Analysis of TDEC Pattern Dependency for 50G-PON Optical Transmitter Characterization

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***Abstract*—The Transmitter Dispersion Eye closure (TDEC) can evaluate the quality of an optical transmitter. Initially introduced by the IEEE and later adapted by the ITU-T, TDEC is an economical experimental technique based on eye diagram characterization, using standard optical receiver. For TDEC compliance with the 50G-PON ITU-T recommendation, it is mandatory to use the reference transmitted bit pattern sequence called "Short Stressed Pattern Random" (SSPR). The SSPR pattern test may be difficult to implement for telecommunications operators, because they generally cannot connect an optical transmitter to transmission equipment that generates a specific sequence. In this Letter, we thus analyze the TDEC dependency on the transmitted bit pattern sequences, by means of experimental demonstrations and simulations (to emulate two other different transmitters), in order to identify which bit pattern sequences may be used to better approximate the correct TDEC. In the experimental case, for every sequence under test, we present the corresponding estimated TDEC value and its statistical analysis over 10 acquisitions. Finally, we explore the clock recovery impact on the TDEC.**

***Index Terms*—Passive Optical Networks, 50G-PON, TDEC, FTTH, SSPR, Clock Recovery**

I. Introduction

THE capacity of optical access network steadily increases over the years. In September 2021, the International Telecommunication Union - Telecommunication (ITU-T) has released the 50G-PON standard, fixing the downstream transmission of the passive optical network (PON) at 50 Gbit/s [1]. To be compliant, a 50G-PON optical transmitter must meet the specified transmission quality, expressed in terms of TDEC (Transmitter Dispersion Eye Closure), a parameter that was never used before for PON standards. TDEC evaluates the quality of a Device Under Test (DUT) optical transmitter in terms of optical sensitivity penalty with respect to a reference ideal one. Since TDEC technique is based on measurements using standard PIN optical receiver and oscilloscope, it is lower cost and very quick to be implemented when compared to other techniques employing real reference optical transmitter or real reference optical receiver (e.g. Transmitter Dispersion Penalty). Furthermore, the experimental measurements required for TDEC estimation, are simply bitstream acquisitions of 32762 bits, so the TDEC has a low complexity compared to the typical one based on BER (Bit Error Rate) measurements. Focusing on TDEC details, its evaluation is based on the comparison between the amount of noise (with standard deviation σ_G) to be added on the DUT received signal, and the amount of noise (with standard deviation σ_{ideal}), when using an ideal virtual transmitter, to reach in both cases, the reference BER target of 10^{-2}. The BER target is obtained adding noise at eye diagram (measured at the optical receiver output in presence of DUT transmitter, optical fiber and custom electrical filtering after PIN detection), for an iterative evaluation of σ_G and by analytical formula for the evaluation of σ_{ideal}. In the TDEC algorithm, the noise is virtually added to the DUT signal in two different time windows within the UI (unit interval) eye diagram: σ_L for 0.4 UI and σ_R for 0.6 UI, selecting for σ_G the smaller one, $\sigma_G = min(\sigma_L, \sigma_R)$. Fig. 1 visually depicts these parameters,

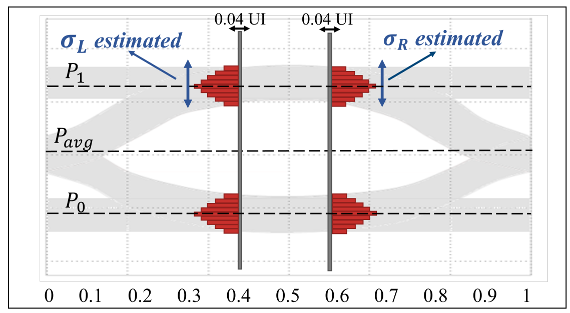

Fig. 1. Eye-diagram at the receiver normalized on the Unit Interval (UI) with the main parameters appearing in the TDEC evaluation. σ_L represents the noise added to the signal under test to achieve a BER of 10^{-2} at $0.4UI$, while σ_R also achieves a BER of 10^{-2} but at $0.6UI$.

