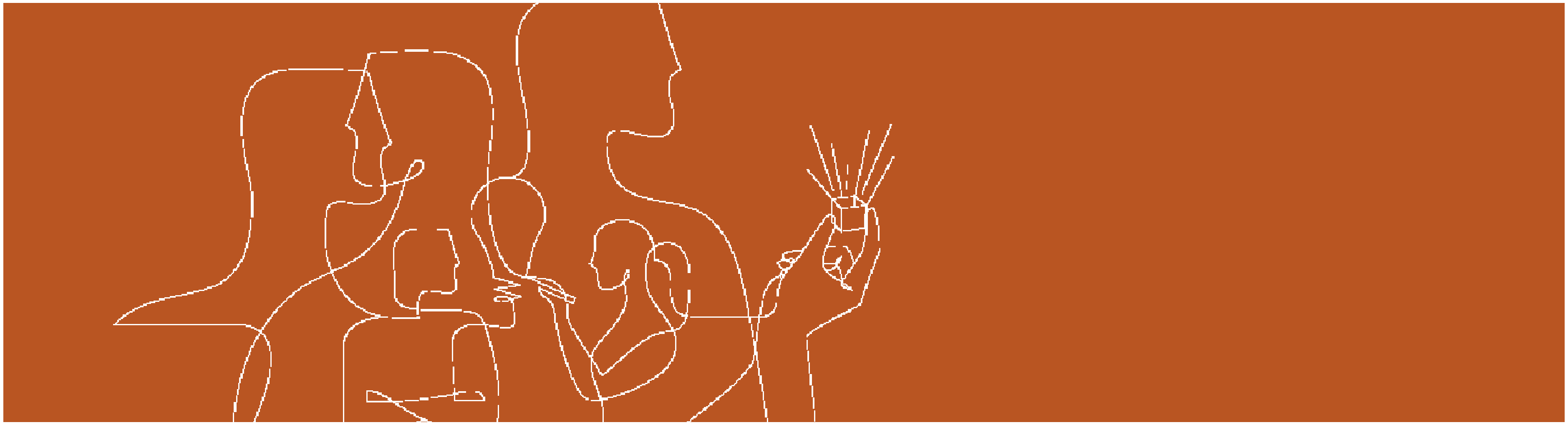

PAM-8 and PAM-16 Optical Receivers for 2km 100G Links with a 4dB loss budget.

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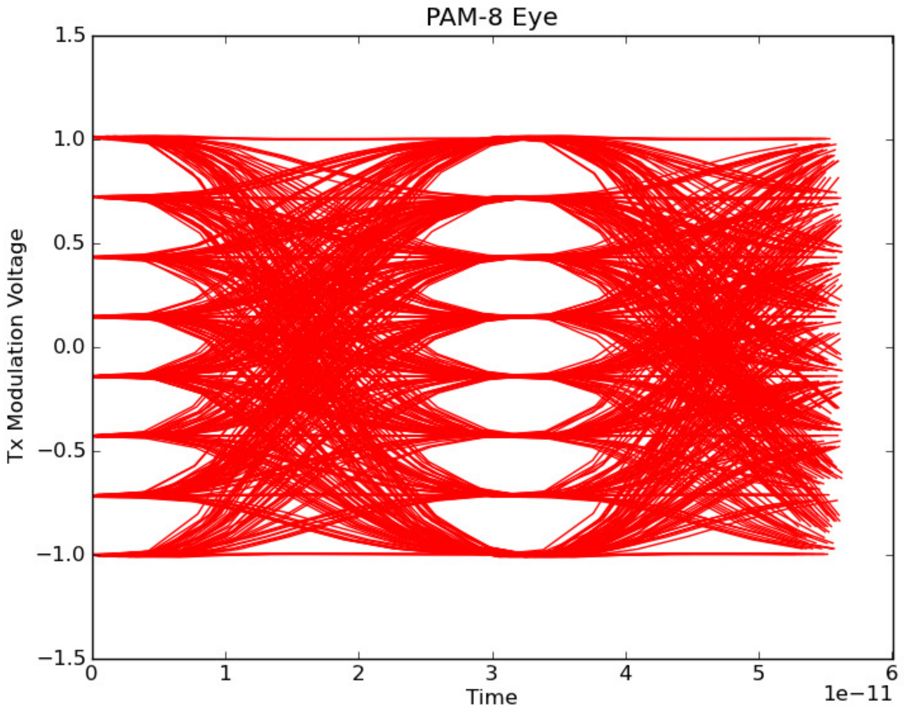
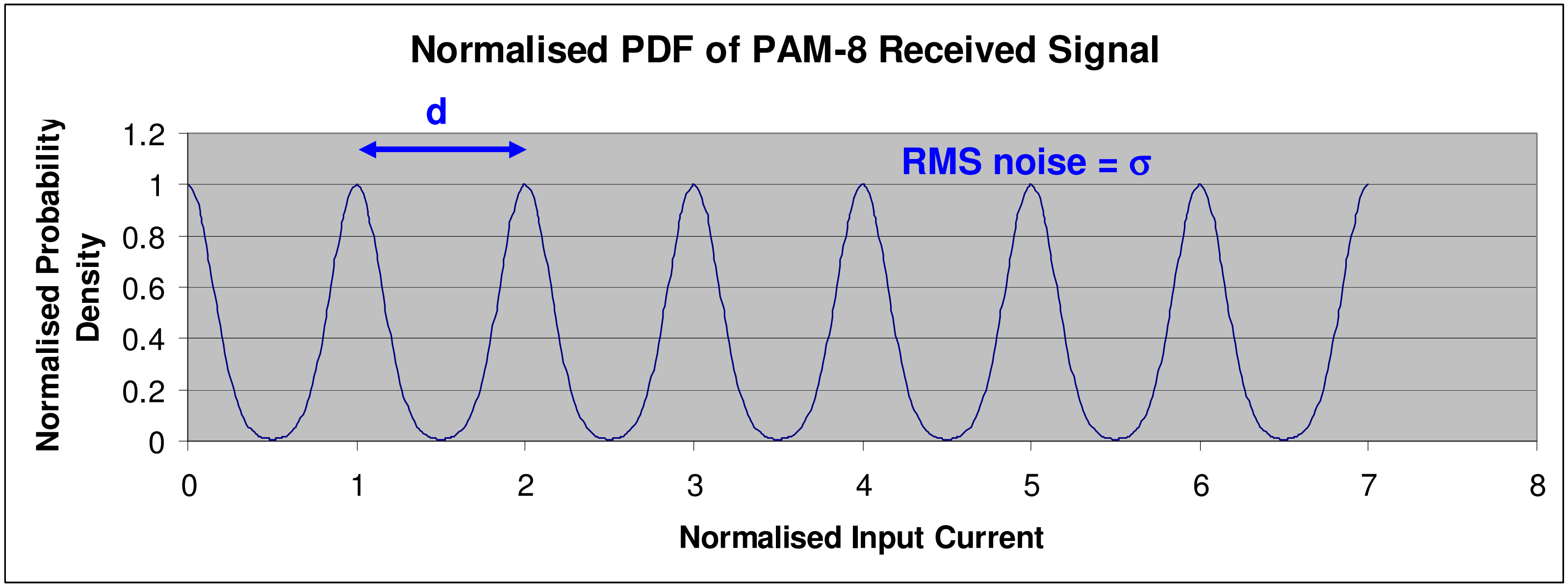
10th March 2012

