Accurate Beyond-400G Transmitter Quality Metric Based on Transmitter Constellation Closure Measurement

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Abstract: We demonstrate the use of transmitter constellation closure (TCC) for accurate quality assessment of beyond-400G coherent transmitters, and show its tolerance to inter-symbol interference and phase noise with and without probability constellation shaping (PCS).

1. Introduction

EVM is one of the most widely adopted metrics in characterizing the quality of constellations [1]. EVM has been considered convenient in practical measurements where direct counting of error bits is infeasible at low bit error rate (BER) thresholds. Specifically, the number of transmitted bits to ensure the convergence of BER measurements exceeded the buffer capacity of real-time digital oscilloscope (DSO). It is known that EVM was found to be unreliable in characterizing optical signal noise ratio (SNR) penalty at the presence non-additive white Gaussian noise (AWGN), such as inter-symbol-interference (ISI) due to transmitter band limitations, IQ skew/imbalance, laser phase noise, and so forth. Those non-AWGN imperfections impose practical limitations on high-speed coherent transmitter for current 400G generation and beyond. In the absence of better metrics, defining suitable metrics for specifying the transmitter quality is being considered as one of the highest priorities in recent standards activities to progress with the specification of 400G and Beyond 400G DWDM systems [2].

In ITU-T Q6/15 July meeting [3], the conceptual basics of Transmitter Constellation Closure (TCC) for accurate assessment of the qualities of B400G coherent transmitters was introduced, in a similar way as transmitter eye closure (TEC), transmitter and dispersion eye closure (TDEC) [1,4], and transmitter and dispersion eye closure for quaternary-PAM (TDECQ) [5] are for intensity-modulation transmitters. In this paper, we further develop the TCC procedures with more details along with numerical simulations, showing that the TCC-based transmitter quality metric is more accurate than the EVM-based metric when inter-symbol interference (ISI) due to transmitter bandwidth limitation and laser phase noise are present. In addition, we quantify the number of signal symbols needed to achieve accurate transmitter quality measurement for unshaped dual-polarization 16-QAM (DP-16QAM) and shaped DP-16QAM with probability constellation shaping (PCS).

2. EVM-based transmitter specification and its limitation

With the assumption of an additive white Gaussian noise (AWGN) channel, the EVM of a *M*-QAM signal is related to its BER as [1]:

$$\mathrm{EVM}(\mathrm{BER}) = \sqrt{\frac{3}{2(M-1)}}\,\mathrm{erfc}^{-1}\left(\frac{\log_2(M)\mathrm{BER}}{2(1-M^{-1/2})}\right)^{-1} \tag{1}$$

since SNR=1/EVM^2, the SNR degradation of a transmitter can be expressed as:

$$\Delta\mathrm{SNR}_{\mathrm{TX}}(\mathrm{dB}) = 10\log_{10}\left(\frac{\mathrm{EVM}(\mathrm{BER}_{\mathrm{th}})^2}{\mathrm{EVM}(\mathrm{BER}_{\mathrm{th}})^2 - \mathrm{EVM}_{\mathrm{TM}}{}^2}\right) \tag{2}$$

where BER_{th} is the target BER threshold (e.g., 1E-2) and EVM_{TX} is the measured EVM of the transmitter alone. This transmitter quality metric based on EVM is only accurate when the transmitter degradation is from AWGN. In real-world coherent transmitters, degradations from ISI and laser phase noise are not AWGN. There have been studies on extending EVM to fit a variety of transmission distortions case by case [6], regardless of its challenges in reflecting genuine BER performance, such extensions to EVM remain alternative “masking” tools to aid characterizations of individual distortion (e.g., IQ skew). Considering that the penalties from individual non-AWGN imperfections could be combined in a sophisticated way, coherent transmitters need to be assessed by a better transmitter quality metric that can accurately reflect its SNR-BER performance to foster link budget allocation.

