TDEC for PAM4

Potential TDP replacement for clause 123, and Tx quality metric for future 56G PAM4 shortwave systems

802.3bs ad hoc

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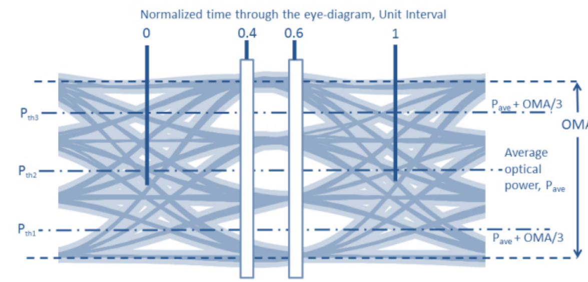
Introduction

- Link budgets close if:
  - Tx eye quality and SRS test source calibration metrics use equivalent methods
  - The Tx eye quality metric yields a dB value which correlates with the system penalty of real transmitters
- Two broad options
  - TDP
    - hardware based sensitivity measurement comparison
    - needs definition of a hardware reference Rx and reference equalizer
    - and live with the knowledge that everyone will have a slightly different implementation of these which may lead to interoperability issues and variability in practice

  or
  - TDEC
    - A real time or sampling 'scope based measurement; real time 'scope is probably easier to standardize; sampling 'scope probably more likely to be used in practice.
    - Requires a short test pattern (< 2^{16} bits), definition of software based reference Rx and reference EQ, post processing using either an error counting or partial error probability calculation on the pattern or a reconstructed eye
  - This presentation looks at a 'scope based metric

Proposal for TDEC for PAM4 signals -1

- Scope based, TDEC variant expanded for all three sub-eyes in equalized PAM4 signal
  - No reference Tx needed
  - Worst case fibre required for SMF
  - Reduced bandwidth (19.6 GHz BT4) Rx for MMF



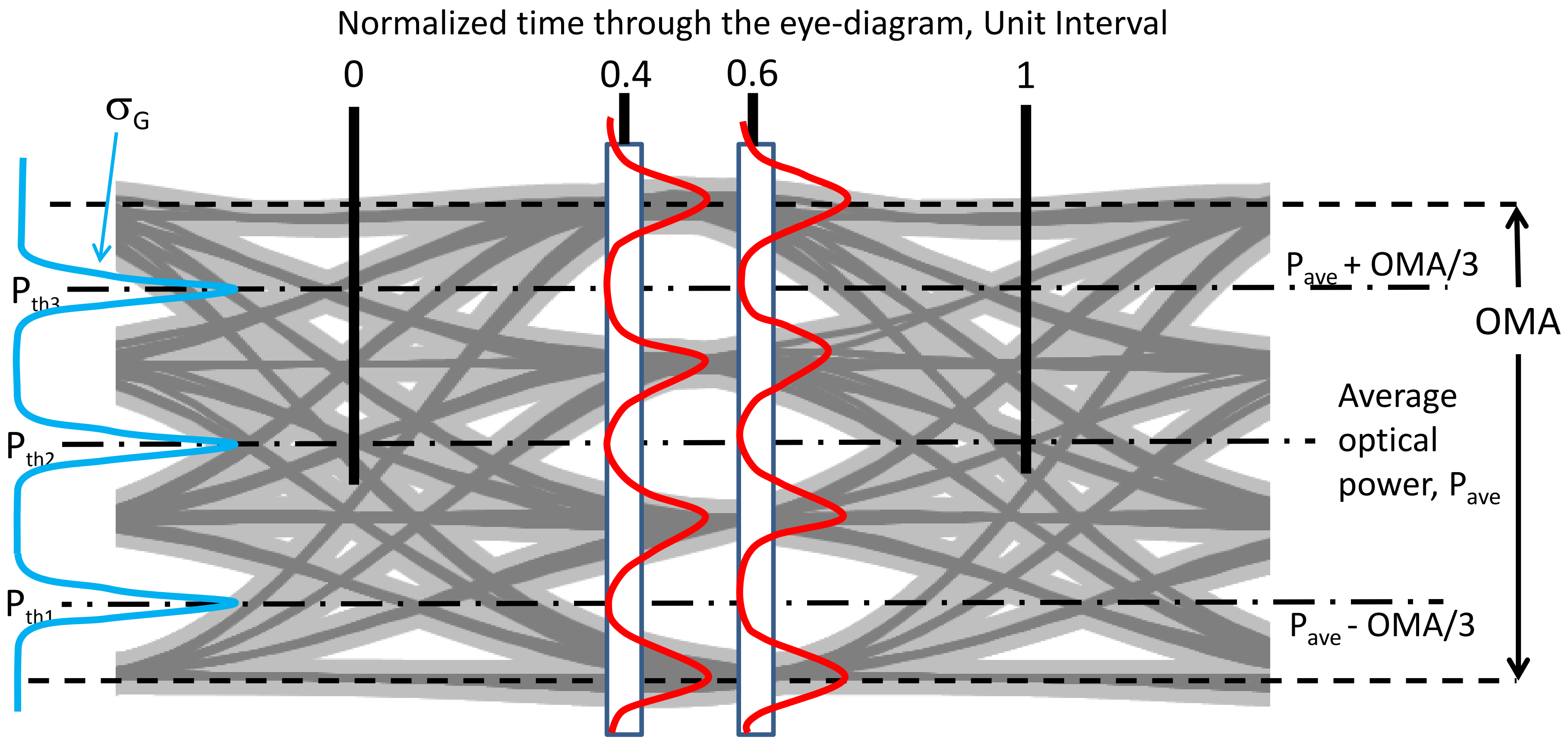
- Reference receiver and equalizer are software based 'in the 'scope'
- **Single timing position in centre of eye for all three sub-eyes**, +/-0.1 UI (TBC)
  - Time centre of eye determined from crossing points
- **TDEC calculated from fixed thresholds**: $\mathrm{P_{ave}}$, $\mathrm{P_{ave}}+\mathrm{OMA}/3$, $\mathrm{P_{ave}}-\mathrm{OMA}/3$
  - Penalizes transmitters which have unequal sub-eyes
  - This isn't how a 'real' PAM4 retimer is expected to work, but it avoids the issue of how to measure accurately the penalty of unequal sub-eyes when received by a 'real' receiver, which may have differing sensitivities for each sub-eye.
    - Part of the motivation for this work is to evaluate how much penalty that may incur
  - Should 400GE decide that optimized thresholds ought to be specified for the TDEC test, an additional (non-trivial) test will be needed to measure how transmitter and receiver sub-eye inequality/non-linearity interact.

