Interoperability and Experimental Evaluation of TDEC(Q) Testing for 50 and 100G PONs

Dora van Veen, Robert Borkowski, Amitkumar Mahadevan & Vincent Houtsma
Nokia, Bell-labs, 600 Mountain Avenue, Murray Hill, NJ 07974 USA
{dora.van_veen,vincent.houtsma}@nokia-bell-labs.com

Abstract: We detail the TDEC(Q) method and its usage in the context of system level specifications for 50 and 100G PONs. Real-time experimental results obtained with representative PON transmitters are used to analyze and validate interoperability of these PONs.

1. Introduction

The 50G PON standard has recently been published in ITU-T G.9804 [1]. Although it still employs NRZ modulation it will require digital signal processing (DSP) in the form of receiver-side equalization to compensate for chromatic dispersion and bandwidth limited transmission and reception of the signal. The transition to DSP comes alongside new quality tests, test patterns and quality parameters which means a substantial change from previous PON standards. Since interoperability of PON equipment is the key factor to ensure reliable operation over the optical distribution network (ODN) it is of high importance to operators. Transmitter and Dispersion Eye Closure (TDEC) testing has been proposed and adopted for 50G PON [1]. Recently [2] some questions were raised on accuracy and repeatability of this new test method to ensure interoperability in the field. It was noted that very few experimental results have been published so far. Even though all PON standards specify optical component requirements like minimum extinction ratio (ER), minimum optical launch power, eye mask testing and sensitivity, only a transmission dispersion penalty (TDP) measurement like TDEC can provide a direct assessment of interoperability. The TDEC measurement technique was developed in [3] for NRZ and has been extended to TDEC Quaternary (TDECQ) for PAM4 [4]. The TDEC measurement is performed on an optical eye diagram captured by an oscilloscope. Since the original TDEC method in [3] is based on a 'regular' full bandwidth receiver several modifications were made for adoption in 50G PON. Most PONs rely on APD based receivers which have limited bandwidth at 50Gbaud operation, so a reference receiver with reference equalizer needs to be adopted for 50G PON. One of TDEC's functions is to screen out transmitters that won't close the link for the worst-case channel in the field assuming a reference equalizer implementation, therefore the reference receiver used to compute TDEC should be well defined. For 50G PON a reference receiver with a bandwidth of 18.75 GHz and 4th order Bessel filter roll-off with 13-tap and 7-tap (for down- and upstream (DS/US) respectively) T-spaced FFE reference equalizer was adopted. The fewer number of taps for the US TDEC increases the margin/interoperability of an US burst mode receiver when the TDEC is measured in continuous mode which might not represent the worst-case US channel.
Compared to TDEC without a reference equalizer [5], TDEC with a reference equalizer will only introduce a simple factor, the noise enhancement factor Ceq (which is the ratio of equalizer output noise to its input) into the calculation, due to amplification of receiver noise by the digital linear equalizer. Also, the original TDEC method was based on a PIN receiver and assumption that the mathematically added noise to observe the target BER is the same for both the optical one and zero levels. This is not the case for an APD receiver [5]. When the system receiver uses an APD, the difference in gain for the two power levels must be considered. The 50G PON TDEC method and associated mathematics are modified to account for this. An additional constraint M is defined for the TDEC calculation (M=1.5 for APD, M=1 for PIN) which is the ratio of the noise between the two optical input signal levels. It should be noted that another purpose of TDEC is to determine the minimum launch power needed to meet the power budget which is defined in the standard as launch power in Optical Modulated Amplitude (OMA) minus TDEC. A maximum value for TDEC is 5 dB at BER/SER(Symbol Error Rate)=1e-2 and it needs to be evaluated for downstream (DS) at λ=1342±2 nm with 0 to 77.1 ps/nm of fiber dispersion and for upstream (US) at λ=1270±10 nm with -140 to 0 ps/nm (option 1) and at λ=1300±10 nm with -66 to +18.4 ps/nm (option 2) of fiber dispersion.