Basics of PAM-M

- Modulate the Optical Tx with M level pulse Amplitude Modulation (PAM)
- 2 bits/symbol for PAM-4
- 3bits/symbol for PAM-8
- 4 bits/symbol for PAM-16



Rx Error Probability Calculation (1)



For levels 0 and M-1 the error probability is: $\frac{1}{M}\int_{d/2}^{\infty} N(0,\sigma)dv$

For levels 1 to M-2 the error probability is: $\frac{2}{M}\int_{d/2}^{\infty} N(0,\sigma)dv$

Hence the total error probability is: $2\frac{M-1}{M}\int_{d/2}^{\infty} N(0,\sigma)dv = \frac{M-1}{M} erfc(\frac{d}{2\sqrt{2}\sigma})$

N(mean, standard deviation) is the standard Gaussian PDF

Rx Error Probability Calculation (2)

Now we can express d in terms of the mean electrical signal and the optical extinction ratio as follows:

$$d = < s > \frac{E-1}{E+1}\frac{2}{M-1}$$

So we can relate the symbol error rate to the mean signal to RMS noise ratio as follows:

$$P_E = \frac{M-1}{M} erfc\left(\frac{< s >}{\sqrt{2}\sigma(M-1)}\frac{E-1}{E+1}\right)$$

Where <s> is the mean signal, σ the rms noise and E the linear extinction ratio:

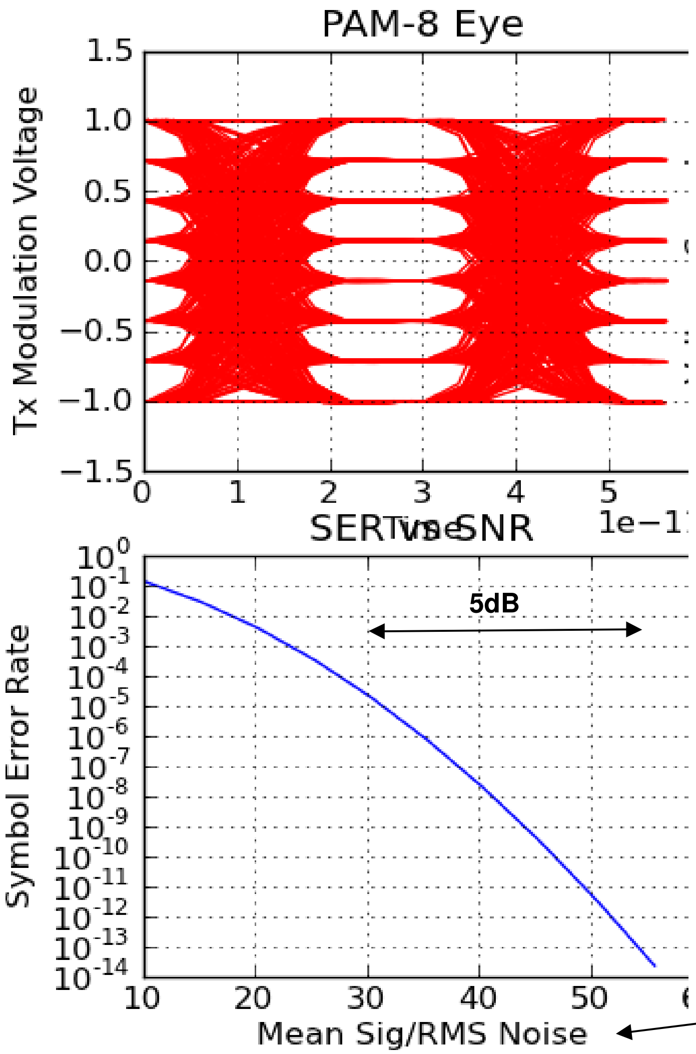
Assumptions: Data is gray coded to make BER equal to symbol error rate / (no bits per symbol)
levels are equally spaced
Noise is independent of signal

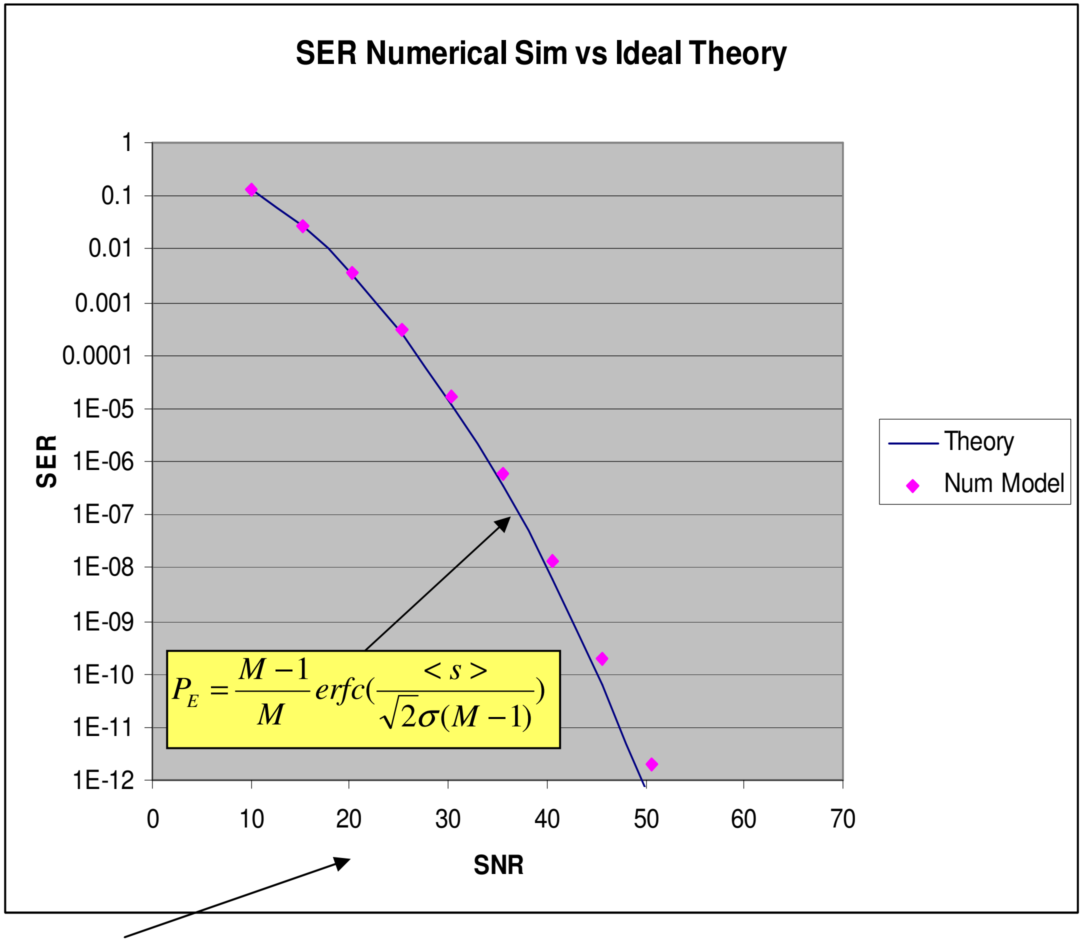
$$BER = \frac{M-1}{M\log_2(M)} erfc\left(\frac{< s >}{\sqrt{2}\sigma(M-1)}\frac{E-1}{E+1}\right)$$