Proposal for TDEC for PAM4 signals -2

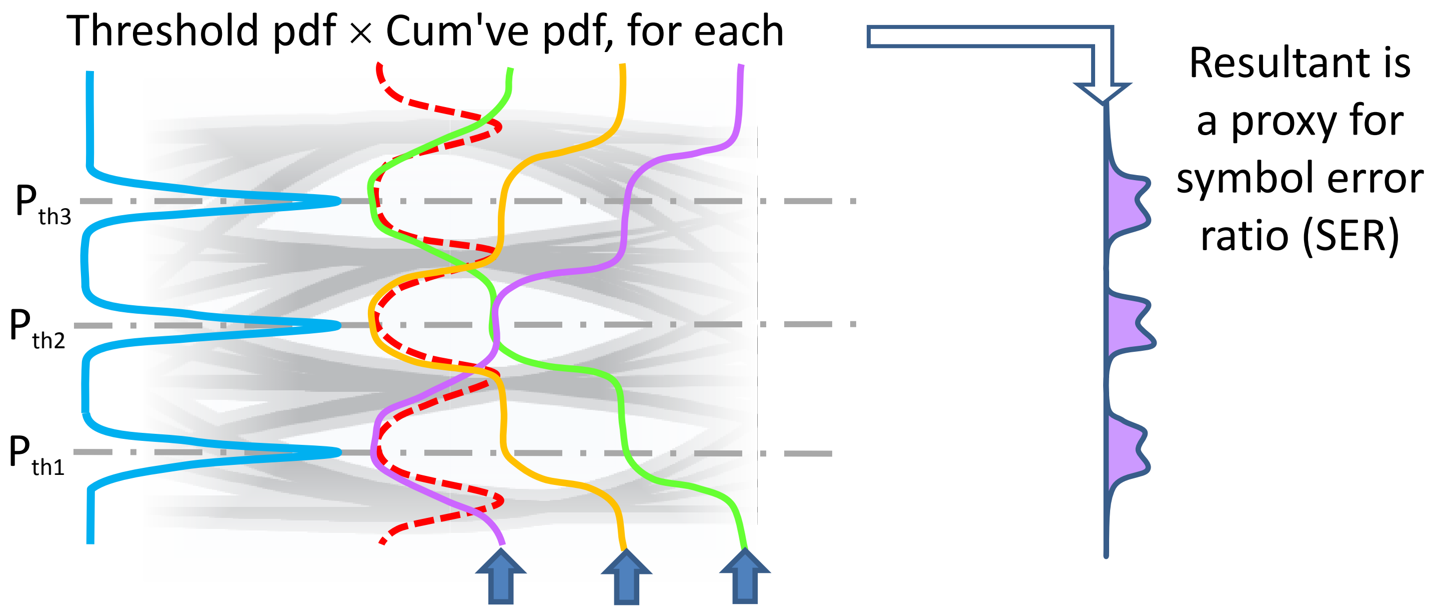
- Conceptual basics
  - Measure the combined O/E and 'scope noise without signal, σ_{OE}
  - Measure histogram through equalized eye to be tested, normalize
    - Equalization is done in the 'scope with a ref. equalizer (eg 5 T/2 tap FFE)
      - A sampling 'scope would need to do the equivalent of: measure the noise on the unequalized pattern, capture the averaged pattern and equalize it, and add back in a noise term which is consistent with the noise frequency spectrum and equalization applied
    - The histogram is a vector representing the vertical probability density function (PDF) through the PAM4 eye
    - Do this for left and right of eye time centre
  - From the vertical PDF through the PAM4 eye, create 3 cumulative probability functions, one around each sub-eye threshold.
  - Add normalized Gaussian noise term σ_G to the sub-eye thresholds
    - to create 3 PDFs consisting of a Gaussian PDF centred around each of the sub-eye thresholds
  - Multiply each threshold PDF by the appropriate cum've eye PDF to calculate a proxy for SER for that threshold; sum the results
  - Find smallest size of σ_G that makes resultant = target SER = 3.2×10^{-4}
  - Root sum square the 'scope noise to σ_G ***see note***
  - Find the equivalent σ_{ideal} for an ideal PAM4 signal: $\sigma_{ideal} = \frac{OMA}{6Qt}$
  - TDEC is the dB ratio of σ_{ideal} and $(\sigma_G^2+\sigma_{OE}^2)^{½}$ ***see note***

Note: additional manipulation of σ_G is needed to account for noise filtering by the EQ

Test Method: Two histograms



Processing, for each histogram through the eye



- Create three cumulative probability functions, one around each threshold
- Find the smallest value of σ_G to make SER = target SER
- Borrowing from 100GBASE-SR4, the noise, R, that could be added by a receiver is:

$$R = (1-M_1).[\sigma_G^2 + \sigma_{OE}^2 - M_2^2]^{½} \qquad \textit{equation (1)}$$

where M_1 and M_2 account for mode partition noise and modal noise (both are zero for SMF applications), and σ_{OE} is the rms noise of the O/E and scope combination.

- TDEC is given by:

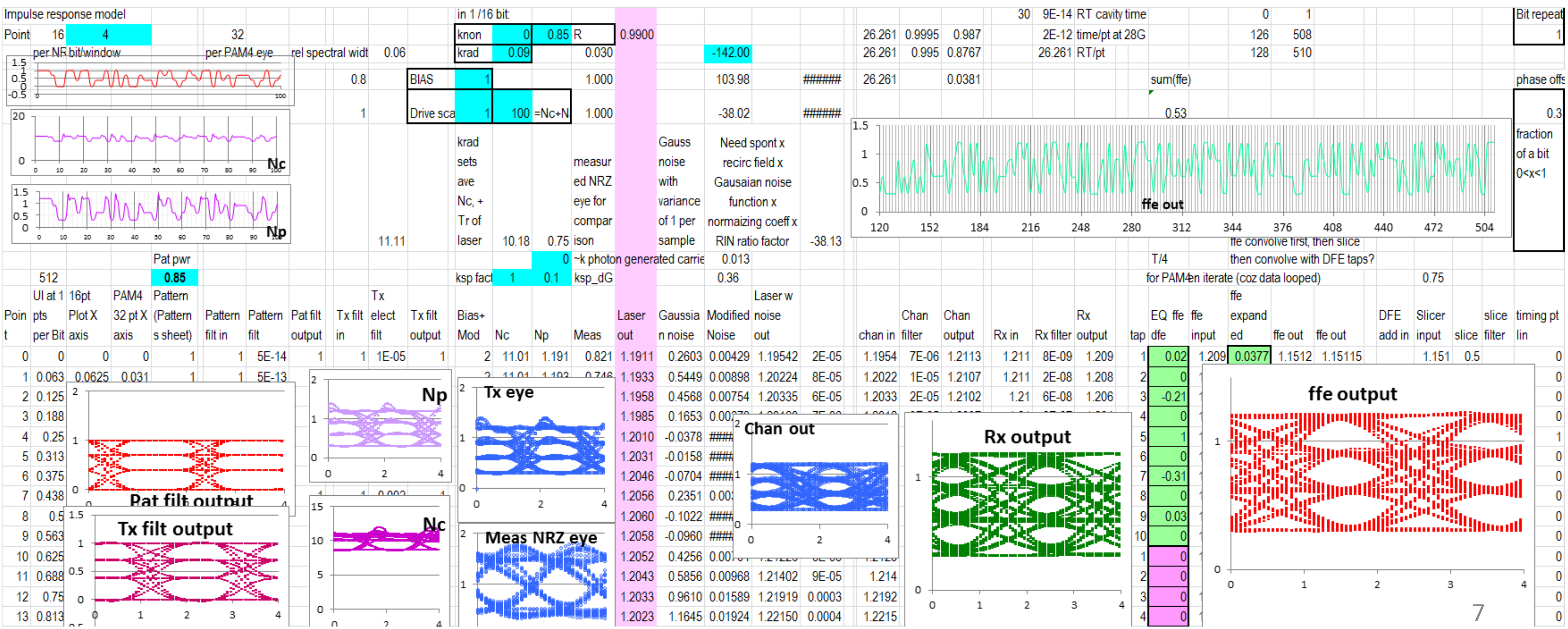
$$\text{TDEC} = 10.\log_{10}\left(\frac{OMA}{6} \times \frac{1}{Q_t R}\right) \qquad \textit{equation (2)}$$

where Q_t is the Q function value consistent with the target symbol error ratio

- The largest TDEC value, calculated for either left or right histogram, is used

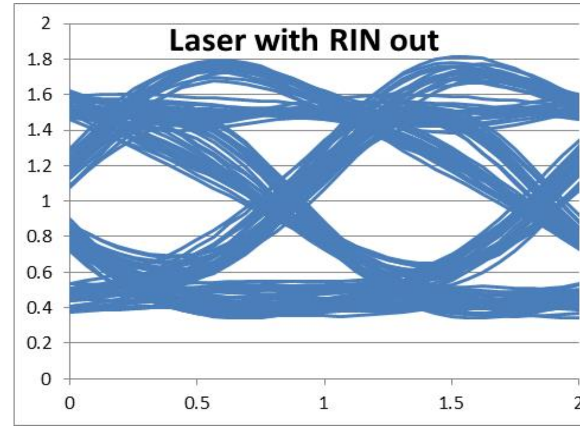
Model to emulate eyes and calculate TDEC

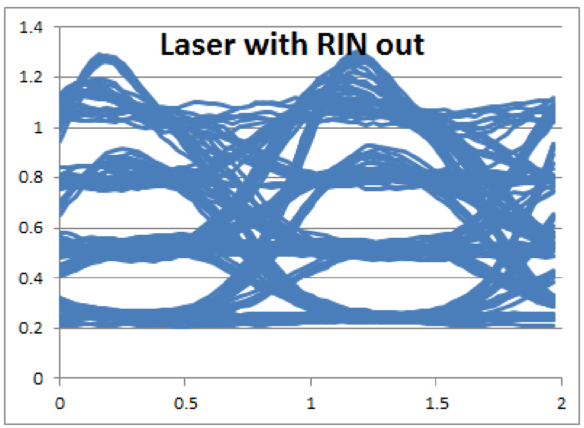
- Dimensionless impulse response based spreadsheet model
  - quasi 'rate equation' laser, with RIN (to produce life-like waveforms)
  - PAM4 data from sequential pairs of bits from a PRBS9 pattern
  - Expanded to 32 samples per bit period
  - Gaussian channel and Rx bandwidths, 5 tap T/2 FFE
  - Output eyes from laser, Rx and FFE
  - Vertical histograms through eye (256 points per time slice per noise instance)
  - 16 noise instances used to build statistics for TDEC calculations

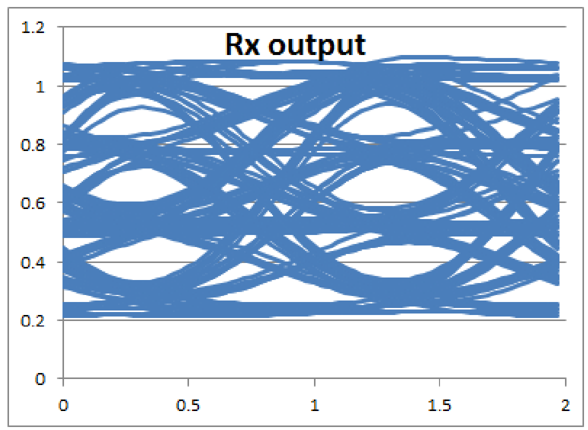


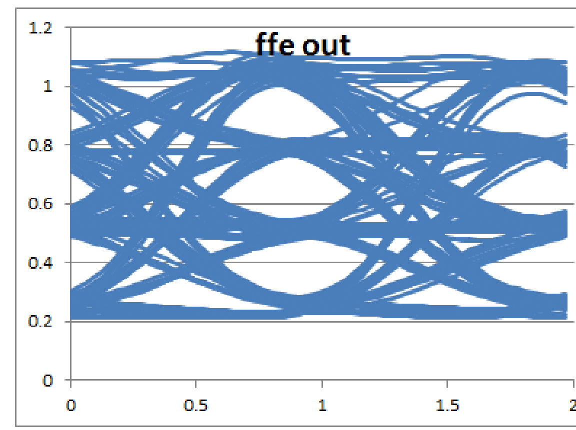
Modeling output: nominal Tx

- Eyes and eye histograms based on a modelled laser with performance similar to a moderately fast 25G laser at high temperature
  - The NRZ eye for the same VCSEL model is very similar to a typical measured 26G VCSEL eye (RHS)