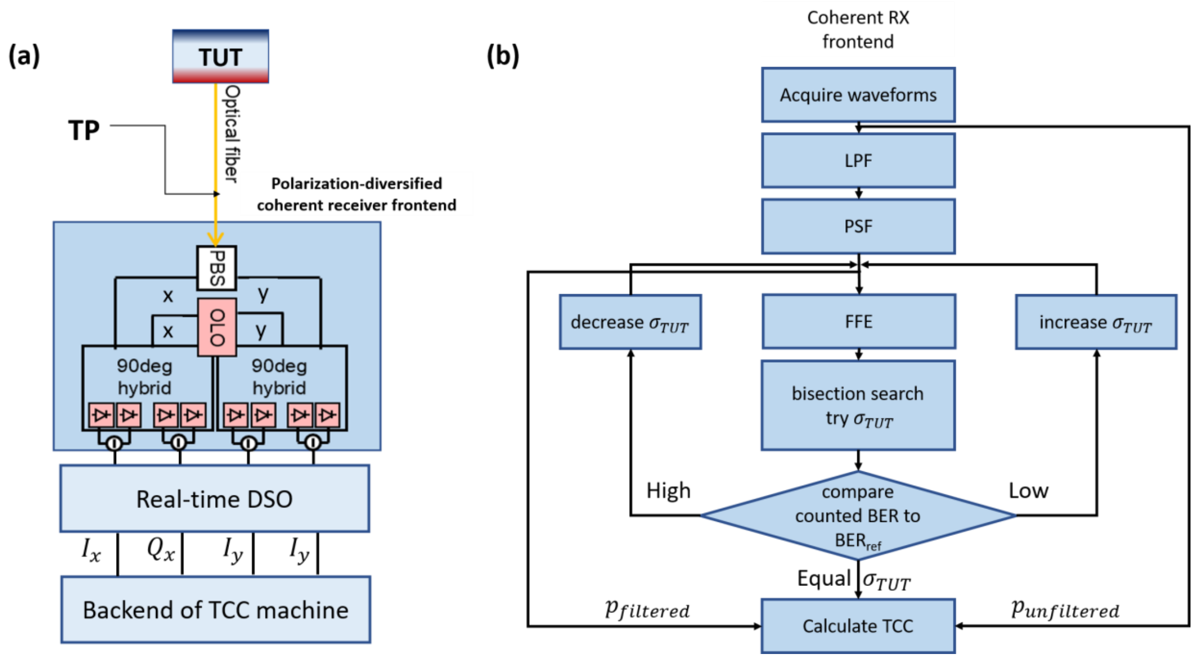

Fig. 1. TCC scheme. (a) A reference optical coherent frontend of TCC machine acquires the signal sent from transmitter under test (TUT) at test point (TP). DSO: digital oscilloscope. (b) flowchart of the TCC machine backend. Constellations are recovered by reference DSP, where a noise search loop is conducted to measure the noise tolerance to reach target BER_{th}, along with power adjustment, giving rise to TCC result.

2. The Transmitter Constellation Closure (TCC) Metric

TDECQ developed for IMDD systems consists of a list of procedures to assess the transmitter quality in terms of SNR degradation of transmitter [5]. For B400G coherent transmission systems, the signal to qualify are constellation symbols, so we introduce the TCC metric, following the methodology of TDECQ. Since chromatic dispersion is compensated in the digital coherent receiver, there is no need to measure the dispersion penalty. Note that in B400G optical transmission, the system is operating with a BER_{th} of 1E-2 or higher, which allows us to measure BER directly by transmitting a reasonable number of symbols and counting the errors at a reference receiver.

The TCC scheme consists of the following five procedural steps as shown in Fig. 1:

1. A coherent receiver frontend and a real-time sampling oscilloscope to acquire *Ix*, *Qx*, *Iy*, *Qy* waveforms.
2. A reference coherent receiver digital signal processor (DSP) is used to recover the constellation of the coherent signal (at one sample per symbol), the reference DSP includes
   a) a low-pass filter (LPF) to emulate the expected bandwidth limitation of the coherent receiver frontend. The LPF can be a Gaussian filter with a 3-dB bandwidth of Bd/2, where Bd is the symbol rate of the signal.
   b) a predetermined pulse-shaping filter (PSF), e.g., a root-raised-cosine (RRC) filter with a roll-off of 0.1, to perform matched filtering.
   c) a reference equalizer, e.g., a 13-tap T/2-spaced feed-forward equalizer (FFE).
3. A numerical bisection search to find the power of the AWGN σ_{TUT}^2 (measured after the PSF) that can be added to the received signal to achieve a given BER_{ref}.
4. The ratio between $\sigma_{TUT}^2 + \sigma_s^2$ (frontend noise variance) and σ_{ideal}^2 (ideal noise tolerance) together with the ratio between the unfiltered signal power ($p_{unfiltered}$) and the signal power after the LPF and the PSF ($p_{filtered}$), is then used to calculate the TCC penalty due to the imperfections of the TUT as follows:

$$TCC(dB) = 10\log_{10}\left(\frac{\sigma_{ideal}^2}{\sigma_{TUT}^2 + \sigma_s^2}\right) + 10\log_{10}\left(\frac{p_{unfiltered}}{p_{filtered}}\right) \quad (3)$$

