

# Issues with TDECQ and the Associated DFE

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IEEE 802.3dj Ad Hoc

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Comments Addressed: I-92, I-180, I-220, I-224, I-391, I-393, I-394, I-395, I-396, I-397, I-415, I-463

# Supporters

- Chris Cole, Coherent
- Mike Dudek, Marvell
- Adee Ran, Cisco
- Ali Ghiasi, Ghiasi Quantum
- Richard Mellitz, Samtec
- Pavel Zivny\*, Lumilens

\*Except for adoption of MMSE

# Background of Reference Equalizer for TP2 Compliance Testing

- The first reference equalizer for 802.3 compliance testing was TWDP (Transmitter Waveform and Dispersion Penalty) in Clause 68.6.6 for 10GBASE LRM
  - December 2004 contribution by Swenson, Voois, Lindsay, and Zeng
    - <https://grouper.ieee.org/groups/802/3/aq/public/tools/>
    - N. Swenson, et al., "Explanation of IEEE 802.3, Clause 68 TWDP," 2006, available as Clause\_68\_TWDP.pdf at [https://standards.ieee.org/wp-content/uploads/2022/07/802.3-2022\\_downloads.zip](https://standards.ieee.org/wp-content/uploads/2022/07/802.3-2022_downloads.zip)
    - N. L. Swenson, et al., "Standards Compliance Testing of Optical Transmitters Using a Software-Based Equalizing Reference Receiver," in *OFC and NFOEC*, 2007, paper NWC3. <https://opg.optica.org/abstract.cfm?URI=NFOEC-2007-NWC3>
  - The final version of the TWDP reference equalizer was a T/2-spaced DFE with 14 feedforward taps and 5 feedback taps
- TDEC was subsequently introduced for binary NRZ waveforms using a T-spaced FFE reference equalizer
- TDECQ followed for PAM-4, also based on a feed forward equalizer

# The Search

Comments I-395, I-396 (Swenson), Comment I-92 (Adee)

Suggested Resolution: Specify that an MMSE solution is compliant whenever TDECQ or TECQ is evaluated.

# Test Definition Must Be Well-Defined and Implementable for Repeatability

- It is impractical to do a brute force search to find a global optimum with 16+ degrees of freedom<sup>\*</sup>
- MMSE optimization is well established for DFE optimization – why aren't we using it?
  - Algorithm is well-defined, implementable, and readily available

<sup>\*</sup>There are (arguably) 23 degrees of freedom to search over: 16 (taps) + 1 (number of precursors) + 1 (phase) + 1 (noise level) + 3 (threshold levels) + 1 (histogram selection)

# Brute Force Search vs MMSE for Decision Feedback Equalizer (DFE) optimization with 15 feedforward taps and 1 feedback tap (16 taps total)

Feature	Brute Force Search	MMSE (Analytical Solution)
<b>Mathematical Goal</b>	Exhaustive search for the lowest Error/BER.	Direct solution of the Wiener-Hopf equations.
<b>Search Space</b>	16 –dimensional hyper-grid.	Single point (intersection of 16 hyper-planes).
<b>Complexity Class</b>	$O(S^N)$ where $S$ is steps and $N = 16$ .	$O(N^3)$ , where $N = 16$ .
<b>Estimated Operations</b>	$\approx 1.2 \times 10^{24}$ (assuming 32 values/tap).	$\approx 4,096$ floating-point operations.
<b>Compute Time</b>	$\approx 38,000$ years (at 1 THz test rate).	$\approx 100$ microseconds (on a standard PC).
<b>Channel Knowledge</b>	None required (blind testing).	Requires Pulse Response or Training Data.
<b>Global Optimality</b>	Guaranteed (eventually).	Guaranteed (instantly) for Mean Square Error.
<b>Noise Handling</b>	Evaluates noise impact per iteration.	Accounts for noise via diagonal regularization.

# Propose edits in page 480

*“The equalizer tap coefficients are optimized using the minimum mean squared error (MMSE) method, with the sampling phase selected to minimize the mean square error.”*

The captured waveform is processed to find the largest noise that could be combined with the signal by an reference receiver when optimally equalized by a reference equalizer. ~~The optimal equalizer tap coefficients are dependent on the amount of noise that can be added to the signal, so finding the noise that can be added and the optimal equalizer setting is an iterative process.~~ One way of doing this, using estimated PAM4 symbol error ratio as the figure of merit for the equalized signal, is described below.

The reference equalizer specified in 180.9.6.3 is applied to the waveform. An eye diagram is formed from the equalized captured waveform.

