802.3cu D1.1 PMD Spec Proposed Changes

P802.3cu 100 Gb/s and 400 Gb/s over SMF at 100 Gb/s per Wavelength Task Force

Geneva, Switzerland

20 January 2020

Chris Cole

Outline

- Introduction
- Transmit Characteristics Proposed Changes
- 400G Clause 151 Transmit Characteristics
- 100G Clause 140 Transmit Characteristics
- Receive Characteristics Proposed Changes
- 400G Clause 151 Receive Characteristics
- 100G Clause 140 Receive Characteristics

Introduction

- 50G and 100G PAM4 optical specs are new to the industry
- Multiple spec choices were made based on limited or no experience to move the standards process forward
- There should be no strong presumption of correctness for existing PAM4 optics specs; none have shipped in volume
- We should be humble with respect to understanding PAM4
- The only way to end up with solid specs in the long term is to continuously refine them as our knowledge increases
- Such refinements were proposed on two Ad Hoc calls:

  http://www.ieee802.org/3/cu/public/cu_adhoc/cu_archive/cole_3cu_adhoc_121119.pdf

  http://www.ieee802.org/3/cu/public/cu_adhoc/cu_archive/cole_3cu_adhoc_010820_v2.pdf
- This deck is a continuation, in support of D1.1 comments

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- ➢ Transmit Characteristics Proposed Changes
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- 400G Clause 151 Receive Characteristics
- 100G Clause 140 Receive Characteristics

Supporters

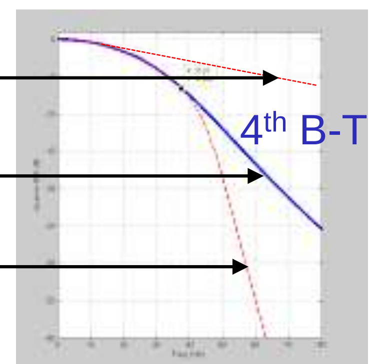
- Frank Chang, SourcePhotonics
- Gang Chen, Baidu
- Ken Jackson, Sumitomo
- Thang Pham, Facebook
- Peter Stassar, Huawei
- Chongjin Xie, Alibaba
- Helen Xu, Huawei

C_{EQ} Definition and Properties

- C_{EQ} ≜ coefficient quantifying Ref EQ noise enhancement
- $H_{EQ}(f)$ ≜ normalized frequency response of the Ref EQ
- $N(f)$ ≜ white noise filtered by 4th B-T w/ BW = 26.6 GHz
- $C_{EQ} = \sqrt{\int_f N(f)\,|H_{EQ}(f)|^2\,df}$

  $\sqrt{\int_f N(f)\,df} = 1$

  $H_{eq}(f = 0) = 1$
- $C_{EQ} > 1$ if $H_{EQ}(f)$ is High Pass
- $C_{EQ} = 1$ if $H_{EQ}(f)$ is All Pass
- $C_{EQ} < 1$ if $H_{EQ}(f)$ is Low Pass



- TX w/ pre-emphasis adapts $H_{EQ}(f)$ to Low Pass ($C_{EQ} < 1$)

II-VI

TDECQ - $10\log_{10}(C_{EQ})$ Explanation

- TDECQ - $10\log_{10}(C_{EQ}) \leq TDECQ_{MAX}$ *Table 140-6, 151-7*

1. TDECQ ≈ $TDECQ_{MAX}$
   - $10\log_{10}(C_{EQ}) \geq 0 \leftrightarrow C_{EQ} \geq 1$
   - $H_{EQ}(f)$ can not adopt to Low Pass
   - TX pre-emphasis qualitatively constrained
2. TDECQ < $TDECQ_{MAX}$
   - $10\log_{10}(C_{EQ})$ unconstrained $\leftrightarrow$ C_{EQ} unconstrained
   - $H_{EQ}(f)$ unconstrained
   - TX pre-emphasis unconstrained

- TDECQ - $10\log_{10}(C_{EQ})$ is just a lousy pre-emphasis spec

Yes, it's that simple!