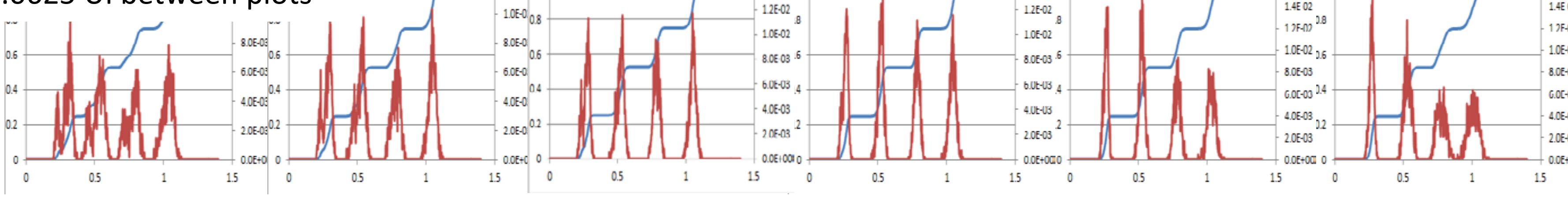








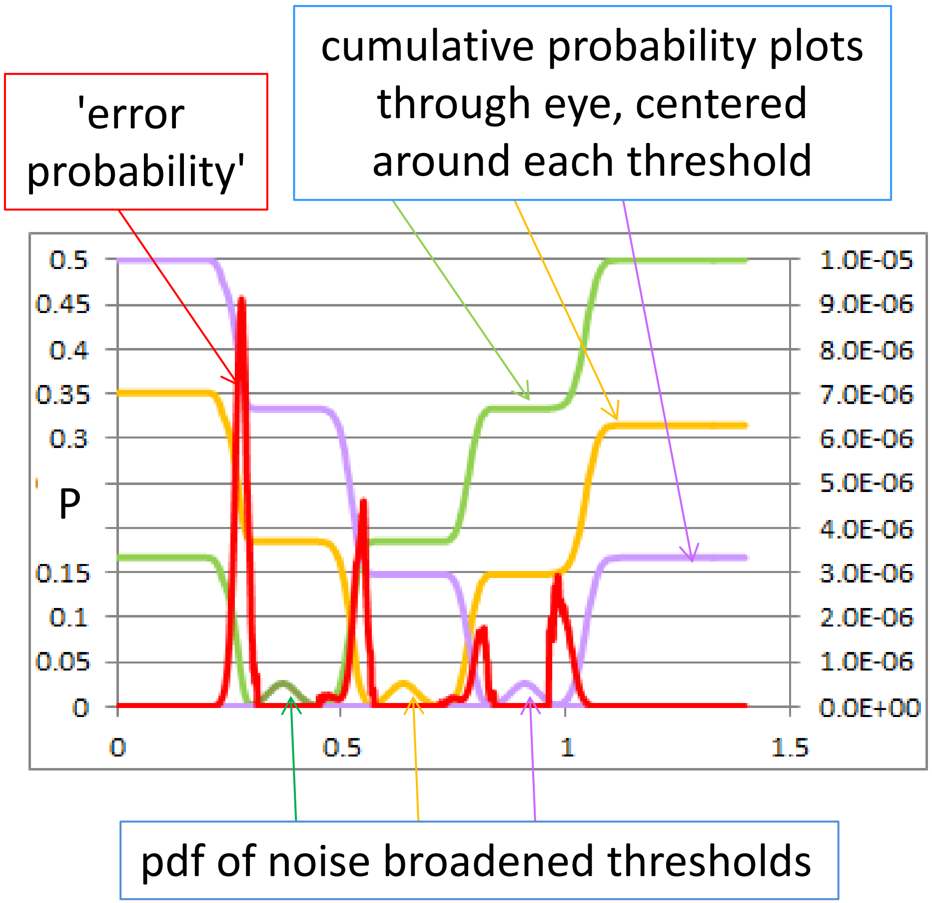
0.0625 UI between plots

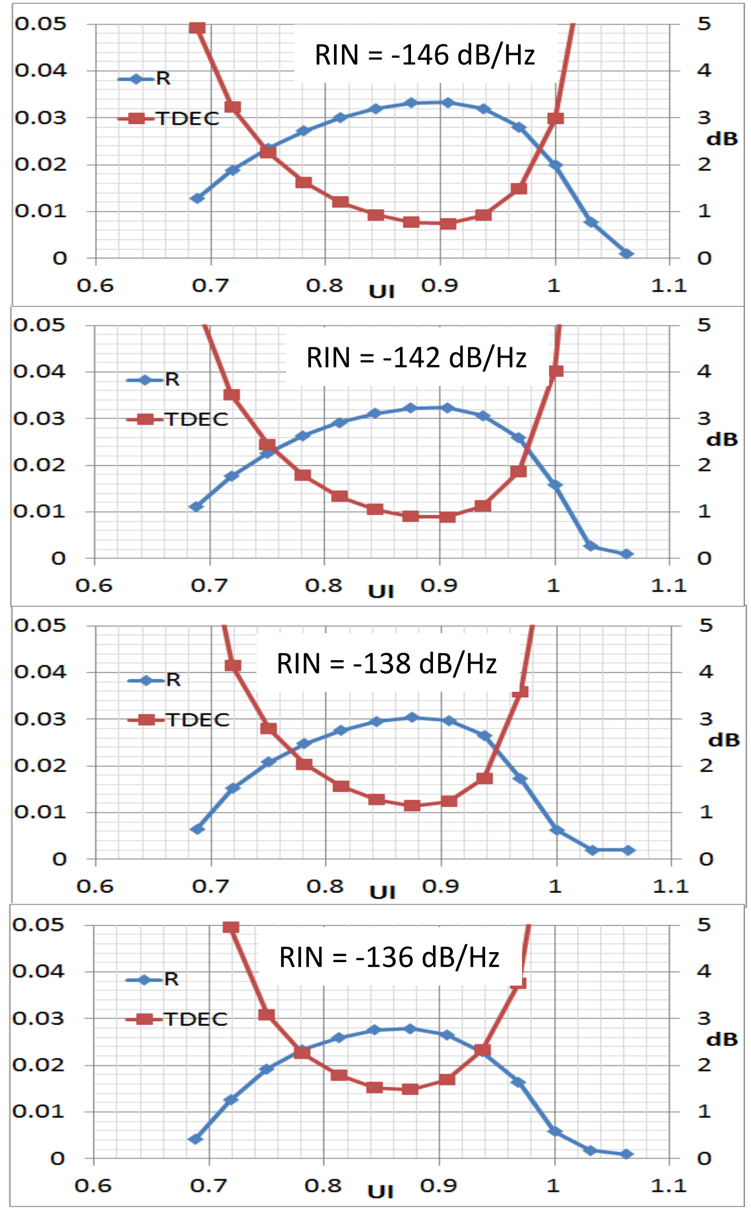


Eyes and eye histograms for a moderately fast 25G VCSEL
The NRZ eye for the same VCSEL model is similar to typical 26G VCSEL at high temp

