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]

\[
\begin{align*}
\text{BT4 BW}_{3\text{dB}} &= 16.4 \text{ GHz} \\
\end{align*}
\]

Model OM3 fiber response at 980nm, 40m

Waveform averaging \( \tilde{u} \)

DC unbias
\[
\begin{align*}
\alpha &= E[\tilde{x}] \\
y &= x - \alpha
\end{align*}
\]

Gain norm
\[
\beta = \max(|y|)
\]

\[
y = \frac{y}{\beta}
\]

Model of TIA input referred noise

\[
H_1(f) = 1 + j \frac{f}{f_1}
\]

Model of TIA response

\[
H_1(f)
\]

\[
\sigma_{\text{in}}
\]

WGN

\[
n_{\text{in}}
\]

Model of antialias filter

1st order \( \text{BW}_{3\text{dB}} = f_3 \)

1st order \( \text{BW}_{3\text{dB}} = f_4 \)

ADC model and timing recovery

Sampler
\( T_s \)

Timing recovery

\( \phi \)

Digital equalizer (MMSE-DFE with ideal feedback)

\[
G(z)
\]

\[
1 - B(z)
\]

\[
G(z)
\]

\[
B(z)
\]

MMSE Calculation

\[
\text{pilot / reference}
\]

\[
p
\]

\[
w
\]

noiseless

noisy

\[
s
\]

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New TDFOM

\[ u \xrightarrow{\text{O/E, Osc.}} \tilde{u} \rightarrow \text{Waveform averaging} \rightarrow x \xrightarrow{\text{DC unbias}} y = x - \alpha \rightarrow y \xrightarrow{\text{Gain norm}} z = y / \beta \]

\[ H_2(f) \rightarrow H_3(f) \rightarrow H_4(f) \rightarrow \text{Sampler} T_s \rightarrow \phi \rightarrow \text{to equalizer} \]

Butterworth 2nd order BW\(_{3dB} = f_2\)

1st order BW\(_{3dB} = f_3\)

1st order BW\(_{3dB} = f_4\)

Model of TIA response

Model of antialias filter

ADC model and timing recovery

Digital equalizer (MMSE-DFE with ideal feedback)

Model OM3 fiber response at 980nm, 40m

\[ G(z) \]

\[ 1 - B(z) \]

\[ G(z) \]

\[ B(z) \]

\[ p \]

\[ n_{\text{in}} \]

\[ \sigma_{n_{\text{in}}} \]

\[ w \]

\[ s \]

noiseless

noisy

MMSE Calculation

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BASE-AU 980nm/OM3 reference receiver and analysis

- The input low pass filter shall be 4\textsuperscript{th} order Bessel-Thomson with BW\textsubscript{-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:

  \[
  f_1 = \frac{1}{10 \cdot T_s} + 5 \cdot 10^8 \text{ (Hz)};
  \]

  \[
  f_3 = \frac{1}{2 \cdot T_s};
  \]

  \[
  f_4 = \left\{
  \begin{array}{ll}
  \frac{1}{5 \cdot T_s}, & \text{NRZ} \\
  \frac{1}{3 \cdot T_s}, & PAM4 \\
  \infty, & \text{NRZ} \\
  \frac{1}{2 \cdot T_s}, & PAM4
  \end{array}
  \right.
  \]
• BER calculation:
  • Calculate the noise sequence in the output of equaliser as \( n = w - s \)
  • Calculate the standard deviation \( \sigma_n \)
  • Define the thresholds vector \( TH_v = [0] \) for NRZ, and \( TH_v = [-2/3, 0, +2/3] \) 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 \( \Delta e \), and \( N_h \) is the number of elements of signal \( s \)
    • \( \Delta e = (\text{max}(s) - \text{min}(s))/N_h \)
    • \( N_h \) shall be \( \geq 500 \)
  • For each \( TH_v(k) \):
    • Calculate \( i_{hp} \) as the bins that meet \( e(i) > TH_v(k) \)
    • Calculate \( i_{hn} \) as the bins that meet \( e(i) \leq TH_v(k) \)
    • Calculate \( SER_{th}(k) \) as:
      \[
      SER_{th}(k) = \frac{1}{2} \sum_{i=\text{min}(i_{hn})}^{\text{max}(i_{hn})} h(i) \cdot \text{erfc}\left( \frac{TH_v(k) - e(i)}{\sigma_n \sqrt{2}} \right) + \frac{1}{2} \sum_{i=\text{min}(i_{hp})}^{\text{max}(i_{hp})} h(i) \cdot \text{erfc}\left( \frac{e(i) - TH_v(k)}{\sigma_n \sqrt{2}} \right)
      \]
      where \( \text{erfc}(x) \) is the complementary error function defined as:
      \[
      \text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} \, dt
      \]

\[
\sigma_n = \sigma_{n_{in}} \cdot \sqrt{\sum_{i=0}^{N_G-1} g_i^2}
\]
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:
    $$OMA_{in} = \frac{OMA_{eq}}{G_{eq}}$$
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:

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

    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: $TDFOM_0 = 2.83113$ dB  
      - For 25 Gb/s: $TDFOM_0 = 3.92395$ dB  
      - For 10 Gb/s: $TDFOM_0 = 3.63153$ dB  
      - For 5 Gb/s: $TDFOM_0 = 3.60715$ dB  
      - For 2.5 Gb/s: $TDFOM_0 = 3.59469$ dB

  - 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

Thank you