which are used in the following equation:

$$TDEC = 10 \cdot log\left(\frac{\sigma_{ideal}}{\sigma_G}\right). \quad (1)$$

We briefly remind that $TDEC = 0dB$ represents an ideal DUT transmitter while higher TDEC values indicate worst performances. Together with other specifications for the optical transmitter, the 50G-PON standard accepts a maximum value of 5 dB. The IEEE [2] initially introduced the definition of TDEC through Eq. 1. Subsequently, the ITU-T adopted this method for the 50 Gbps PON system, incorporating three main variations in its implementation. First, the ITU-T TDEC equation for PONs considers also the asymmetric noise factor denoted as 'm' when using Avalanche Photo Detector (APD) receivers, very common in access networks to achieve higher power budgets. Previous studies [3] showed how to correctly set this 'm' parameter and how to implement the equalization technique to compensate the bandwidth limitations introduced in real opto-electronic components. Secondly, ITU-T standardizes the electronic reference equalizer to be used for 50G-PON, introducing the noise enhancement factor of the equalizer, C_{eq}, proportional to the noise spectrum filtered by the equalizer. Third, the ITU-T 50G-PON selects two time windows that are

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close but different from the IEEE: 0.425 UI for σ_L evaluation and 0.575 UI for σ_R evaluation. Considering it, the TDEC can be evaluated as:

$$TDEC = 10 \cdot log\left(\frac{\sigma_{ideal}(m)}{\sigma_G(m)}\right) + 10 \cdot log(C_{eq}). \quad (2)$$

where also in this case, $\sigma_{G(m)} = min(\sigma_{L(m)}, \sigma_{R(m)})$.
This $TDEC$ is evaluated for different fiber lengths from 0 to 20 km, and then the highest one (corresponding to the worst case of TDEC) is selected. To correctly evaluate TDEC in the 50G-PON scenario, the standard emphasizes the use of a well-defined bit sequence known as SSPR (Short Stressed Pattern Random) [4], for testing the quality of an optical transmitter. In this paper, we analyze the TDEC dependency (implemented considering [7]) on the transmitted bit pattern sequences emitted by three different transceivers, two through simulations and one physically, showing, in Section II, the setup used. In Section III we present the results obtained and their discussion exploring also the clock recovery impact on the TDEC. Finally we show the conclusions in Section IV.

II. Analysis of TDEC dependency versus Test Pattern Bit Sequences: Setup

The SSPR is the reference test pattern recommended by ITU-T [1] for 50G-PON TDEC evaluation. It has a length of 32762 bits, or another version extended to 32768 bits (2^{15}) for test equipment restrictions [4]. Considering this latter case, the SSPR described in [4], is based on concatenation of eight different blocks. The first SSPR block, composed by 5437 bits, is a specific subset of $PRBS_{28}$ with seeds ”0080080”. The second SSPR block, called CID, is composed by bit ”1” followed by 72 bits ”0” corresponding to overall 73 bits. The third SSPR block, composed by 5437 bits, is a specific subset of $PRBS_{28}$ with seeds ”$FFFFFFF$”. The fourth SSPR block composed by 5437 bits, is generated by SSPR block 1 performing differential encoding. Finally, SSPR blocks 5 to 8 are the inverse of blocks 1 to 4 respectively, for a SSPR overall length of 3768 bits.

To estimate the average power level, the algorithm for TDEC evaluation uses the measured transmitted signal samples corresponding to the SSPR block 2 (i. e. 72 consecutive ”0”), estimating P_0, and then those corresponding to the SSPR block 6 (with inside 72 consecutive ”1”), to estimate the average power level P_1. Both standard deviations σ_G and σ_{ideal} used in eq. 2 for TDEC computing, are very sensitive to their average, P_{avg}, so both power levels have to be estimated very carefully. The pattern bit sequence affects P_0 and P_1 estimation, so it may affect also TDEC. Indeed ITU-T recommends the SSPR pattern test, and for accurate P_0 and P_1 evaluations, keep in account only samples referred to the 50 central bits over the available 72 equal ones present in the SSPR blocks 2 and 6.
In the following Section, we study the variation in terms of TDEC when different transmitted binary sequences are used. They include the reference SSPR, which is compared with typical Pseudo-Random Binary Sequences (PRBSs) commonly used in telecommunications, as well as different hybrid versions combining elements of both, e.g. PRBS which includes long sequence of consecutive ‘1’ and consecutive ‘0’ respectively. Furthermore, we evaluate the TDEC for a completely unknown sequence generated directly from a commercial Optical Line Terminal (OLT), which represents the simpler case for a telecom operator. In all these cases, when the sequences’ length is shorter than the SSPR’s length of 32768 bits, we repeat the sequence until it reaches this 32768-bit length. For OMA evaluation, we average the central 70% of bits within the longest sequences of consecutive ’0’ and ’1’ bits. This approach is consistent with the ITU-T standard, which uses the central 50 bits within a sequence of 72 consecutive bits [1].