Time Domain Numerical Model

- To investigate the effect of non linearity and other pulse distortions it is necessary to do a symbol by symbol numerical model. This has been implemented in a Matlab-Simulink like environment (Python/SciPy)
- A long data pattern is sampled at eye centre using a CDR triggered off the zero crossings of the PAM input signal. The M-1 slicing thresholds are distributed evenly between the measured Max and Min voltages of the data signal.
- The vector distances between each sample and the M-1 thresholds are calculated and then the probability of crossing the adjacent thresholds due to added Gaussian noise is computed. The error probability is then averaged over the pattern length

Numerical Model: Comparison of near Ideal Eye with Closed Form Expression for Error rate

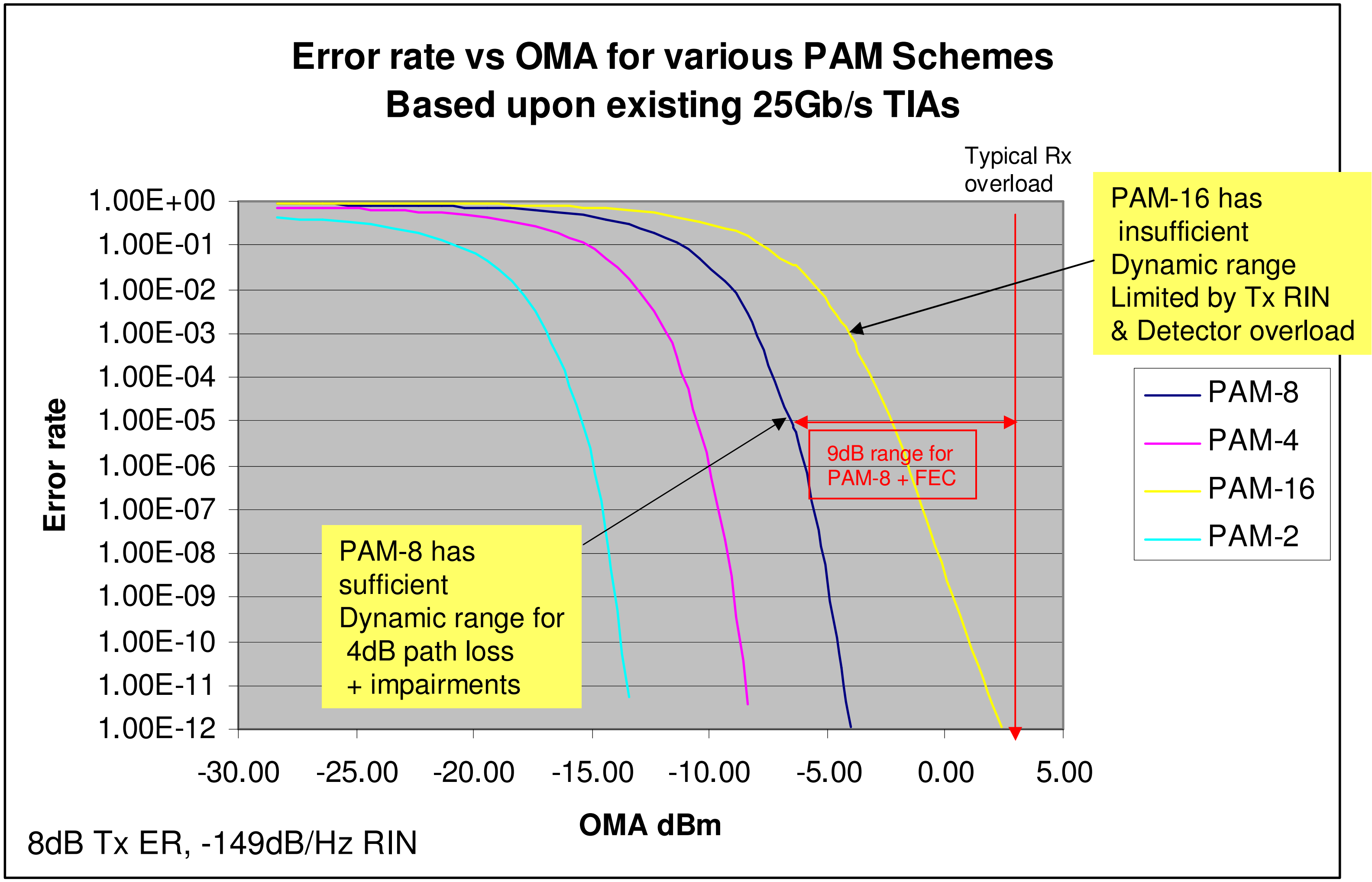




$$P_E = \frac{M-1}{M} erfc(\frac{<s>}{\sqrt{2}\sigma(M-1)})$$

Linear

Rx Dynamic Range Comparison For different PAM Schemes

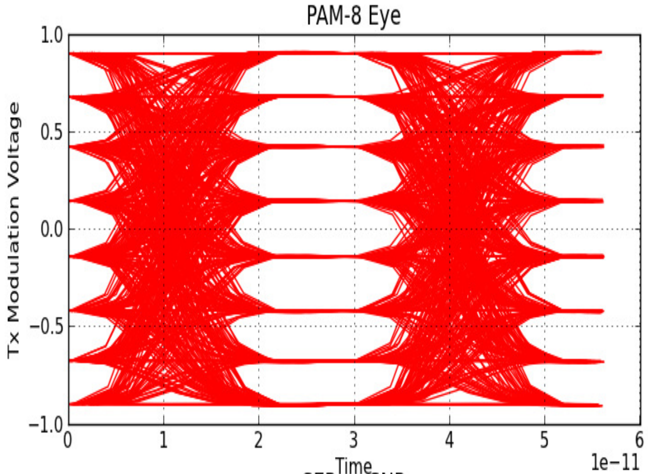


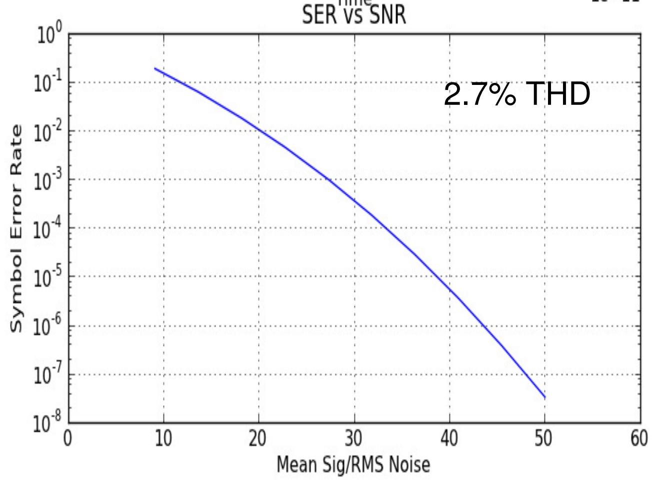
PAM-16 has insufficient Dynamic range Limited by Tx RIN & Detector overload

