BER and TDECQ Correlation for Different Impairments in 400Gbps PAM4 system

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Abstract: Closed-form bit-error rate (BER) expression as a function of transmitter dispersion eye closure quaternary (TDECQ) is derived. Based on a silicon-photonics 400-Gbps PAM4 transceiver, BER and TDECQ correlation is verified for different impairments.

1. Introduction

Optical 4-level pulse amplitude modulation (PAM4) has been prevalently adopted in industry for up to 2-km transmission. To ensure interoperability, the transmitter and receiver must have independently verifiable quality metrics. For the transmitter, the metric is transmitter dispersion eye closure quaternary (TDECQ) [1] and can be calculated based on the transmit optical eye diagram. As a key metric to measure the quality of a PAM4 transmitter, TDECQ delivers well-accepted system level transmitter compliance specifications in IEEE 802.3 [2] and MSA 400Gbps FR4 [3]. For the receiver, the metric is based on bit-error rate (BER) assuming an appropriately stressed transmitter. While TDECQ plays a leading role in assessing transmitter quality in industry [4,5], limited efforts [6] have been made to explore the link between TDECQ and BER.

This paper presents a closed-form expression for BER as a function of TDECQ, so that an explicit correlation is established between ultimate system performance and easily accessed metrics. The experimental verifications are based on a silicon-photonics and silicon-germanium 4×100-Gbps PAM4 optical engine that meets IEEE DR4 specifications. Under different system impairments such as additive white Gaussian noise (AWGN), inter-symbol interference (ISI) and modulator/driver nonlinearity (MOD-NL), good agreement is shown between theoretical predictions and experimental measurements. The accuracy and limitations are discussed.

2. BER-TDECQ Correlation

The physical meaning of TDECQ is how much extra noise can be added to a transmit signal before reaching the FEC limit, assuming an ideal receiver. $TDECQ = Q_V/Q_T$, where Q_T is the Q-factor for a $BER\ of\ 2.4 \times 10^{-4}$ (KP4 FEC limit) and equals 3.414; and Q_V is a “visual Q-factor” and is equal to $OMA_{outer}/(6 \cdot \sigma_V)$. Q_V is determined by the outer optical modulation amplitude (OMA_{out}) and the extra Gaussian noise strength σ_V. A higher Q_V means less σ_V can be added, indicating a worse system performance. A perfect transmitter has TDECQ = 0 dB.

Assuming white Gaussian noise and an ideal receiver, a PAM4 $BER = 3/8 \cdot erfc\ (Q_R/\sqrt{2})$, where Q_R is the system “real” Q factor. We can write $Q_R = \sqrt{1/Q_T^2 - 1/Q_V^2}$. Thus BER can be linked to TDECQ as

$$BER = \frac{3}{8} erfc\left(\frac{Q_T}{\sqrt{2}} \cdot \sqrt{\frac{TDECQ^2}{TDECQ^2-1}}\right) \tag{1}$$

Note Eq. (1) is supposed to be used to only evaluate Tx performance, since TDECQ is a Tx performance indicator.

A perfect Tx has a $TDECQ = 1\ (0dB)$, giving $BER = 0$; a poor Tx has a $TDECQ = inf$, giving $BER = 2.4 \times 10^{-4}$.

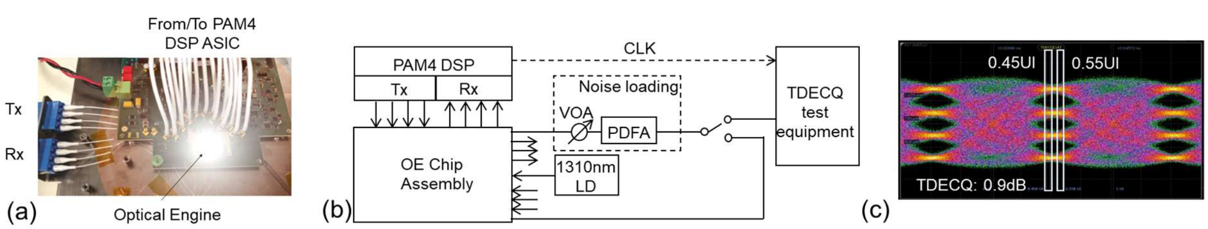

Fig. 1 4×100Gbps PSM4 system based on OE assembly. (a) Silicon photonics optical engine on an evaluation board; (b) TDECQ/BER measurement system; (c) 5-tap equalized eye diagram with TDECQ measurement. LD: 1aser diode; OE: optical engine; PDFA: praseodymium-doped fiber amplifier; VOA: variable optical attenuator

