In Response to TDECQ/SECQ Questions for Threshold Adjustments and Proposed Changes

(Comments r01-98, r01-104, r01-99, r01-103, r01-102, r01-97)*

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David Leyba, Keysight; Hai-Feng Liu, Intel
Marco Mazzini, Cisco; Kohichi Tamura, Oclaro
Mingshan Li, AOI; Mark Heimbuch, Source
Winston Way, NeoPhotonics; Mark Kimber, Semtech
Phil Sun, Credo Semiconductors

Special thanks to Ali Ghiasi for fruitful discussion on making the point that TDECQ value without threshold adjust may require module manufacturers to add additional guard banding during manufacturing (increase cost), but adjustable threshold receiver would require adjustable threshold SRS stressor.

*: With data to support comment resolutions for adding Adaptive Threshold Adjustments in computing TDECQ values (floating slicing)

IEEE P802.3cd March Plenary; 5 March 2018; Rosemont, IL

Update supporter list from Liu_3cd_01b_0118

Test instrument vendors
- Kan Tan (Tektronix)
- Greg LeCheminant (Keysight)
- Stephen Didde (Keysight)

Module/component vendors
- David Chen (AOI)
- Huanlin Zhang (AOI)
- David Lewis (Lumentum)
- David Li (Hisense)
- Mike Wang (Hisense)
- Scott Schube (Intel)
- Karen Liu (Kaiam)
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- Mizuki Shirao (Mitsubishi Electric Corp.)
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- Rang-Chen Yu (Molex)
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- Jeff Twombly (Credo)
- Atul Gupta (Macom)
- Matt Brown (Macom)
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- Vasu Parthasarathy (Broadcom)
- Bharat Taylor (Semtech)
- Mike Li (Intel)
- Kevin Zhang (Integrated Device Technology)

Systems vendors/users
- David Piehler (Dell EMC)
- Samuel Liu (Nokia)
- Chongjin Xie (Alibaba)
- Zuowen Shen (Google)
- Earl Parsons (CommScope)
- Pirooz Tooyserkani (Cisco)
- Jane Lim (Cisco)
- Matt Traverso (Cisco)
- Tomoo Takahara (Fujitsu Lab)
- Tongqing Wang (Alpine Optoelectronics)
- Nathan Tracy (TE Connectivity)

Outline

- Problem Statements
  - To follow up discussion/questions from January interim
- Why threshold adjustment is necessary
  - Make the reference receiver close to real receiver by adding threshold adjustments
- Improved correlation between TDECQ and BER with threshold adjustment
  - Current correlation with D3.1 is considered arguably “poor”.
- Small amounts of threshold adjustment have minimal impact on receiver sensitivity (SRS)
  - Using real ASICs under low power DSP to mode mimic reference 5T equalizers.

Problem Statements

- Strong support to add Adaptive Slicing in Ref. equalizers to resolve TDECQ specs dilemma (mazzini_120617_3cd_adhoc-v2)
  - Supported by 30+ companies including majority module and IC vendors as well as systems vendors/users.
  - Extensive data demonstrated some improvements (~0.3-0.4dB) across all transmitter types: DML, VCSEL, EML, and MZM.
  - Keysight and Tektronix have just released in mid Feb new beta FW with floating thresholds as defined in recent proposal. It includes setting an adjustable limit.
- Some questions asked “why threshold adj. is needed?” in real RX IC implementation – a tutorial.
- No analog equalizers available with 5T for link BER measurements.
- Follow up questions from the editorial team (cite JonathanK)
  - Show improves correlation between TDECQ vs measured receiver sensitivity.
  - Show not too high a stress for the receiver in SRS tests

