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ABSTRACT The Transmitter and Dispersion Eye Closure (TDEC) is a metric originally introduced by IEEE 802.3 for short reach optical transmission in datacenters and later adopted for 50G-PON in ITU-T Recommendation G.9804.3. TDEC evaluates the performance of a transmission system as a penalty due to eye-diagram closure, comparing it to a reference ideal transmitter. To this end, the standard defines a procedure to be followed involving filtering, equalization and the definition of time windows inside the eye diagram. The purpose of this article is to show the correlation between TDEC and the Optical Modulation Amplitude receiver sensitivity in 50G-PON scenario using optical amplifiers either as booster at transmitter side (for the downstream direction) or as pre-amplifiers at receiver (in the upstream direction).
Keywords: Passive Optical Networks, 50G-PON, TDEC, FTTH.

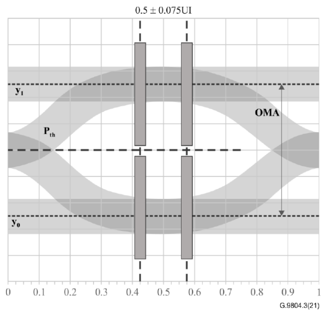
1. INTRODUCTION

The capacity of Passive Optical Networks (PON) is continuously growing. In September 2021, ITU-T published its latest recommendation for 50G-PON [1], which defines a downstream bit rate equal to 50 Gbps using non-return to zero (NRZ) binary modulation. In this standard, observing that the actual implementation will be strongly affected by optoelectronic bandwidth limitations and nonlinear distortion, the ITU-T adapted the IEEE 802.3 Transmitter Dispersion Eye Closure (TDEC) metric for PON [2]. The TDEC metric was originally introduced in the datacenter short-reach ecosystem in order to characterize optical transmitter performance by using an algorithm applied on the eye-diagram, without requiring direct Bit Error Rate (BER) evaluation. The basic principle behind the TDEC metric (visually shown in Fig. 1) is to estimate the amount of Gaussian noise (with standard deviation $\sigma_{calculated}$) that can be added on signal until a target bit error rate (BER_{ref}, for 50G-PON set to 10^{-2}), is reached. The same procedure is then applied to an ideal received eye-diagram, evaluating the amount of noise σ_{ideal}. The ratio between these two standard deviations (indicated as k) is one of the two parts for the definition of TDEC. The other part is related to the equalization effect. In particular, for 50G-PON downstream, the ITU-T recommends to apply this procedure to an equalized eye diagram, using a 13 taps T-spaced feed-forward equalizer (FFE), optimized by the commonly adopted minimum mean square error algorithm. The effect of this equalization impacts on TDEC calculation with the parameter C_{eq}, which represents the noise enhancement factor due to the typical high-frequency boost of the equalizer. Finally, TDEC is computed as the sum (in dB) of the two contributions k and C_{eq}.

For a correct TDEC implementation, some precautions must be taken in order to obtain proper results. Indeed, the eye-diagram should be sampled in specific time windows and, to meet this request, it is necessary to have a sufficient high number of samples for bits [5]. Only with resampling operations or selecting specific kind of oscilloscopes, it is possible to define the correct instants for TDEC evaluation. In addition, the evaluation of the high power level, 'y_1', and low power level, 'y_0', must be carried out on a large number of equal consecutive bits (50), and the resolution of signal histograms in the defined time windows must have a value below which no TDEC variation is observed.

Due to the demanding power budgets required for PON, Avalanche Photodiode (APD) based receivers are a common technology, due to their higher sensitivity compared to more common (and less expensive) PIN-receivers. It can moreover be useful to evaluate TDEC for optically amplified systems (either at TX or RX), which are also currently under investigation in the preliminary experiments for 50G-PON. Both APD and optically amplified systems may generate asymmetric noise on the received eye-diagrams, since the resulting noise variance is, in the electrical domain, proportional to the received power. The TDEC definition introduced for the 50G-PON standard takes this asymmetry into account, by introducing the asymmetric noise correction factor m in the noise evaluation part (k) of the TDEC equation. The ITU-T standard suggests that for a PIN PD (Photo-Diode) receiver $m = 1$ whereas for an APD m is set 1.5.

