European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

# Experimental Analysis of TDEC for Higher Speed PON Including Linear Equalization

Gaël Simon[(1)], Flavio Nogueira Sampaio[(1)], Fabienne Saliou[(1)], Jérémy Potet[(1)], Philippe Chanclou[(1)]

[(1)] Orange, 2 avenue Pierre Marzin 22307 LANNION cedex, France, gael.simon@orange.com

**Abstract** *TDEC is the reference metric to characterize transmitters in terms of sensitivity and penalty, in downstream HS-PON. We investigate on its tolerance and focus on the noise enhancement factor "Ceq". We plead for a clarification in the method to determine the optimal equalizer. ©2022 The Author(s)*

## Introduction

The International Telecommunication Union (ITU-T) recently released the specifications of its last Passive Optical Network (PON) generation under the name of Higher Speed PON (HS-PON) [1]. HS-PON is the first ITU-T PON technology recommending the use of signal processing by design, such as the Decision Feedback Equalization (DFE) and the Feedforward Equalization (FFE), to compensate inter-symbol interference induced by the bandwidth limitations of the relatively cheap optoelectronic devices required for broadband applications. Another novelty is the introduction of new metrics as the Optical Modulation Amplitude (OMA) or the Transmitter and Dispersion Eye Closure (TDEC). TDEC is a well-known metric in core/metro/datacentres networks developed to characterize emitters characteristics, usually employing 4-levels Pulse Amplitude Modulation (PAM4), and thus usually referred as TDECQ [2], [3]. In HS-PON using Non-Return to Zero (NRZ) modulation, TDEC is used to estimate the quality of the optical transmitter based on histograms distributions and consequent post-processing to emulate the worst possible receiver and an equalizer. While specifications are provided for the extinction ratio or launch/received powers as in former PON specifications, they refer to TDEC and OMA as keystones for HS-PON.

Few publications propose a study related to TDEC measurement applied to PON technologies [4], [5], while taking into account experimental acquisitions instead of full simulations. Several metrology equipment already proposes the TDEC measurement feature. However, the TDEC measurement remains sensitive and subject to implementation choices as we will show.

We propose to study the tolerance of TDEC to metrology impairments, and to focus on the effect of equalization on the measurement.

## Experimental Setup and Methodology

The experimental setup is depicted on Fig. 1.a). The emitted signal is generated by a $2^{31}$-1 bits long Pseudo Random Binary Sequence at 50Gb/s, applied to an integrated Externally Modulated Laser (EML) consisting of a Distributed Feedback Laser (DFB) emitting at 1309 nm (almost no chromatic dispersion), monolithically integrated with an Electro-Absorption Modulator (EAM), presenting a bandwidth of 32 GHz. The resulting signal, whose optical eye diagram is showed on Fig. 1.b), presents an OMA of +5.0 dBm. The signal then propagates through 20 km of standard single mode fibre (SSMF) and is detected by a 40 GHz bandwidth PIN receiver, before being acquired by a Digital Storage Oscilloscope (DSO) having 80 GSa/s sampling rate and 33 GHz bandwidth.

In order to measure the TDEC, the acquired signal is numerically filtered by a 18.75 GHz $4^{th}$ order Bessel-Thompson filter, to emulate a limited optical receiver, as recommended [1]. The resulting eye diagram is showed on Fig. 1.c). The filtered signal is equalized by a 13 "taps" T-spaced Feed-Forward Equalizer (FFE), as specified [1], to re-open the eye diagram, as can be seen on Fig. 2.a). The FFE taps were calculated through least mean square method based on the signal of the received waveform, as proposed by Sato et al. [6]–[8]. This algorithm calculates the FFE coefficients by successive iterations, in adding the previous FFE coefficients

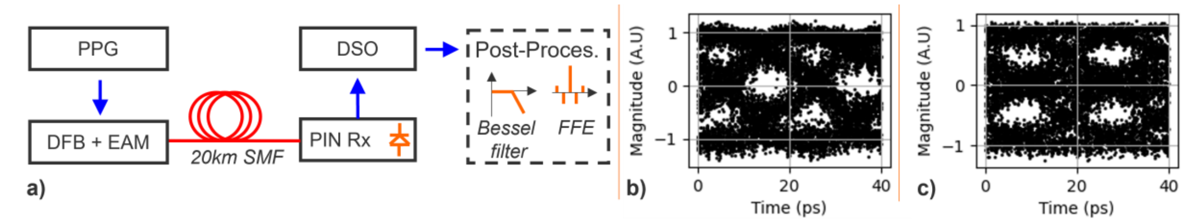


**Fig. 1:** a) Experimental setup used to measure the TDEC. b) Eye diagram at DSO's input. c) Eye diagram after the 18.75 GHz $4^{th}$ order Bessel-Thompson filter which emulates a low-quality receiver (before FFE)

to a vector denoting the difference between the measured signal and the ideal signal. The initial FFE set of coefficients consists in zeros, except for the middle coefficient, set to one, as recommended [1].

