TDFOM simplification proposal

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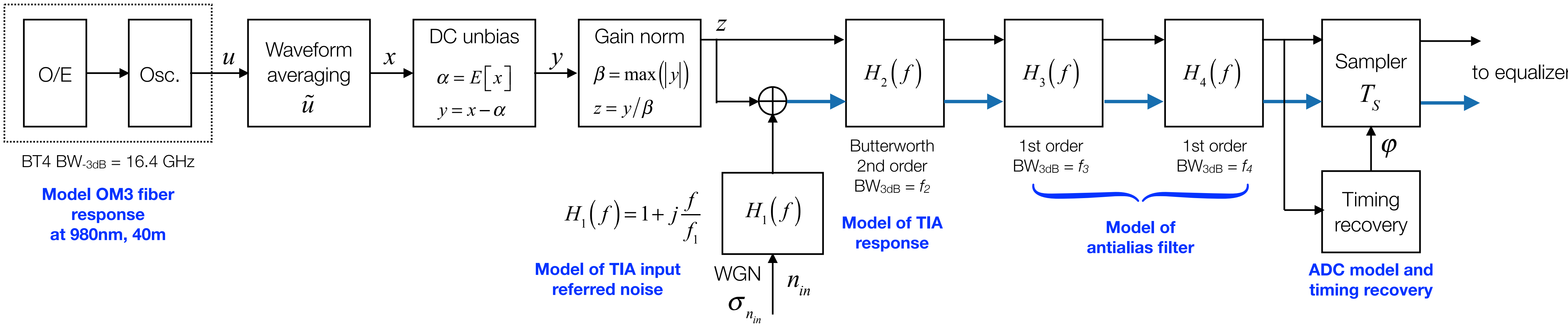
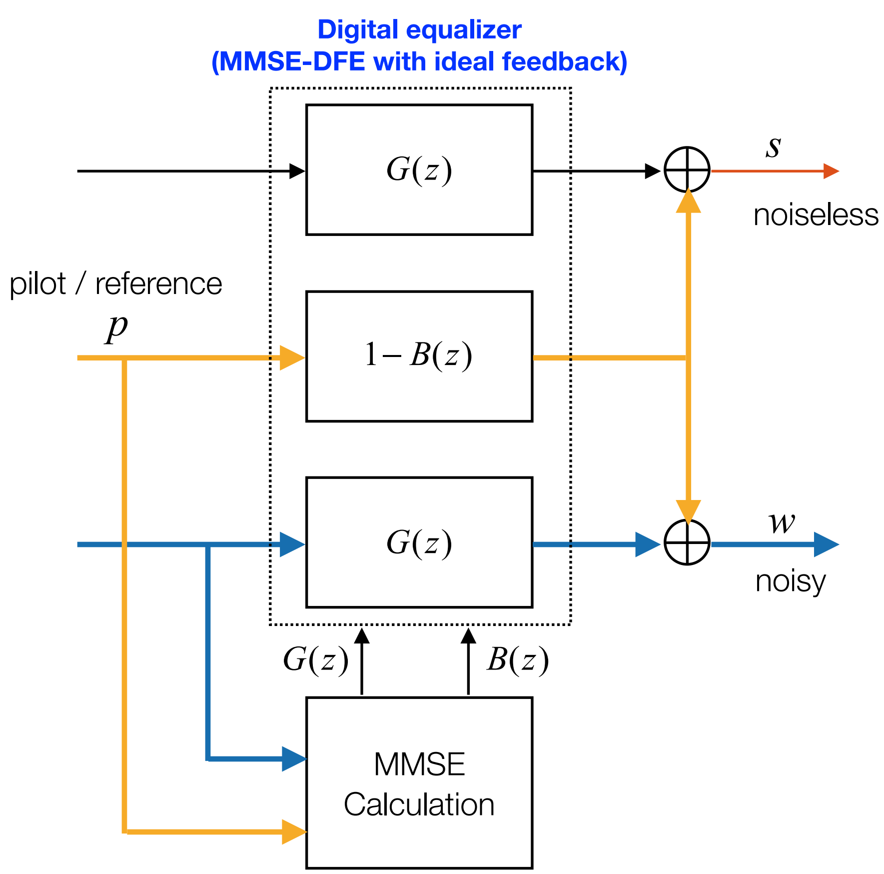
Objective