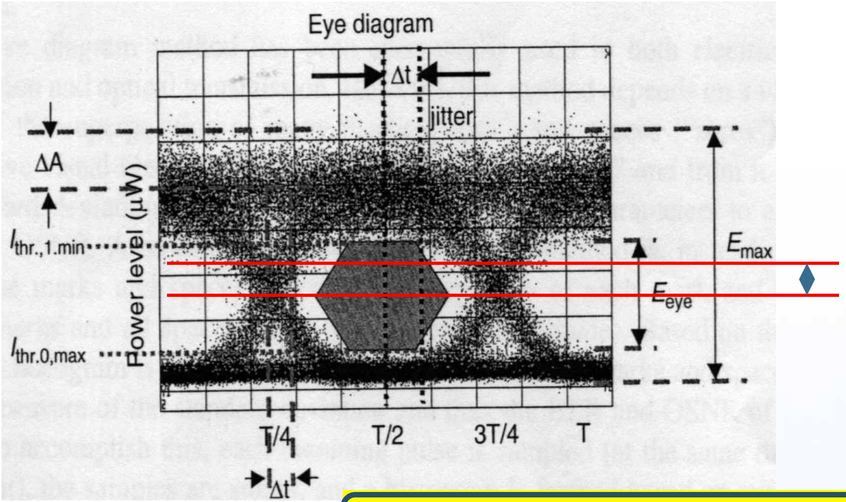
Why Threshold Adjustment is Necessary (1)

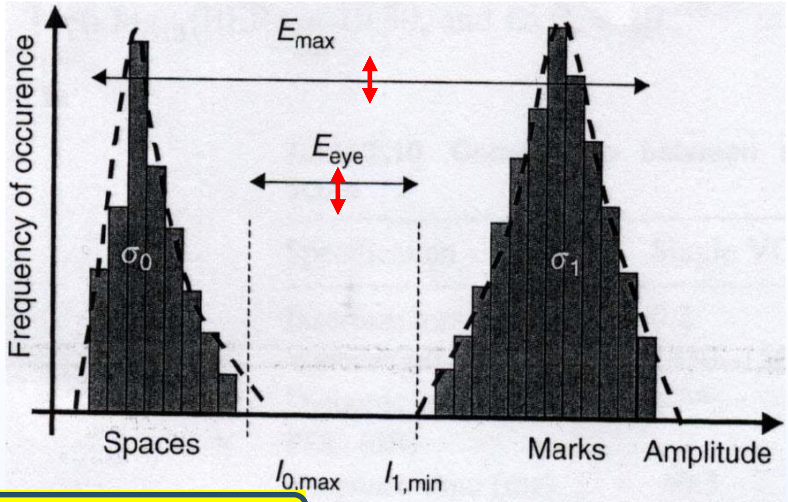
- The benefits of adaptive decision thresholds have been pointed out in many studies on CDRs & SerDes ICs for direct detect NRZ systems
  - Either manual or adaptive for optimized BER, refs. e.g.
    1) Matsumoto et al. "*An adaptive decision threshold control of the optical receiver for multi-gigabit terrestrial DWDM transmission systems*"; OFC 2001, Paper TuR2, March 2001. (2.5G NRZ)
    2) Park et al. "*Performance Analysis for Optimizing Threshold Level Control of a Receiver in Asynchronous 2.5 Gbps/1.2 Gbps Optical Subscriber Network with Inverse Return to Zero(RZ) Coded Downstream and NRZ Upstream Re-modulation*"; J. OSK V.13, No.3. pp361-366, Sept 2009. (2.5G/1.25G NRZ)
    3) Yan et al. "Performance enhancement in *10-Gb/s long-haul fiber links with adaptive eye mapping in an integrated Si-CMOS 16-bit transceiver IC*"; IEEE Photonics Tech. Letters, Vol.17, No.8, pp1752-4, Aug. 2005. (10G NRZ)
    4) Chang et al; "*Accurate in-situ monitoring of Q-factor and BER using adaptive sampling in a 10Gb/s CMOS optical receiver IC*"; IMS05, Paper WEPL-3, June 2005. (10G NRZ)

- Adaptive decision thresholds have also been studied for coherent DSPs in QAM systems like QPSK & 16QAM for 100+G coherent DSP, refs. e.g.
    1) Chiba et al. "*Adaptive threshold adjustment for signal distortion-free digital-coherent optical demodulation system*"; Vol.16, No.26, Opt. Express, pp21647-55, Dec. 2008.