The limited bandwidth of some receivers, as the APD devices in commerce today, can be emulated in the TDEC standard for 50G-PON by introducing a fourth-order Bessel filter and a cut-off frequency equal to 18.75 GHz, which has impact on the C_{eq} factor described above. As previously mentioned, the TDEC can estimate the performance of a transmitter system without requiring lengthy BER measurements on the receiver optical signal. Indeed, it was found that the TDEC penalty in dB between two transmitters is correlated to the receiver sensitivity and, ideally, the graph between the two quantities should have a unitary slope [6], meaning that, for



$$TDEC = 10 \cdot log_{10}\left(\frac{\sigma_{ideal}}{\sigma_{calculated}}\right) + 10 \cdot log_{10}(Ceq)$$

$$TDEC = k + Ceq$$

$$k \rightarrow f(m)$$

$$Ceq \rightarrow H_{Bessel}(f), H_{Equalizer}(f)$$

Figure 1: Evaluation of the TDEC metric. On the left: an example of the eye diagram with the sampling instants required by the standard. On the right: the main formulas behind the standard (the arrow means a dependency by the right factors).

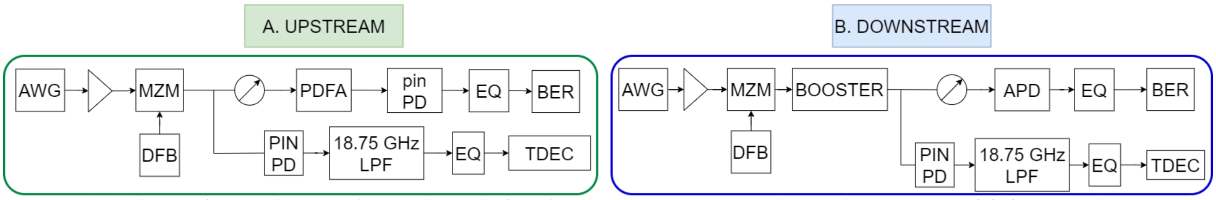


Figure 2: Schematic used to evaluate the relation between TDEC penalty and OMA sensitivity penalty. On the left the set-up for the upstream, both for experiments and simulations, while in the right the set-up for the downstream, for simulations.

a specific transmitter, a 1dB increase in TDEC would correspond to a 1dB worsening in receiver sensitivity. In this paper, we want to determine if the same TDEC procedure can be used also for optically amplified system, i.e. pre-amplified PIN PD receivers for upstream transmission and transmitters with a booster amplifier for the downstream direction, and verify if the relation between TDEC and Rx sensitivity still holds.

2. Optically pre-amplified 50G-PON receivers

In this Section, we investigate both experimentally and by simulation the impact on TDEC when using optically pre-amplified receivers, and in particular we focus on the relation between Optical Modulation Amplitude (OMA) received sensitivity and TDEC. In order to show this correlation, we studied the set-up shown in the Fig. 2 (left), which we used for both experiments and simulations.

In our experiments, the signal is emitted by a distributed feedback laser (DFB) and then modulated with a Mach-Zehnder modulator (MZM) by the bit sequence coming from an arbitrary waveform generator (AWG). At the receiver side, two branches are used in parallel: in the upper, we measure BER versus OMA received sensitivity, while in the bottom we evaluated the TDEC metric. More specifically, in order to evaluate BER as function of OMA received sensitivity, in the upper branch the optical signal is attenuated and then acquired with a pre-amplified PIN PD receiver. For the experiment, we use a praseodymium-doped fiber amplifier (PDFA) while in the simulation we consider a generic amplifier with a gain and a noise figure emulating a Semiconductor Optical Amplifier (SOA). After a PIN PD, the signal is equalized with the same equalizer defined into the 50G-PON ITU-T standard for the TDEC evaluation. Finally, BER is evaluated for different received OMA, to obtain the classical receiver sensitivity characterization. In the bottom branch, used for TDEC evaluation, the signal is detected by a PIN PD and then it is filtered with a fourth-order Bessel Low Pass Filter (LPF) having a cut-off frequency of 18.75 GHz as required by the 50G-PON standard. Afterwards, the signal is equalized with the same equalizer used for the upper branch and finally the TDEC is evaluated in post-processing.

For the simulation analysis, we start by generating a Short Stress Pattern Random (SSPR, [3]) sequence of 32762 bits, as required by the recommendation for the TDEC evaluation. The presence of inter symbol interference (ISI) is then simulated with a second order Bessel filter whose cut-off frequency is changed in order to produce different OMA receiver sensitivity and different TDEC. On the receiver side, for the BER count, we assumed to use a SOA with noise figure equal to 7.5 dB and gain equal to 15 dB. The signal is then optically filtered with a band-pass filter with bandwidth equal to either 1 nm and 10 nm. The current 50G-PON standard has not defined yet the optically amplified case, so we wanted to investigate the two cases of a relatively narrow optical filter and a much larger one. Finally, the resulting signal is detected by a PIN PD and equalized with a 13 T-spaced taps feed-forward equalizer optimized with a minimum mean square error (MMSE) algorithm. BER count is performed optimizing the decision threshold and selecting the best sampling instant. The results are presented in Fig. 3, which shows the relation between OMA received sensitivity and TDEC for different electrical filter cut-off frequencies, from 12.5 GHz (higher TDEC) to 25 GHz (lower TDEC)