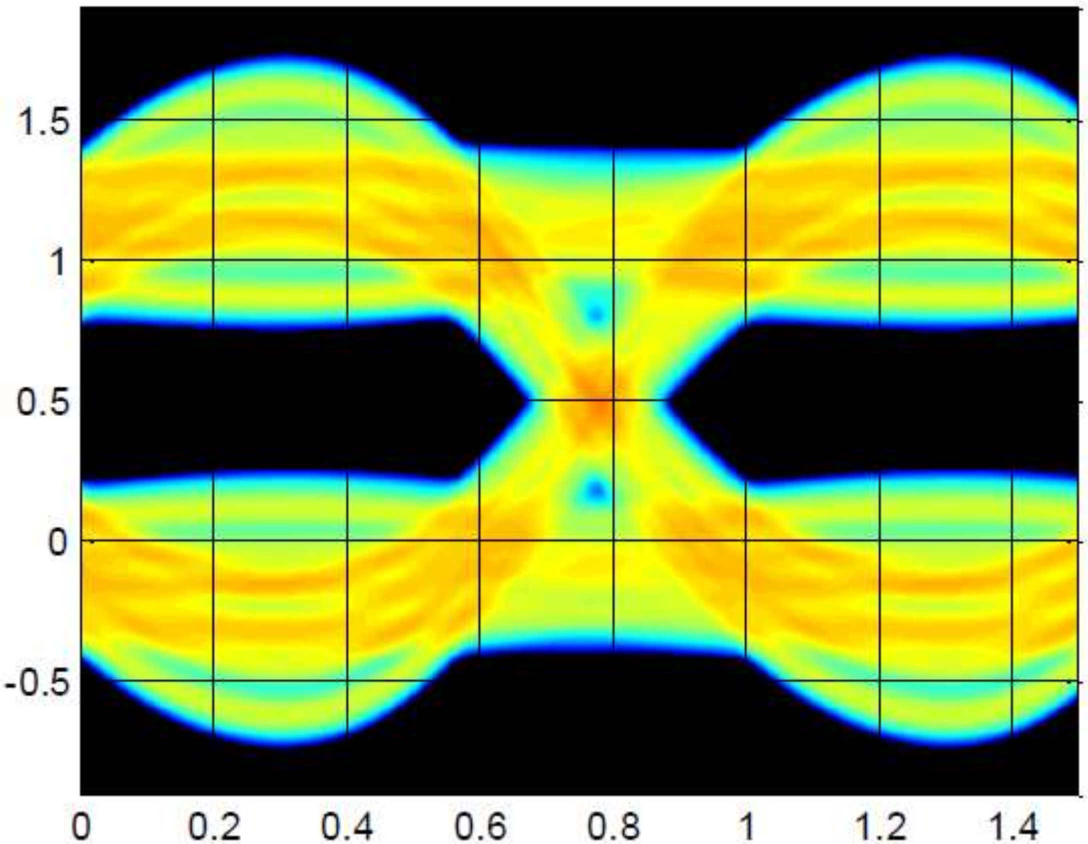
TDECQ - $10\log_{10}(C_{EQ})$ Explanation Confirmation

- Jonathan King Analysis
  http://www.ieee802.org/3/cd/public/July18/king_3cd_02a_0718.pdf
- "TDECQ - $10\log_{10}(C_{EQ})$ is not a good indicator of how hard the EQ has to work, nor of it's likely resilience to receiver impairments."
- "The transmitter most likely to be affected by receiver non-linearity, quantization, or other sampling errors, is the TX with the most severe effective eye-closure out of the O/E"
- "There is no value in adding a TDECQ - $10\log_{10}(C_{EQ})$ limit. Adding one unnecessarily ***limits*** the use of a tool (***transmitter pre-emphasis***) which can improve transmitter yield and cost, and link margins."
- Jonathan correctly points out that TDECQ - $10\log_{10}(C_{EQ})$ limit can exclude good TX, i.e. it's a lousy spec

TDECQ - $10\log_{10}(C_{EQ})$ Explanation Confirmation

- Piers Dawe analysis

  http://www.ieee802.org/3/cd/public/July18/dawe_3cd_01b_0718.pdf#page=11



"very bad" TX eye that can be stopped by TDECQ - $10\log_{10}(C_{EQ})$ i.e. "bad" or "very bad" = pre-emphasis

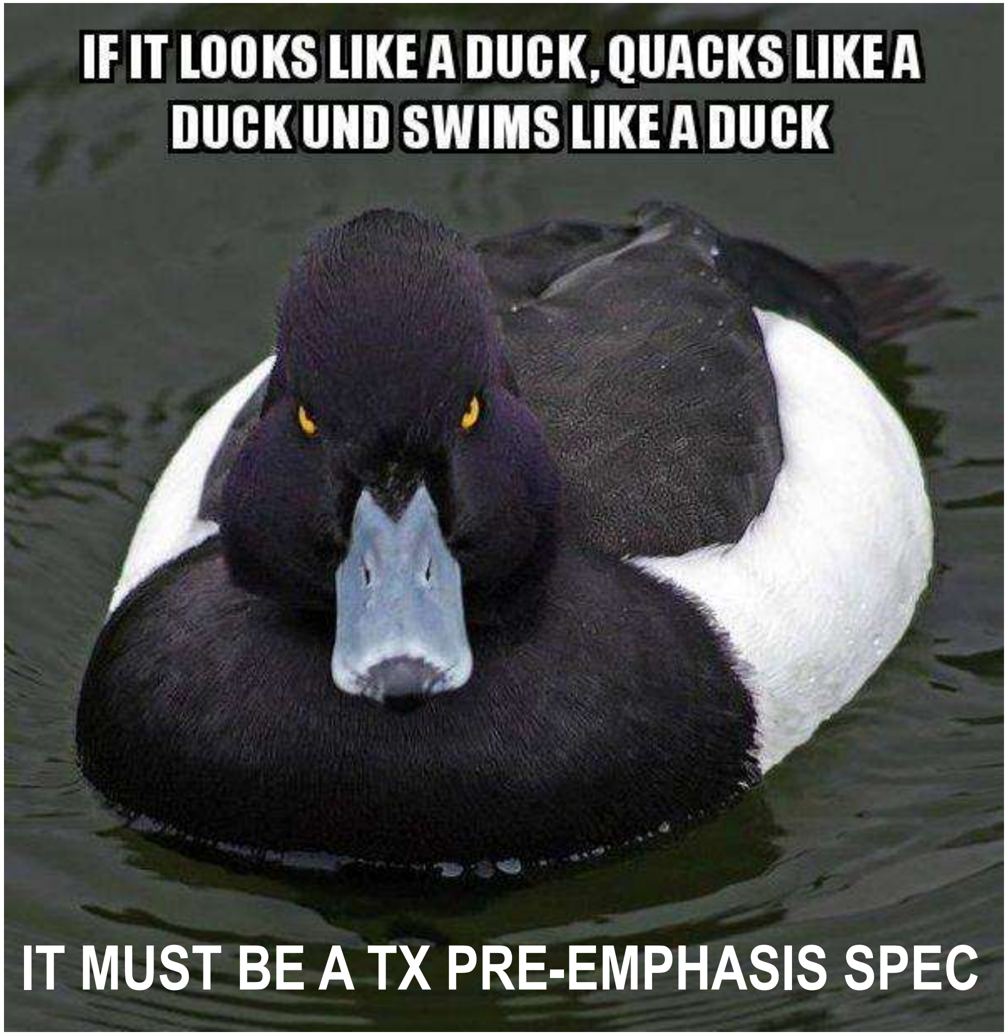
TDECQ - $10\log_{10}(C_{EQ})$ Explanation Confirmation