2. BER performance and TDEC correlation

The relationship between Bit-Error-Rate (BER) performance and TDEC of an ideal receiver is given in Figure 1a, assuming an additive white gaussian noise (AWGN) penalty only. From this it can be noted that a perfect transmitter has a TDEC=1 (0 dB) resulting in a BER=0, while a poor transmitter has a TDEC= ∞ resulting in a BER=1e-2. What can also be noted from Figure 1a is that for large TDEC values beyond 5 dB, TDEC is very sensitive to impairments. Therefore, an appropriate range to use TDEC to predict BER performance is from 0 to 5 dB.

$$BER = 0.5 \cdot erfc\left(\frac{Q_T}{\sqrt{2}}\sqrt{\frac{TDEC^2}{TDEC^2-1}}\right) \quad (TDEC > 1)$$

$$TDEC \;=\; 10\;\cdot log_{10}\left(Ceq\,\frac{\sigma_{ideal}}{\sigma_{eq}}\right)$$

Equalizable Penalty **Ceq**

Non-equalizable Penalty **K**

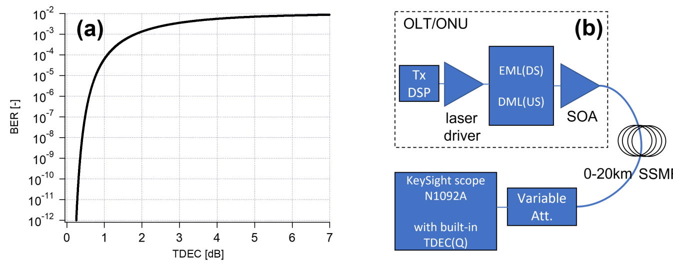

Figure 1: (a) Calculated BER as function of TDEC and (b) TDEC(Q) measurement setup used for high speed PON based transmitters.

Besides a non-equalizable penalty K due to noise and residual ISI, the transmitter can also exhibit a penalty due to bandwidth limitations for instance. Even though this penalty is equalizable, it will lead to enhancement of noise in the equalized signal which is captured by Ceq. A realistic PON transmitter can have both and will pass if it stays within the allowable TDEC=5 dB region as given in Figure 2b. Fig 1b shows the experimental setup for TDEC(Q).

3. Experimental Verification

Figure 2a shows the measured eye-diagrams of an EML(DS) as well as DML(US) based transmitter as used for 50G PON. Even though our DS transmitter is almost full bandwidth, the b2b TDEC is measured to be 1.78 dB with Ceq=1.45 dB. This large TDEC penalty is because the reference receiver is non ideal since it is already bandwidth limited by definition. This means that a large part of the equalizable TDEC penalty is due to the limited BW reference receiver and not due to the transmitter. This is confirmed by measuring TDEC with a full BW receiver resulting in a b2b TDEC of only 0.3 dB for the same transmitter. After 20 km of worst-case fiber (zero dispersion at 1300 nm) the DS TDEC was measured to be 4.94 dB (OPP=3.16 dB) with a Ceq of 3.99 dB, meeting the 5 dB maximum TDEC requirement (see Figure 2b). For US DML at λ=1291 nm, TDEC b2b is 1.93 dB with Ceq=0.94dB while after 20 km of nominal fiber (~-43 ps/nm) the TDEC is only 0.84 dB with Ceq=0 dB. For very negative dispersion (~-160 ps/nm) TDEC=3.2 dB, and Ceq=0 dB. The decrease in Ceq after fiber transmission with DML at λ=1291 nm is related to the accumulated negative dispersion which effectively increases the system bandwidth so the equalizable penalty is reduced after fiber transmission. The TDEC increases again for a lot of negative dispersion due to increased jitter in that case (see Figure 2a). The measured eye diagrams and TDECQ values for 100G PAM4 using the same DS transmitter are shown in Figure 2a as well. A b2b TDECQ of 3.3 dB with Ceq=1.17 dB was measured indicating that this transmitter has an increased non-equalizable penalty (2.13 dB) for 100G PAM4 compared to 50G NRZ (0.33 dB) due to the more stringent requirements for a PAM4 signal (linearity).