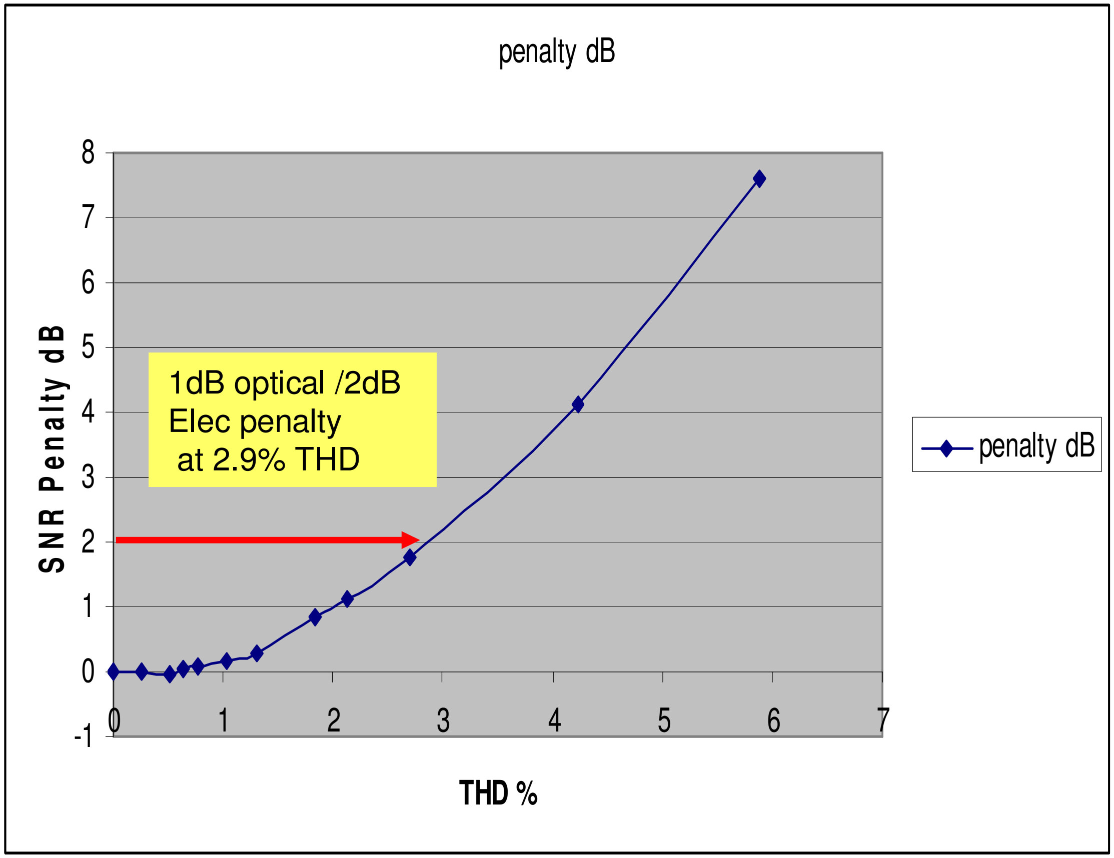
PAM-8 has sufficient Dynamic range for 4dB path loss + impairments

8dB Tx ER, -149dB/Hz RIN

PAM-8 THD Penalty from Symmetrical Compression (Calculated at 10^{-5} BER sensitivity)

