Relation Between TDEC, Extinction Ratio and Chromatic Dispersion in 50G PON

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***Abstract*—We evaluate TDEC in a 50G-PON downstream through experiments and show the relation with receiver sensitivity at different fiber lengths and ER. The results show that TDEC effectively follows the penalty induced by transmission impairments.**

Keywords—PON, 50G-PON, high speed optical access, TDEC, APD

I. Introduction

Passive optical networks (PON) have successfully enabled residential broadband access around the world. Currently, network operator offer commercial terminals capable to handle bitrates up to 10 Gb/s. Due to the rapid development and adoption of bandwidth hungry applications and bearing in mind the demand for 10G-PON, ITU-T started to develop the next step standard since 2018 [1].

ITU-T recently published the recommendation G.9804.3 for 50G-PON [2]. For the downstream, a bandwidth (BW) limited receiver (Rx) based on mature 25G avalanche photodiodes (APD) is considered followed by digital signal processing (DSP) implementing an equalizer (EQ) to reduce the effect of the BW limitation. In addition, the EQ helps to reduce the intersymbol interference caused by chromatic dispersion (CD) [1], [3]. With the introduction of DSP, some flexibility can be added to the transmitter (Tx) specifications instead of having to adhere to all the worst case parameters. The aim is to increase the optical Tx technology options which would enable a diverse supply chain. However, a metric must be in place to guarantee the interoperability among the different transceiver options.

In order to ensure physical layer interoperability, 50G-PON adopts the transmitter and dispersion eye closure (TDEC) metric for NRZ signals used in IEEE Ethernet transceivers (TRx) [4]. TDEC can perform transmission penalty analysis through eye-diagrams captured in an oscilloscope. In other words, it can predict the performance of a Tx and simplify the penalty impairment measurement when the target bit error ratio (BER) is sufficiently high [5]. TDEC has also been extended to PAM4 signals as TDECQ [5], [6]. 50G-PON extends TDEC by defining a 13-taps T-spaced FFE reference EQ preceded by a 4th order Bessel-Thompson low-pass filter with 18.75 GHz BW which emulates the frequency response of a 25G APD.

In this paper we test the TDEC metric in a 50G-PON downstream setup and show how accurately it can predict the performance penalty caused by CD and different extinction ratio (ER). The results show that TDEC follows the Rx sensitivity in the range considered. We also provide a mathematical review of the variables used to account for the asymmetric noise in APDs commonly used in PON. We also describe how TDEC helps 50G-PON TRx to have more flexibility and keep the interoperability.

II. Adapting TDEC for 50G-PON

A. Asymmetric noise

PONs Rx employ mainly APDs to achieve sufficiently good Rx sensitivity and high power budget. As a result, shot noise is higher for the "1" level than for the "0" level. In order to account for this unbalanced noise, the noise asymmetry variable m is defined as [1]:

$$m = \frac{\sigma_1}{\sigma_0} \tag{1}$$

where σ_0 and σ_1 are the noise for low and high levels respectively. In order to define a value for m, we can consider that each noise level term consists of a shot (σ_{sh}) and a thermal (σ_{th}) noise component.

$$\sigma_{0,1} = \sqrt{\sigma_{sh0,1}^2 + \sigma_{th}^2} \tag{2}$$

In particular, σ_{sh} depends directly on the power level: $\sigma_{sh0,1}^2 = a \cdot P_{0,1}$ where $P_{0,1}$ is the power for the "0" or "1" level and $a = 2qM^2F_M R\Delta f$, where q is the electron charge, M is the avalanche gain, F_M is the excess noise factor, R is the responsivity and Δf the BW [7]. We can then consider:

$$ER = \frac{\sigma_{sh1}^2}{\sigma_{sh0}^2} \tag{3}$$

where ER is the extinction ratio. Then we define the ratio of the thermal to the shot noise in the high level as:

$$\rho_1 = \frac{\sigma_{th}^2}{\sigma_{sh1}^2} \tag{4}$$

We then substitute (2), (3), and (4) into (1), and obtain:

$$m = \sqrt{\frac{1+\rho_1}{\frac{1}{ER}+\rho_1}} \tag{5}$$

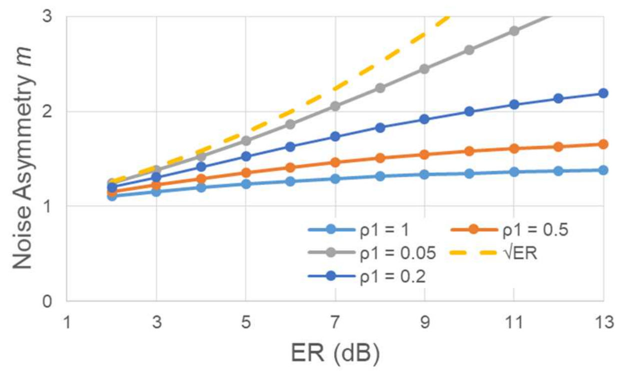

Fig. 1 Noise asymmetry variable *m* against ER for several ρ_1.