- Piers Dawe and Mellanox team analysis
- TDECQ - $10\log_{10}(C_{EQ})$ stops use of "… excessive emphasis to make a bad (noisy and/or distorted and/or inappropriate chirp) transmitter pass when it should have failed"

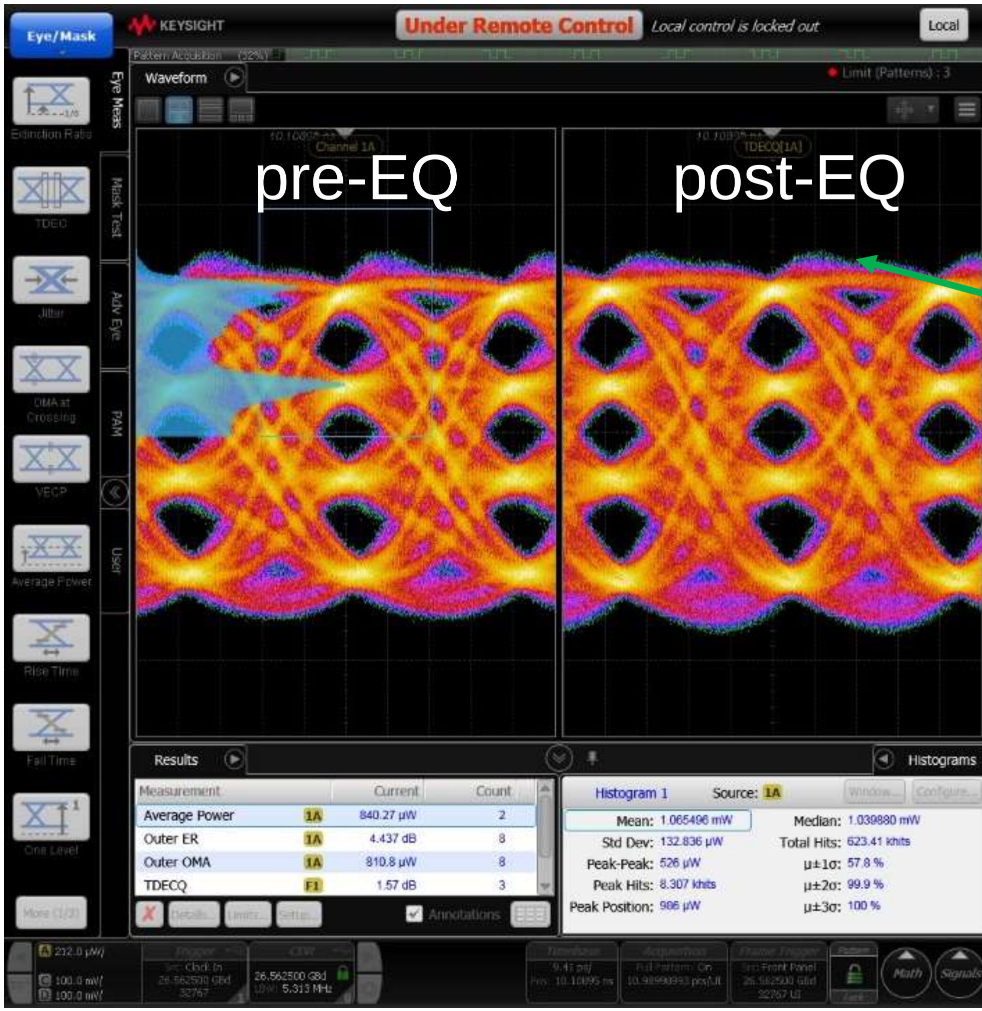
  Piers Dawe 11/10/19 email
- "Note that FFE equalization at the transmitter, better known as pre-emphasis, … {means} receiver will compensate high frequency gain from the pre-emphasis with an FFE that has $C_{EQ} < 1$. Also observe, that signals with pre-emphasis may present overshoot, which is not necessarily optimal for the system, despite the fact that TDECQ is minimized."