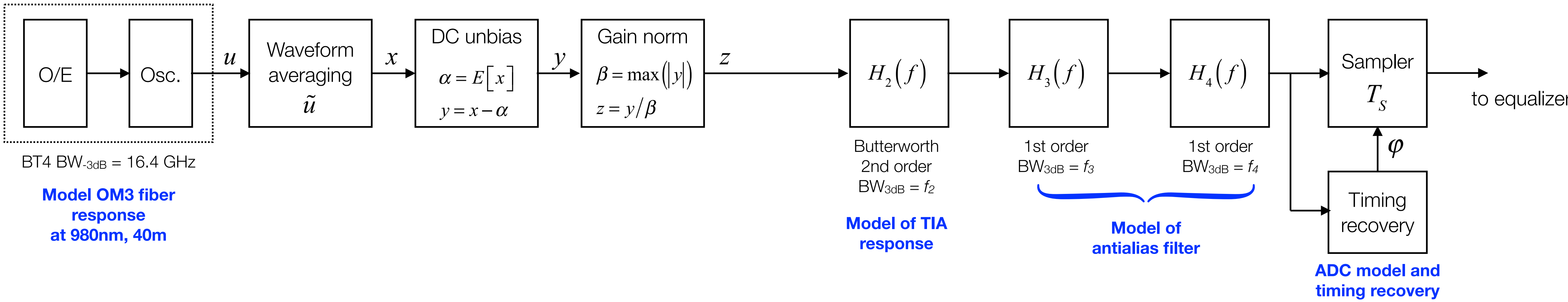
- This contribution proposes a simplification of the TDFOM reference receiver and figure of merit of [1]
- Simplification is addressed in several ways:
  - Added noise is white, so noise filter is removed
  - Noise is added at the sampler output, so analytical calculation of standard deviation after equalizer is direct (noise variance measurement is removed)
  - Because noise is added at sampler output, the dependency with oversample factor (samples per UI) is also removed
- Improvement in OMA calculation for PAM4 is also proposed
  - CID length and pre/post cursors lengths is updated according to SSPR-PAM4 pattern
- New TDFOM proposal has been validated vs OMA receiver sensitivity

Original TDFOM from [1]

