# TDECQ Sensitivity to Algorithmic Implementation and Noise Characterization

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**Abstract:** We demonstrate that TDECQ is sensitive to algorithmic implementation and to receiver noise. It is inherently challenging to quantify transmitter performance when receiver equalization is estimated computationally. Methods to reduce uncertainty are identified. 

## 1. Introduction

Newer generations of optical direct-detect links are moving towards PAM-4 to increase the throughput over throughput of PAM-2 without doubling bandwidth requirements. A key PAM-2 interoperability metric, the transmitter and dispersion penalty (TDP), required measuring the BER and comparing it against an ideal physical transmitter. Such measurement relied a near-perfect optical transmitter and was both costly and time consuming. Therefore, a simple PAM-2 eye mask became the more popular approach to gauge interoperability: a simpler to implement but less relevant metric. As rates increase, it is becoming increasingly difficult to achieve the low BER levels required for TDP as it requires a near-perfect optical transmitter. Furthermore, the presence of multiple eyes in the PAM-4 eye renders the TDP even less practical. Hence, the transmission and dispersion eye closure quaternary (TDECQ) metric has been standardized in IEEE 802.3cd for indirect measurement of the PAM-4 transmitter's quality [2]. TDECQ measurement does not require TDP's near-perfect transmitter. TDECQ employs the vertical eye closure in the left and right histograms of the samples measured on either side of the eye center. However, qualifying PAM-4 system performance without counting errors comes with its own set of challenges. Some suggestions for the robust application of TDECQ were provided in [1]. The TDECQ standard allows a degree of freedom in the implementation of the TDECQ receiver. Hence, the specific approaches chosen by the designer can lead to over or under optimistic TDECQ values, while maintaining consistent relative trends for various impairments.

Though there have been studies that have investigated TDECQ sensitivity to link impairments, to the best of our knowledge, there is yet to be a study of the TDECQ sensitivity to the specifics of the algorithm. In this paper, we demonstrate the uncertainties in TDECQ measurement due to algorithmic freedom and inaccurate receiver noise.

## 2. Experimental Setup

The reference transmitter of Fig. 1 was used to generate a broad range of transmitter impairments that exist with PAM-4 transmitters and span the allowable ranges in IEEE 802.3cd. Specifically, the transmitter's launch power, extinction ratio (ER) and transition time were varied. Varying the ER and launch power enabled us to span the allowable outer optical modulation amplitude (OMA). Varying the ER and transition time also resulted in an accompanying eye-skew and unequal eyes for certain combinations. Dispersion imposed by single mode fiber at 1310nm is negligible for short fiber lengths. Hence, we restricted our analysis to the back-to-back scenario.

The reference transmitter consisted of a 1310nm DFB laser that was modulated using an EOSpace Lithium Niobate modulator. This was driven by a Tektronix AWG70001A arbitrary waveform generator (AWG) and a SHF807 amplifier. The waveforms were captured using a Tektronix DPO7OE1 optical to electrical (O/E) converter that connected directly to the Tektronix DPO73304D oscilloscope. The pre-compensation plug-in in the AWG was used to generate 25GBaud PAM-4 eyes.

## 3. TDECQ Algorithm

The short stress pattern random quaternary (SSPRQ) PAM-4 pattern was employed. In our implementation of the TDECQ algorithm, the timing-recovered and synchronized signal was used in the Weiner approach to compute initial tap weights for the 5 tap T-spaced equalizer. These tap weights were subsequently optimized to minimize the TDECQ using the interior-point optimization approach. The eye was sampled to generate the left and right histograms and the

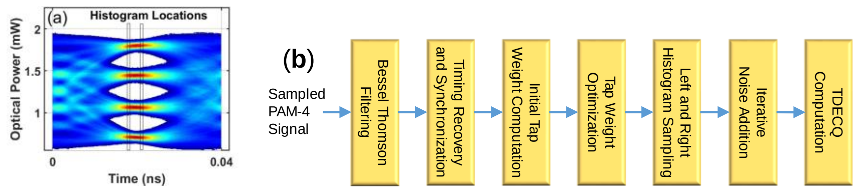


Fig 1. (a) Experimental 25GBaud equalized eye (b) Block diagram of TDECQ algorithm implementation

noise margin to the BER threshold was measured. Finally, the differential noise penalty from an ideal PAM-4 signal having the same outer OMA was computed to generate the TDECQ.