  Santiago Echeverri-Chacón, Piers Dawe, et. al, "Transmitter and Dispersion Eye Closure Quaternary (TDECQ) and Its Sensitivity to Impairments in PAM4 Waveforms", Journal of Lightwave Technology, Vol. 37, No. 3, Feb. 1, 2019, p.855, (all seven authors with Mellanox)

TDECQ - $10\log_{10}(C_{EQ})$ Explanation Summary



26.6 GBaud PAM4 1305nm λ 13.3GHz RX BW



8% pre-EQ overshoot

400G LR8 BtB

3.3V 25°C

H_{EQ} (f) is mild Low Pass

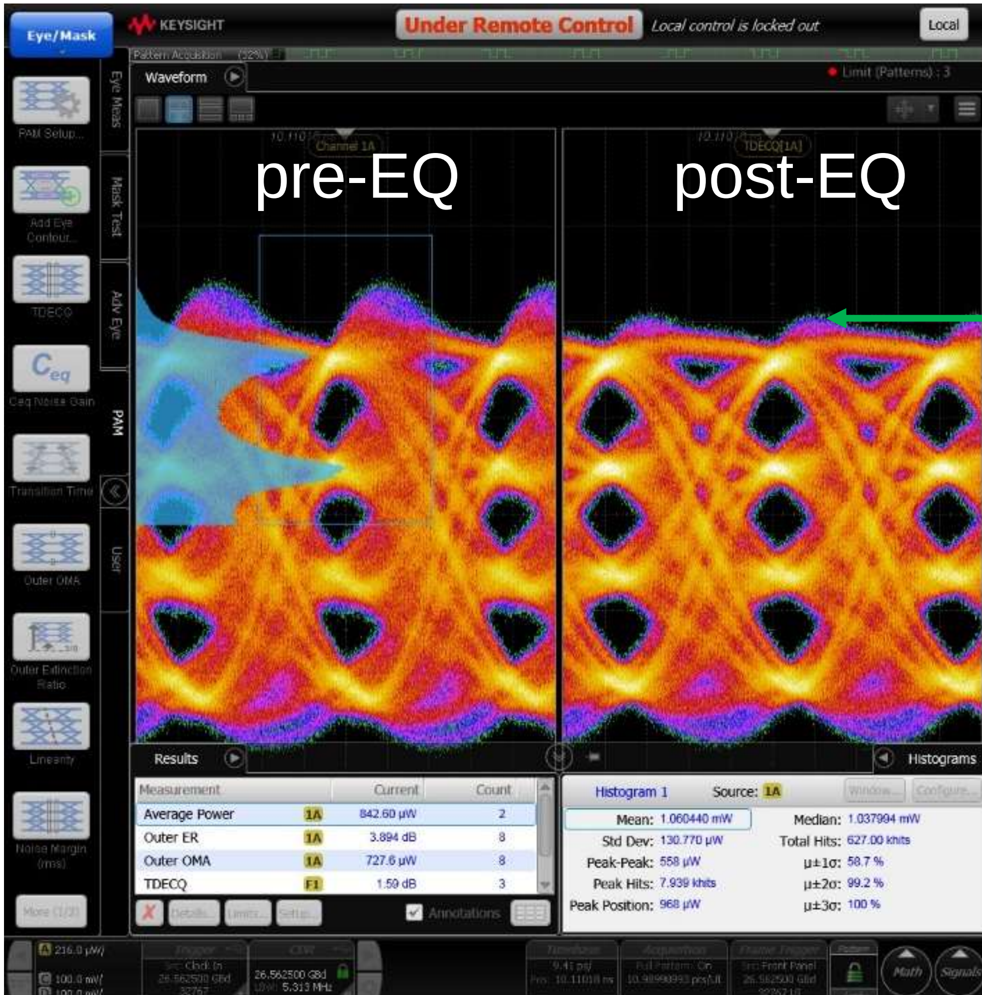
C_{EQ} = 0.96

TDECQ - $10\log_{10}(C_{EQ})$

= 1.4 dB

This spec would not limit TX pre-emphasis

26.6 GBaud PAM4 1305nm λ 13.3GHz RX BW



13.5% pre-EQ overshoot

400G LR8 BtB

3.3V 25^{o}C

H_{EQ} (f) is Low Pass

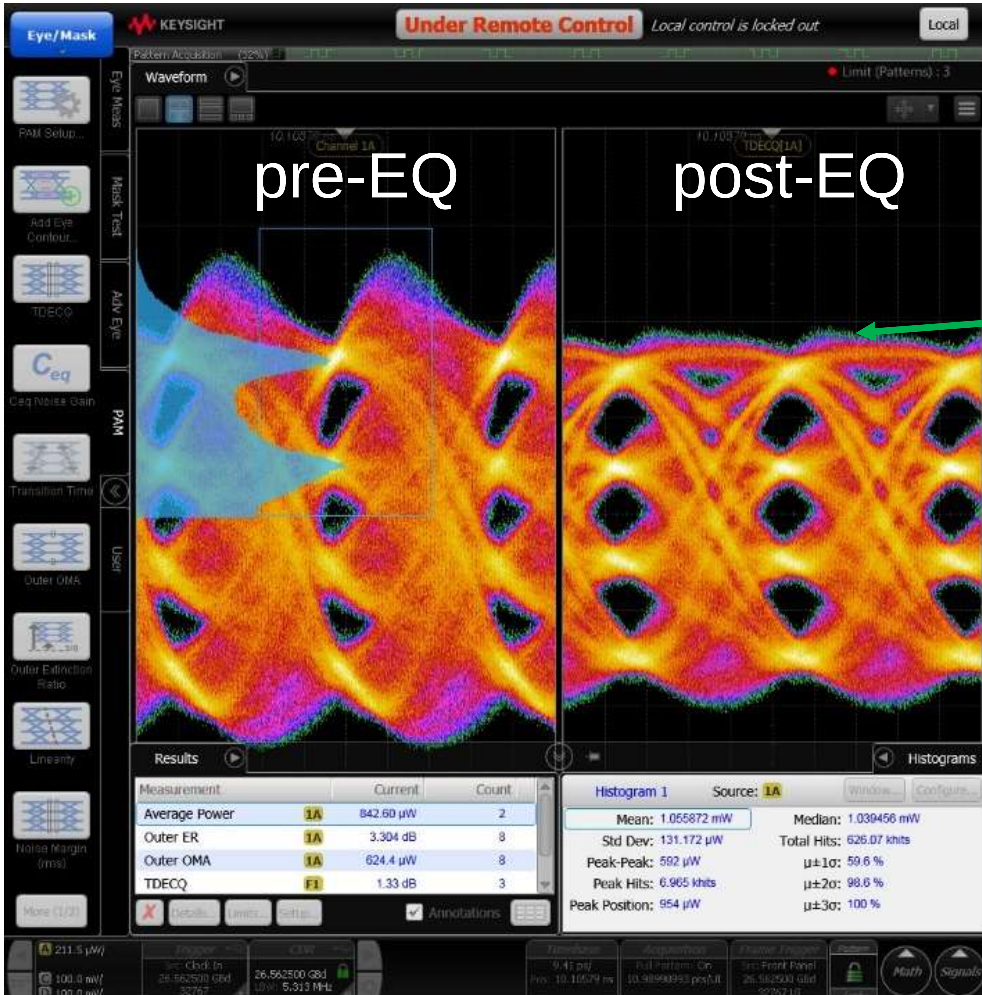