The average optical power ( $P_{ave}$ ) of the equalized eye diagram is determined, and the 0 UI and 1 UI crossing points are determined by the average of the eye diagram crossing times, as measured at  $P_{ave}$ , as illustrated in Figure 180-11.

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# Propose edits in page 481

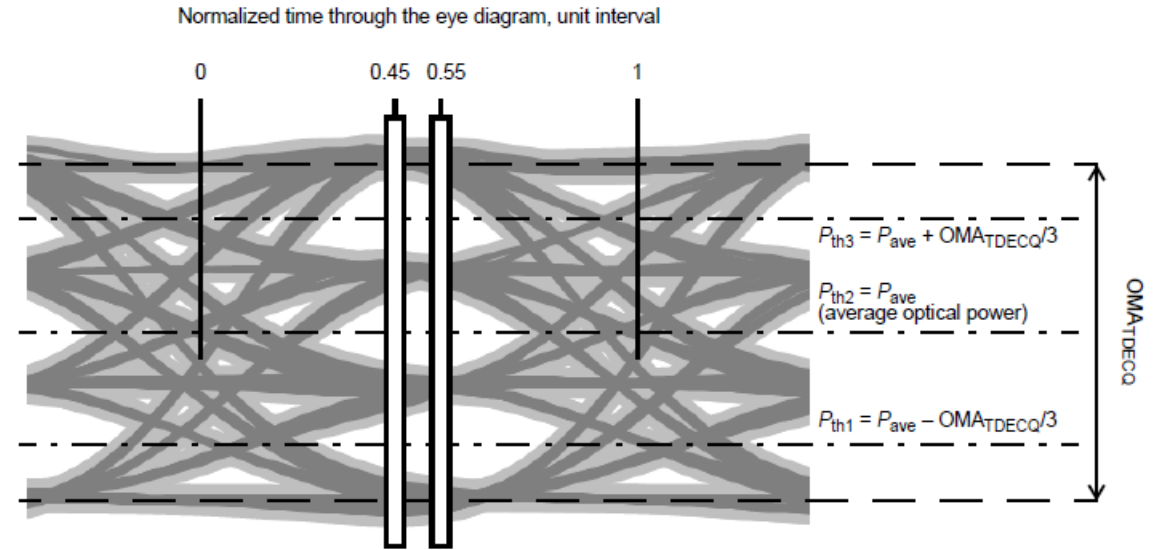


Figure 180-11—Illustration of the TDECQ measurement

*“... are measured using samples taken at  $\pm 5\%$  UI from the equalizer optimization sampling phase.”*

Two vertical histograms are measured ~~through the eye diagram, nominally centered at 0.45 UI and 0.55 UI.~~ Each of the histogram windows spans all of the modulation levels of the eye diagram, as illustrated in Figure 180-11. The precise time position of the pair of histograms is adjusted to minimize TDECQ while keeping the histograms spaced 0.1 UI apart.

Each histogram window has a width of 0.04 UI. Each histogram window has outer height boundaries which are set beyond the extremes of the eye diagram (so that no further samples would be captured by increasing the vertical separation of the height boundaries).

# Propose edits in page 483

The equalizer tap coefficients are ~~iteratively adjusted~~ and  $SER_L$  and  $SER_R$  calculated until the larger of  $SER_L$  and  $SER_R$  is minimized. Then, if the larger of  $SER_L$  and  $SER_R$  is greater than the target PAM4 SER of  $4.56 \times 10^{-4}$ , the value of  $\sigma_G$  is decreased ~~and the process of equalizer optimization is repeated~~. If the larger of  $SER_L$  and  $SER_R$  is lower than the target PAM4 SER of  $4.56 \times 10^{-4}$ , then the value of  $\sigma_G$  is increased and ~~the process of equalizer optimization is repeated.~~

$P_{th1}$ ,  $P_{th2}$ , and  $P_{th3}$  are varied from their nominal values by up to  $\pm 1\%$  of  $OMA_{TDECQ}$  in order to optimize TDECQ. The same three thresholds are used for both the left and the right histogram.

When the larger of  $SER_L$  and  $SER_R$  is equal to the target PAM4 SER of  $4.56 \times 10^{-4}$ , and the value of  $\sigma_G$  cannot be increased ~~by further optimization of the equalizer tap coefficients or the sub-eye threshold levels~~, then TDECQ is calculated.