3. Experimental Verification

3.1. System Setup

A 4×100-Gbps parallel single mode (PSM4) system based on a silicon-photonics and silicon-germanium optical engine (OE) assembly on an evaluation board was used. The OE consists of a driver die and a transimpedance amplifier (TIA) die flip-chipped on a silicon-photonics integrated circuit (PIC). The transmitter and receiver are on a single PIC die, using a similar technology as [7]. It has one fiber connection for a single 50-mW 1310nm laser that is split four ways inside the PIC, four fiber connections for the transmitter output, and four fiber connections for the receiver input. The OE is wire-bonded to a printed circuit board as shown in Fig. 1(a). As shown in Fig. 1(b), a PAM4 DSP line-side Tx operating at 53 Gbaud with Gray coding is connected to the OE assembly. One of 4 Tx channels is optionally connected to an AWGN loading module based on a praseodymium-doped fiber amplifier (PDFA) to emulate noise impairment. The optical path is either routed to a TDECQ test equipment or looped back to the OE Rx to detect BER.

The TDECQ measurement is compliant to IEEE 802.3bs [2] with a 5-tap equalizer. The eye diagram is sampled at two vertical histograms centered at 0.45UI and 0.55UI; each histogram window has a width of 0.04UI, as shown in Fig. 1(c). Note that the histogram position and width affect TDECQ value significantly for an extreme bandwidth-limited or high-jitter case.

3.2. AWGN Scenario

The AWGN impairment is induced by changing the input power to the PDFA. The PDFA is operating in output-power control mode to maintain a constant OMA, so that the PDFA output can be regarded as a Tx with AWGN level tunability. With different AWGN levels, the measured TDECQ and BER are plotted in Fig. 2(a) and compared with Eq. (1) predictions. Good agreement between the measured and predicted results is observed. With TDECQ less than 4.0 dB, TDECQ accurately reflects BER variation; and for TDECQ beyond 5 dB, TDECQ is overly sensitive to impairments. An appropriate range to use TDECQ to predict BER is from 1.0 dB to 4.0 dB. Note that this is under the assumption that the TDECQ impairment is AWGN. If TDECQ is also impaired by other effects, such as bandwidth limitation, that are not equalized fully by the TDECQ measurement but can be equalized in the receiver, the received BER can be better than the Eq. (1) prediction. For instance, if the transmitter is over-equalized for improved BER, it may exhibit a degraded TDECQ yet improved BER.

3.3. ISI Scenario

The transmitter ISI level is induced by changing PAM4 DSP pre-equalization tap coefficients. The OE transceiver is operating at maximal driver gain with back-to-back (B2B) connection to minimize Rx influences (to get the optimium BER/TDECQ floor). As shown in Fig. 2(b), with TDECQ beyond 1.5dB, the measurement shows good consistency with the theoretical calculation. Similar to the AWGN case, around 1×10^{-4} BER, TDECQ changes dramatically while BER changes little with increasing ISI, so TDECQ shows an "earlier" saturation at 2.4×10^{-4} for performance evaluation. Due to the nature of TDECQ being a metric of "noise margin" and BER being a metric of "real noise", it is understandable that TDECQ has steep slope for high impairment and BER has steep slope for low impairment.

The leftmost measurement point in Fig. 2(b) shows the best TDECQ (~1.0dB) and BER (~1x10^{-7}) the system achieves. The reason why this point is off the prediction is the Rx influence starts to appear. At a TDECQ of 1.0dB, a pure Tx BER of 1×10^{-8} is predicted, showing the high equality of the silicon photonics OE transmitter.