A. Simulation set-up

This subsection describes the implementation of two different simulated transceivers for the TDEC evaluation when employing several different transmitted binary sequences. The simulations have been performed using the follow test patterns:

- 6 PRBSs with different order: 5, 7, 9, 11, 13 and 15.
- SSPR: we use this sequence as a benchmark.
- SSPR “no-72”: we consider the standard sequence, changing only the SSPR blocks 2 and 6 as follow: we substitute the 72 ‘0’ bits (in block 2) and the 72 ’1’ bits (in block 6) with random sequences of 72 bits, both with the same amount of ‘1’ and ‘0’.

Then, we simulate the transmission as follow. The transmitter is a distributed feedback laser (DFB) modulated by a Mach-Zehnder modulator (MZM). The transmitted power is 10 dBm, the ER (Extinction Ratio) is 8 dB and the bit rate (Rb) is 50 Gbit/s. In order to emulate two different optical modulators (producing two different transmitted signals), we use two different electrical low-pass filters producing different effects in terms of symbol shaping and Inter-Symbol Interference (ISI). The first one is a order 3 SuperGaussian (SG) filter with 19 GHz bandwidth, while the second one, is a order 4 Bessel filter with 14 GHz bandwidth. The optical transmitters parameters have been chosen in order to be realistic and targeting reasonable TDECs between 0 and 5 dB. The transmission wavelength is 1342 nm to emulate 50G-PON transmitter in O-band so we set the fiber attenuation to 0.35 dB/km and the dispersion to 3 ps/nmKm. We evaluate the $TDEC$ values versus optical fiber length between 0 km to 20 km, for identifying the $TDEC$ worst case [1]. In our cases, for both simulated optical transmitters, worst $TDEC$ value corresponds to a fiber length of 20 km as shown in the Fig. 2. We simulate the use of PIN receiver, so according to the ITU-T standard, we fix to 1 the asymmetric noise factor ‘m’ used for TDEC evaluation.

B. Experimental set-up

This Subsection describes the experimental set-up for the TDEC evaluation using the following experimental bit sequences:

- 2 PRBSs with different order: 11 and 15.
- SSPR sequence as reference.
- SSPR “no-72” (as in the simulation case).
- Real unknown sequence: the data comes from a real commercial OLT.

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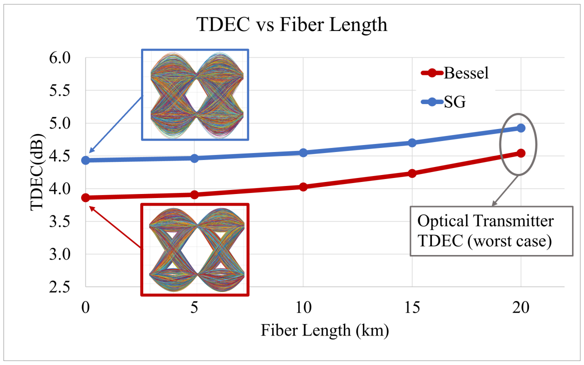

Fig. 2. $TDEC$ vs fiber length for two simulated optical transmitters, emulated by different electrical filtering: 4 order Bessel of 14 GHz's bandwidth, in red, and 3 order SuperGaussian (SG) at 19 GHz, in blue, using SSPR pattern test in both cases.

- $PRBS_{15}$ with CID 72: it is a $PRBS_{15}$ including 72 consecutive '1' and 72 consecutive '0' bits respectively.

The transmitter is a 50G-PON Transceiver prototype, based on a distributed feedback laser (DFB) at 1342 nm, and an Electro-absorption modulator (EAM) with ER of 5 dB. The setup fixes the constant power before the PIN receiver inside the oscilloscope, while the bit rate is 49.7664 Gbit/s according to the ITU-T standard. We perform experimental measurements using five different fiber lengths: 0 km, 10.2 km, 14.6 km, 17.5 km and 20 km. The receiver is a high bandwidth PIN photodector and we use a 200 GSamples/s real time oscilloscope for bit-stream acquisitions (4 samples/bit). For each sequence, we collect 10 different acquisitions and we estimate the final value as the average between them. In the next Section we also present experimental results about the clock recovery (which we implemented in DSP) impact on TDEC.

III. Results and Discussion

This section shows the TDEC results obtained with the setups explained in the previous section.

A. Simulation results

We simulated two different optical transmitters by means of different electrical filtering at the transmitter side.

1) Order 3 SG filter with 19 GHz bandwidth: Fig. 3 illustrates the Optical Transmitter TDEC for various bit sequences evaluated at 20 Km, corresponding to the worst $TDEC$ value versus fiber length. In horizontal axes is present the PRBS order. Highest TDEC value is observed for the SSPR sequence, corresponding to the benchmark. Following that, the TDEC improves for the "SSPR no-72" (SSPR excluding consecutive '1' and consecutive '0'). Best TDEC are obtained with the shortest PRBSs where TDEC values fluctuate versus PRBS order. However, the TDEC comparison between the SSPR and PRBS sequences, is about 0.1 dB for order higher than 5, so approximately the same. As a first important results of our paper, we point out that all the analyzed bit sequences are about equivalent for TDEC evaluation.