Why Threshold Adjustment is Necessary (2)

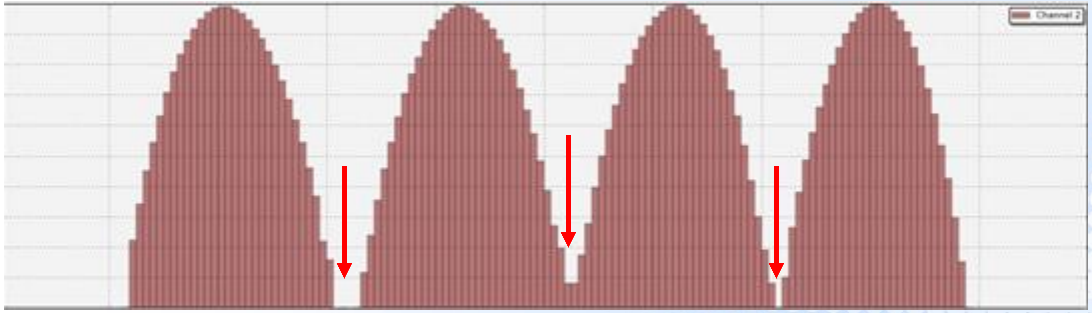
- Results from unevenly distributed noise on 0/1 levels





Average threshold ≠ Optimum point

- Actually measured PAM4 histograms show similar



In real ASIC implementations, decision threshold level and phase of received data in the decision circuit are automatically adjusted to the optimum position

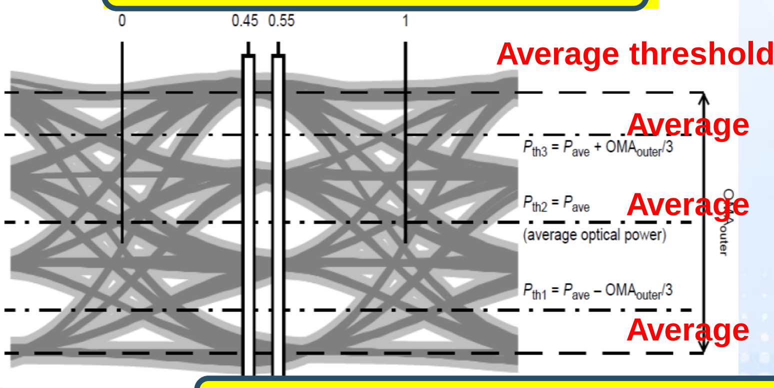
Why Threshold Adjustment is Necessary (3)

- Threshold adjustment help improve implementing TDECQ
  - With threshold adj, TDECQ is consistent across temperature so no guardband required in manufacturing (less test, higher yield, lower cost).
  - D3.1 case: 0.3-0.4dB, guardband needed in manufacturing (increase test over temp, lower yield, and high cost)

