BASE-AU 980nm/OM3 baseline Reference receiver and transmitter and distortion figure of merit

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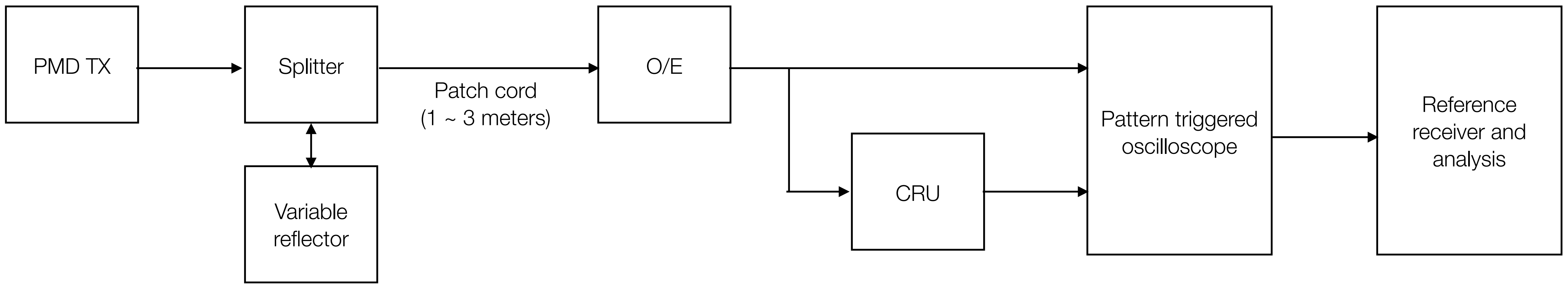
Objective

- This contribution proposes a reference receiver and a figure of merit of transmitter and distortion (TDFOM) assessment for the BASE-AU PHY based on 980nm and OM3
- Reference receiver and TDFOM are defined to reflect the most representative receiver implementation, which is consistent with the receiver implementation used in the link budget assessment and the definition of TX/RX characteristics
- Definition of the reference receiver as well as TDFOM has as objective to guarantee the interoperability of different implementations
- TDFOM will be used as part of the transmitter characteristics specification
- TDFOM will be used to define stress receiver sensitivity conditions

Introduction to reference receivers and signal quality analysis

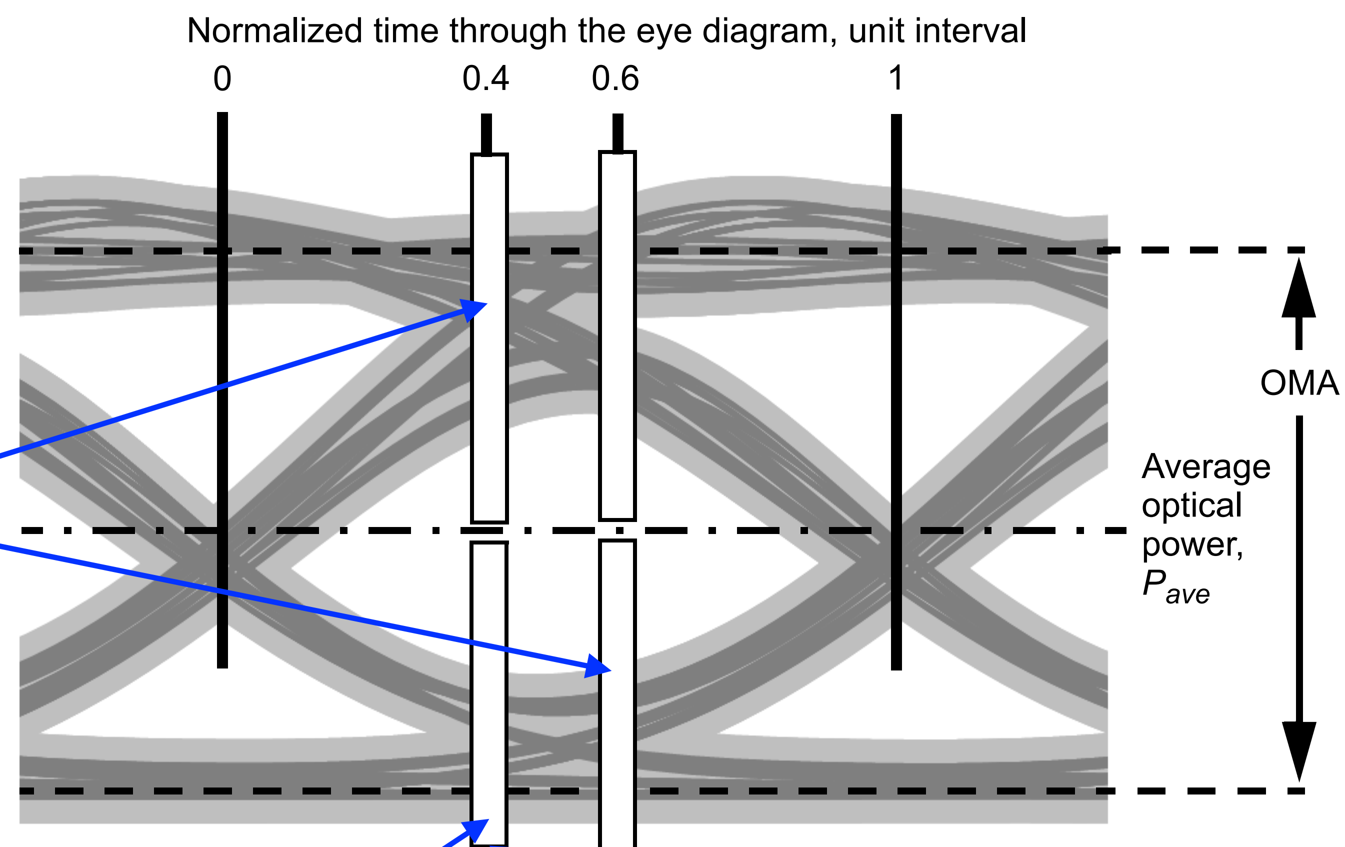
Intro to reference RX and analysis — general



- PMD TX generates a pseudo-random periodic pattern with a determined length, modulation format, baseline and clock wander characteristics
- The optical splitter and variable reflector are adjusted so that each transmitter is tested with an optical return loss equal to the max value specified
- A O/E converter is used to receive optical signal generated by PMD TX under test and convert it into electrical domain
  - O/E is usually integrated within CRU and oscilloscope equipments
- A CRU (clock recovery unit) is used to generate a low jitter clock locked in phase to PMD TX signal. The CRU OJTF (observed jitter transfer function) needs to be specified according to the communications system specifications
- Pattern triggered oscilloscope is used to capture the full signal pattern with given samples per unit interval
- Equivalent response of O/E plus oscilloscope is specified in terms of a low pass filter type and order as well as its -3dB bandwidth
  - It is usual BT4 (Bessel-Thomson 4th order low pass) filters with specified bandwidth, e.g. $BW_{-3dB} \sim 0.7/T_S$, being T_S the nominal symbol period
  - BT4 filters are convenient for eye analysis because good tradeoff between rejection and passband linear phase and HW implementation
- Reference receiver and signal quality analysis (e.g. TDEC, TDECQ) is **defined to reflect the most representative receiver IC implementation, for sake of interoperability and not precluding different implementations**
- Quality analysis determines the amount of noise to be added to the signal so measured BER is equal to the specification limit

Intro to reference RX and analysis — e.g. TDEC

25GBASE-SR reference RX and analysis is inspired on possible **PHY IC RX implementations**



Symbol error rate is evaluated with histograms in the 2 sampling times for 1 threshold, i.e. P_{ave}

Figure 95–4—Illustration of the TDEC measurement

- At least 2 comparators in the lower and upper side, left and right, for clock recovery
- 1 extra comparator in P_{ave}, for data recovery
- 10 comparisons per symbol

2 separate sampling times are usually needed for clock recovery

(Disclaimer: many other IC receiver implementations are possible)

Intro to reference RX and analysis — e.g. TDECQ

50GBASE-SR reference RX and analysis is inspired on possible **PHY IC RX implementations**