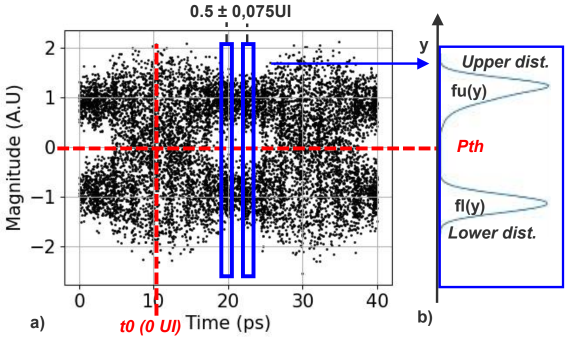


**Fig. 2:** a) Eye diagram after Bessel filtering and Feed Forward Equalization (310k iterations) and b) histogram of a window, employed to extract the lower and upper distributions, and the TDEC

The FFE taps obtained after the convergence of the error curve are used to process the transfer function of the FFE and calculate the noise enhancement factor called "Ceq", as described in [1]. The latter quantifies the amplification of the emitter's noise due to the FFE filtering, as the FFE transfer function usually amplifies the high frequencies to compensate the Bessel filtering.

The eye diagram of the equalized signal is exploited in extracting the upper and lower distributions (fu(y) and fl(y) on Fig. 2.b) of two windows having a width of 0.04 Units of Interval (UI) and centered at 0.5+/-0.075UI.

The next step requires to find the solution $\sigma_G$ of the Eq. 1, where Q is the error probability function, Pth is the threshold, and the $BER_{target}$ (target Bit Error Ratio) is set to $10^{-2}$ [1]. The left and middle terms calculate the BER contributions due to the upper and lower levels, respectively.

$$\frac{1}{2}\left(\frac{\int f_u(y)Q\left(\frac{y-P_{th}}{C_{eq}\cdot\sigma_G(y)}\right)dy}{\int f_u(y)dy}\right)+\frac{1}{2}\left(\frac{\int f_l(y)Q\left(\frac{P_{th}-y}{C_{eq}\cdot\sigma_G(y)}\right)dy}{\int f_l(y)dy}\right)=\mathrm{BER}_{\mathrm{target}} \quad (1)$$

Finally, the TDEC is extracted in making the ratio of the $\sigma_G$ solution of the previous equation for a perfect receiver, with the $\sigma_G$ experimentally determined. A perfect emitter should provide a TDEC of 0dB, while the maximum TDEC affordable according to [1] is 5.0dB. The noise asymmetrical distribution between zeros and ones when using avalanche photodiodes was also considered.

## Results and Discussion

To assess the TDEC measurement reliability, we first propose to study the impact of the decision time accuracy. We shifted the "t0" parameter (see Fig. 2.a), which corresponds to the beginning of the eye (equivalent 0 UI). An error on such parameters will shift the windows providing the distributions, and then the TDEC measurement.

Fig. 3 shows the TDEC versus timing shift to the best TDEC. It can be observed that within a +/-2ps (+/-100mUI) the TDEC variations suffers from deviations as high as 1.6dB (when the max. TDEC specified is 5dB). The reason for such a need in timing accuracy is the fact that the worst case among two windows (see Fig. 2.b) is to be employed for the TDEC calculation, and a timing inaccuracy eventually drags one of the windows to the edges of the regions where the eye is open.