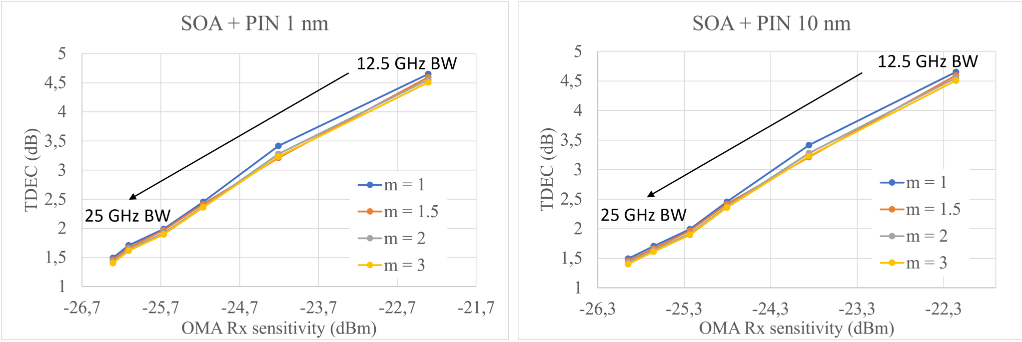


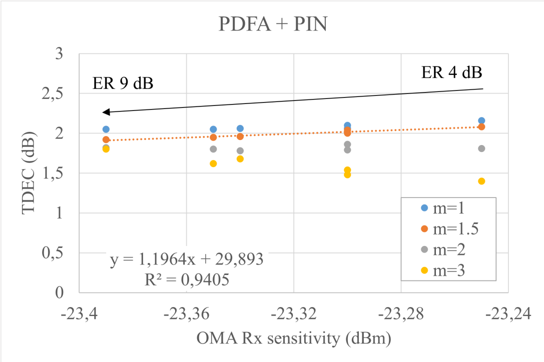
Figure 3: Simulation TDEC and OMA Rx sensitivity with pre-amplified Rx for different electrical filter cut-off, from 12.5 GHZ to 25 GHz, frequencies: (left) 1 nm optical filter BW, and (right) 10 nm optical filter BW.

and, consequently, different inter-symbol interference impact on the eye diagram. The TDEC is also evaluated for different m values (from m =1 to 3). The results in Fig. 3 show a good correlation between TDEC and OMA received sensitivity, with a slope of about 0.8 (in dB/dB). This means that a penalty between two transmitters in term of OMA received sensitivity produces the same penalty multiplied for 0.8 in dB in terms of TDEC. This correlation is observed both with a bandwidth filter of 1 nm and 10 nm. Fig. 3 also shows that simulations obtained using different m values produce approximately the same TDEC values showing that, in this case, the m correction factor is not relevant to obtain "ideal" 1dB/1dB slope in these kind of graphs. We investigate this result, and we found that in our simulations the variation in filter bandwidth produces only a change in the C_{eq} factor [4], while k remains almost constant and near to 0 dB for all the situations. As mentioned before, the m parameters affects only the k factor, that anyway in our set-up turned out to be close to 0 dB, so we cannot appreciate significant differences with different value of m. Anyway, apart from the slope value slightly lower than the ideal 1dB/1dB target, the graphs shows that also for optically pre-amplified receivers TDEC is a reasonably accurate estimation metric.