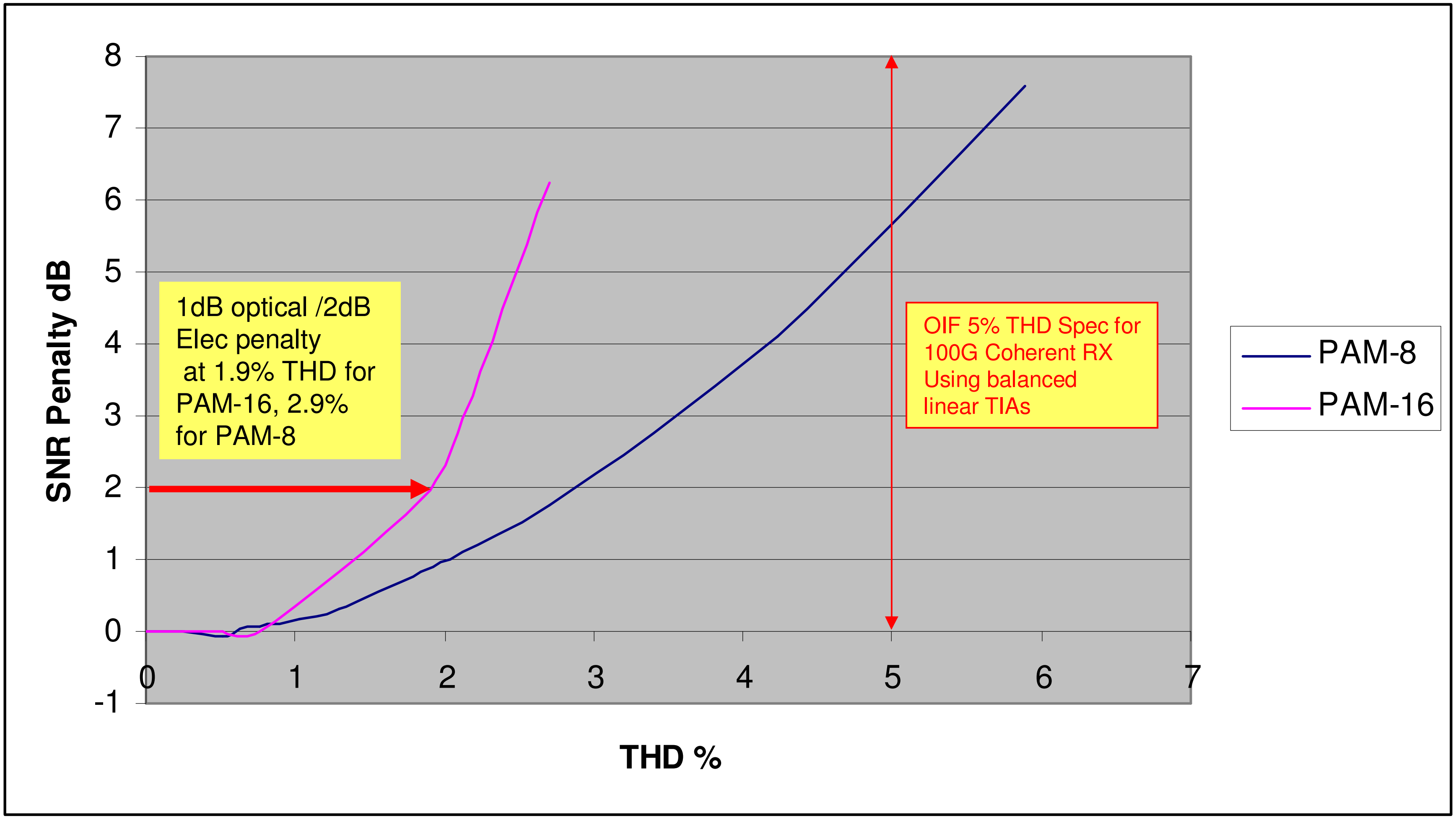






1dB optical /2dB Elec penalty at 2.9% THD

PAM-8 vs PAM-16 Simulated THD Penalty

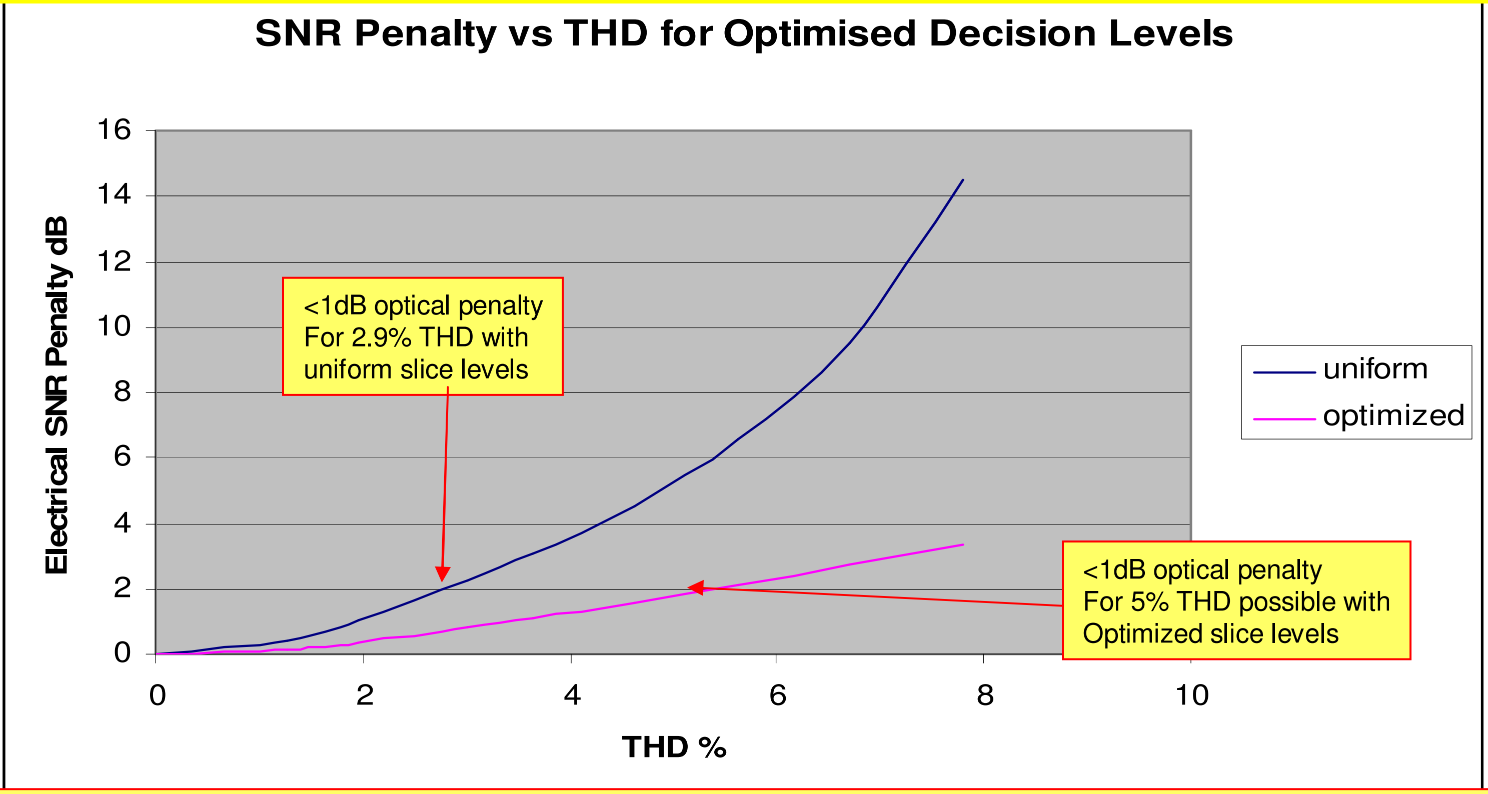


PAM-8 and PAM-16 Receivers will need strict linearity specifications

PAM-16s small dynamic range will be further eroded by linearity constraints

PAM-8 Slice Threshold Optimization for Improved THD Tolerance (and numerous other impairments)

As non linearity affects the outer eyes more than the inner ones we should be able to compensate by adjusting the decision thresholds