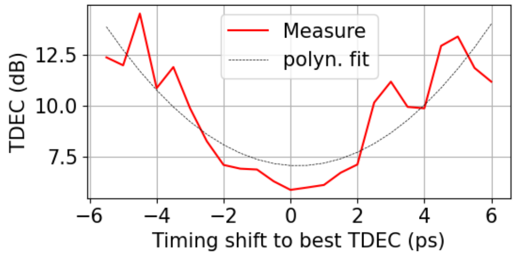


**Fig. 3:** Influence of t0 measurement imprecision on TDEC measurement.

We propose then to extend a similar study to the amplitude threshold position. The threshold is used to separate the lower and the upper distributions to estimate the associated errors (see Eq. 1), in each of the two windows of Fig. 2.b. Fig. 4 shows the TDEC depending on the threshold position in percent of OMA. 50% means that the threshold is equally spaced between the mean level of the logical 1 and 0. The "t0" parameter was optimized in each measurement. It appears that in our case the minimum is very close to the median (51% of OMA). It can also be seen than a shift of +/-5% in the threshold positioning could lead to a TDEC increase of 0.5dB. Fortunately, the parabolic profile helps to converge to the minimum TDEC value. The over-modulation on Fig. 4 is assumed to be a measurement artifact originating from the discrete nature of the data generating the histograms.

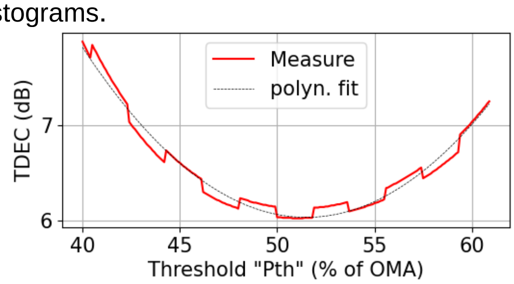


**Fig. 4:** Influence of Pth measurement imprecision on TDEC measurement.

Finally, we focus on the noise enhancement factor called "Ceq", introduced in the methodology section. Ceq is calculated from the normalized noise spectrum obtained by filtering white noise with the reference filter (fixed), and from the frequency response of the FFE, which may vary depending on the methodology employed to make sure the filter converged. The black-dashed curve on Fig. 5 shows the Mean-Squared Error (MSE), depending on the number of iterations of the FFE-convergence algorithm previously introduced. The MSE is inversed on Fig. 5 for practical presentation reasons, and denoted MSE$^{-1}$. It can be observed on Fig. 5 that MSE$^{-1}$ grows rapidly during the first 40k iterations, and then remains almost constant (MSE$^{-1}$=5.2 dB) until the 280k$^{th}$ iteration (280k bits; 5.6 µs at 50 Gb/s) at which the MSE$^{-1}$ reaches 9.5 dB.

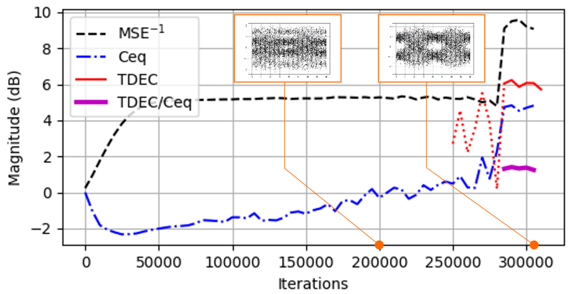


**Fig. 5:** MSE, Ceq and TDEC variations depending on FFE convergence (SMF: 20 km)

The corresponding Ceq is simultaneously processed (see blue dash-dotted curve on Fig. 5). Ceq is negative for the first 200k iterations, meaning that the FFE contribute to filter the signal and the noise, instead of counterbalancing the 18.75GHz Bessel-Thompson filter. But the algorithm slowly converges, as testifies the slowly increasing Ceq, and eventually “jumps” to 5dB, after the 280k$^{th}$ iteration, as for the MSE$^{-1}$. The TDEC is also measured simultaneously (see red solid line curve on Fig. 5). The TDEC reaches about 6.0 dB after the 280k$^{th}$ iteration, with variations of +/-0.25dB, while the Ceq is about 5.0dB (+/-0.25dB), meaning that the Ceq is the main contribution to the TDEC, but also that it already reaches the maximum specifications in this case. The threshold observed around the 280k$^{th}$ iteration corresponds to the opening of the eye diagram, as shows the insights on Fig. 5. The TDEC measurement for less than 280k iterations, depicted by the red dotted line, are then non-relevant.