DUT TX → Room Temp → Scope
TDECQ≤**3-3.1dB**

DUT TX → Higher Temp → Scope
TDECQ≤**3.4dB**

More risk in compliance

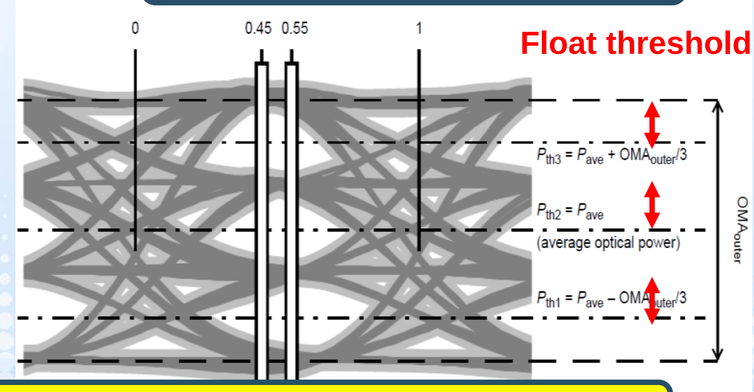


\- With threshold Adjustments

DUT TX → Room Temp → Scope
TDECQ≤**3.4dB**

DUT TX → Higher Temp → Scope
TDECQ≤**3.4dB**

Less risk in compliance



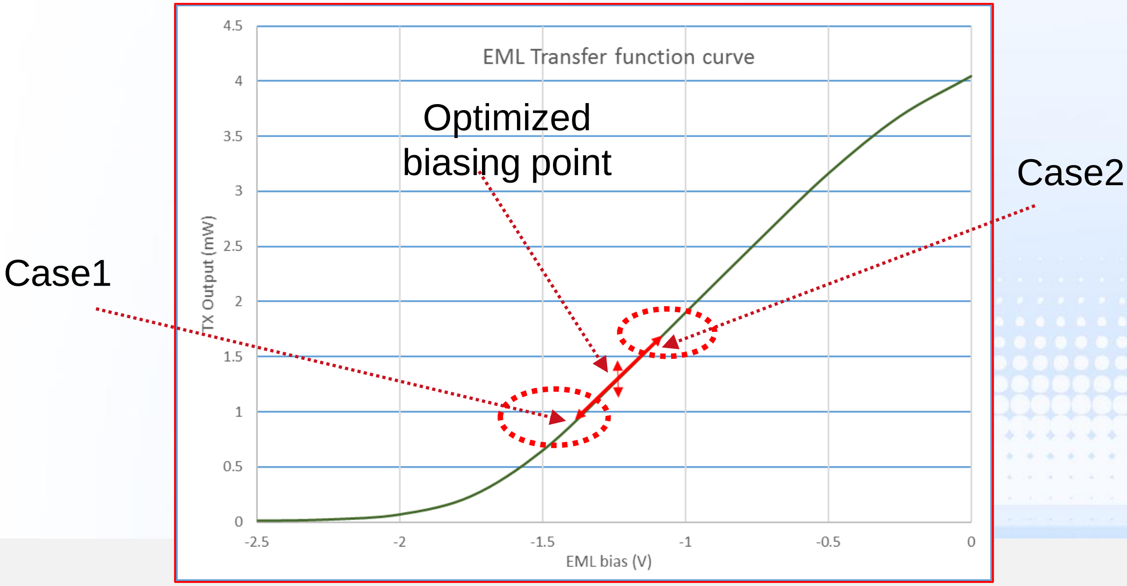
Threshold Adjustment help reduce the risk in product test compliance

Correlate TDECQ with Rx Sensitivity

Under well controlled lab environments with golden EML TOSA, following 3 scenarios are considered for threshold adjustment within the limit of <2%

- (Setup refer to chang_011018_3cd_02_adhoc-v2 & chang_3cd_01a_0917)