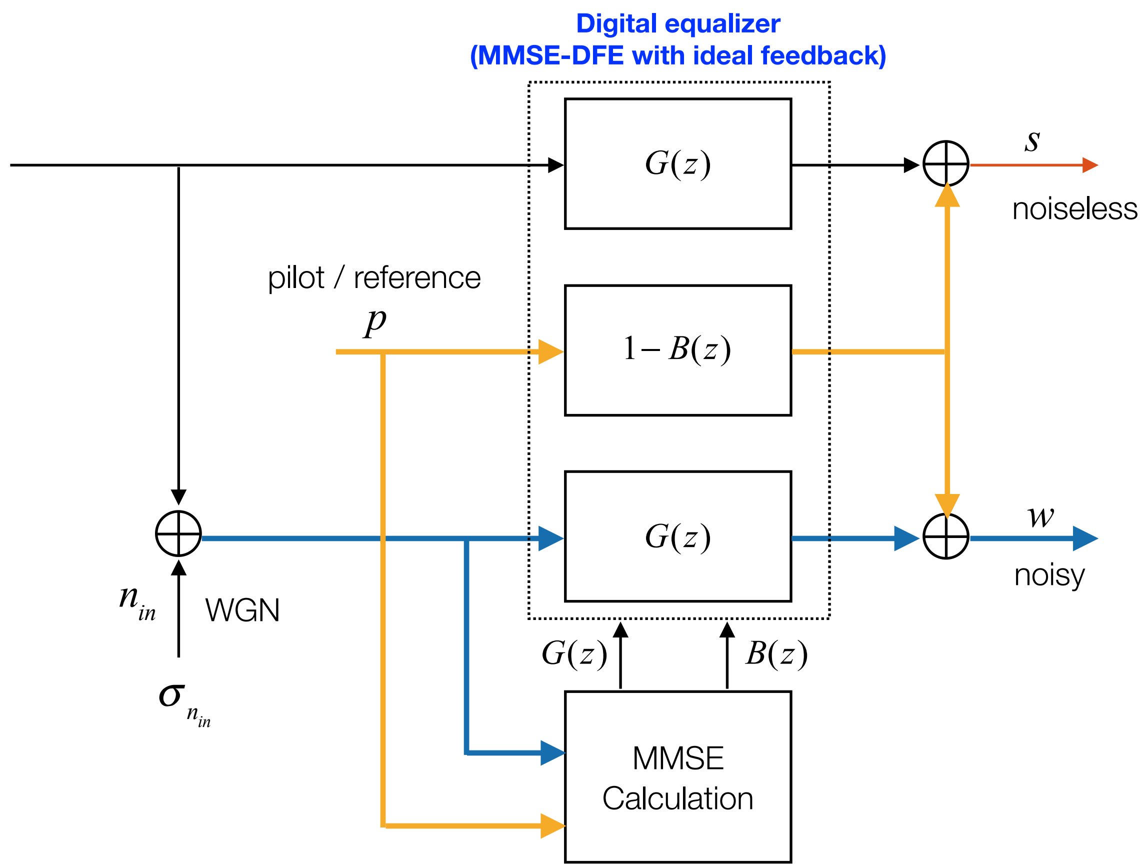




New TDFOM



O/E
Osc.
u
Waveform averaging
ũ
x
DC unbias
$\alpha = E[x]$
$y = x - \alpha$
y
Gain norm
$\beta = \max(|y|)$
$z = y/\beta$
z
$H_2(f)$
$H_3(f)$
$H_4(f)$
Sampler
T_S
to equalizer
φ
Timing recovery
BT4 BW-3dB = 16.4 GHz
Model OM3 fiber response at 980nm, 40m
Butterworth 2nd order BW3dB = f2
Model of TIA response
1st order BW3dB = f3
1st order BW3dB = f4
Model of antialias filter
ADC model and timing recovery



Digital equalizer
(MMSE-DFE with ideal feedback)
G(z)
s
noiseless
pilot / reference
p
1 − B(z)
G(z)
w
noisy
n_{in}
WGN
$\sigma_{n_{in}}$
G(z)
B(z)
MMSE Calculation

H1 is removed

BASE-AU 980nm/OM3 reference receiver and analysis

Knowledge Development POF

- 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:

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

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

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

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

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Standard deviation

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:

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

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

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

$$\sigma_n = \sigma_{n_{in}} \cdot \sqrt{\sum_{i=0}^{N_G-1} g_i^2}$$

OMA calculation for PAM4

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:

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

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TDFOM calculation

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:

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

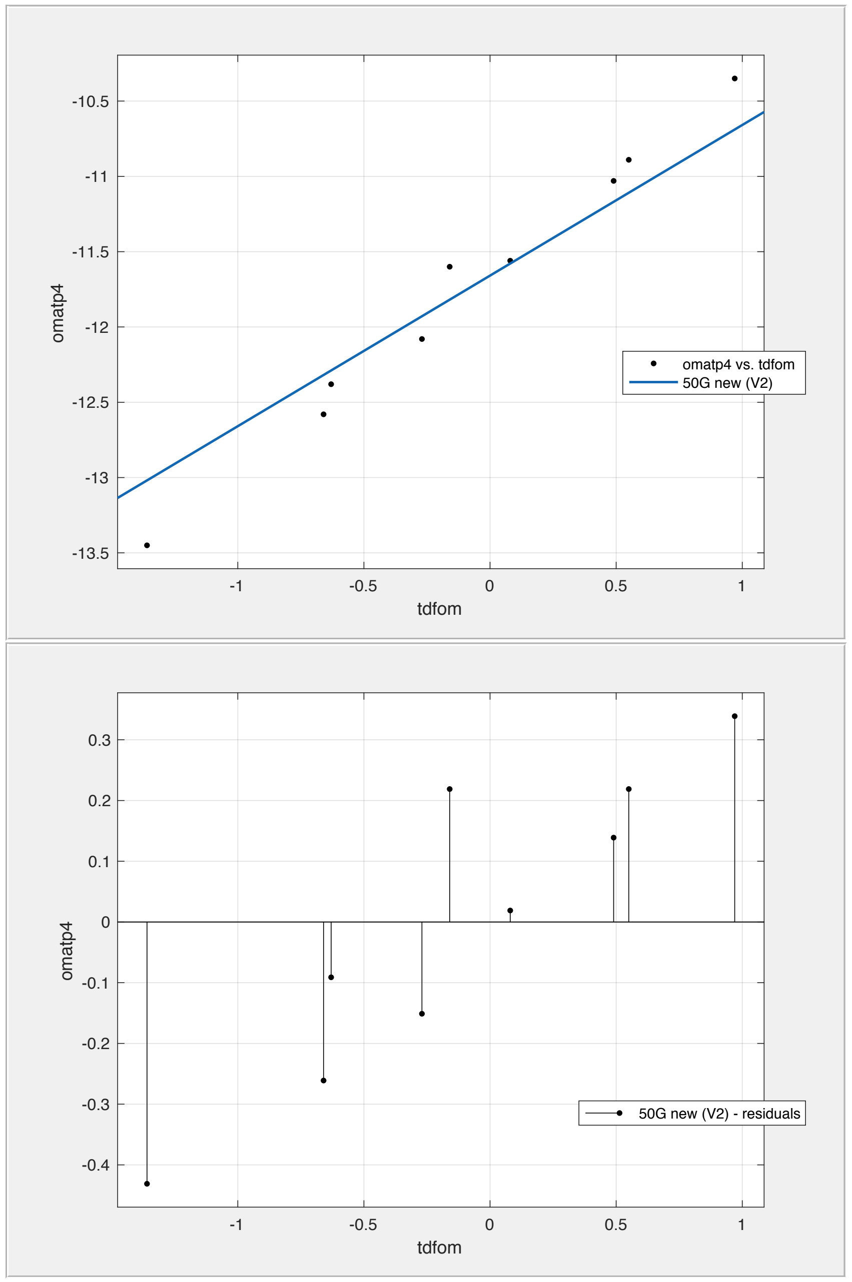
$$TDFOM = 10 \cdot \log_{10}\left(\frac{OMA_{in}}{2(M-1)\sigma_{n_{in}} Q_0}\right) - TDFOM_0$$