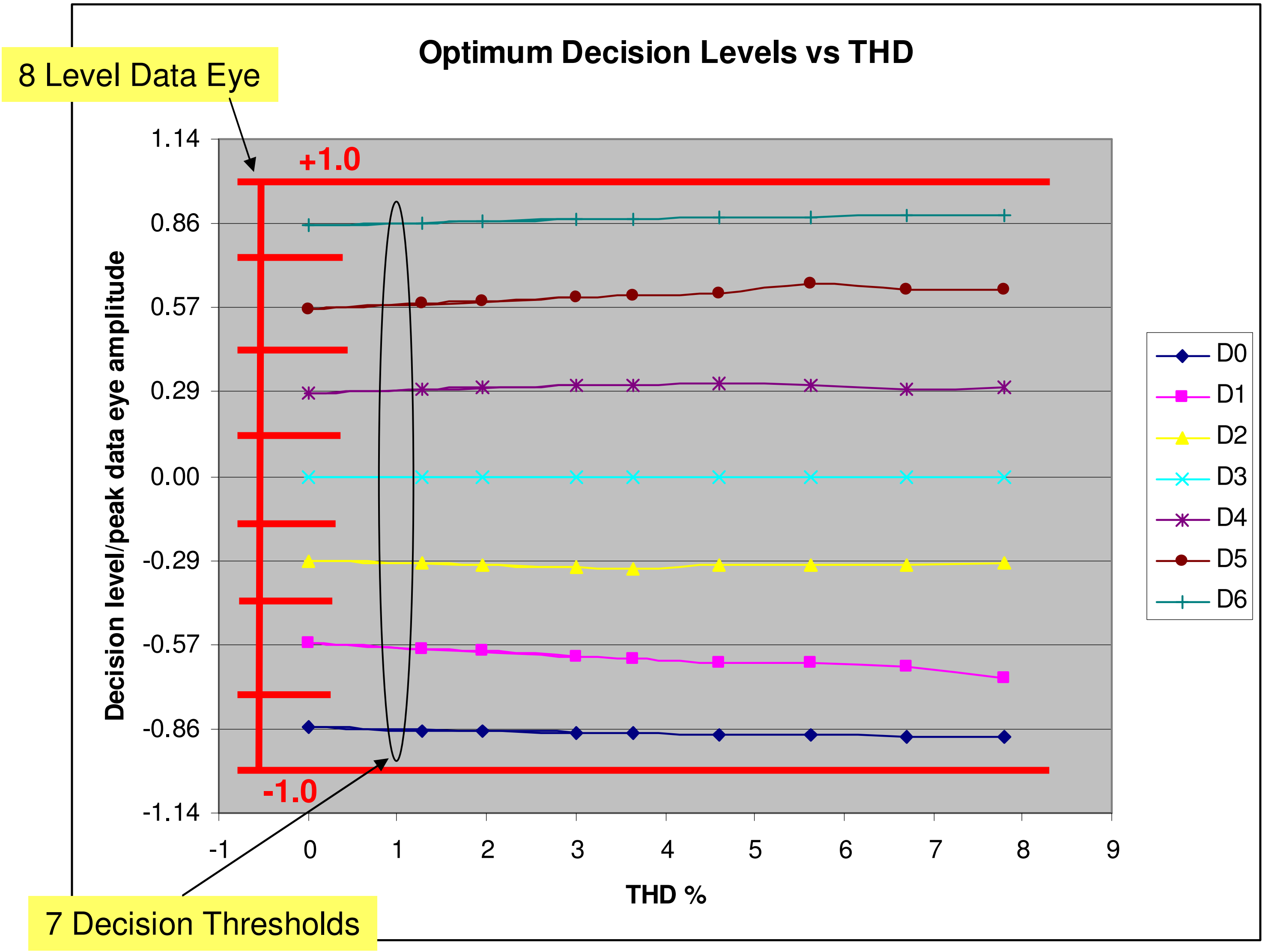
SNR Penalty vs THD for Optimised Decision Levels

<1dB optical penalty
For 2.9% THD with
uniform slice levels

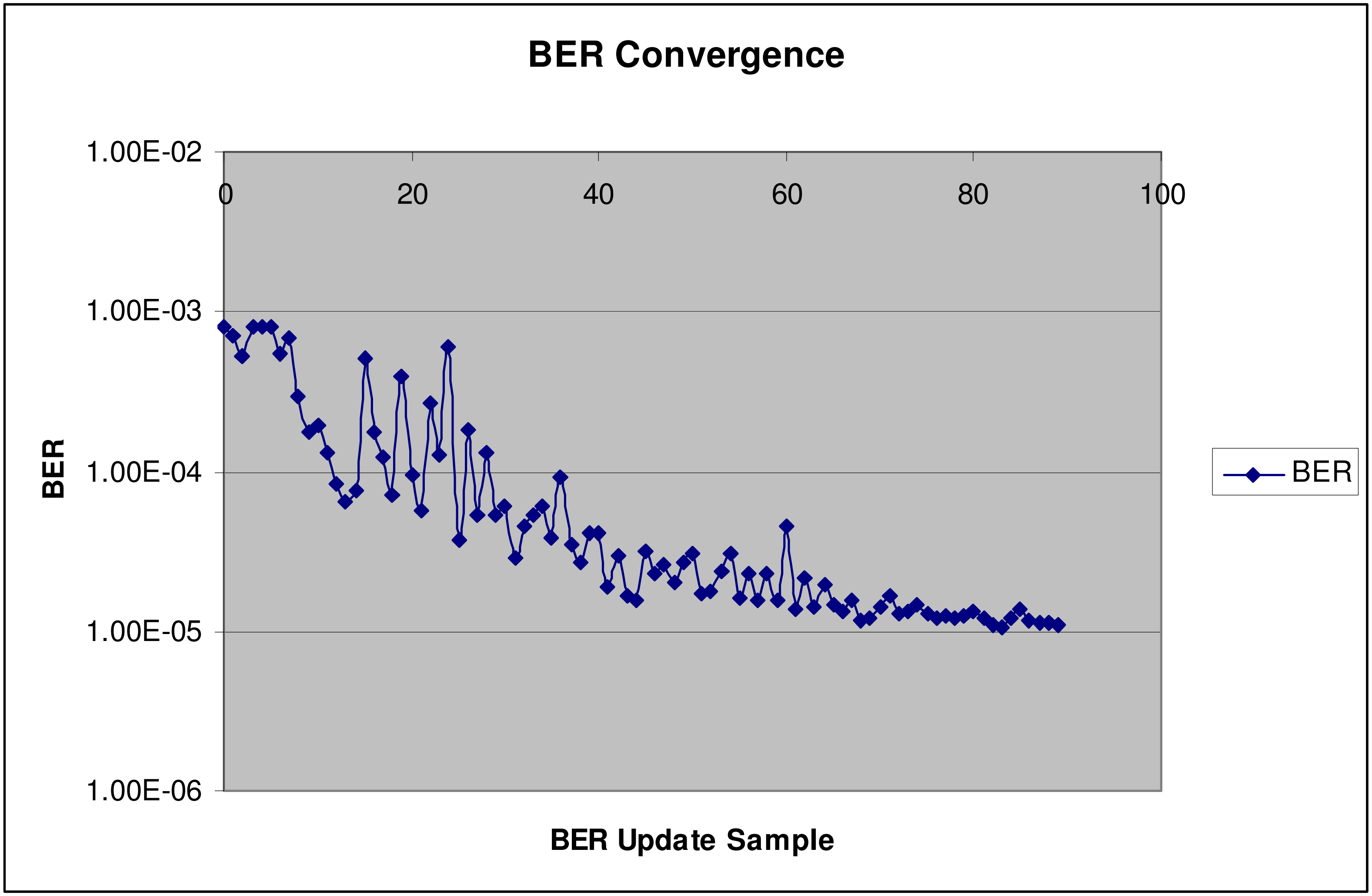
<1dB optical penalty
For 5% THD possible with
Optimized slice levels

Simulation using “Nelder – Mead Downhill Simplex” optimization of slice levels
For lowest SNR giving 10^{-5} BER. For details of the algorithm see
Nelder, J.A. and Mead, R. (1965), “A simplex method for function minimization”, The Computer Journal, 7, pp. 308-313