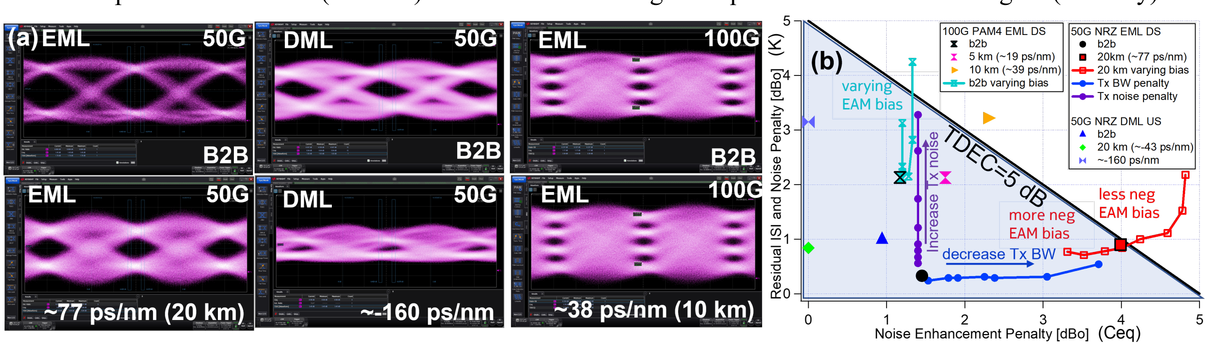

Figure 2: (a) Measured TDEC eye-diagrams and (b) values for b2b and after fiber. Shade area is acceptable TDEC(Q) region with 5 dB max

To investigate the influence of various penalties on TDEC(Q) [6] the bias voltage of the EAM of the DS EML was varied around the optimum bias point. This will change the chirp as well as the ER of the transmitter. From Figure 2b it can be observed that a more negative EAM bias voltage will result in a lower TDEC after fiber, mostly due to a decrease in chirp. However, it will also result in a reduction of the output power (OMA). Therefore, for optimum performance the EML DFB bias current and EAM bias voltage must be tuned to simultaneously meet OMA, ER and TDEC (CD penalty) at each temperature. Also, the input signal to the SOA was reduced in steps of 1 dB to introduce an increasing noise penalty. Separately, the electrical driving signal of the b2b DS EML transmitter was low pass filtered with a 4th order Bessel filter with 3 dB roll-off from 30 GHz down to 12.5 GHz. From Figure 2b it can be observed that both increase the TDEC penalty however more low-pass filtering will result in an increased equalizable penalty while increasing the noise will result in an increase in non-equalizable penalty.

In addition to its equalization properties, the sampling time should also be considered. Since this varies in a real system, this parameter should be included in the reference TDEC(Q) receiver as well. For 50G PON the TDEC eye diagrams are sampled at two vertical histograms centered at 0.425 UI and 0.575 UI (15% spacing around optimum sampling point) with each histogram window having a sampling width of 0.04 UI. This is done to emulate BER degradation in the real-system due to sampling jitter. From Figure 3a it can be observed that the 15% histogram positions have small impact on the TDEC value in most cases, however it can affect TDEC values significantly for extreme high sampling jitter cases (for US DML after significant negative dispersion). From Figure 3a it can be observed that for 100G PAM4 the sampling jitter tolerance is reduced significantly. Therefore, sampling jitter in the real system needs to be improved for PAM4 and 10% histogram spacing was adopted for 100G PAM4 TDECQ [4]. The tap weights of the receiver equalizer are generally set to enhance the observed performance of the transmitter. Some optimization routine is used to define the tap settings. However, there are several means to optimize the tap weights. A minimum mean-squared error for the eye closure could be used or alternatively, the computed TDEC penalty could be minimized. If the optimization method is not clearly documented the likelihood of disagreement between the two test systems increases. To ensure interoperability, the optimization scheme that best emulates the behavior of actual system receivers is likely the best candidate. Since equalizing receivers often employ sophisticated and proprietary digital signal processing, it will be difficult to always emulate real receiver behavior. Therefore, the reference receiver needs to be defined for the worst case allowed receiver which means that it should always be less powerful (limited FFE taps only) than a real receiver implementation. We studied the influence of the number of FFE taps on the TDEC performance. From Figure 3b it can be observed that reducing the FFE taps to 7 has negligible impact on the TDEC value for the transmitters we tested but will improve interoperability in the US via selection of ONU transmitters with a bit more margin to accommodate BM related effects.