Eq. (5) shows the relation between the ER and the asymmetric noise. For a p-i-n PD, σ_{th}^2dominates which results in $\rho_1 \gg 1$, and leads to *m*=1 (lower limit). In a shot noise limited Rx (which is the case in APDs error free BER without FEC, e.g. 10^{-10}), $\rho_1 \ll 1$, the noise asymmetry value, then, becomes dependent on the ER, $m = \sqrt{ER}$. This relation is seen in the dotted line plotted in Fig. 1 and represents the upper limit. However, at the pre-FEC BER level of 10^{-2}, the signal power is so low that σ_{th}^2 becomes non-negligible and even comparable to the shot noise. Fig. 1 plots the value of the asymmetric noise m against ER for different ρ_1. We can observe, that in the range 0.2< ρ_1<1, the value of m is bound to 1< m <2.5 depending on the ER. Moreover, in the limit when $ER \rightarrow \infty$, m converges. Hence, for ER values of up to 8 dB, the asymmetric noise is in the range 1<*m*<2. In the current 50G-PON recommendation [2], the value of 1.5 is selected.

B. *Equalization*

In the 50G-PON application, TDEC is measured on the received and equalized signal. The link assumed in the 50G-PON standardization discussions incorporates a 25G-class APD for the ONU Rx. Hence, the noise enhancement effect caused by the EQ must be considered. In [4], for TDECQ the noise enhancement factor, C_{eq}, is introduced to account for the effect of the EQ in a PAM4 signal. The C_{eq} definition for 50G-PON is described in section 9.2.7.8 in [2].

III. TDEC as Enabler for Interoperability

The objective of TDEC is to guarantee a minimum quality level of the Tx with a powerful enough EQ in Rx. Fig. 2 shows how the OLT Tx optical modulation amplitude (OMA) and ONU Rx sensitivity in OMA vary with TDEC to ensure a link budget of 29/32 dB [2]. A very low TDEC value would be obtained with a high quality Tx which requires a low Tx OMA power for a certain power budget. On the other hand, a higher TDEC means that the eye after equalization is more closed. Still, this Tx can comply with the link budget provided that it transmits a higher OMA. At the Rx side, the minimum Rx sensitivity also increases when measured with a signal with higher TDEC. It can be noted that the same increase in TDEC is reflected in the minimum Tx OMA and Rx sensitivity.

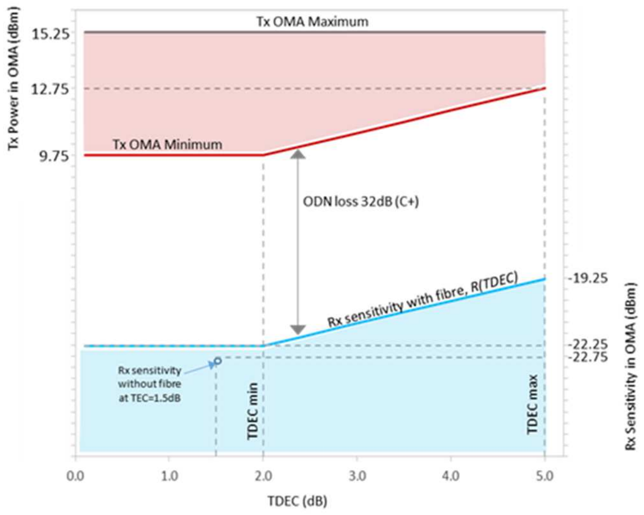

Fig. 2 Relation between Tx power and Rx sensitivity, both in OMA, and TDEC [2]

Conventional metrics for the optical line terminal (OLT) Tx like eye-mask or ER can be too restrictive when considering the worst case transmission system. Instead, as seen in fig. 2, TDEC allows flexibility in the TRx as long as the OMA – TDEC is kept within the permitted range. This means that the Tx can trade-off parameters as ER or chirp which have an impact on TDEC, yet achieving the link budget. Such flexibility allows more optical technologies to comply with the standard and thus generate a competitive supply chain without sacrificing interoperability.