C_{EQ} = 0.87

TDECQ - $10\log_{10}(C_{EQ})$

= 2.1 dB

This spec would not limit TX pre-emphasis

26.6 GBaud PAM4 1305nm λ 13.3GHz RX BW



19% pre-EQ overshoot

400G LR8 BtB

3.3V 25°C

H_{EQ} (f) is hard Low Pass

C_{EQ} = 0.79

TDECQ - $10\log_{10}(C_{EQ})$

= 3.2 dB

This spec would not limit TX pre-emphasis

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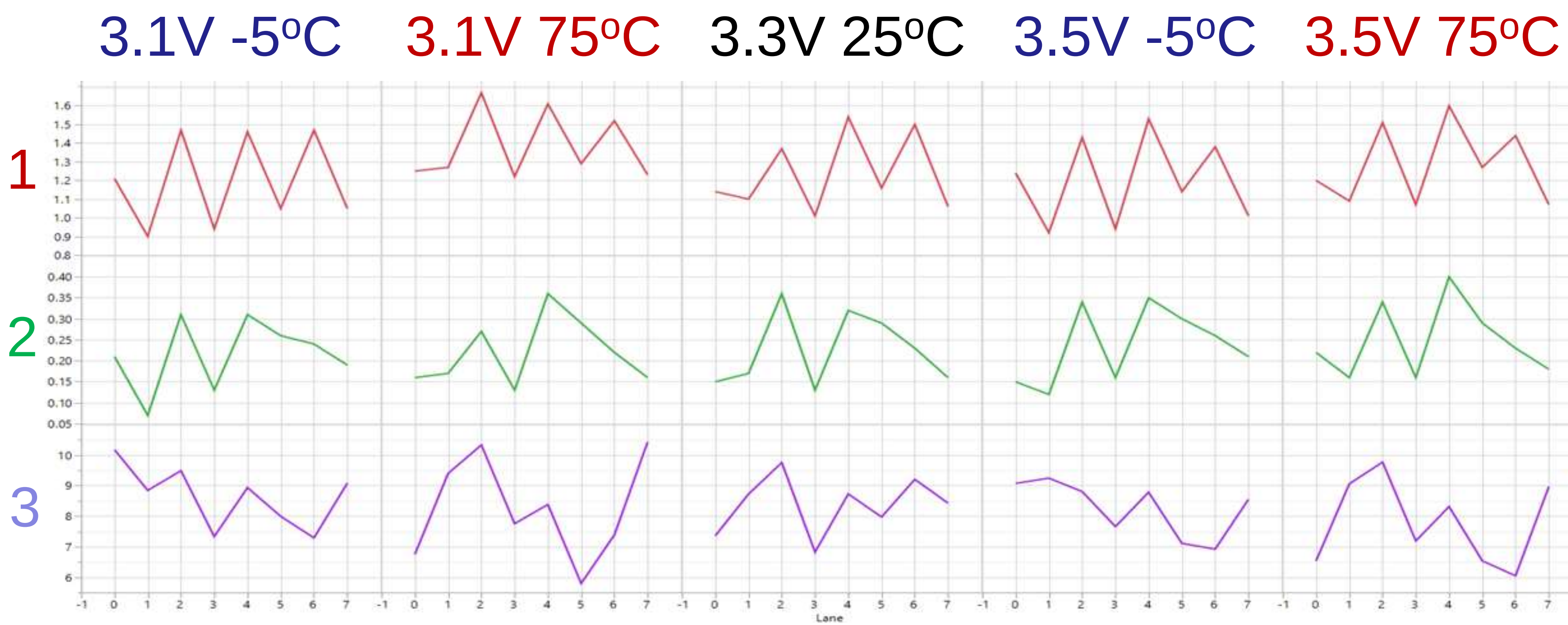
26.6 GBaud PAM4 1305nm λ Link Operation

Summary of data from pages 12, 13, 14

Overshoot (13.3GHz RX BW) %	TECQ (BtB) dB	TECQ $- 10\log_{10}(C_{EQ})$ dB	TDECQ (disp = -30ps/nm) dB	TDECQ $- 10\log_{10}(C_{eq})$ dB	Operation (BtB)
8	1.6	1.4	1.2	1.4	normal
13.5	1.6	1.8	1.5	2.1	LOL
19	1.3	2.0	2.2	3.2	LOL