TDEC vs time through eye

(nominal speed laser)

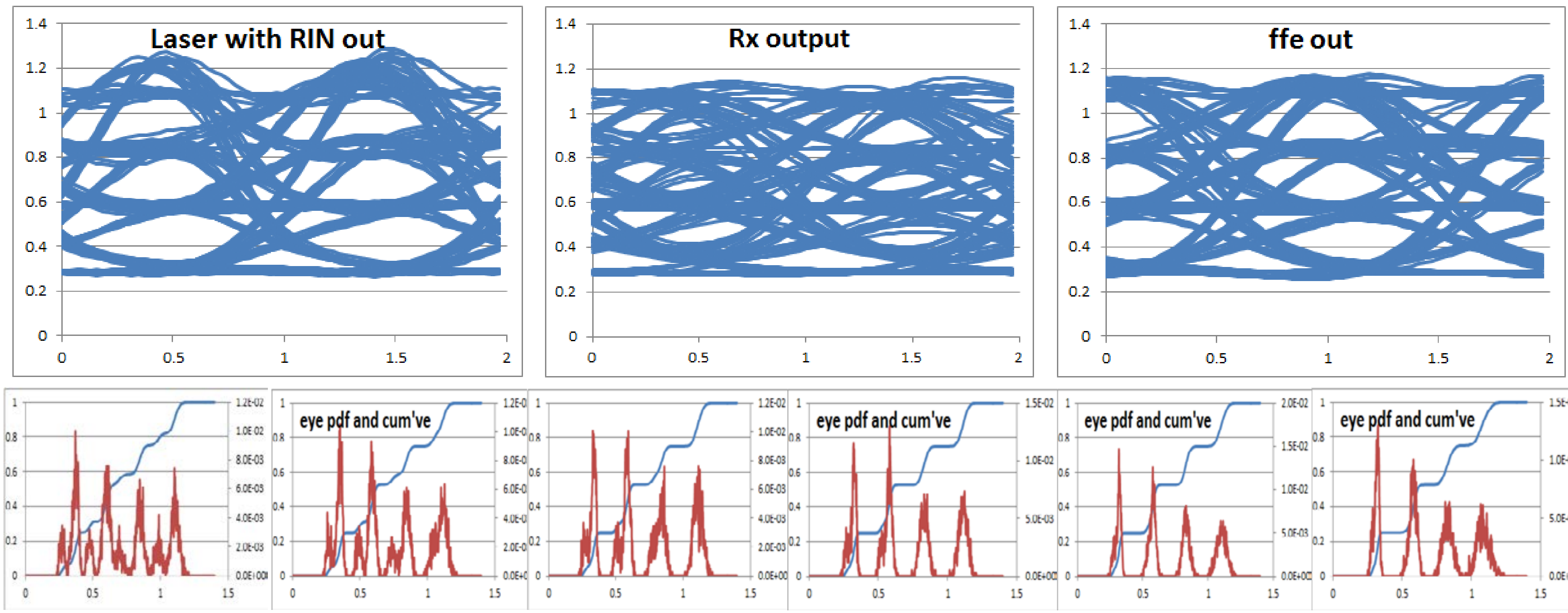




- TDEC ~1 dB at centre of eye
- TDEC ~2.5 dB at +/- 0.1 UI

Modeling output: slow Tx

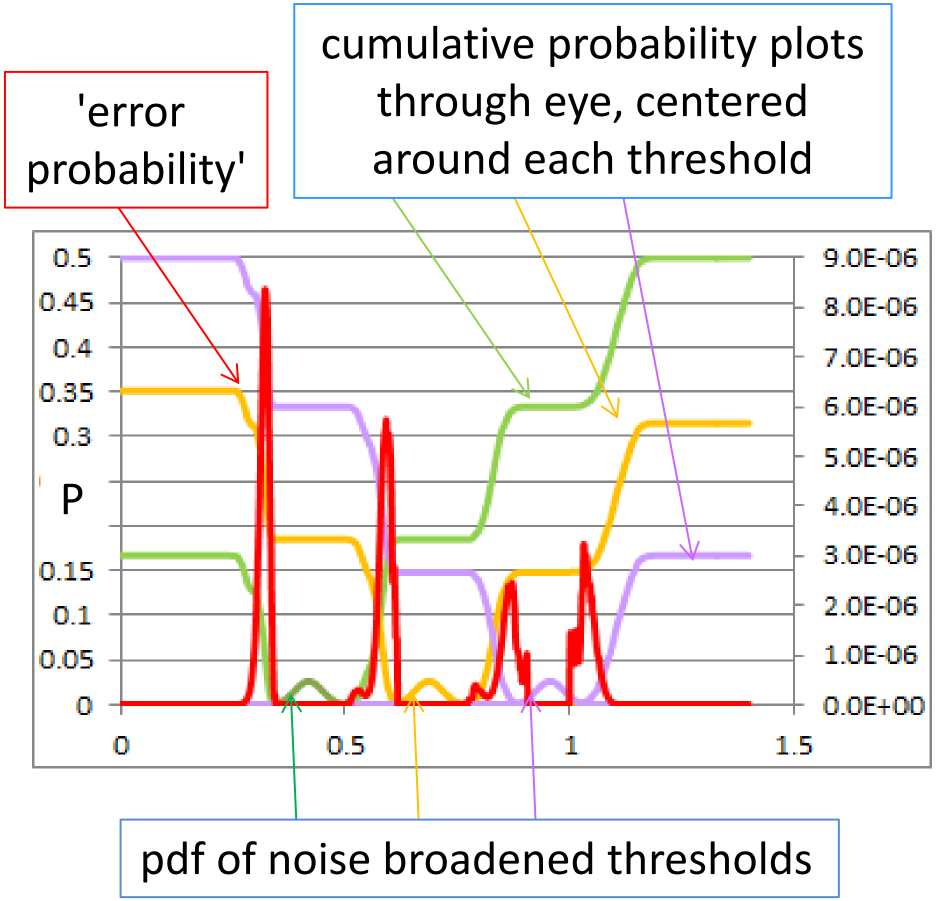