Current addition by simple nodal connection

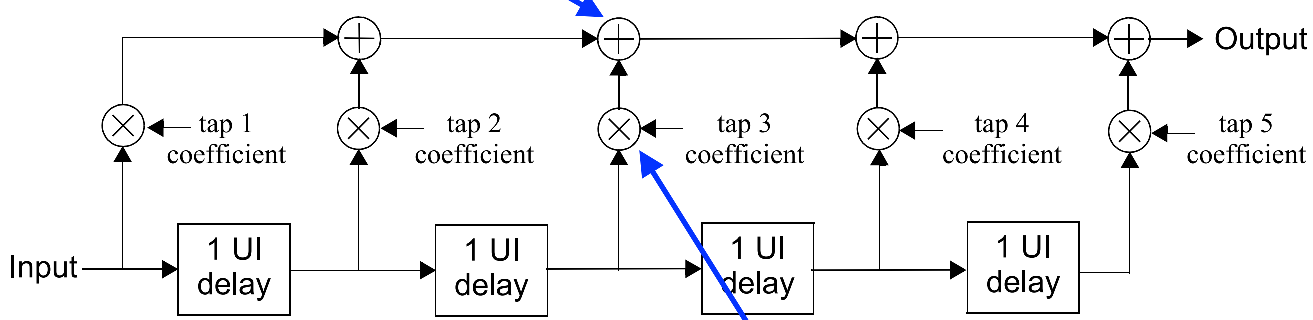


Figure 138–3—TDECQ reference equalizer functional model

Switched capacitance to store and delay data in form of current

Tap weighting by means of current mirrors

Actually, 2 EQ filters are implemented in IC, one for each sampling time

Pros:

- FIR filter implementation in analog domain
- Very efficient in terms of speed/power tradeoff

Cons:

- Tap coefficients adaptation is difficult in IC implementation
- Linear EQ is sub-optimum in terms of channel capacity due to the noise autocorrelation and enhancement produced by the FIR filter (vs capacity approaching MMSE-DFE,u), [1, 2, 3]
- Unable to deal with strong non-linearities

Symbol error rate is evaluated with histograms of the EQ signal in the 2 sampling times for the 3 thresholds

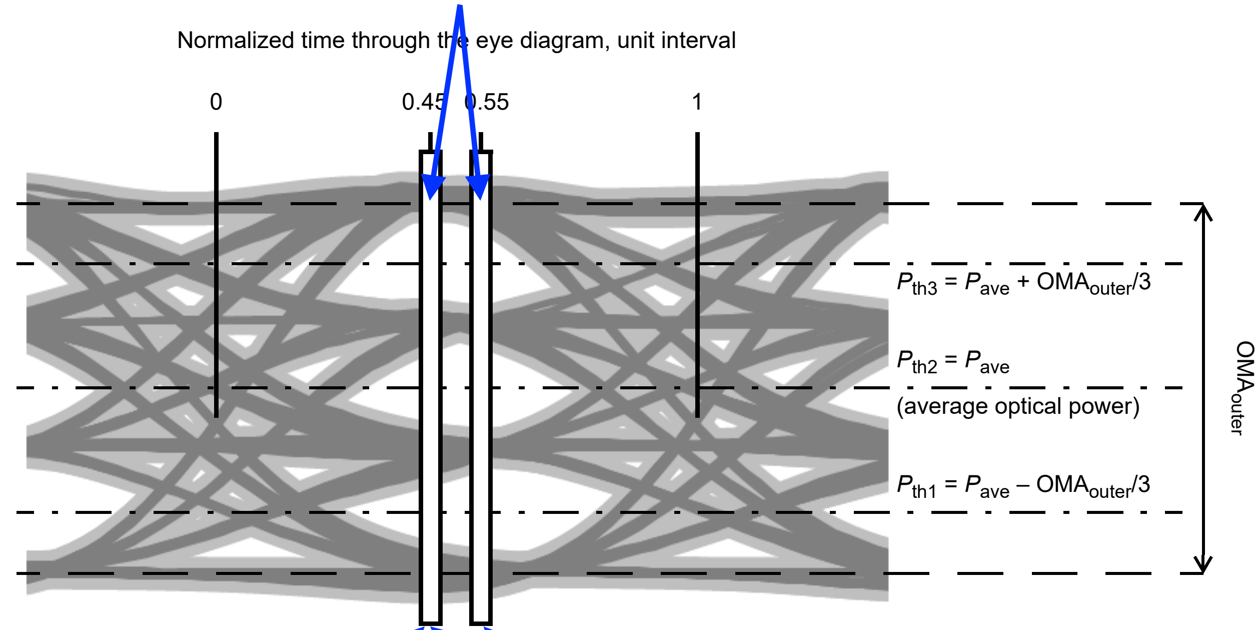


Figure 121–5—Illustration of the TDECQ measurement

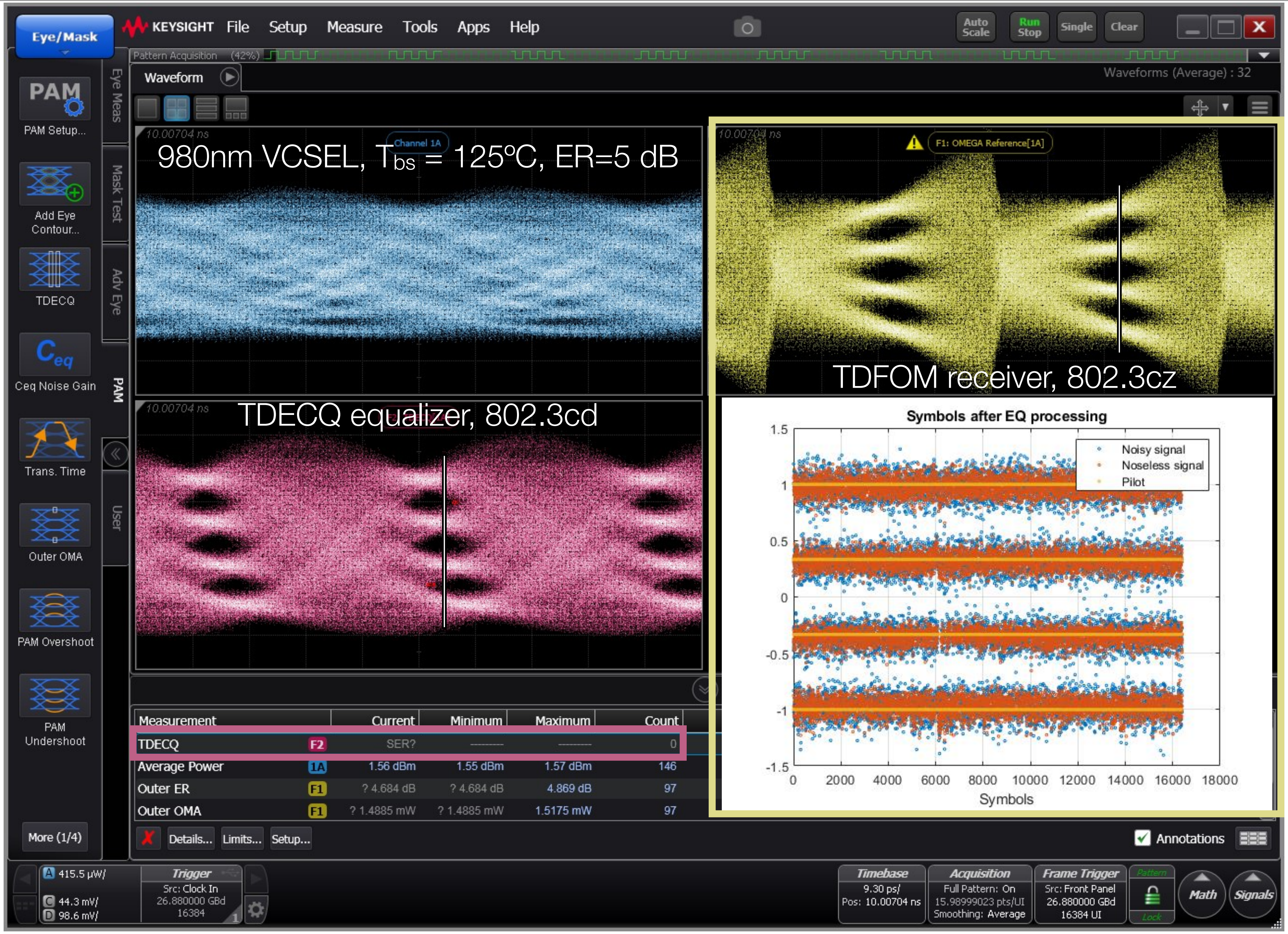
- At least 11 comparators in right and left sides
- 22 comparisons per symbol