2) Order 4 Bessel filter with 14 GHz bandwidth: we repeated the same test using a Bessel filter of order 4 with 14 GHz bandwidth, instead of previous Supergaussian one. In this case, the TDEC values produced by the three sequences

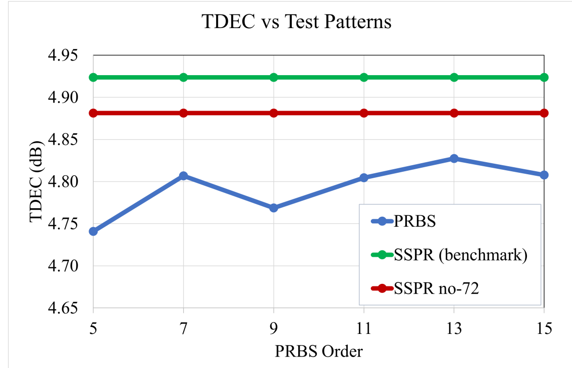

Fig. 3. Simulation TDEC of Optical Transmitter with filtering SG of order 3, 19 GHz bandwidth and 20 km fiber length, when using different sequences: the PRBSs in blue (with relative order in horizontal axes), the SSPR in green and the SSPR without the 72 consecutive '0' and '1' respectively, in red.

(SSPR, SSPR no-72, and PRBS) differ by less than 0.05 dB, except for the PRBS of order 5 (see Fig. 4). These results confirm that the sequences have negligible impact on TDEC, except for order 5 PRBS (composed by 31 bits), which presents a difference of 0.2 dB in terms of TDEC.

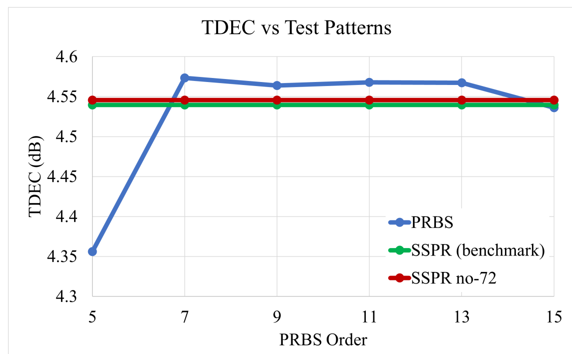

Fig. 4. Simulation TDEC of Optical Transmitter with filtering Bessel of order 4, 14 GHz bandwidth and 20 km fiber length, when using different sequences: the PRBSs in blue (with relative order in horizontal axes), the SSPR in green and the SSPR without the 72 consecutive '0' and '1' respectively, in red.

B. Experimental results

This Section presents TDEC results obtained using the experimental setup described in Section II B, where various bit sequences were transmitted by means of an actual prototype 50G-PON transceiver. Fig. 5 provides a summary of these results, also indicating the dependence on fiber lengths. The $TDEC$ values are again the average on 10 acquisitions, and each measurement point shows a standard deviation less than 0.1 dB, except for the random sequence taken directly from an Optical Line Terminal (OLT), which exhibits a slightly larger standard deviation of 0.2 dB.

Similar to the simulation cases, the $TDEC$ shows an increase with the length of the fiber, reaching its worst case in the range of 17.5 to 20 km, corresponding to the final TDEC of the DUT 50G-PON Optical transmitter. In this instance, the SSPR sequence (benchmark) yields the best TDEC, while the PRBSs result in higher values. The worst case is observed with a completely unknown sequence, very close also to the PRBS 11 case.

In the experimental characterization, the variations are more pronounced than in the simulation analysis: the Optical Transmitter TDEC range from 2.1 dB (achieved with the SSPR at 17.5 km) to 2.5 dB (using the unknown sequence sourced from an Optical Line Terminal at 17.5 km). We point out that, a real random sequence acquired from an OLT, the typical case for telecom operators, results in a 0.4 dB over estimation with respect to the TDEC benchmark using SSPR. In contrast, the use of a high-order PRBS (e.g., 15) differs only by 0.2 dB from the benchmark, suggesting an almost equivalence between SSPR and PRBS 15 in TDEC characterizations.