- Slower laser

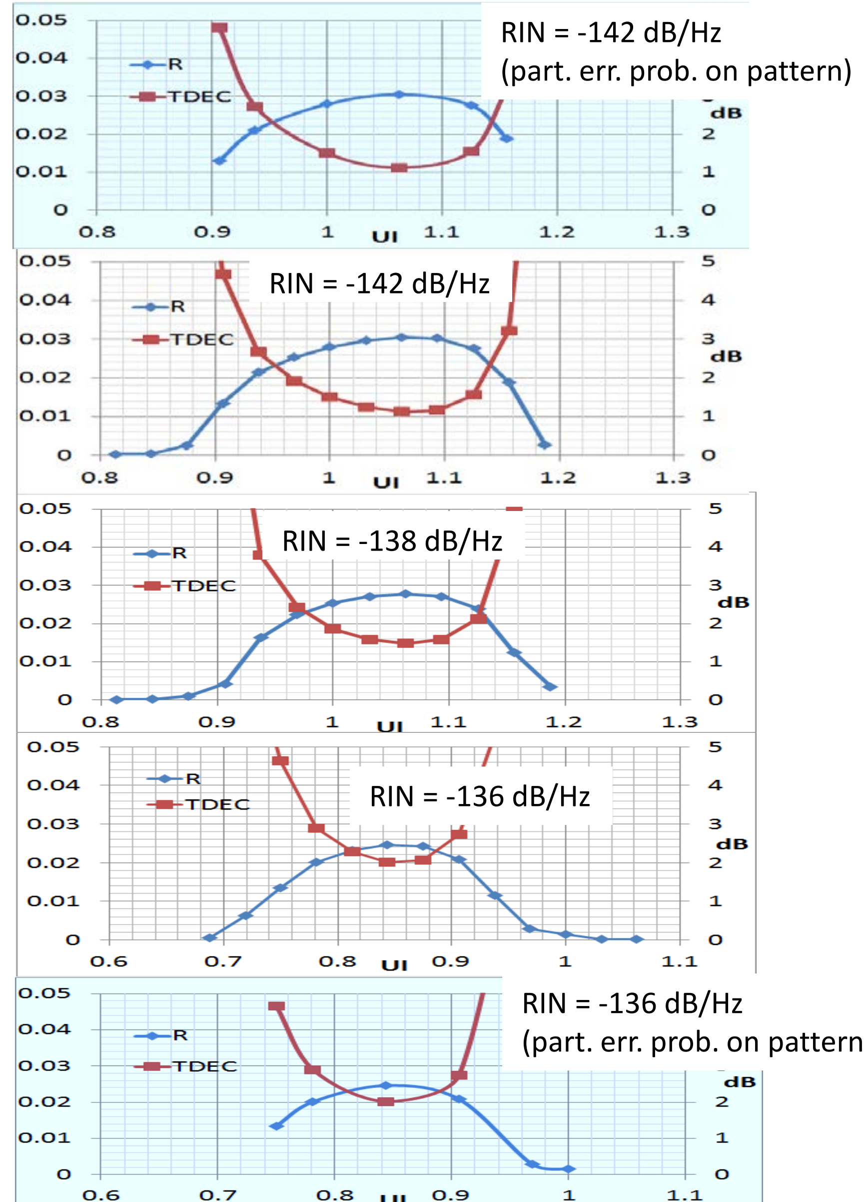


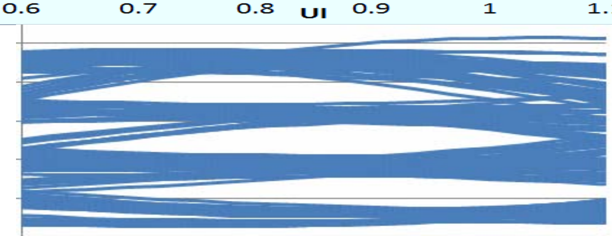
Eyes and eye histograms for a slow 25G VCSEL.

TDEC vs time through eye

(low speed laser)