IV. Experimental Setup

We implement the point to point setup depicted in Fig. 3. An O-Band Mach-Zehnder modulator (MZM) converts a PRBS-15 stream from a pattern generator (PG) into an optical NRZ signal. The light source is an external cavity laser (ECL) emitting at 1360 nm. Such wavelength is used to emulate the highest accumulated CD that could appear in 20km of the worst case G.652 fiber at the longest 50G-PON downstream wavelength of 1344 nm. The optical signal ER is limited to 9 dB and it is sent through single mode fiber (SMF). At the Rx, a digital sampling oscilloscope (DSO) captures the optical signal either directly or after it is transformed into electrical by means of a 25G class APD. For the latter, a variable optical attenuator (VOA) controls the input power. In the DSO, we apply a 4th-order Bessel low-pass filter (18.75 GHz BW) and then a 13-tap T-spaced FFE to the optical signal and measure the TDEC as defined in [2]. We apply the same equalizer to the detected electrical signal and sample it with 8 Sa/bit. Afterwards we make the symbol decision and compute the BER.

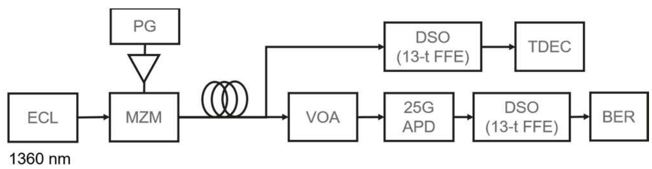

Fig. 3 Experimental setup

V. RESULTS

We measure the TDEC and Rx sensitivity at pre-FEC BER of 10^{-2} in back-to-back (BtB) varying the optical signal ER from 5dB to 9dB in steps of 1dB. These ER values are reasonable for an EML based Tx at the OLT. We also change the asymmetric noise m for the TDEC measurement to validate the range written in section II.A. The results are plotted in Fig. 4 where a clear relation between the two measurements is visible as both increase when the ER also varies. The same trend is seen for all the asymmetric noise values. After a linear regression on the points, the slopes are 1.14, 1.05, 1.14, and 0.93 for m = 1, 1.5, 2 and 3 respectively. From these results, we corroborate that the asymmetric noise should be in the range $1<m<2$ as higher values start to deviate from an optimum correlation (slope=1). The inset in Fig. 4, shows the straight line equation for m=1.5. The slope is almost 1 and the computed correlation coefficient is around 0.95.

We then keep ER = 7 dB and measure the relation between TDEC (m=1.5) and Rx sensitivity after fiber transmission. Fig. 5 shows the results after several SMF lengths. The path penalty obtained with TDEC and Rx sensitivity after 25 km with respect to BtB is almost identical (~1.4 dB). Furthermore, a linear regression yields a slope of 0.97 indicating almost perfect correlation between the two variables. Hence, TDEC clearly follows the Rx sensitivity and is a good indicator of the penalty that the system can experience after transmission.

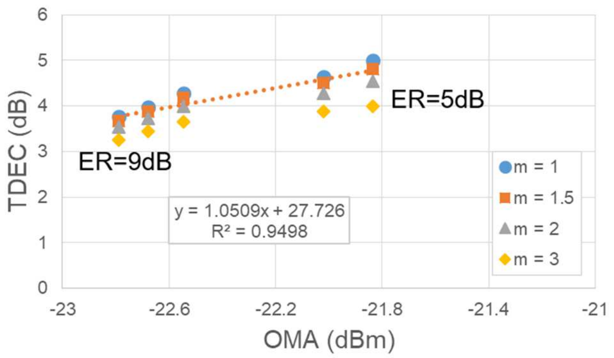

Fig. 4 TDEC against received OMA Rx sensitivity when varying the ER from 5 dB to 9 dB for several asymmetric noise values *m*.

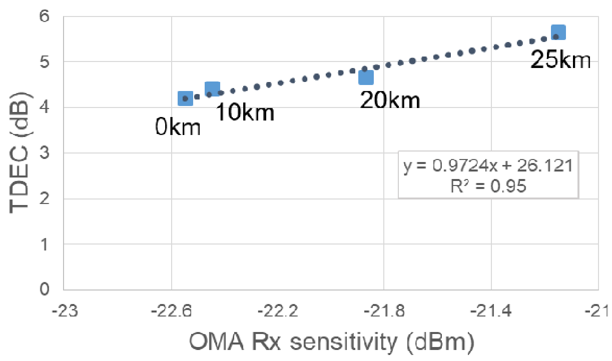

Fig. 5. TDEC against OMA Rx sensitivity for different fiber lengths

VI. CONCLUSIONS

We carried out measurement for TDEC and Rx sensitivity at different ER and after several fiber distances. In both cases there is a clear relation between the two and the correlation is very close to 1 when the asymmetric noise variable m is equal to 1.5. We also provided a theoretical approach for the values of asymmetric noise and determined that it must be in the range $1<m<2$ which is also corroborated through experiments with different ER. These results show that the TDEC metric can predict the link performance and enable interoperable optical interfaces in 50G PON.

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