- TDECQ $- 10\log_{10}(C_{EQ})$ would pass problem TX (lousy spec)
- Production LR8 units are limited to ≤12% overshoot, despite no IEEE 802.3 spec, to prevent interop problems in the field

26.6 GBaud PAM4 LR8 λs 5 Corner Data

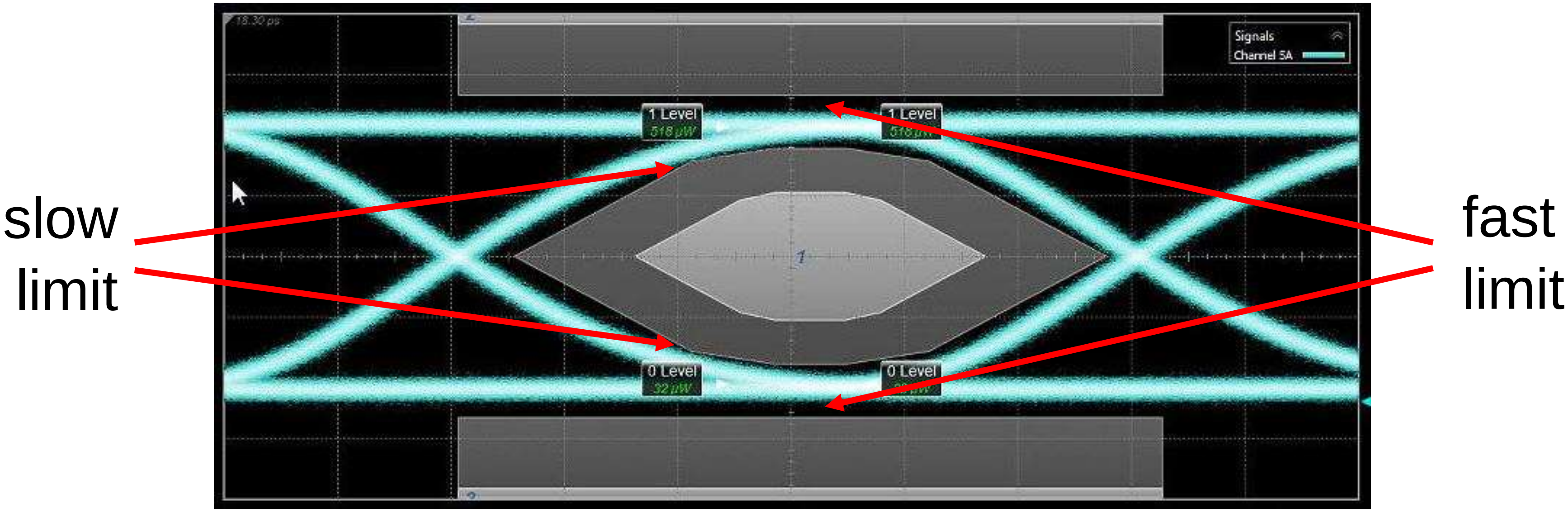


1: TECQ (dB) 2: $10\log_{10}C_{EQ}$ (dB) 3: Overshoot (%)

- Only qualitative correlation between C_{EQ} and Overshoot; TDECQ - $10\log_{10}(C_{EQ})$ is a lousy spec

TX Signal Historical Time Domain Spec Limits

- Eye Mask (ex. 10G NRZ eye using Keysight DCA)

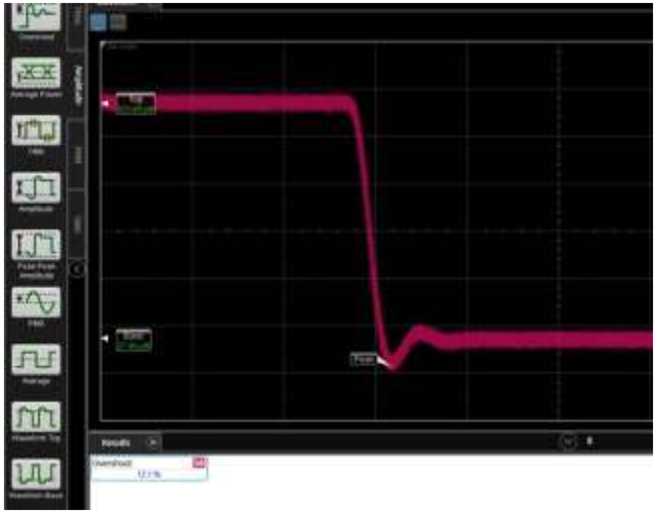


- Successfully used with BER spec limits for decades
- Requires open TX eye, which NRZ signals have
- Dropped as spec for PAM4 signals because the TX eye can be closed, yet still recoverable by adaptive equalizer $H_{eq}(f)$
- Simple solution: use NRZ signal for TX time domain tests

Mask Limit Jonathan King 2/15/19 Proposal

- Square wave is perfect for time domain basics
- Easy to generate and lock to
- Long stretch of “0s” and “1s” either side of each transition
- TX measurement with short patch cord to the scope generating no significant timing wander
- Over-shoot and under-shoot in OMA units

email to Greg D Le Cheminan, Steve Sekel; Keysight, Pavel Zivny; Tektronix, Qing Wang; Facebook