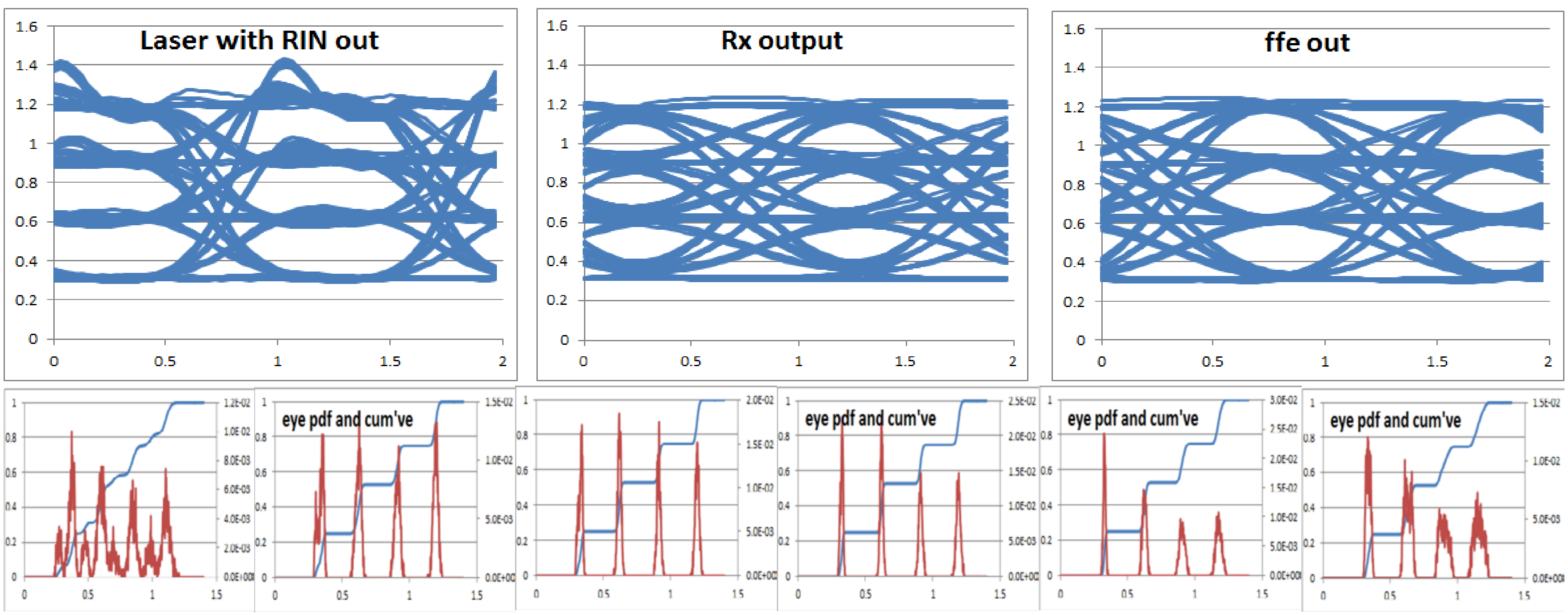




- TDEC ~1-2 dB at centre of eye
- TDEC >5 dB at +/- 0.1 UI

Modeling output: fast Tx

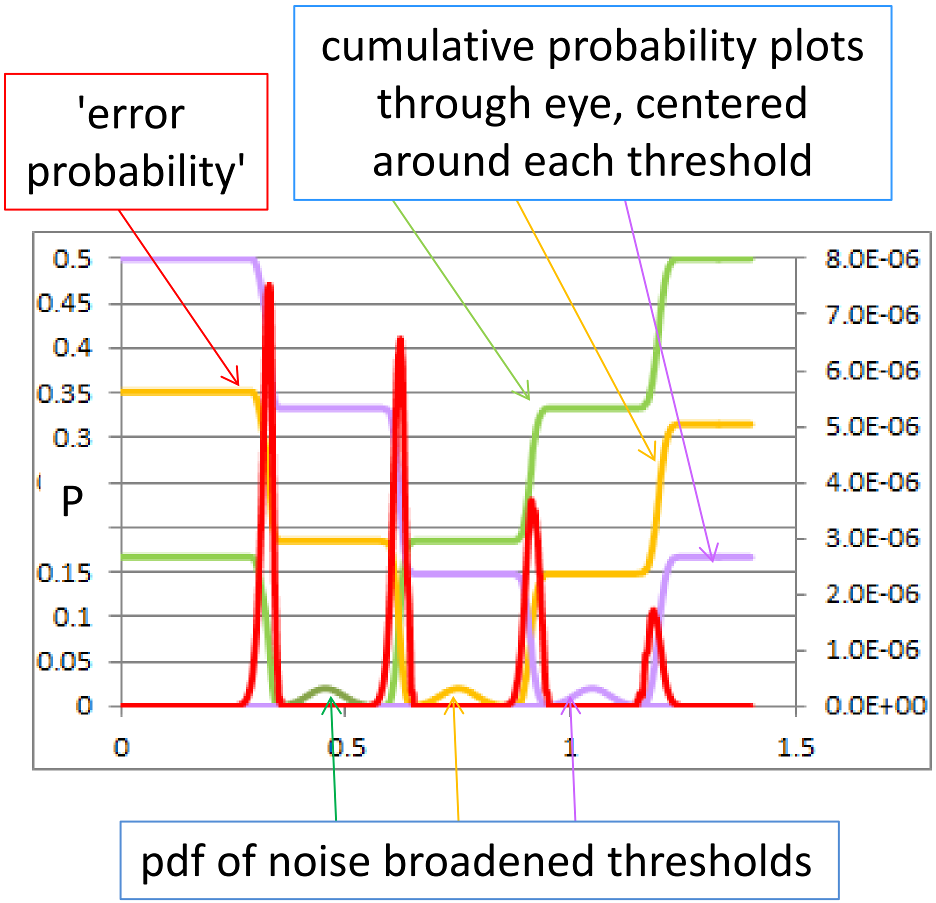
- Faster laser

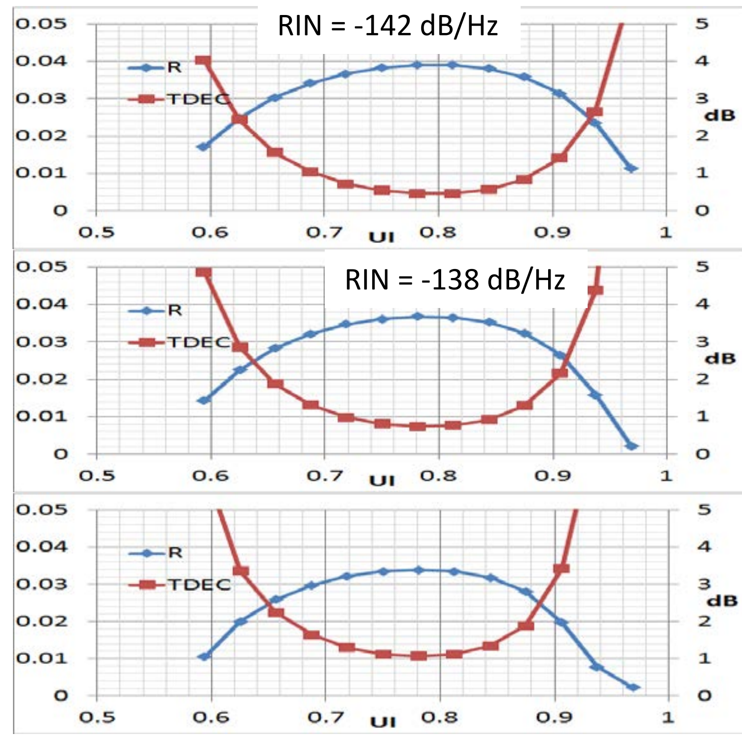


Eyes and eye histograms for a fast 25G VCSEL.