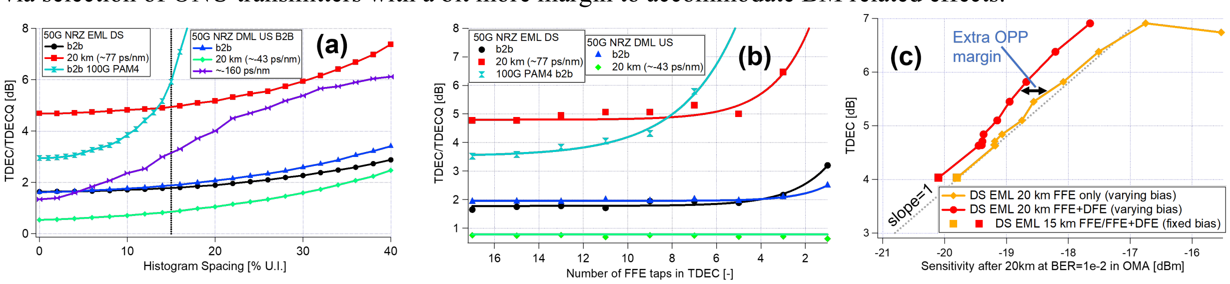

Figure 3: (a) TDEC(Q) values as function of histogram position and (b) number of FFE taps. (c) Correlation TDEC- receiver sensitivity.

Figure 3c also shows the correlation between TDEC and obtained OMA sensitivity at BER=1e-2 after 15 and 20 km of worst-case fiber obtained using a real-time system for 50G PON [7]. Good correlation between TDEC and sensitivity has been obtained using a real-time FFE-based equalizer only. By enabling a more powerful equalizer at the receiver for the real system (FFE+DFE instead of FFE only) it can be observed that for the same TDEC values the sensitivity after fiber can be improved upon. This will result in a lower optical path penalty (OPP) after 20 km of fiber for the real system FFE+DFE based equalizer. Since the minimum launch power in the standard needs to overcome worst-case OPP and is specified in OMA-TDEC this will provide extra margin for reliable operation in the field over 0-20 km. Also, it can be noted that for very large TDEC values >6 dB it no longer correlates well with the measured sensitivity, hence a maximum TDEC of 5 dB with max OPP=3.5 dB was adopted for DS in the 50G PON standard.

4. Conclusions

We have experimentally evaluated TDEC for symmetrical 50G and TDECQ for 100G PAM4 downstream PONs. Good reproducibility and correlation between TDEC and various penalties from representative transmitters as well as real-time BER performance has been observed for 50G PON which will ensure interoperability in the field. As expected, for PAM4 higher TDECQ values at SER=1e-2 were found for the same transmitters due to non-linearities.

5. References

[1] Draft Recommendation ITU-T G.9804.3, “50-Gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification Amendment 1”,2022 https://www.itu.int/rec/T-REC-G.9804.3/
[2] G. Simon, et al., “Experimental Analysis of TDEC for Higher Speed PON Including Linear Equalization”, ECOC 2022
[3] IEEE P802.3bm-2015: IEEE Standard for Ethernet - Amendment 3: Physical Layer Specifications and Management Parameters for 40 Gb/s and 100 Gb/s Operation over Fiber Optic Cable
[4] IEEE P802.3bs (TM)/D2.0: Draft Standard for Ethernet Amendment: Media Access Control Parameters, Physical Layers and Management Parameters for 200 Gb/s and 400 Gb/s
[5] 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.
[6] 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.
[7] V. Houtsma and D. van Veen, “A real-time 25-50-100G Flex-Rate PON Implementation”, in ECOC 2022 Tu4C.2