To show the advantages of the TCC metric over the EVM metric, we conduct extensive simulations using simulation cases summarized in Fig 2 (a). Fig 2 (b) shows dependence of the received raw BER on the received optical signal-to-noise ratio (OSNR) for each of the four cases using the EVM and TCC metrics. For the ideal transmitter case, both the EVM and TCC metrics give the same results, as expected. When the DAC bandwidth limitation induced ISI is present, both the EVM and TCC metrics capture the transmitter quality degradation, but the

(a)

Case	DAC bandwidth	DAC resolution	Residual laser noise	Improvement over EVM by TCC
Ideal	Infinity	15 bit	0	0 dB
1	67 GHz	4 bit	0	0.15 dB
2	55 GHz	4 bit	0	0.39 dB
3	55 GHz	4 bit	3 kHz (equivalent laser linewidth)	0.52 dB

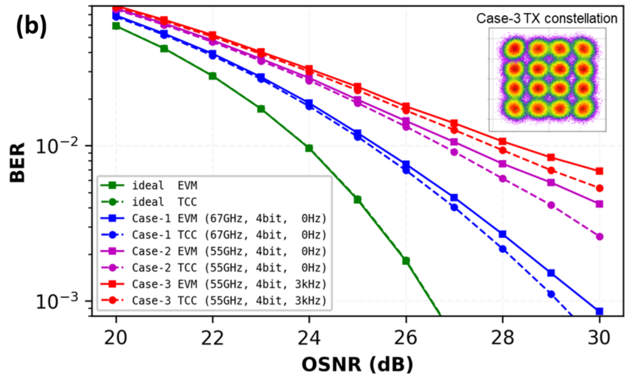

Fig. 2. Simulation setup: 125GBaud, up shaped DP-16QAM, PCS: 4, 3.5, or 3 bits/symbol, 0 roll-off RC, ideal reference receiver, over 1 million symbols measured for each case, BERth=1E-2. (a) simulation cases (b) BER versus OSNR for the four cases measured by the EVM and TCC metrics.

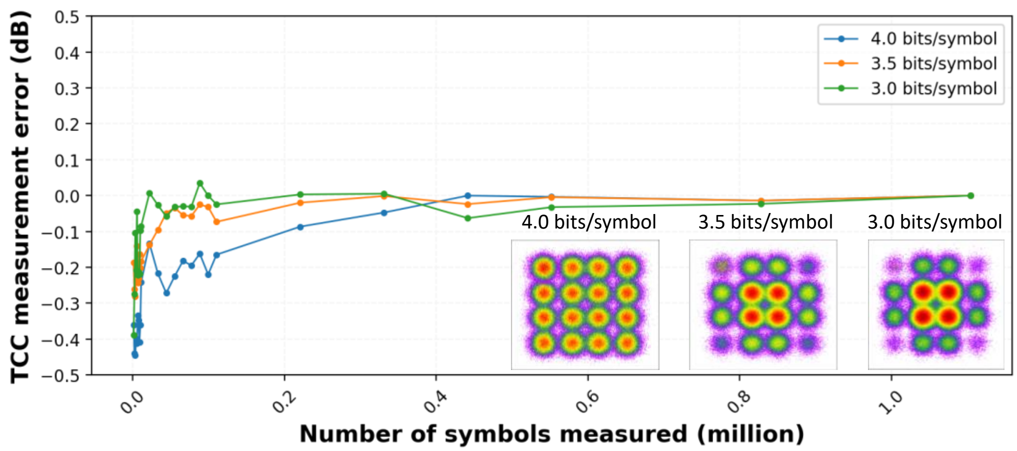

Fig. 3. TCC measurement error at BERth=1E-2 for DP-16QAM and PCS-shaped DP-16QAM.

EVM metric underestimates the performance. When the residual laser phase noise after the receiver-side phase recovery is further introduced, both the EVM and TCC metrics also capture the transmitter quality degradation, and the EVM metric still underestimates the performance. Evidently, the TCC metric provides better transmitter quality assessment accuracy than the EVM metric when the ISI is present. When both ISI and residual laser phase noise are present, the TCC metric can provide an assessment improvement of over 0.5 dB, which is quite significant in modern coherent transmission systems.

Fig. 3 shows the TCC measurement error at BER_{th}=1E-2 for DP-16QAM (4 bits/symbol) and PCS-shaped DP-16QAM with 3.5 bits/symbol and 3 bits/symbol. At BER_{th}=1E-2, about 3E5 total measured symbols, or about 2E4 symbols per constellation point on average, are required for TCC to converge to within ±0.1 dB. This is readily achievable in modern real-time sampling scopes.

4. Conclusion

We have numerically shown that the Transmitter Constellation Closure (TCC) metric is accurate in assessing the coherent transmitters based on DP-16QAM and PCS-shaped DP-16QAM. In addition, it follows the similar methodology as TDECQ with direct BER counting and can be readily implemented.

5. References

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