Images courtesy of Greg D Le Cheminan (Keysight) 2/27/19

Transmitter Over/under-shoot Test Patterns

- Square wave NRZ test pattern (in oscilloscope mode)
  - Measures fundamental characteristic of TX signal
  - More sensitive measure of overshoot for all TX types
- SSPRQ PAM4 test pattern (in eye mode with histograms)
  - Measures multiple characteristics of the TX signal
  - More accurate measure of 11 and 00 PAM4 levels

Dispersion Penalty (D) Limit

- Spec limit: TDECQ - TECQ *Table 140-6, 151-7*
- D = TDECQ - TECQ
- Only limit on positive dispersion penalty
- Not a limit on negative dispersion penalty
- Missing (max) qualifier
- Complete spec description: |TDECQ - TECQ| (max)
- This is required remedy to go along with proposed spec value changes

Lack of TECQ Spec Problem

- TX with negative dispersion penalty (D) over max. reach, i.e. TX chirp pre-compensation of fiber dispersion:
  - TDECQ = TECQ + D
  - D < 0
  - TDECQ < TECQ
- Most PMDs are used at reaches shorter than max. spec.
- Most datacenter reaches are <500m, i.e. dispersion is ~0
- If TX D < 0, most applications operate with
  - TECQ > TDECQ
- TECQ limit prevents interoperability problems for TX D < 0
- TECQ is free because it’s required for TDECQ - TECQ

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Draft 1.1 Clause 151 Transmit Characteristics

Table 151–7—400GBASE-FR4 and 400GBASE-LR4-6 transmit characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5		nm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	3.5	dB
~~TDECQ – $10\log_{10}(C_{eq})$ (max) [c]~~	~~3.4~~	~~3.5~~	dB
~~TDECQ – TECQ~~	—	2.5	dB
Average launch power of OFF transmitter, each lane (max)	–16	–16	dBm
Extinction ratio, each lane (min)	3.5	3.5	dB
Transmitter transition time (max)	17		ps

~~[c] C_{eq} is a coefficient defined in 121.8.5.3, which accounts for reference equalizer noise enhancement.~~

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Proposed Clause 151 Transmit Characteristics

Table 151–7—400GBASE-FR4 and 400GBASE-LR4-6 transmit characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5		nm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	3.5	dB
TECQ, each lane (max)	3.4	3.5	dB
|TDECQ – TECQ|, each lane (max)	2.5	2.5	dB
Average launch power of OFF transmitter, each lane (max)	–16	–16	dBm
Extinction ratio, each lane (min)	3.5	3.5	dB
Transmitter transition time[c] (max)	17		ps
Transmitter over/under-shoot[c] (max)	12		%

[c] Using Square Wave or SSPRQ pattern, defined in 120.5.11.2.4 or 120.5.11.2.3, respectively

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- **100G Clause 140 Transmit Characteristics**
- Receive Characteristics Proposed Changes
- 400G Clause 151 Receive Characteristics
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Draft 1.1 Clause 140 Transmit Characteristics

Table 140–6—100GBASE-DR, 100GBASE-FR1, and 100GBASE-LR1 transmit characteristics

Description	~~Value~~ 100GBASE-DR	100GBASE-FR1	100GBASE-LR1	Unit
Signaling rate (range)	53.125 ± 100 ppm			GBd
Modulation format	PAM4			—
Transmitter and dispersion eye closure for PAM4 (TDECQ) (max)	3.4	3.4	3.4	dB
~~TDECQ – $10\log_{10}(C_{eq})$[c] (max)~~	3.4	~~3.4~~	~~3.4~~	dB
Average launch power of OFF transmitter (max)	–15	–15	–15	dBm
Extinction ratio (min)	3.5	3.5	3.5	dB
Transmitter transition time (max)	17	17	17	ps

~~[c] C_{eq} is a coefficient defined in 121.8.5.3, which accounts for reference equalizer noise enhancement.~~

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Proposed Clause 140 Transmit Characteristics

Table 140–6—100GBASE-DR, 100GBASE-FR1, and 100GBASE-LR1 transmit characteristics

Description	~~Value~~ 100GBASE-DR	100GBASE-FR1	100GBASE-LR1	Unit
Signaling rate (range)	53.125 ± 100 ppm			GBd
Modulation format	PAM4			—
Transmitter and dispersion eye closure for PAM4 (TDECQ) (max)	3.4	3.4	3.4	dB
TECQ (max)	-	3.4	3.4	dB
|TDECQ – TECQ| (max)	-	2.5	2.5	dB
Average launch power of OFF transmitter (max)	–15	–15	–15	dBm
Extinction ratio (min)	3.5	3.5	3.5	dB
Transmitter transition time[c] (max)	17			ps
Transmitter over/under-shoot[c] (max)	-	12		%

[c] Using Square Wave or SSPRQ pattern, defined in 120.5.11.2.4 or 120.5.11.2.3, respectively

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- 100G Clause 140 Transmit Characteristics
- ➢ **Receive Characteristics Proposed Changes**
- 400G Clause 151 Receive Characteristics
- 100G Clause 140 Receive Characteristics

Supporters

- Shamim Akhtar, Apple
- Rich Baca, Microsoft
- Gang Chen, Baidu
- Sun Mewmin, Tencent
- Thang Pham, Facebook
- Zuowei Shen, Google
- Chongjin Xie, Alibaba

802.3 Receive Characteristics Formats

- Equation reference entry in main spec table is a new, unnecessary format to represent range of spec values
- The need to flip back and forth between the table and referenced equation makes routine use cumbersome
- Single number entry, the minimum value from the full range, is easy to understand and easy to routinely use
- All successful prior 802.3 optical standards use single number entries in main spec tables (.3ae, .3ba, .3bm, .3bs)
- If it ain’t broken, don’t fix it