## 3. TDECQ Algorithm Sensitivities

*3.1 Uncertainty in OMA measurement*

Accurate and repeatable outer OMA measurement of PAM-4 signals for TDECQ computation is challenging due to the large number of transitions. The $P_3$ and $P_0$ power levels are measured over the central two unit interval (UI) of a run of 7 threes and 6 zeros, respectively. However, these sub-patterns exist at multiple locations in the SSPRQ pattern, with different locations having different transitions. Therefore, considerable spread in the measured outer OMA is observed, Fig. 3(a). Figure 3(a-c) shows the spread of outer OMA and the associated ER, where it becomes clear that these variations occur due to the specific low frequency link characteristics. One method to reduce the uncertainty is using the longest run of 0s and 3s, which occur only once; or an average of OMA over all specified runs (7 threes and 6 zeros) could be used.

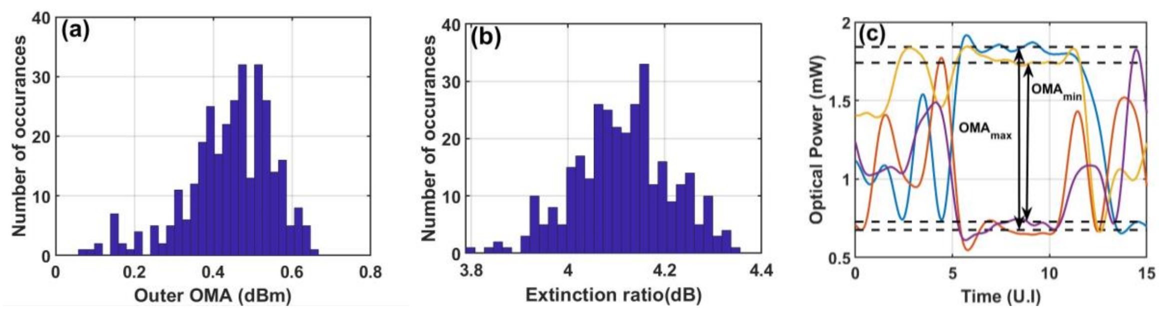


Fig 3. (a) Outer OMA spread (b) Extinction ratio spread (c) sub-patterns for highest and lowest outer OMA

*3.2 Uncertainty in transmitter transition time measurement*

The transmitter transition time is affected by both linear phenomena like dispersion or bandwidth constraints and by the transient response of nonlinear effects. Hence accurate measurement of the transition time is critical for transmitter qualification. The IEEE specified patterns to measure the rising and fall edges occur at multiple points in the SSPRQ pattern resulting in a spread in the measured transmitter transition time. For a bandwidth constrained transmitter, a spread of up to ~3ps was observed – a sizable spread given the 40 ps UI. Nonlinear transmitters could potentially have a greater spread in the measured transition time. The exact transition times depends not just on the pattern but on the preceding and succeeding transitions as well. Using patterns that occur only once would reduce this uncertainty, as would averaging of results gained from all instances of specified runs.

*3.3 TDECQ variations owing to oversampling*

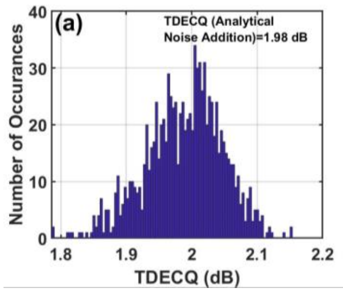
A signal's PDF after oversampling is partially dependent on the oversampling technique employed. When using a real-time oscilloscope with an integer number of samples per symbol, a significant variation (~0.3 dB) in TDECQ was observed based on whether oversampling was implemented before or after the equalizer. This uncertainty may be reduced by employing a non-integer number of samples per symbol from the scope, thereby eliminating the need for oversampling to generate the eye. Having an integer number of samples per symbol from the scope results in the samples always being at the same relative time instances in the eye and hence they would not fill all time instances within the eye.