2 separate sampling times are usually needed for clock recovery

(Disclaimer: many other IC receiver implementations are possible)

The reference receiver — e.g. TDECQ vs TDFOM

TDECQ cannot be calculated for the output signal of TDECQ EQ

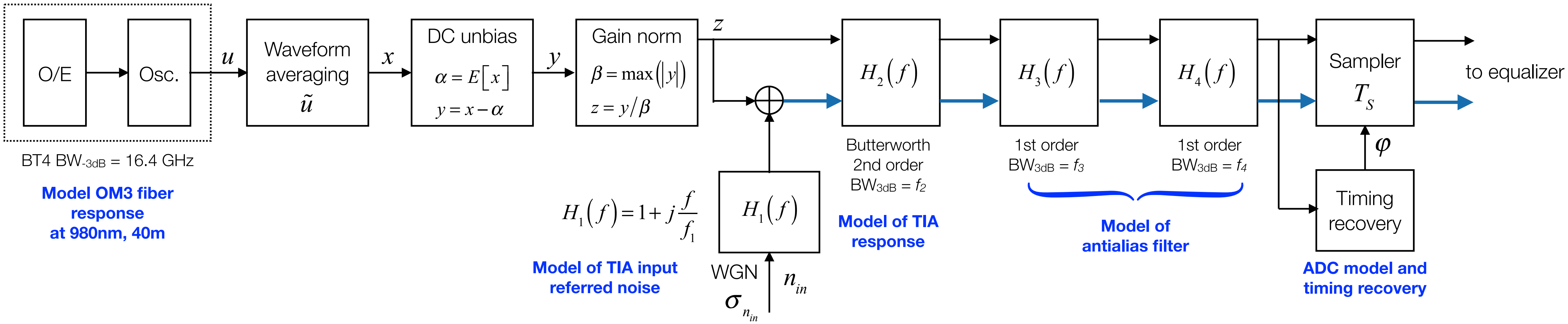


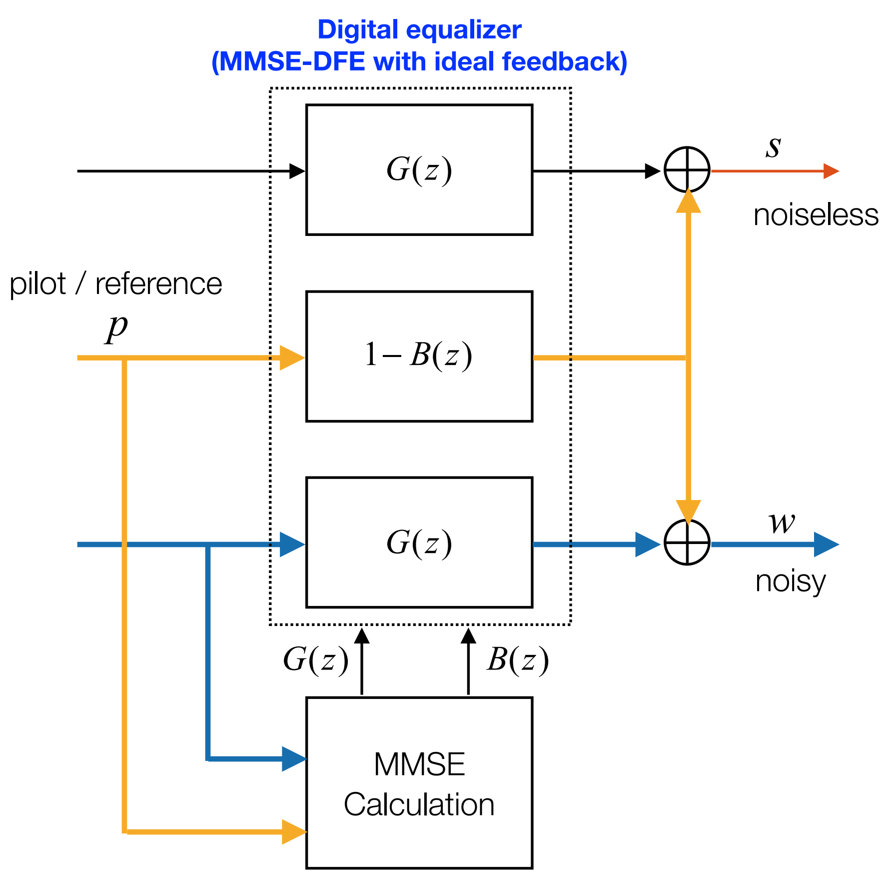
TDFOM receiver is able to deal with non linear ISI

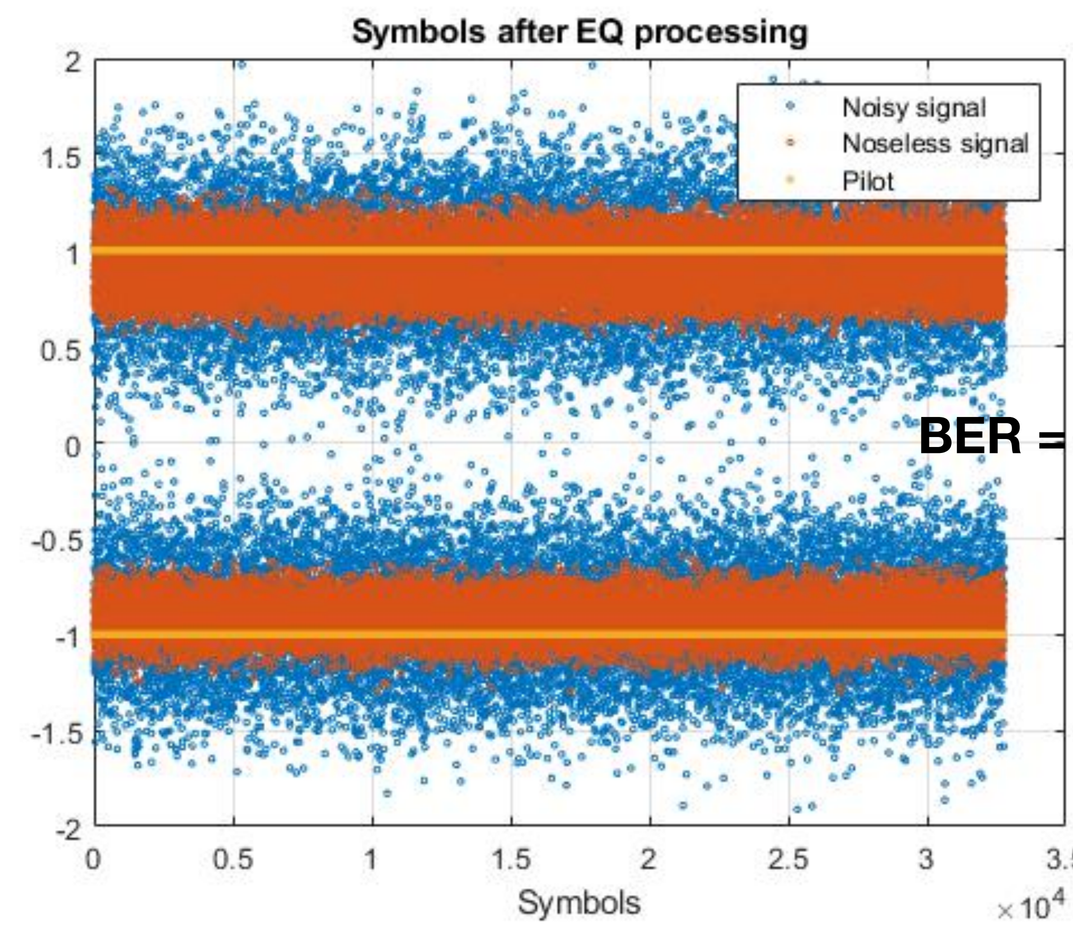
Comparison of TDECQ equalizer performance vs TDFOM receiver performance, both doing processing of VCSEL signal operating at T_{BS} = 125ºC, 26.88 GBd, PAM4