802.3 Receiver Sensitivity (RS)

- Historical 802.3 RS definition is with an ideal, zero penalty reference TX, ex. .3ae, .3ba, making the spec conceptual
- Direct measurement is impractical, therefore an informative RS spec has been a pragmatic approach in past standards
- Many end users require RS testing, which in practice is done with non-ideal, non-zero penalty reference TX
- Resulting RS is better than required, or ad hoc penalty is subtracted which can result in interoperability problems
- Definition of reference TX with finite TECQ makes RS measurement practical, and normative RS spec pragmatic
- Normative RS spec definition leads to consistent testing and reduced risk of interoperability problems

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Draft 1.1 Clause 151 Receive Characteristics

Table 151–8—400GBASE-FR4 and 400GBASE-LR4-6 receive characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5		nm
Receiver sensitivity (OMA_{outer}), each lane[c] (max)	Equation (151–1)	Equation (151–2)	dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[d] (max)	–2.6	–4.7	dBm

[c] Receiver sensitivity (OMA_{outer}), each lane (max) is informative and is defined for a transmitter with a value of SECQ up to 3.4 dB for 400GBASE-FR4 and up to 3.5 dB for 400GBASE-LR4-6.
[d] Measured with conformance test signal at TP3 (see 151.8.11) for the BER specified in 151.1.1.

$$RS = \max(-4.6, SECQ - 6) \quad \text{(dBm)} \qquad (151\text{–}1)$$

$$RS = \max(-6.8, SECQ - 8.2) \quad \text{(dBm)} \qquad (151\text{–}2)$$

Proposed Clause 151 Receive Characteristics

Table 151–8—400GBASE-FR4 and 400GBASE-LR4-6 receive characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5		nm
Receiver sensitivity (OMA_{outer}), each lane[c] (max)	-4.6	-6.8	dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[d] (max)	–2.6	–4.7	dBm

[c] Receiver sensitivity (OMA_{outer}), each lane (max) is defined for a reference transmitter with a value of SECQ up to 1.4 dB. For SECQ greater than 1.4 dB, see equations (151-1), (151-2), for 400GBASE-FR4, 400GBASE-LR4-6, respectively.

[d] Measured with conformance test signal at TP3 (see 151.8.11) for the BER specified in 151.1.1.

$$RS = \max(-4.6, SECQ - 6) \quad \text{(dBm)} \qquad (151\text{–}1)$$

$$RS = \max(-6.8, SECQ - 8.2) \quad \text{(dBm)} \qquad (151\text{–}2)$$

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Draft 1.1 Clause 140 Receive Characteristics

Table 140–7—100GBASE-DR, 100GBASE-FR1, and 100GBASE-LR1 receive characteristics

Description	~~Value~~ 100GBASE-DR	100GBASE-FR1	100GBASE-LR1	Unit
Signaling rate (range)	53.125 ± 100 ppm			GBd
Modulation format	PAM4			—
Wavelengths (range)	1304.5 to 1317.5			nm
Receiver sensitivity (OMA_{outer})[c] (max)	Equation (140–1)	~~Equation (140–2)~~	~~Equation (140–3)~~	dBm
Stressed receiver sensitivity (OMA_{outer})[d] (max)	−1.9	−2.5	−4.1	dBm

~~[c]Receiver sensitivity (OMA_{outer}) (max) is informative and is defined for a transmitter with a value of SECQ up to 3.4 dB.~~
[d]Measured with conformance test signal at TP3 (see 140.8) for the BER specified in 140.1.1.

$$RS = \max(-3.9, SECQ - 5.3) \quad (\text{dBm}) \qquad (140–1)$$

$$RS = \max(-4.5, SECQ - 5.9) \quad (\text{dBm}) \qquad (140–2)$$

$$RS = \max(-6.1, SECQ - 7.5) \quad (\text{dBm}) \qquad (140–3)$$

Proposed Clause 140 Receive Characteristics

Table 140–7—100GBASE-DR, 100GBASE-FR1, and 100GBASE-LR1 receive characteristics

Description	~~Value~~ 100GBASE-DR	100GBASE-FR1	100GBASE-LR1	Unit
Signaling rate (range)	53.125 ± 100 ppm			GBd
Modulation format	PAM4			—
Wavelengths (range)	1304.5 to 1317.5			nm
Receiver sensitivity (OMA_{outer})[c] (max)	-	-4.5	-6.1	dBm
Stressed receiver sensitivity (OMA_{outer})[d] (max)	–1.9	–2.5	–4.1	dBm

[c] Receiver sensitivity (OMA_{outer}), each lane (max) is defined for a reference transmitter with a value of SECQ up to 1.4 dB. For SECQ greater than 1.4 dB, see equations (140-1), (140-2), (140-3), for 100GBASE-DR, 100GBASE-FR1, 100GBASE-LR1, respectively.

[d] Measured with conformance test signal at TP3 (see 140.8) for the BER specified in 140.1.1.

$$RS = \max(-3.9, SECQ - 5.3) \quad \text{(dBm)} \qquad (140–1)$$

$$RS = \max(-4.5, SECQ - 5.9) \quad \text{(dBm)} \qquad (140–2)$$

$$RS = \max(-6.1, SECQ - 7.5) \quad \text{(dBm)} \qquad (140–3)$$

802.3cu D1.1 PMD Proposed Changes

Thank You