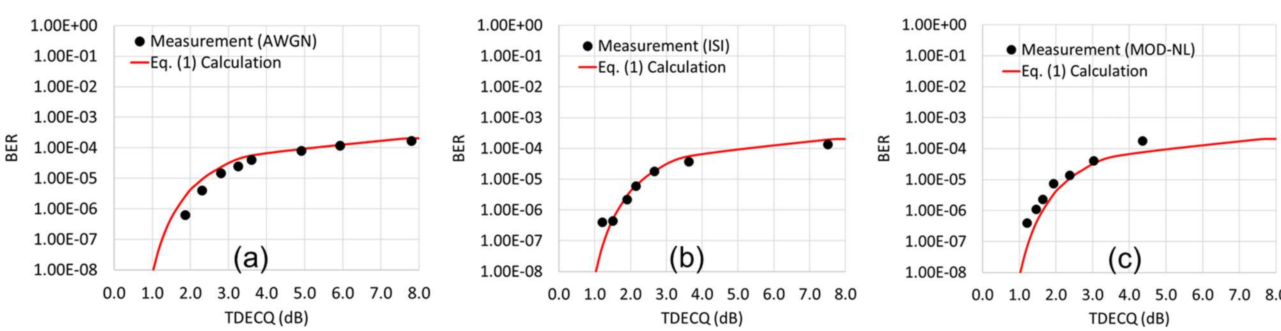

Fig. 2 BER/TDECQ correlations for 3 different impairments. (a) PDFA AWGN scenario; (b) Tx ISI scenario; (c) Modulator nonlinearity scenario

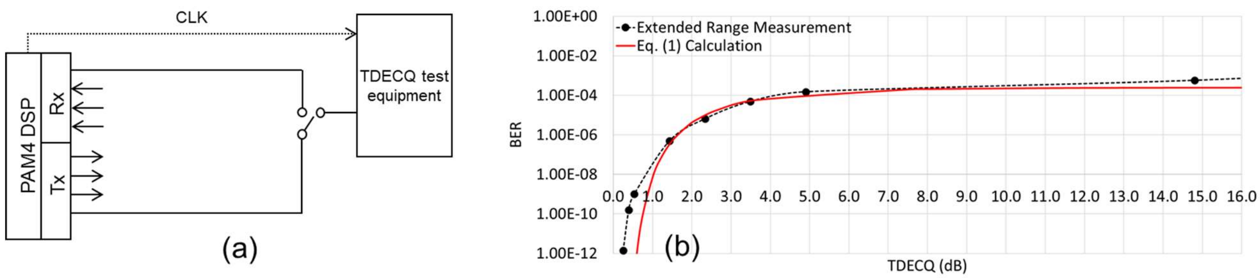

Fig. 3 (a) DSP B2B connection for extended range measurements; (b) Measurements at extreme TDECQ value and comparison with the prediction

The other note for ISI impairment is the noise enhancement factor C_{eq}, which is the ratio of equalizer output noise to its input [2]. In the derivation of Eq. (1), we implicitly assumed the noise enhancement factor of TDECQ is equivalent to that of BER. However, it has been seen that in a significant bandwidth limited case, C_{eq} of TDECQ might be much different from C_{eq} of BER. Based on current investigations, Eq. (1) is applicable providing C_{eq} less than ~1.5dB.

3.4 MOD-NL Scenario

Since Eq. (1) is under Gaussian assumption, it may not be applicable to nonlinear impairments. To study BER-TDECQ correlation with nonlinear impairments, the modulator is biased off the linear modulation point. With increasing of the bias offset, the eye diagram is asymmetrically distorted. In this case, it can be seen from Fig. 2(c) that the theoretical prediction tends to overestimate BER performance. In other words, BER is more vulnerable than TDECQ to the modulator bias deviation. Fitting factors can be considered in Eq. (1) to get better accuracy for nonlinear impairments.

3.5 Extended Range Discussions

It is also meaningful to know the system performance for extreme TDECQ values, i.e. $TDECQ < 1.0dB$ or $TDECQ > 4.0dB$. So an electrical DSP B2B link is set up to explore the extended TDECQ range, as shown in Fig. 3(a); and ISI impairment is added to degrade the performance. With much lower device impairments, measured TDECQ can be down to ~0.2dB and BER can be down to ~$1\text{x}10^{-12}$. From Fig. 3(b), under BER of 1×10^{-9}, TDECQ makes too optimistic predictions since DSP Rx penalty dominates the extreme low BER end. At the extreme high BER end, TDECQ saturation makes BER error at ~1×10^{-4} order.

In conclusion, to evaluate PAM4 system performance, a closed-form correlation has been established between TDECQ and BER. Based on a fully integrated silicon photonics platform, the TDECQ prediction accuracy and the applicable range have been analyzed under three different impairment scenarios. The advantage, integrity and limitation of using TDECQ as a performance indicator are investigated.

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