Specification of BASE-AU 980nm/OM3 reference receiver and analysis

BASE-AU 980nm/OM3 reference receiver and analysis

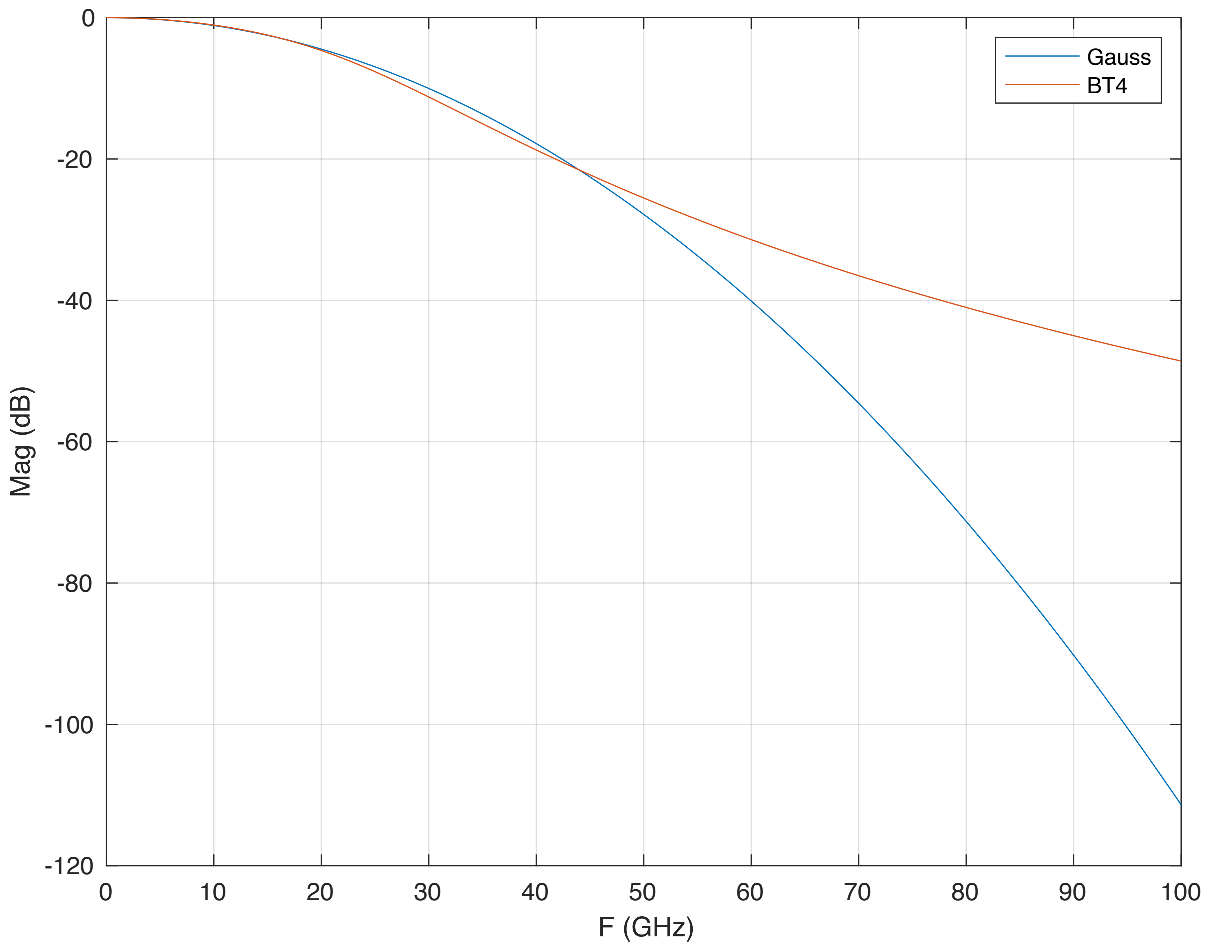


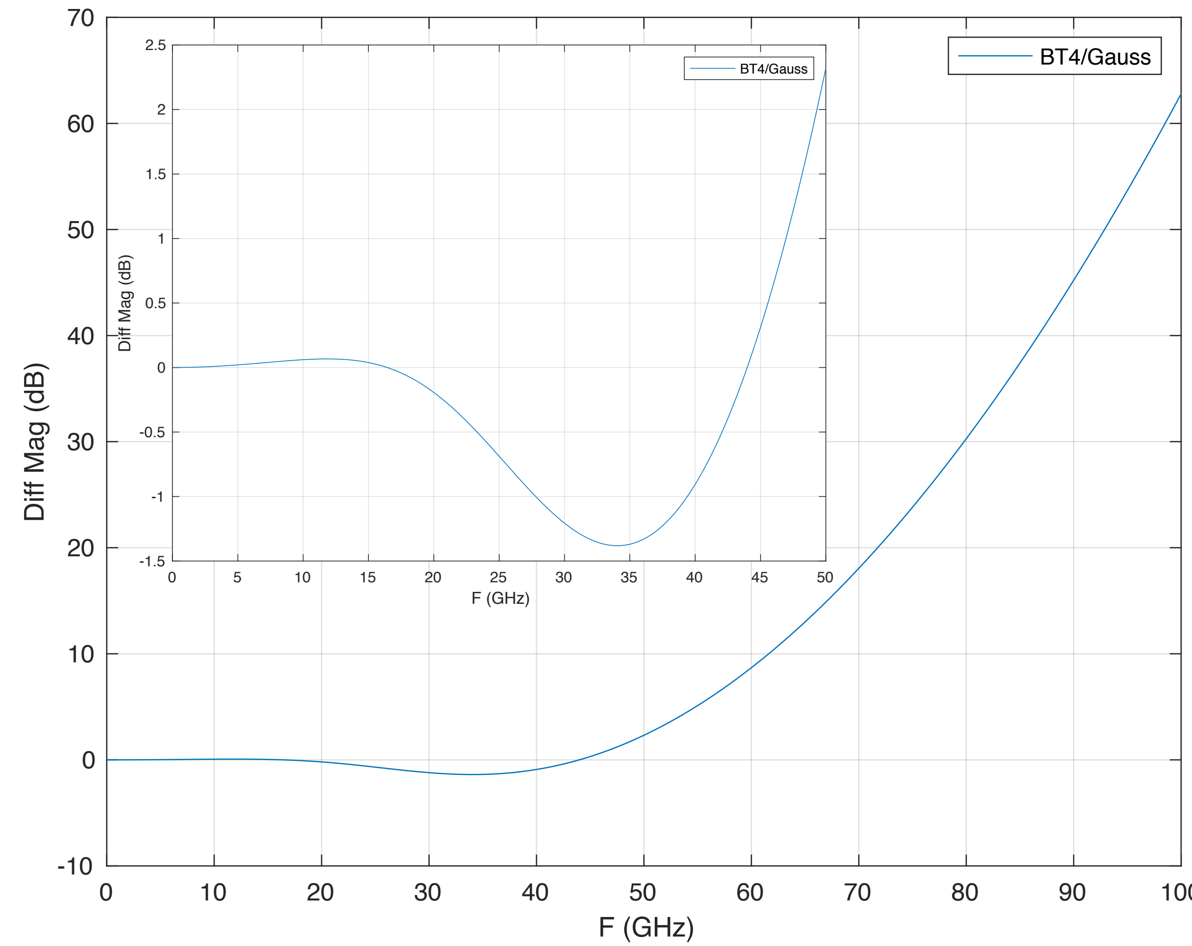




BER = 0.00017

Fiber modelling: BT4 vs Gauss response





- Both filters, Gaussian and BT4, present linear phase response in the passband
- Both filters are compared in magnitude for the same electrical BW_{-3dB} = 16.4 GHz

- Considerations for BW calculation:
  - EMB = 945 MHz·km
  - BWcd = 5498 MHz·km
  - BWeff = 931 MHz·km
  - 931/40/sqrt(2) = 16.4 GHz (electrical bandwidth, assuming gaussian response)

BASE-AU 980nm/OM3 reference receiver and analysis

- The input low pass filter shall be 4th order Bessel-Thomson with BW_{-3dB} = 16.4 GHz
- Acquisition oversampling (samples per unit interval) shall be, Ov > 15
- Waveform averaging shall be enabled to eliminate noise; averaging factor shall be selected high enough to avoid noise affecting the TDFOM analysis (error below 0.05 dB)
- Filters shall be scaled according to symbol period and modulation format as:

$$f_1 = \frac{1}{10 \cdot T_S} + 5 \cdot 10^8 \quad \text{(Hz)};$$

$$f_2 = \begin{cases} \dfrac{1}{5 \cdot T_S}, & \text{NRZ} \\ \dfrac{1}{3 \cdot T_S}, & PAM4 \end{cases};$$

$$f_3 = \frac{1}{2 \cdot T_S};$$

$$f_4 = \begin{cases} \infty, & \text{NRZ} \\ \dfrac{1}{2 \cdot T_S}, & PAM4 \end{cases};$$