The RMS noise,  $R$ , that could be added by a receiver is given by Equation (180-11).

$$R = \sqrt{\sigma_G^2 + \sigma_S^2} \quad (180-11)$$

TDECQ is given by Equation (180-12).

$$TDECQ = 10 \log_{10} \left( \frac{OMA_{outer}}{6} \times \frac{1}{Q_t R} \right) \quad (180-12)$$

where

$OMA_{outer}$  is measured as defined in 180.9.5  
 $Q_t$  is 3.428, consistent with the target symbol error ratio for Gray mapped PAM4, and can be calculated according to Equation (180-27)

**delete** → Alternative optimization methods such as minimum mean squared error (MMSE) may be used to determine equalizer tap weights to reduce test time, and are expected to report equal or higher values of TDECQ. These alternative methods should not be used for receiver sensitivity and stressed receiver sensitivity calibration.

# Explaining the Eye Diagram

Comment I-463 (Dawe), I-180 (Healy), I-393 (Swenson), I-224(Maniloff)

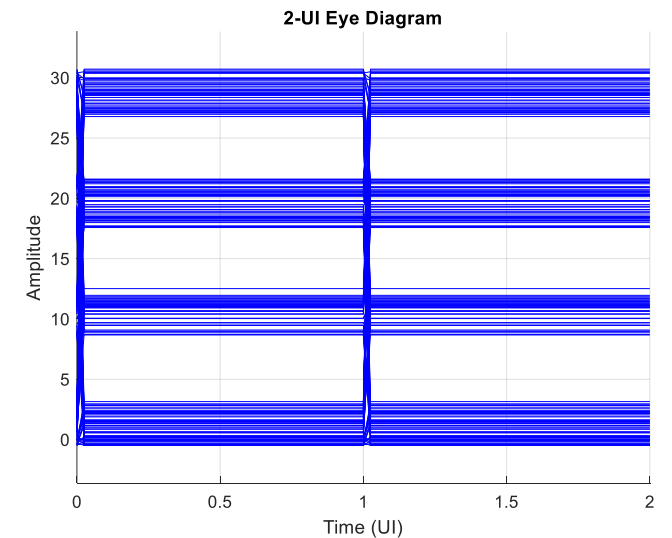
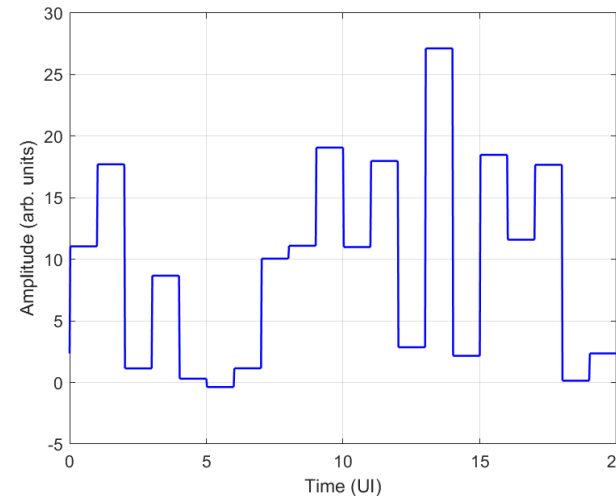
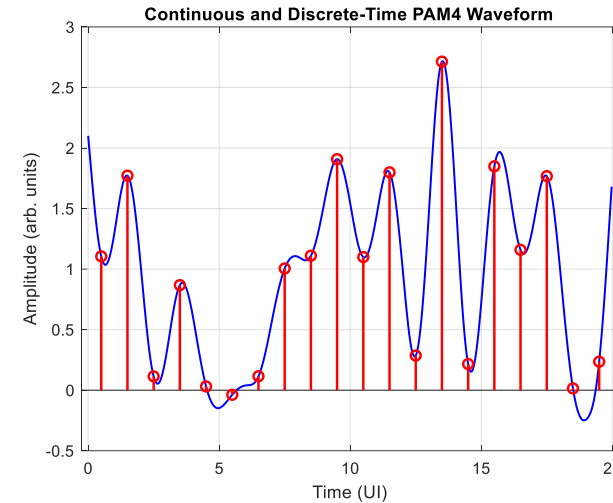
Suggested resolution: Propose a wording that is mutually acceptable to these commenters.

Comments I-394 (Swenson), I-396 (Swenson)

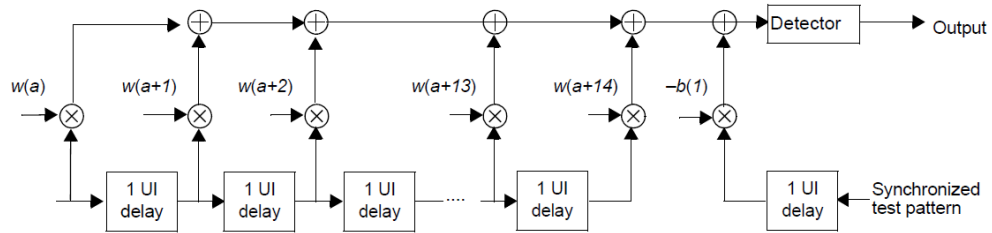
Suggested remedy: Delete the eye diagram. Or if we keep it, add the “bat-wings”.