*3.4 TDECQ dependency on the iterative noise addition approach*

TDECQ computation requires iterative noise addition to the PAM-4 signal till a target BER is achieved. The standard does not enforce a specific way of achieving this, while recommending an analytic way of adding noise by combining the sampled histogram's PDF with the Gaussian noise PDF. We investigated the alternative option of adding noise through a random noise generator, where we observed TDECQ dependence on the seed employed, Fig. 5(a). This is because one pattern length was insufficient to accurately generate the tail of the Gaussian PDF. Always using the analytic approach would resolve this uncertainty.

*3.5 TDECQ dependency on the initial equalizer weights*

Tap weights, histogram location and threshold values of the reference equalizer are optimized to minimize TDECQ. This is a nonlinear process. The algorithm gives freedom in the specific optimization approach used. TDECQ was sensitive to our initial tap weights as these initial values often lead to the optimization being stuck in a local minimum. We used samples from different eye positions to get different initial Weiner tap weights, Table 5(b). Enforcing a uniform and robust weight optimization technique would reduce this uncertainty.




| Position of samples used in Weiner computation of initial tap weights [initial weights] | TDECQ (post tap optimization) |
|---|---|
| 0.525 UI [1.0652, -0.0782, 0.0224,-0.0082, -0.0012] | 2.12 dB |
| 0.500 UI [1.0756, -0.0914, 0.0261, -0.0095,-0.0007] | 2.24 dB |
| 0.475 UI [1.0875, -0.1064, 0.0303, -0.0112, -0.0001] | 1.98 dB |
| 0.450 UI [1.1009, -0.1234, 0.0351, -0.0133, 0.0007] | 1.97 dB |
| 0.425 UI [1.1158, -0.1429, 0.0410, -0.0157, 0.0017] | 1.98 dB |

(**b**)

Fig 5. (a) TDECQ variation for various random noise generator seeds (b) TDECQ sensitivity to initial tap weights

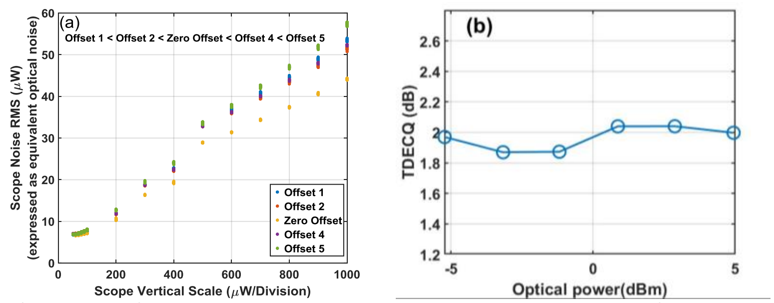



Fig 6. (a) Variation of scope noise for various settings (b) TDECQ variation with launch power for accurate noise characterization

*3.5 TDECQ dependency on receiver noise characterization*

Finally, accurate characterization of the measurement receiver (oscilloscope+O/E) noise is critical for robust TDECQ measurement. The change in scope noise floor with the scope scale is typically accounted for but the change w.r.t offset is often overlooked by the user [3]. On a real-time oscilloscope we varied the scale in a ramp fashion for various offsets and measured the noise, Fig 6(a). For all other impairments being the same, the TDECQ computed by the oscilloscope should ideally not vary with the launch power, provided the receiver noise has been accurately measured by the user, Figure 6(b).

## 3. Conclusion

Qualifying PAM-4 system components' performance without counting errors is both challenging and highly desirable. In this paper, we demonstrated the sensitivity of TDECQ to the specifics of the algorithm implementation and to receiver noise characterization. We also identify potential solutions for reducing this uncertainty.

## 5. References

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