BASE-AU 980nm/OM3 reference receiver and analysis

- MMSE-DFE filters are defined as:

$$G(z) = \sum_{i=0}^{N_G-1} g_i \cdot z^{-i};\ B(z) = 1 + \sum_{i=1}^{N_B-1} b_i \cdot z^{-i};$$

- Equalizer DC gain is calculated as:

$$G_{eq} = \left| \frac{\sum_{i=0}^{N_G-1} g_i}{1 + \sum_{i=1}^{N_B-1} b_i} \right|$$

- Number of taps for each filter depends on bit rate:
  - For 50 Gb/s: $N_G = 8$, $N_B = 2$
  - For 25 Gb/s: $N_G = 8$, $N_B = 3$
  - For 2.5, 5, and 10 Gb/s: $N_G = 4$, $N_B = 3$
- G(z) and B(z) shall be calculated to minimise the mean square error (MMSE) between signals *p* and *w*, and sampler delay ϕ and G(z) delay shall be optimised for minimum BER after equalisation at each value of $\sigma_{n_{in}}$
- An iterative algorithm shall find the max value of $\sigma_{n_{in}}$ so measured BER is equal to the specification limit $1.757 \cdot 10^{-4}$ (BER before FEC)
- $\sigma_{n_{in}}$ is the standard deviation of the white gaussian noise sequence n_{in}
- *p* is the periodic test pattern, that takes values {-1, +1} for NRZ, and {-1, -1/3, 1/3, 1} for PAM4

BASE-AU 980nm/OM3 reference receiver and analysis

- BER calculation:
  - Calculate the noise sequence in the output of equaliser as n = w - s
  - Calculate the standard deviation σ_n
  - Define the thresholds vector *THv = [0]* for NRZ, and *THv = [-2/3, 0, +2/3]* for PAM4
    - Define N_{th} = 1 for NRZ, and N_{th} = 3 for PAM4
  - Calculate the histogram of signal *s*, where the value of each bin *h(i)* is normalised to relative probability, such that $h(i) = c(i)/N_h$, where *c(i)* is the number of elements in the bin centred in *e(i)* with width *Δe*, and N_h is the number of elements of signal *s*
    - $\Delta e = (max(s) - min(s))/N_h$
    - N_h shall be ≥ 500
  - For each *THv(k)*:
    - Calculate ih_p as the bins that meet *e(i) > THv(k)*
    - Calculate ih_n as the bins that meet *e(i) ≤ THv(k)*
    - Calculate $SER_{th}(k)$ as:

$$SER_{th}(k) = \frac{1}{2}\sum_{i=\min(ih_n)}^{\max(ih_n)} h(i)\cdot \operatorname{erfc}\left(\frac{THv(k)-e(i)}{\sigma_n\sqrt{2}}\right) + \frac{1}{2}\sum_{i=\min(ih_p)}^{\max(ih_p)} h(i)\cdot \operatorname{erfc}\left(\frac{e(i)-THv(k)}{\sigma_n\sqrt{2}}\right)$$

where erfc(x) is the complementary error function defined as:

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}\,dt$$

BASE-AU 980nm/OM3 reference receiver and analysis

- Calculate the total *SER* as:

$$\sum_{k=1}^{N_{th}} SER_{th}(k)$$

- Calculate *BER* as:
  - *BER* = *SER* for NRZ,
  - *BER* = *SER/2* for PAM4 (Gray mapping as in C/166 is considered)

BASE-AU 980nm/OM3 reference receiver and analysis

- OMA calculation at EQ output:
  - Define OMA_{eq} as the OMA of signal s
  - OMA shall be measured using continuous identical digits (CID)
  - Search for positive CID as continuous samples of signal s with value > 0, for NRZ, or with value > 2/3, for PAM4
  - Search for negative CID as continuous samples of signal s with value < 0, for NRZ, or with value < -2/3, for PAM4
  - CID sequence length shall be ≥ 14 for NRZ, ≥ 7 for PAM4
  - For all the CID sequences that meet length constraint, remove:
    - For NRZ: first 6 and last 6 samples
    - For PAM4: first 3 and last 2 samples
  - For the remaining symbols of all the CID sequences calculate the average value
    - For positive CID sequences, we obtain OMA_p
    - For negative CID sequences, we obtain OMA_n
  - $OMA_{eq} = OMA_p - OMA_n$
- OMA calculation at EQ input
  - Calculate:

$$OMA_{in} = \frac{OMA_{eq}}{G_{eq}}$$

BASE-AU 980nm/OM3 reference receiver and analysis

- TX DC parameters calculation:
  - Calculate transmitter OMA as:

$$OMA_{tx} = OMA_{in} \cdot \beta \quad \text{(watts)}$$

  - Calculate transmitter AOP as:

$$AOP_{tx} = \alpha \quad \text{(watts)}$$

  - Calculate transmitter extinction ratio:

$$ER_{tx} = 10\log_{10}\left(\frac{OMA_p \cdot \beta + G_{eq} \cdot \alpha}{OMA_n \cdot \beta + G_{eq} \cdot \alpha}\right) \quad \text{(dB)}$$

  - Calculate OMA to AOP ratio as:

$$\Gamma_{tx} = \frac{OMA_{tx}}{AOP_{tx}} = \frac{OMA_{in} \cdot \beta}{\alpha}$$

BASE-AU 980nm/OM3 reference receiver and analysis

- TDFOM calculation
  - Define reference Q-factor Q_0 as:
    - Q_0 = 3.5741 for NRZ, consistent with BER = $1.757 \cdot 10^{-4}$
    - Q_0 = 3.4981 for PAM4, consistent with BER = $1.757 \cdot 10^{-4}$
  - Calculate transmitter and distortion figure of merit (TDFOM) as:

$$TDFOM = 10 \cdot \log_{10}\left(\frac{OMA_{in}\sqrt{Ov}}{2(M-1)\sigma_{n_{in}}Q_0}\right) - TDFOM_0$$

  where M = 2 for NRZ, and M = 4 for PAM4.

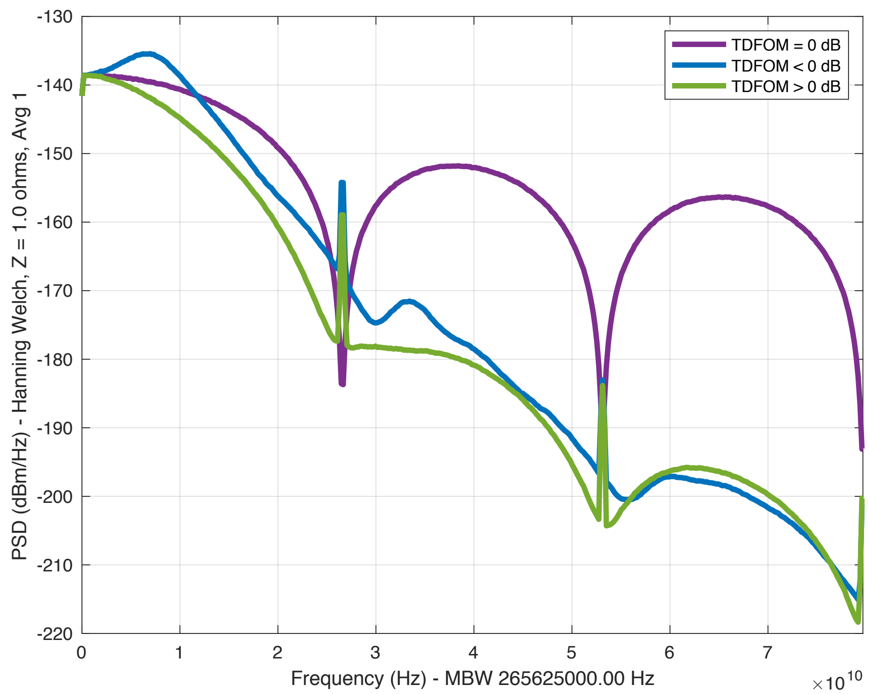
  - $TDFOM_0$ is calculated to get TDFOM = 0 dB when an ideal transmitter (square pulse) is connected to the reference receiver
  - It depends on bit-rate:
    - For 50 Gb/s: $TDFOM_0$ = 4.47 dB
    - For 25 Gb/s: $TDFOM_0$ = 4.27 dB
    - For 10 Gb/s: $TDFOM_0$ = 3.29 dB
    - For 5 Gb/s: $TDFOM_0$ = 2.59 dB
    - For 2.5 Gb/s: $TDFOM_0$ = 1.84 dB
  - $TDFOM_0$ values are obtained by simulation connecting a square pulse transmitter to the reference receiver input