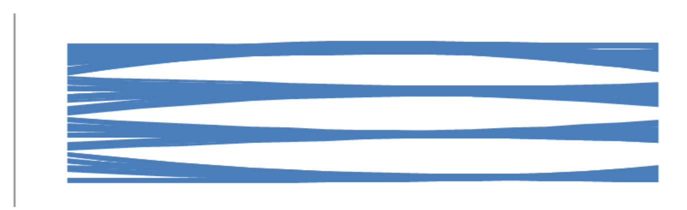
TDEC vs time through eye

(fast laser)





- TDEC ~0.5 dB at centre of eye
- TDEC ~1 dB at +/- 0.1 UI

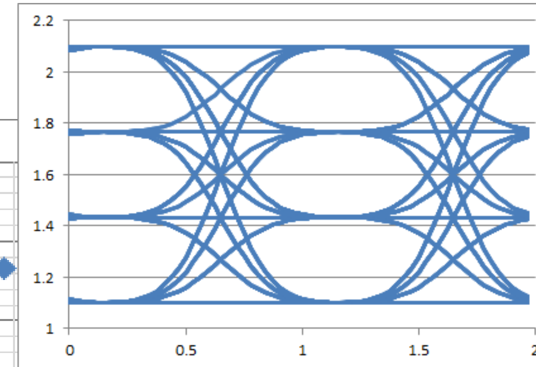


Further work

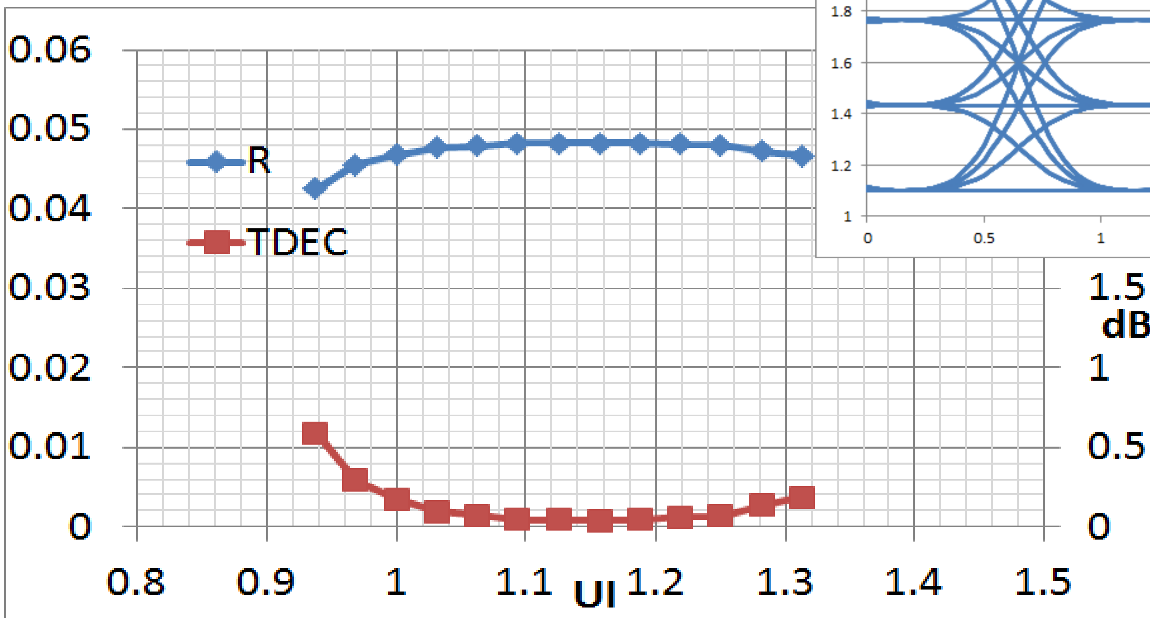
- Check the math's, and noise treatment
  - and write out how to treat the noise when capturing the transmitter pattern, and when adding noise to thresholds when calculating TDEC
- TDEC time sampling points
  - +/- 0.1 UI timing offset is probably too large and may represent an unrealistically large Tx penalty
  - to be reviewed in light of real PAM4 CDR data
    - E.g. a PAM4 CDR with +/-1.25 ps timing errror from centre of eye, and 0.18 ps RJ, would suggest +/-0.05 UI timing offset should be used
- TDEC validation
  - show good correlation between TDEC and system sensitivity measurements with reference receiver
  - and show good correlation between TDEC and system simulations
    - TDEC calculated by histogram and pattern methods are identical
    - 0 dB TDEC achieved at centre of clean eye; Value of σ_G for 0dB TDEC consistent with PAM4 modulation penalty and target SER

Appendix A: TDEC validation

- 0 dB TDEC at the centre of an ideal eye

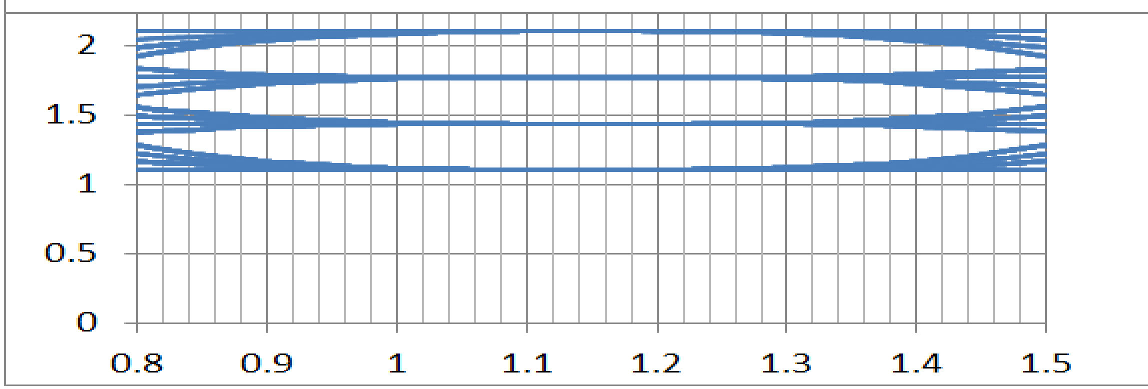


Max R = 0.0484



OMA_{inner} = 1/3

$OMA_{inner}/(2R)$ = 3.44



Appendix B: Notes on noise treatment

- Noise is effectively added at the receiver to calculate TDEC
- Since the Rx precedes the EQ, the noise density vs frequency matters. Assuming an FFE implementation for simplicity:
  - Typically, the FFE is boosting high frequencies to open the eye
    - high frequency noise is increased by the FFE
      - if the noise term present at each tap is uncorrelated, the relative noise amplitude increases as the RSS of the tap ratios (typically >1)
    - low frequency noise is reduced
      - if the noise terms at the taps are correlated, the relative noise amplitude increases as the sum of the tap ratios (typically < 1)
    - for TDEC calculations, the frequency content of the noise after the EQ is not important, but the amplitude of the noise is
  - Maybe assuming pink noise which is uncorrelated at each FFE tap is a reasonable starting point …

Changes needed to incorporate TDEC into clause 123

- *work in progress – to be presented separately*