# What is the origin of the eye diagram?

- A discrete-time equalizer has no eye diagram
  - A discrete-time signal is not defined in between samples
- Or you could say it has a “boring” eye diagram if you maintain that the signal stays constant between samples

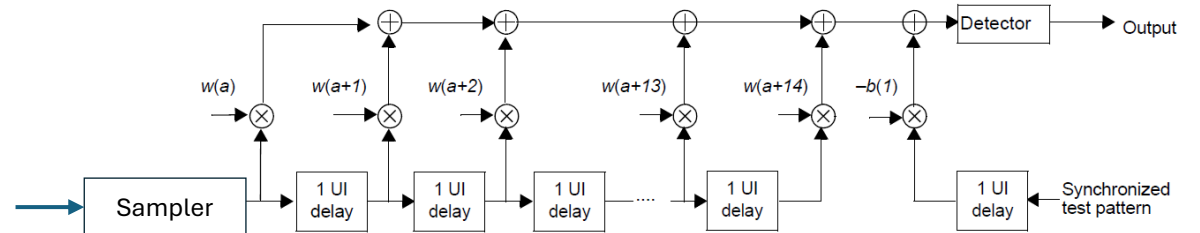


# Two Options



NOTE—The variable  $a$  is an integer in the range  $-3$  to  $0$

Figure 180–10—TDECQ reference equalizer functional model



NOTE—The variable  $a$  is an integer in the range  $-3$  to  $0$

Figure 180–10—TDECQ reference equalizer functional model

- 1) Continuous time equalizer

- Taps are adjusted based on 1UI - spaced samples
- Components shown are ideal (infinite bandwidth)

- 2) Discrete time equalizer

- 1UI –spaced Sampler is at the input
- For a given tap setting, the phase of the sampler can be swept to produce the eye diagram

# The DFE Eye Diagram

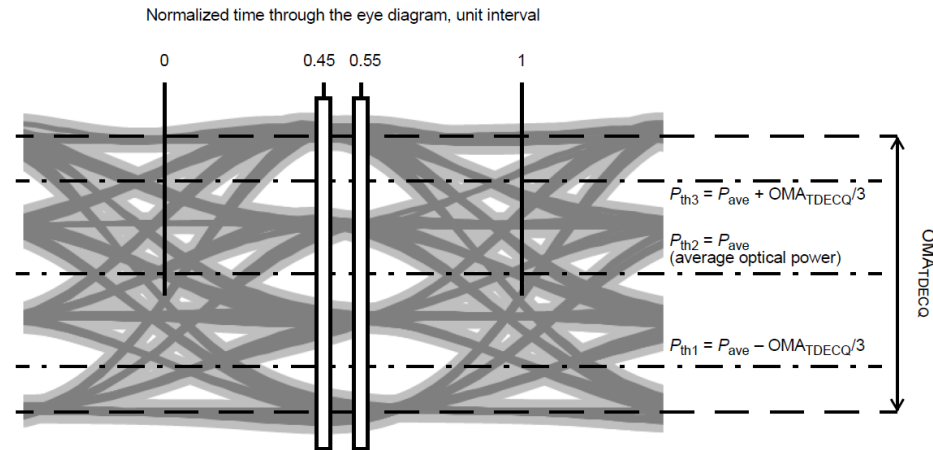
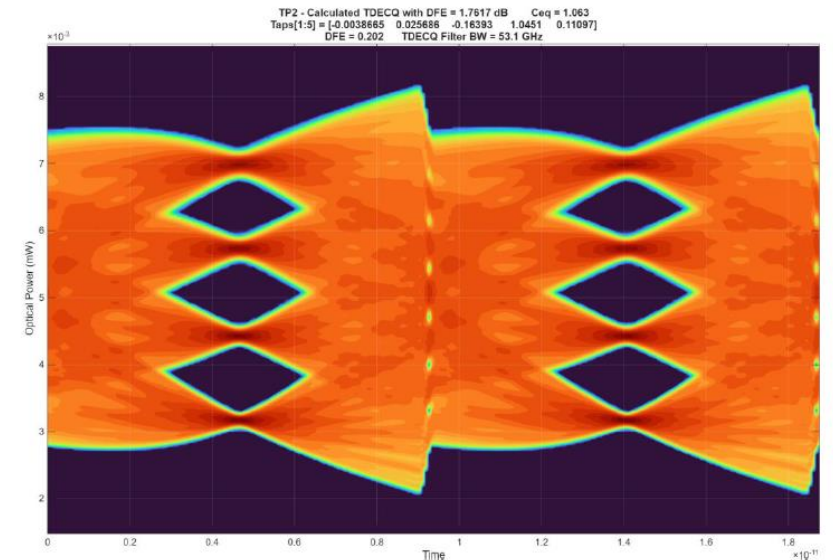