We also investigated the TDEC dependency on clock recovery

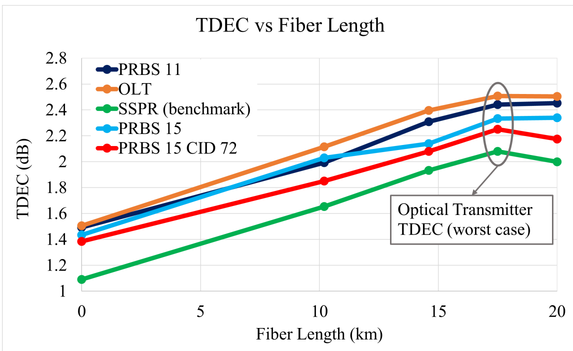

Fig. 5. Experimental $TDEC$ values for different fiber lengths and bit sequences, with clock recovery at the receiver side. Each $TDEC$ value results are averaged over 10 acquisitions.

by implementing two different sampling methods, 'Clk Rec A' and 'Clk Rec B'. In the first method, 'Clk Rec A,' the spectral line method [5] [6] is used to find a fixed baud rate, which is then used to upsample the entire signal. In the second method, 'Clk Rec B,' the same initial baud rate is modified using a Phase-Locked Loop (PLL) [6] to adjust the phase shifts.

Fig. 6 illustrates the variations in $TDEC$ on the same signal with these two procedures. All the results are achieved using the 50G-PON optical transceiver and the same set of fiber lengths as used before. The comparison is performed for two different sequences: the SSPR and the unknown from a real OLT. Fig. 6 shows a TDEC difference (comparing 'Clk rec A' and 'Clk rec B') of 0.2 dB for both bit sequences, corresponding to the worst-case scenario at 17.5 km. The resulting standard deviations with the 'Clk rec B' are the same as the previous measurements (maximum 0.1 dB for the SSPR and 0.2 dB for the OLT) while, with 'Clk Rec A', the standard deviations remain approximately constant for the SSPR slightly above 0.1 dB and increase to 0.3 dB for the OLT. We point out that, if the phase adjustment is nor performed, the penalty on TDEC is limited to 0.2 dB. Indeed, in ITU-T compliant transmitter, the jitter impact is quite limited on the 32768 bits sequence to be used for TDEC evaluation.

IV. Conclusions

In this Letter, we studied the test pattern impact on TDEC for 50G-PON optical transmitter, by means of simulations and experimental demonstrations. We tested several test patterns: standard SSPR, several PRBSs with different orders, hybrid sequences and unknown sequences, versus different fiber lengths. The simulations about test pattern impact, showed a

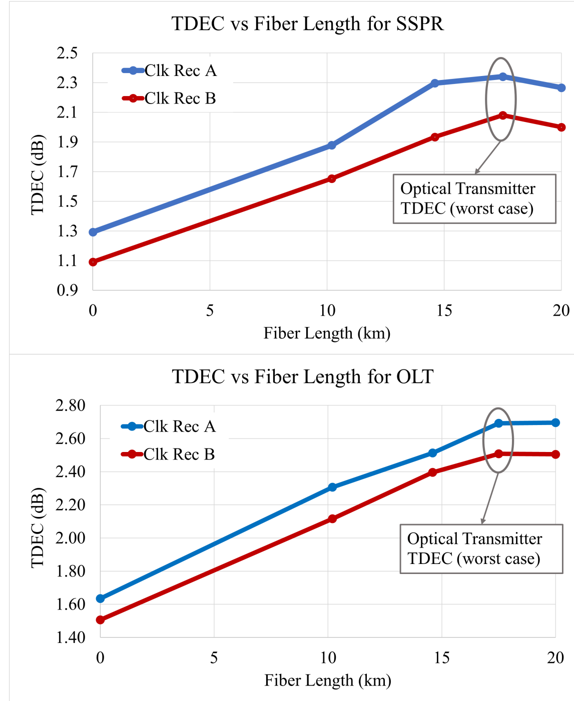

Fig. 6. Comparison between $TDEC$ values obtained with 'Clk Rec A' (blue curves) and 'Clk Rec B' (red curves)
. On the top, the case using the SSPR, on the bottom, the one using random sequence taken from an OLT.

maximum TDEC deviation of 0.13 dB with respect to SSPR reference sequence, excluding PRBS of order 5, too short for a correct TDEC evaluation. In the experimental cases, the TDEC is over estimated of 0.4 dB and 0.2 dB for OLT random traffic and PRBS order 15 respectively. In conclusion, PRBS order 15 is very close to SSPR for all simulations and experimental cases. OLT real traffic, may be used for TDEC evaluation, but accepting an overestimation of 0.4 dB.

Finally, we have experimentally demonstrated that the clock recovery impact on TDEC is limited to 0.2 dB.

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