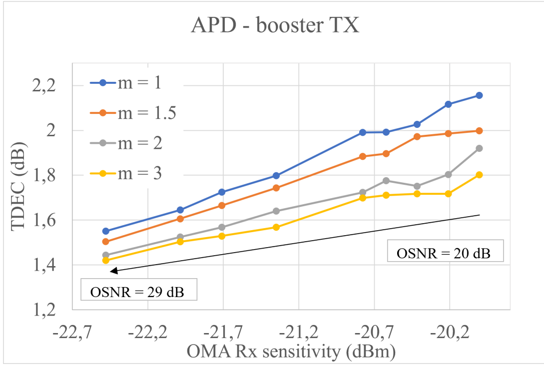
Regarding the experimental set-up, the AWG generates a 50 Gb/s pseudorandom binary sequence (PRBS) of $2^{15} - 1$ bits on a signal of wavelength of 1311 nm, then we changed the amplitude of the electrical signal to get different extinction ratio (ER). The optical pre-amplified receiver consists of a praseodymium-doped fiber amplifier (PDFA) with gain of 15 dB and noise figure of 7 dB followed by a 35 GHz PIN PD. The input power to the pre-amplified receiver is controlled by a variable optical attenuator (VOA). After the optical signal is photodetected, the electrical waveform is captured by a Digital Sampling Oscilloscope (DSO) with 8 Sa/bit. The samples pass through a 7-tap FFE filter with 2 precursors, optimizing the FFE equalizer taps, and the same equalizer is used also for the TDEC evaluation. Finally, we measured the BER by direct error counting and we measure the OMA received sensitivity at pre-FEC threshold of 10^{-2} for each ER. For the bottom branch in Fig. 2 (left), we compute the TDEC changing the asymmetric noise factor m from 1 to 3 as we did for the simulation set-up. Fig. 4a plots the experimental results in terms of TDEC vs. OMA when modifying the ER from 4 to 9 dB and for different m values. We notice that m=3 is a value too high because the TDEC and OMA vary in opposite directions, i.e. a lower TDEC should correspond to a lower OMA since the eye has a better quality. For values $1 < m < 2$, the variation of TDEC and OMA go in line. The correlation factors (and slopes) for $m = 1$, 1.5, and 2 are 0.73 (0.75), 0.94 (1.19), and 0.01 (0.1) respectively. Hence, like in the APD case, m=1.5 give the best correlation between TDEC and OMA. While the values of OMA and TDEC do not show a big difference in this specific experiment (0.2 dB difference), the results experimentally show that the method proposed in [1] for measuring the TDEC with an APD can be applied also for a pre-amplified receiver.

3. 50G-PON USING OPTICAL AMPLIFICATION AT THE TRANSMITTER

In this Section, we study by simulation the case of downstream 50G-PON transmission using a booster optical amplifier placed at the transmitter, i.e. inside the central office OLT side. The set-up shown in Fig. 2 (right) is modified compared to the one depicted in Fig. 2 (left), introducing a booster SOA (15 dB gain, 7.5 dB noise figure) after the MZM block and removing the PDFA at the receiver side. We substitute the PIN PD block in the upper branch with an APD (multiplication factor of 7). The electrical filter bandwidth was set to 25 GHz (to produce a minimum TDEC=1.5 dB in absence of optical amplification [1]) while the MZM output power was changed from -15 dBm to -23.8 dBm and sent to the input of the booster SOA that, besides amplifying the optical power level, also introduces amplified spontaneous emission (ASE) noise, thus generating different transmitted OSNR values, varying in our case from 20 to 29 dB (the OSNR is measured with 50 GHz bandwidth). In Fig. 4b, we show the relation between TDEC and OMA received sensitivity in this situation, evaluating it again



(a) Experimental results of TDEC vs OMA Rx sensitivity when changing the ER from 4 dB to 9 dB.



(b) Simulation results of TDEC vs OMA Rx sensitivity with optical booster amplifier in Tx and APD based Rx with several OSNR.

Figure 4

for different m values. Also for this downstream case, we observe a linear relation between OMA received sensitivity and TDEC. In this case, when varying the OSNR, the resulting TDEC k factors are different from zero and thus a slope variation appears for different values of m [4]. While no value of m produces a slope close to 1 (dB/dB), it is still evident that there is an almost linear relation on the graph, so that again the TDEC parameter is a reasonable metric also in this case. Moreover, we observed that TDEC shows a significant penalty in the analyzed scenario only when the transmitted OSNR goes below 20 dB, but this happens for very low power levels at the optical amplifier input (i.e. at the output of the MZM) in the order of -15 dBm, which are anyway significantly lower that the expected modulator output power. For more reasonable MZM output power levels, let's say around 0 dBm, our results thus show that the ASE noise at the SOA output would give negligible impact on TDEC penalty.

4. Discussion and conclusion

We have discussed in this paper, both experimentally and by simulation, the applicability of TDEC definition introduced for 50G-PON for optically amplified systems, in view of the future use of SOA in 50G-PON. Although the performed tests were not exhaustive, these initial results indicate that TDEC metric algorithm described for an APD in the recommendation can also be used for an optical amplified system. In particular, in the case of pre-amplified based Rx, we observed that the asymmetric noise factor must be in the range $1 < m < 2$ to keep a linear correlation with $m = 1.5$ that achieves a correlation coefficient close to 1.

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