Simulated Optimized Decision Levels vs THD

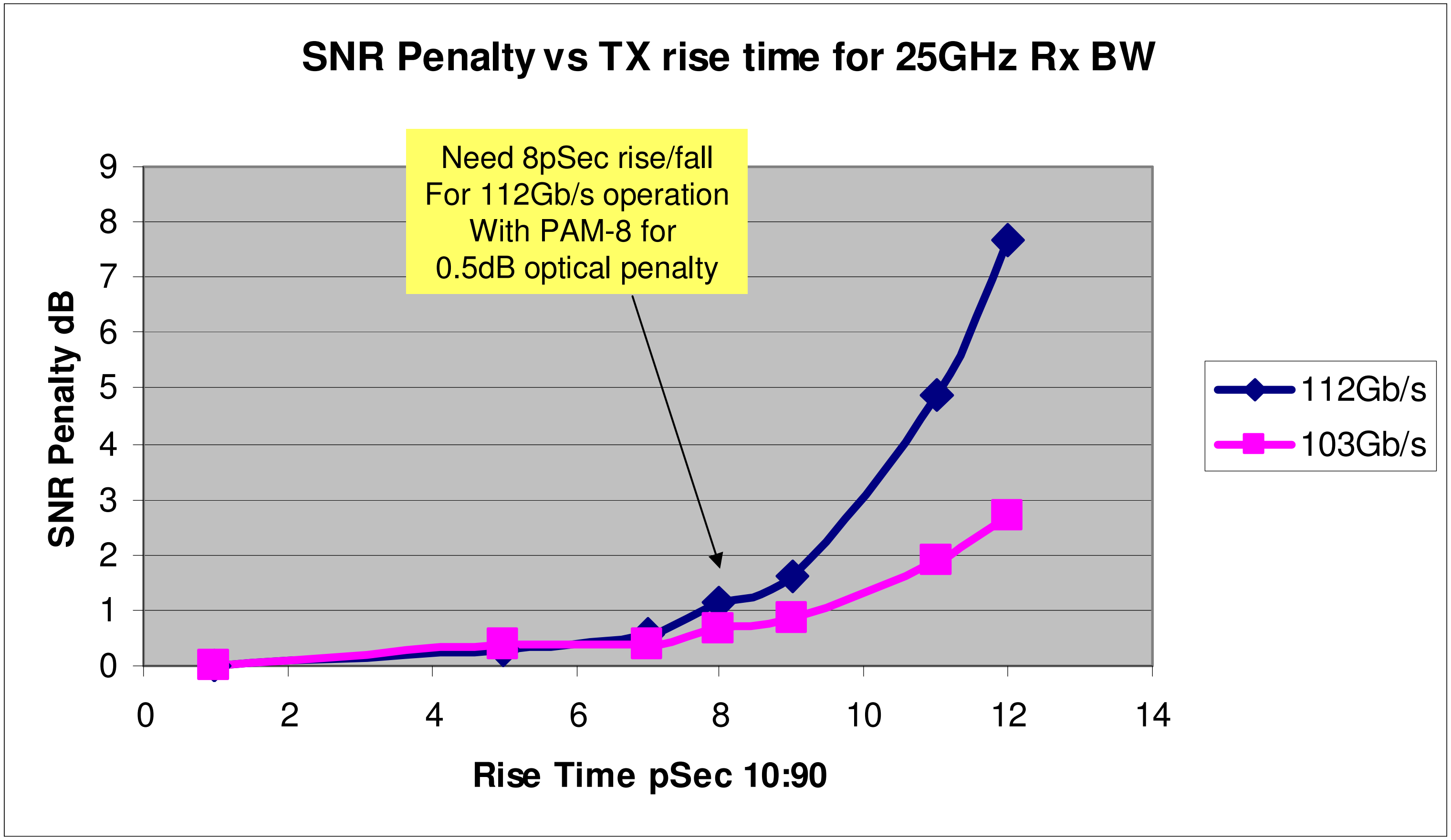


Convergence of PAM-8 Threshold Optimization

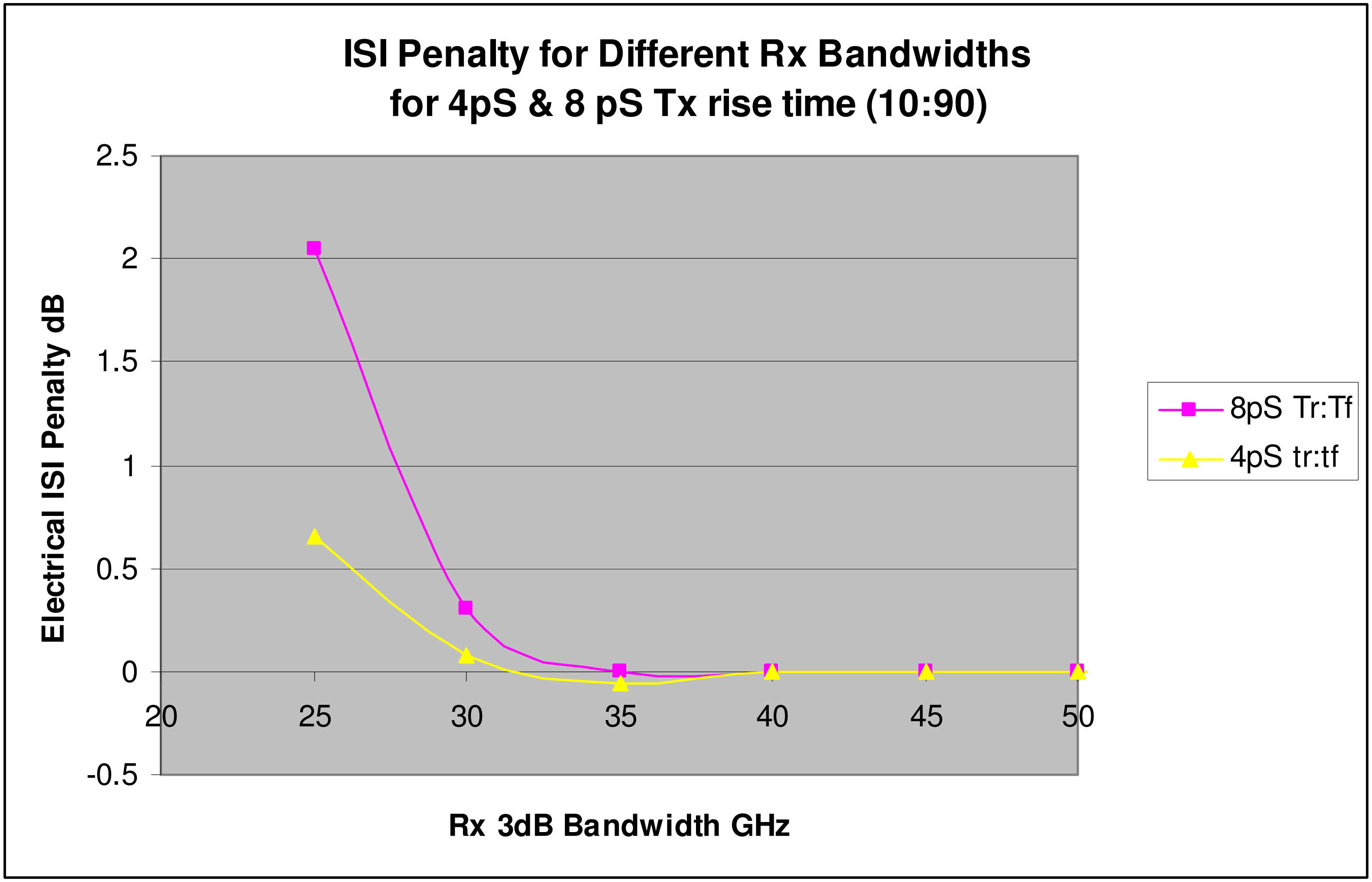


N-M simplex algorithm converging from an initial high BER and with 5% THD using raw BER feedback only – this could be implemented In hardware/firmware.