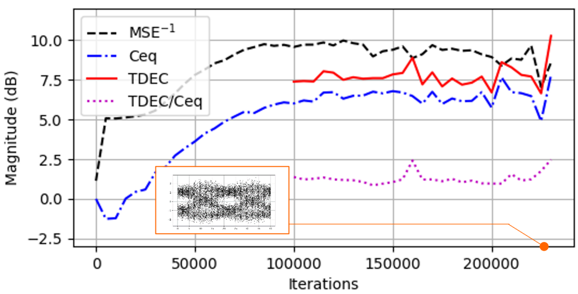


**Fig. 6:** MSE, Ceq and TDEC variations depending on FFE convergence (SMF: 20 km)

Fig. 6 is like Fig. 5, except that the processing is realized from another capture, where only a few meters of SSMF were inserted between the emitter and the receiver. It appears that the FFE parameters converge faster, as the best MSE (MSE$^{-1}$=10 dB) is reached after 125k iterations. However, the corresponding TDEC equals 7.5 dB which is not the best measured TDEC. Surprisingly, the TDEC equals 6.8dB after 225k iterations, while MSE$^{-1}$=7 dB, demonstrating that MSE optimization may not be the absolute tool to obtain the final TDEC. The corresponding eye diagrams is depicted on Fig. 6’s insights. It also appears on Fig. 6 that the Ceq is the main contribution to TDEC, as their difference is about 1.2dB (see purple dotted curve). However, Ceq and thus TDEC vary a lot on the 100k-200k iteration range: from 6.8 to 8.9 dB for the TDEC.

## Conclusions

TDEC is a major emitter’s performance indicator for transceivers in general and has become the keystone for HS-PON specifications. We implemented the TDEC measurement procedure and assessed its reliability and ability to converge to a fixed value, employing experimental acquisitions. We observed that a shift in the timing reference of the eye diagram of 2ps could lead to an error of 1.6dB (when the requirements are to limit the TDEC to less than 5dB). We also showed similarly that a special care should be taken to apply the amplitude threshold used in the TDEC calculation. Finally, we showed that the Ceq noise enhancement factor is from far the main contributor to the TDEC, as can also be mathematically demonstrated. However, the Ceq calculation requires a correct optimization of the FFE parameters which may depends on the implementation, or the ability for the algorithm to converge. Special care should be taken there, as the divergence in the methods employed to converge to a set of FFE parameters, calculate the Ceq may differ. From an operator point of view, such divergences are not affordable, especially when considering the strong constraints supported by the physical layer of HS-PON. A solution could be to organize interoperability and metrology test meetings (“plugfests”), where the tenants could measure the TDEC in the same conditions and compare their results. Another option could be for the standardization bodies to share waveforms and the associated TDEC as references, to compare the algorithms progression.

## Acknowledgements

This work was carried out in 5G-COMPLETE H2020-ICT-2019 and MARSAL H2020-ICT-52 projects. We also thank ALMAE technologies for the EML, and Teledyne-LeCroy for the oscilloscope.

## References

[1] ITU-T, G.9804.3 (G.hsp.50Gpmd) – Physical Medium Dependent Layer for 50G single Channel PON systems – consent (April 2021).

[2] Y. Zhao et al., "BER and TDECQ Correlation for Different Impairments in 400Gbps PAM4 System," in 2020 Optical Fiber Communications Conference and Exhibition (OFC), Mar. 2020, pp. 1–3.

[3] S. Echeverri-Chacón et al., "Transmitter and Dispersion Eye Closure Quaternary (TDECQ) and Its Sensitivity to Impairments in PAM4 Waveforms," Journal of Lightwave Technology, vol. 37, no. 3, pp. 852–860, Feb. 2019, doi: 10.1109/JLT.2018.2881986.

[4] V. Houtsma and D. van Veen, "TDEC, OMA and TDP Evaluation for 25G EPON," IEEE P802.3ca 100G-EPON Task Force Meeting, Orlando, FL, November 2017, p. 14.

[5] B. Li et al., "DSP enabled next generation 50G TDM-PON," Journal of Optical Communications and Networking, vol. 12, no. 9, pp. D1–D8, Sep. 2020, doi: 10.1364/JOCN.391904.

[6] S. U. H. Qureshi, "Adaptive equalization," Proceedings of the IEEE, vol. 73, no. 9, pp. 1349–1387, Sep. 1985, doi: 10.1109/PROC.1985.13298.

[7] Y. Sato, "A Method of Self-Recovering Equalization for Multilevel Amplitude-Modulation Systems," IEEE Transactions on Communications, vol. 23, no. 6, pp. 679–682, Jun. 1975, doi: 10.1109/TCOM.1975.1092854.

[8] G. Coudyzer et al., "Study of burst-mode adaptive equalization for >25G PON applications [Invited]," IEEE/OSA Journal of Optical Communications and Networking, vol. 12, no. 1, pp. A104–A112, Jan. 2020, doi: 10.1364/JOCN.12.00A104.