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

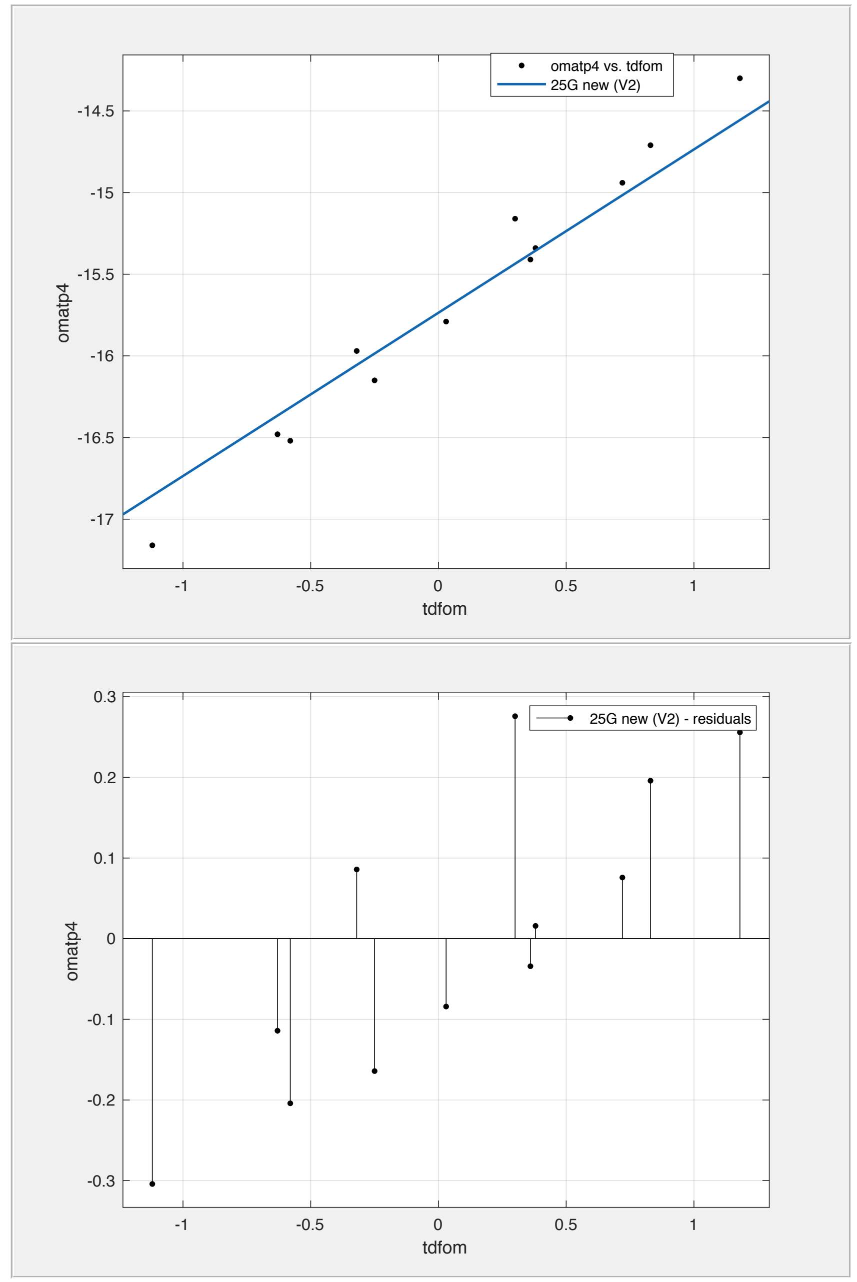
  - $TDFOM_0$ is calculated to get TDFOM = 0 dB when an ideal transmitter (square pulse) is connected to the reference receiver
  - It depends on bit-rate:
    - For 50 Gb/s: $TDFOM_0$ = 4.47 dB **2.83113**
    - For 25 Gb/s: $TDFOM_0$ = 4.27 dB **3.92395**
    - For 10 Gb/s: $TDFOM_0$ = 3.29 dB **3.63153**
    - For 5 Gb/s: $TDFOM_0$ = 2.59 dB **3.60715**
    - For 2.5 Gb/s: $TDFOM_0$ = 1.84 dB **3.59469**
  - $TDFOM_0$ values are obtained by simulation connecting a square pulse transmitter to the reference receiver input