BASE-AU 980nm/OM3 reference receiver and analysis

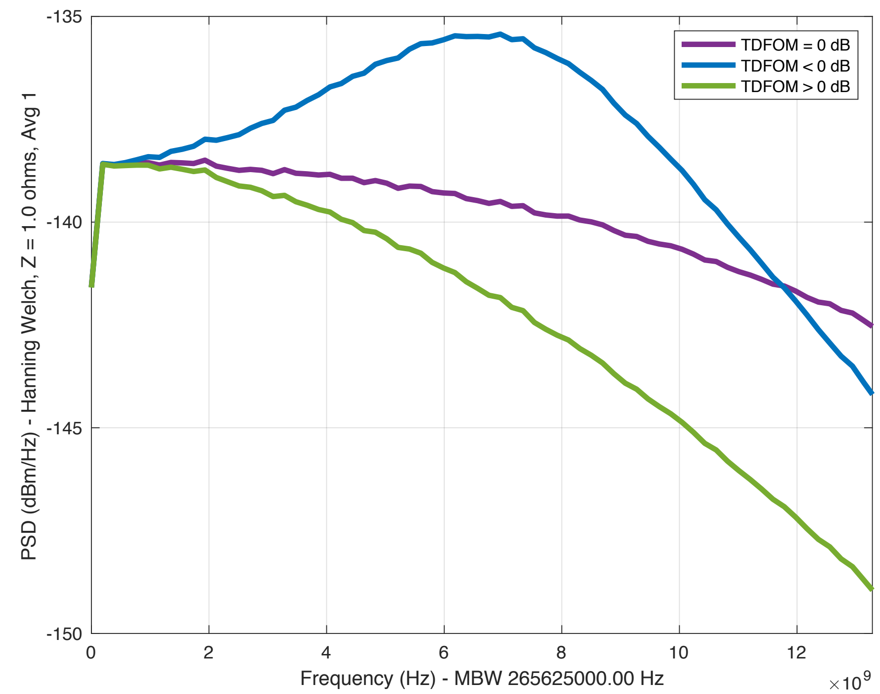
- Why $\sqrt{Ov}$ factor?
  - Noise n_{in} is added in a point of the signal processing path were signal is sampled a rate of $\frac{Ov}{T_S}$
  - The noise added is gaussian and white. Therefore, $\sigma^2_{n_{in}} = S^2_{n_{in}} \frac{Ov}{2 \cdot T_S}$, where time domain power $\sigma^2_{n_{in}}$ relates with the single-sideband power spectral density $S^2_{n_{in}}$ by means of the sampling frequency $\frac{Ov}{T_S}$
  - After noise addition, H_2, H_3 and H_4 filter the signal and noise low pass before sampler operating at $\frac{1}{T_S}$, so the noise and signal power spectral densities in the low pass band are preserved
  - Therefore, in order to make TDFOM independent of oversampling factor, normalization of standard deviation is introduced as $\frac{\sigma_{n_{in}}}{\sqrt{Ov}}$
- How Q_0 is calculated?
  - For NRZ, $Q_0 = \sqrt{2} \cdot \text{erfc}^{-1}(2 \cdot BER)$
  - For PAM4, $Q_0 = \sqrt{2} \cdot \text{erfc}^{-1}\left(\frac{4}{3} \cdot 2 \cdot BER\right)$

Illustrative examples for 25 Gb/s (980nm VCSEL)

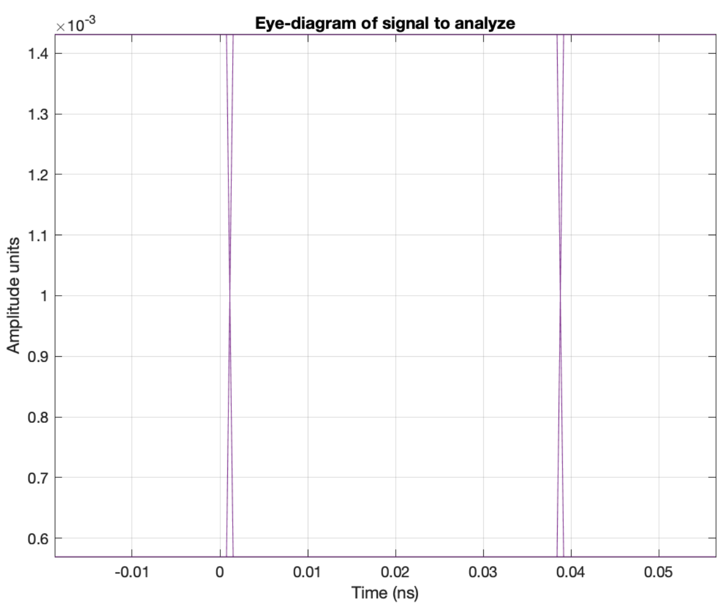
AC PSD, from 0 to $3/T_s$



AC PSD, from 0 to Nyquist

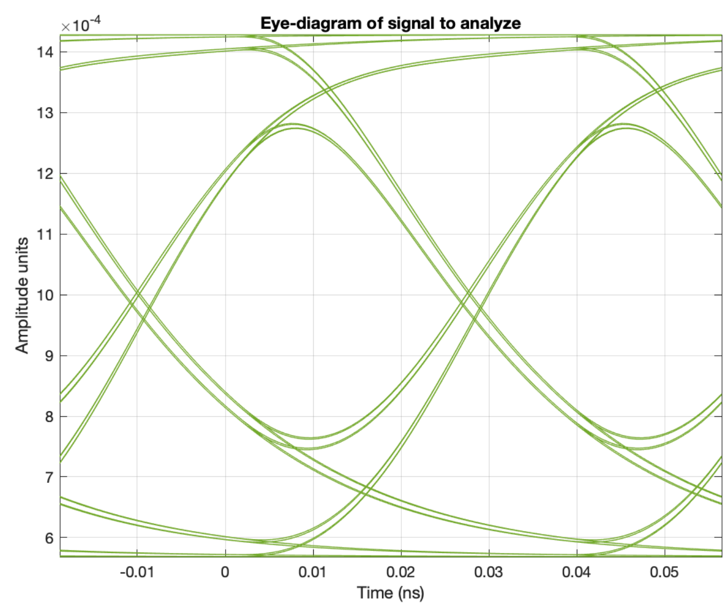


TDFOM = 0 dB (reference)



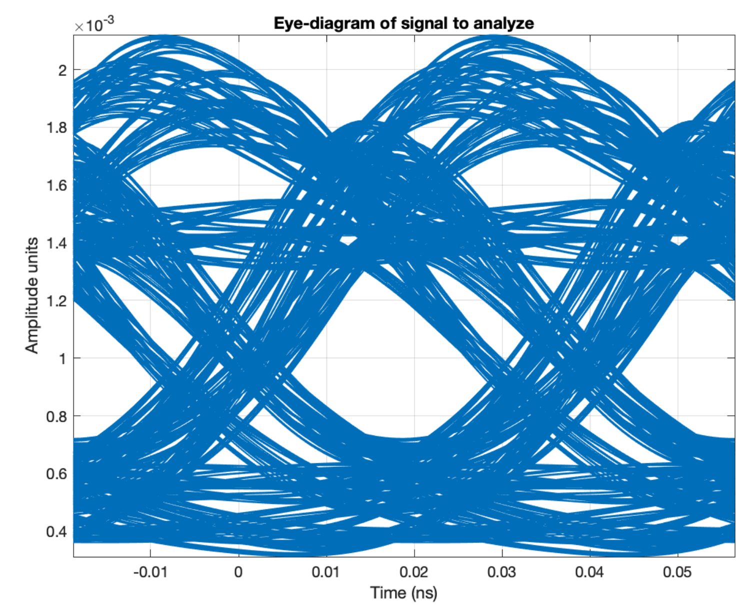
TX ideal eye diagram

TDFOM = 1.2 dB (will produce worse sensitivity)