PAM8 TX Rise Time Requirements



Rx Bandwidth Simulations
112Gb/s Data



Conclusions

- PAM-16 without FEC requires a high SNR that is incompatible with practical optical receiver overload limits. With FEC the dynamic range is improved but not enough to budget for 4dB path loss and 3-4 dB of impairment margin.
- PAM-8 without FEC is similarly too restrictive on dynamic range but PAM-8 with FEC seems capable of working with a reasonable loss budget.
- PAM-8 would need to achieve <3% max THD for 1dB optical penalty and PAM-16 would need <2%. These represent challenging targets particularly given the need to operate at high peak-peak photocurrents to maintain adequate SNR.
- Adaptive threshold approaches need to be used to relieved distortion requirements to realistic 5% range.
- Operation at 112Gb/s with an 8pS rise time Tx requires Rx bandwidths of the 30-35GHz. Improvement over current 25G modulator rise times (12pS) will be necessary.
- Further work:
    - Model development to establish realistic budget numbers. This must include Tx imperfections (nonlinearity, phase response) and the Rx CDR & demux plus any equalization.
    - Dual PAM4 approaches

Should we consider “dual PAM4”?

- PAM16
  - Simple implementation (no gearbox, simple clocking)
  - Optical system does not support the approach
- PAM8
  - Optical system can support it but it is challenging (more power, cost)
  - Increased complexity, gearbox required, optical symbol rate is higher than electrical bit rate (power, cost)
- “dual PAM4”
  - I&Q require coherent receiver
  - Dual polarization requires good separation
  - Dual laser may be a reasonable compromise

- Additional Material

Nonlinearity Shape used in Simulations

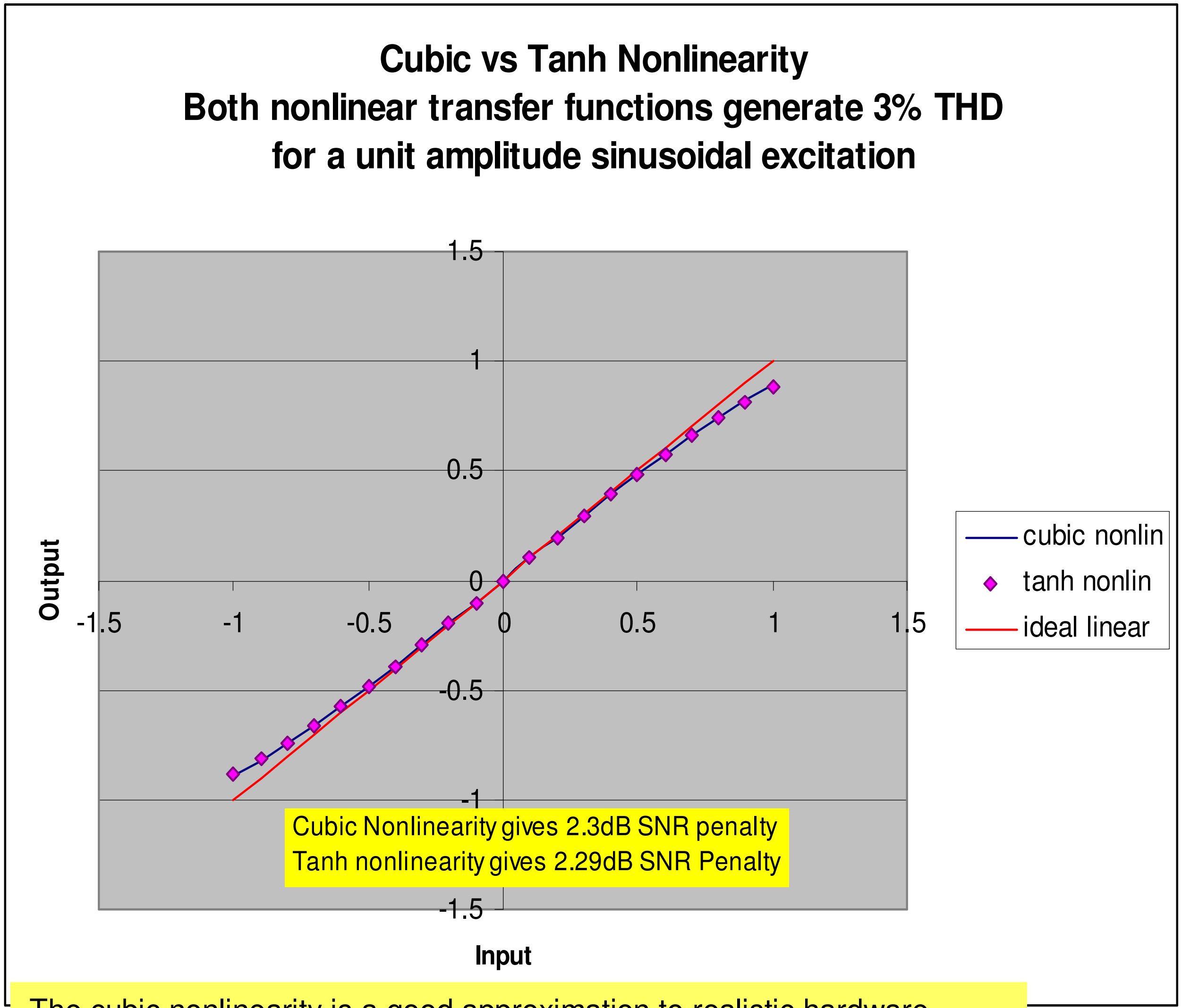
- The THD simulations were done with a notional cubic nonlinearity to produce a given THD i.e a transfer function of the form:

$$y(x) = x - \alpha x^3$$

- Where α determines the harmonic distortion level. The THD can be calculated in a simple expression as THD=$\alpha/(4-3\alpha)$ for a unit amplitude sinusoidal signal. Whilst this may be convenient for the mathematics a better description of a real hardware nonlinearity may be:

$$y(x) = \frac{1}{\beta}\tanh(\beta x)$$

- In this case β determines the harmonic distortion. The THD level can be calculated numerically using a discrete fourier transform.


Cubic vs Tanh Nonlinearity
Both nonlinear transfer functions generate 3% THD for a unit amplitude sinusoidal excitation

Cubic Nonlinearity gives 2.3dB SNR penalty
Tanh nonlinearity gives 2.29dB SNR Penalty

The cubic nonlinearity is a good approximation to realistic hardware nonlinearities and does not significantly affect the simulated SNR penalty