New TDFOM vs. RX sensitivity

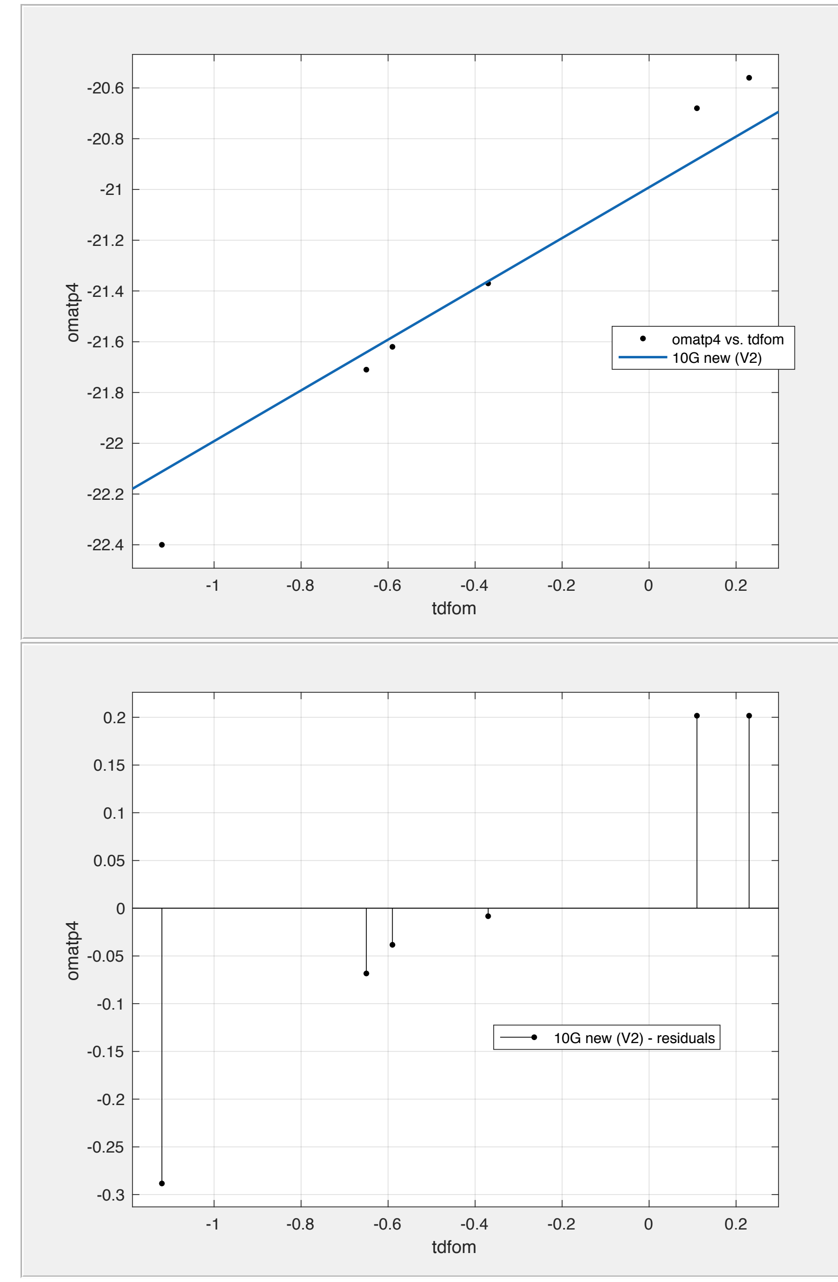
Fitting: OMA_{TP4} = *TDFOM + K*



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 driver designs
Tbs = -40, 25 and 125 ºC
1 RX design at 125ºC

References

- [1] R. Pérez-Aranda, “BASE-AU 980nm/OM3 baseline. Reference receiver and transmitter and distortion figure of merit,” February 2022, [Online], Available: https://www.ieee802.org/3/cz/public/8_feb_2022/perezaranda_3cz_01c_080222_TDFOM.pdf

Thank you