VCSEL @ -40 ºC, Driver 3, eye diagram

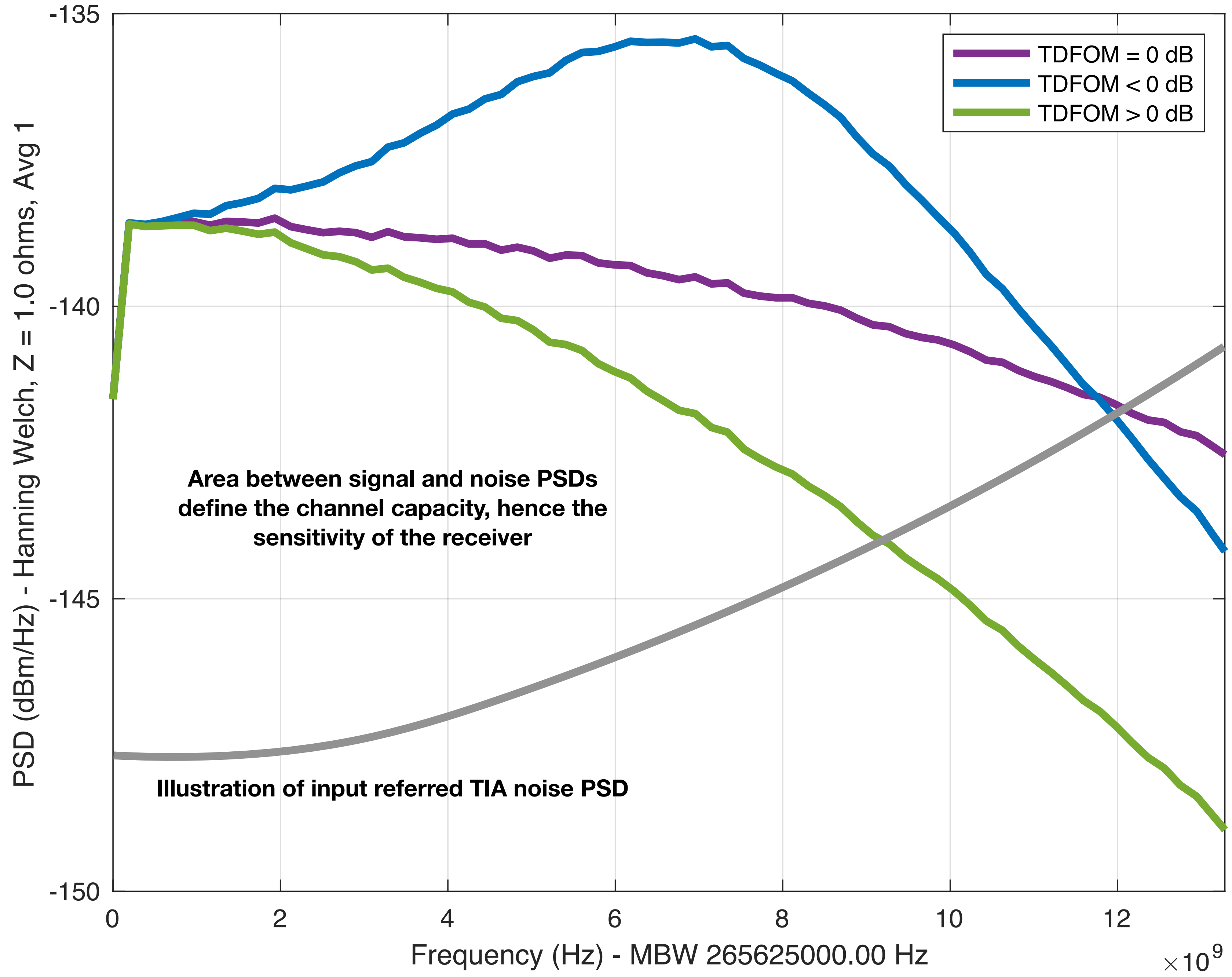
TDFOM = -0.7 dB (will produce better RX sensitivity)



VCSEL @ +125 ºC, Driver 1, eye diagram

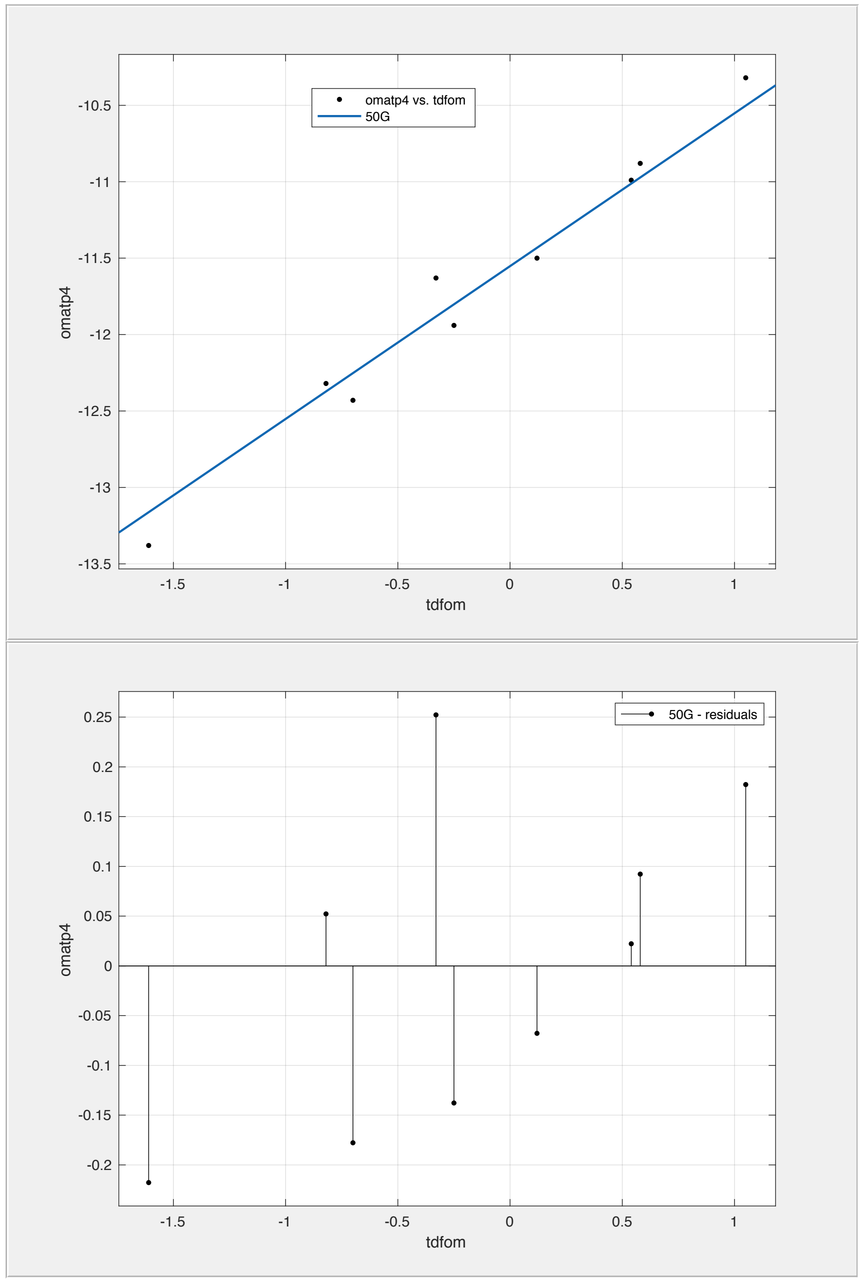
(Note: the OMA_{tx} has been normalised in these examples for comparison)