Figure 180-11—Illustration of the TDECQ measurement



Eye diagram courtesy Mark Kimber, Semtech

- However we define it, we need to include the “bat-wing” if we show the eye diagram
  - This is a unique feature of the DFE eye diagram. The amount added to the waveform is constant over 1UI.
- Timing: The value must change outside of the two histogram windows
  - Nominally 1/2 UI from the center eye opening is a good choice
  - We need to say something about this in the text
    - Perhaps “1/2 UI from the nominal point at which the TDECQ is measured”
  - This needs better description in the text and figure

# Nomenclature

Comments I-391 (Swenson), I-224 (Maniloff)

Suggested resolution: Some mutually acceptable combination of the two suggested remedies.

# Nomenclature

- The D3.0 TDECQ reference equalizer is a T-spaced DFE with 15 feedforward taps and 1 feedback tap
  - It is not an FFE followed by a DFE
    - It is a single equalizer with the taps jointly optimized. If it were two separate equalizers, the taps for each would be independently optimized.
    - The feedforward (FF) section of the DFE serves a different role than that of a standalone FFE
      - FFE attempts to minimize ISI
      - FF section of DFE attempts to minimize *pre-cursor* ISI, leaving post-cursor ISI for the feedback section to handle
- The terminology proposed here is supported in:
  - Reference textbooks
  - Peer-reviewed literature
  - Industry
  - IEEE 802.3, Clause 68

# Textbook Definition

- John G. Proakis and M. Salehi, *Digital Communications*, 5th ed. 2008, p.661
  - “The nonlinear equalizer consists of two filters, a feedforward filter and a feedback filter, arranged as shown in Figure 9.5-1, called a *decision-feedback equalizer (DFE)*.”
- E. A. Lee and D. G. Messerschmitt, *Digital communication*, 2nd ed., 1994, p.541.
  - From the caption for Figure 11-10: “The DFE for finite precursor and postcursor equalizer transversal filters.”

# Literature Definition

M. E. Austin, “Decision-feedback equalization for digital communication over dispersive channels,” MIT Lincoln Lab., p. 102, 1967, [Online]. Available:  
<http://dspace.mit.edu/handle/1721.1/4282>

M.E. Austin invented the DFE, described in this 1967 report.

# Industry Definition

MATLAB & Simulink, Communications Toolbox User Guide

- p. 14-7: “A DFE ... contains a forward filter and a feedback filter. The forward filter is similar to a linear equalizer. The feedback filter contains a tapped delay line whose inputs are the decisions made on the equalized signal.”
- p. 15-12: Gives an example of a DFE equalizing a BPSK modulated signal “specifying a decision feedback LMS equalizer having eight forward taps [and] five feedback taps”

# IEEE 802.3 Definition

- Clause 68.6.1
  - “The reference equalizer is a decision feedback equalizer with defined tap number and spacing, as specified in 68.6.6.2.”
- Clause 68.6.2
  - “14 T/2-spaced feedforward equalizer taps; 5 T-spaced feedback equalizer taps”
- Please see these contributions to 802.3aq for 10GBASE-LRM, as pointed out by Chris Cole:
  - [https://grouper.ieee.org/groups/802/3/10GMMFSG/public/jan04/bhoja\\_2\\_0104.pdf#page=8](https://grouper.ieee.org/groups/802/3/10GMMFSG/public/jan04/bhoja_2_0104.pdf#page=8)
  - [https://grouper.ieee.org/groups/802/3/10GMMFSG/public/jan04/baek\\_1\\_0104.pdf#page=5](https://grouper.ieee.org/groups/802/3/10GMMFSG/public/jan04/baek_1_0104.pdf#page=5)
  - [https://grouper.ieee.org/groups/802/3/10GMMFSG/public/mar04/swenson\\_1\\_0304.pdf#page=13](https://grouper.ieee.org/groups/802/3/10GMMFSG/public/mar04/swenson_1_0304.pdf#page=13)
- Nowhere in 802.3 is a DFE consisting of a feedforward filter and a feedback filter referred to as “an FFE followed by a DFE”. In particular, clause 168 does not use that terminology.