Shannon capacity illustration for 25 Gb/s

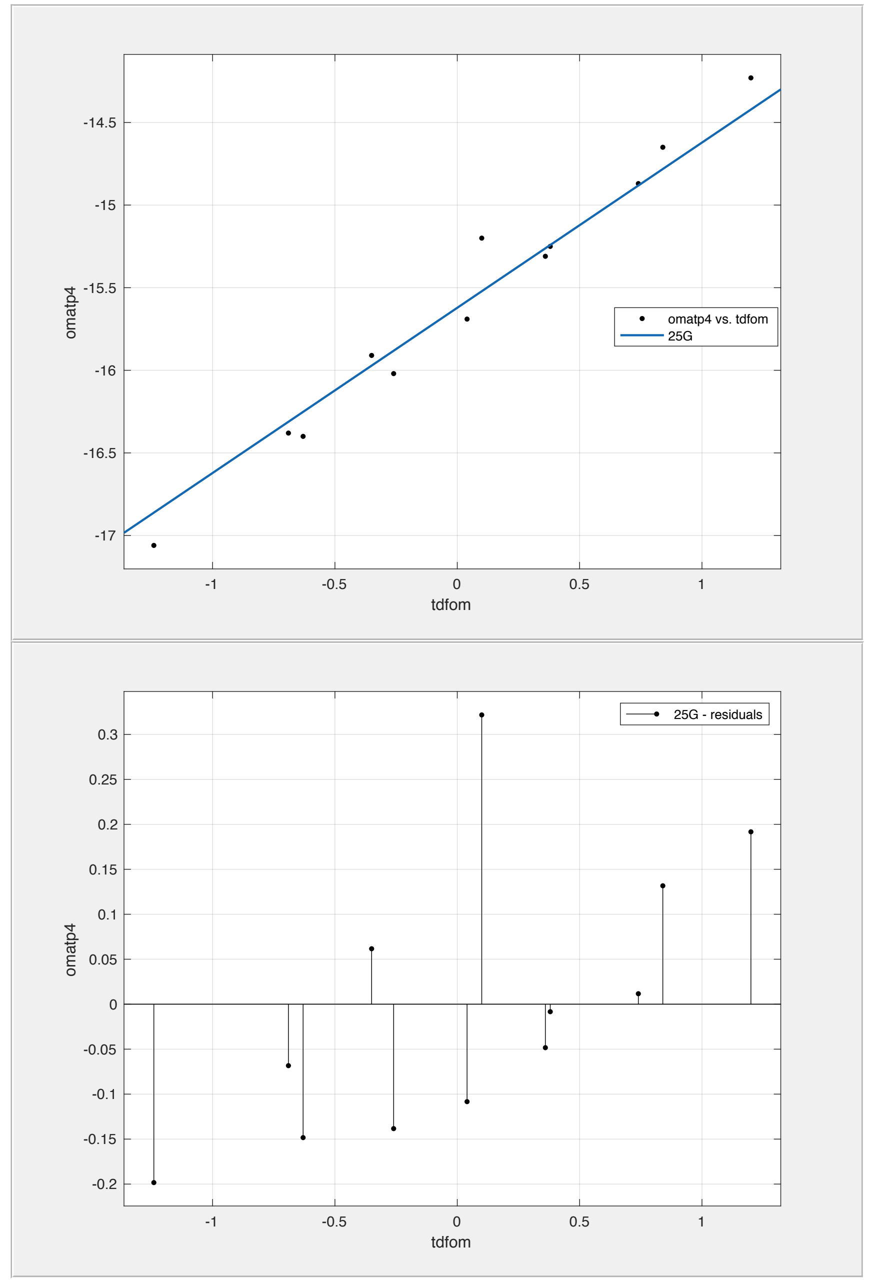


TDFOM vs. RX sensitivity

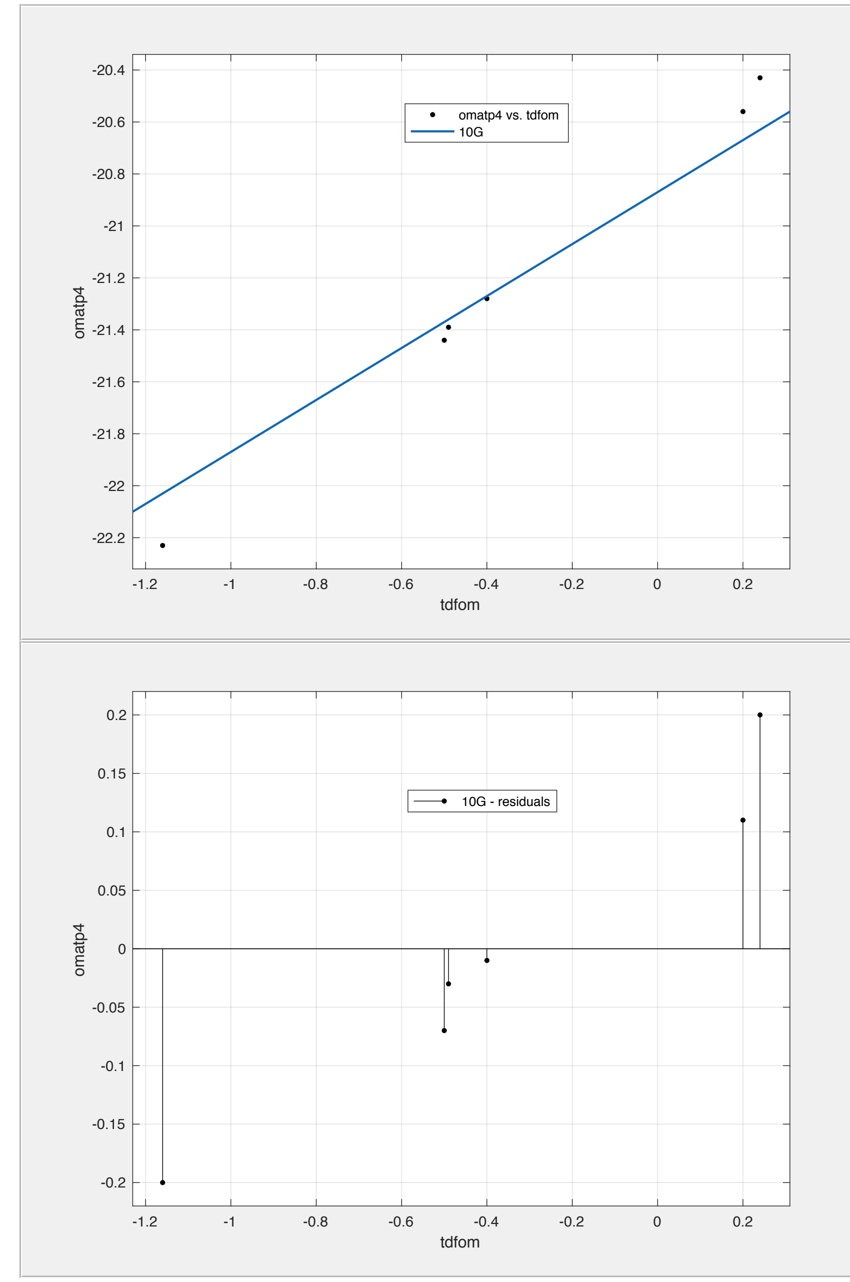
Fitting: *OMA_{TP4} = TDFOM + K*



50 Gb/s
3 VCSEL driver designs
Tbs = -40, 25 and 125 ºC
1 RX design at 125ºC



25 Gb/s
4 VCSEL driver designs
Tbs = -40, 25 and 125 ºC
1 RX design at 125ºC



10 Gb/s
2 VCSEL designs
Tbs = -40, 25 and 125 ºC
1 RX design at 125ºC

Conclusion

- Reference receiver and TDFOM measurement method have been defined for transmitter characteristics specification and stress receiver sensitivity conditions of BASE-AU 980nm/OM3 PHY
- Reference receiver and TDFOM are defined to reflect the most representative receiver implementation, for sake of interoperability, but not precluding different implementations
- Reference receiver and TDFOM are proposed to be included in the BASE-AU 980nm/OM3 PMD baseline

References

- [1] John M. Cioffi et al., "MMSE Decision-Feedback Equalizers and Coding-Part I: Equalization Results," October 1995, IEEE Transactions on Communications, Vol. 43, No. 10
- [2] John M. Cioffi et al., "MMSE Decision-Feedback Equalizers and Coding-Part II: Coding Results," October 1995, IEEE Transactions on Communications, Vol. 43, No. 10
- [3] John M. Cioffi, "Equalization", Course EE379A: Digital Communications - Signal Processing, Chapter 3, Stanford University, [Online], Available: https://cioffi-group.stanford.edu/doc/book/chap3.pdf

Thank you