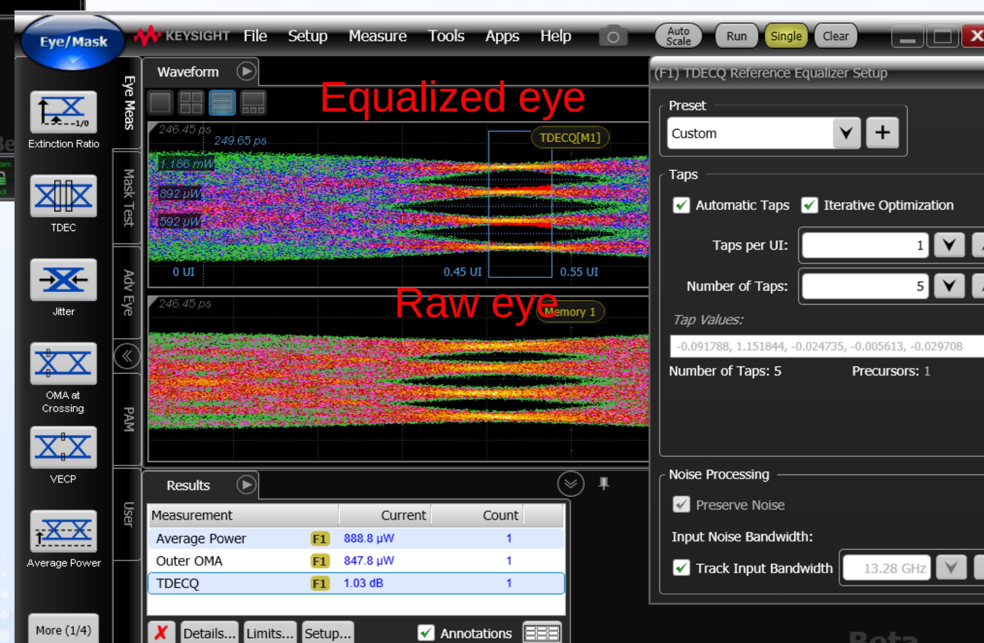
- Full optimized EML condition, full link optimized with best BER condition.
  - Optimized EML Bias voltage, and Linear driver nonlinearity
- Off-optimized conditions,
  - Keep default EML bias voltage (VEML), vary Linear driver nonlinearity
- Unoptimized Case 1: Move two TX setting downwards;
  - Vary VEML bias down by ~ 150mV, and vary driver gain accordingly (all the rest no change)
- Unoptimized Case 2: move TX setting upwards;
  - Vary VEML bias up by ~ 150mV and vary driver gain accordingly (all the rest no change)



TX eye diagrams: optimized condition (D3.1)

Full optimized case (D3.1) ER=6.1dB
TDECQ/SECQ=1.26dB, RLM=0.955

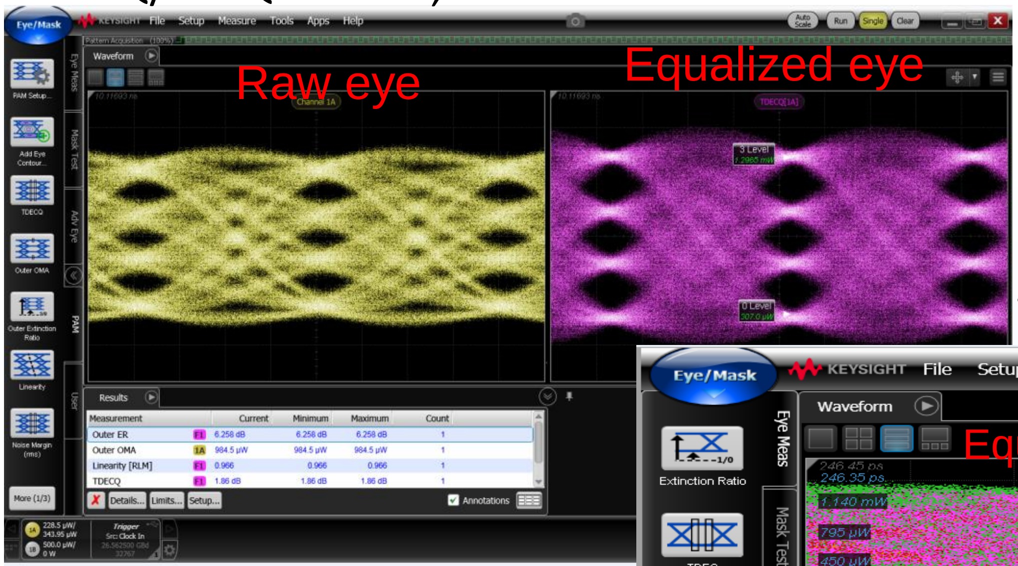
Optimized case D3.1 with threshold Adj
TDECQ/SECQ=1.03dB



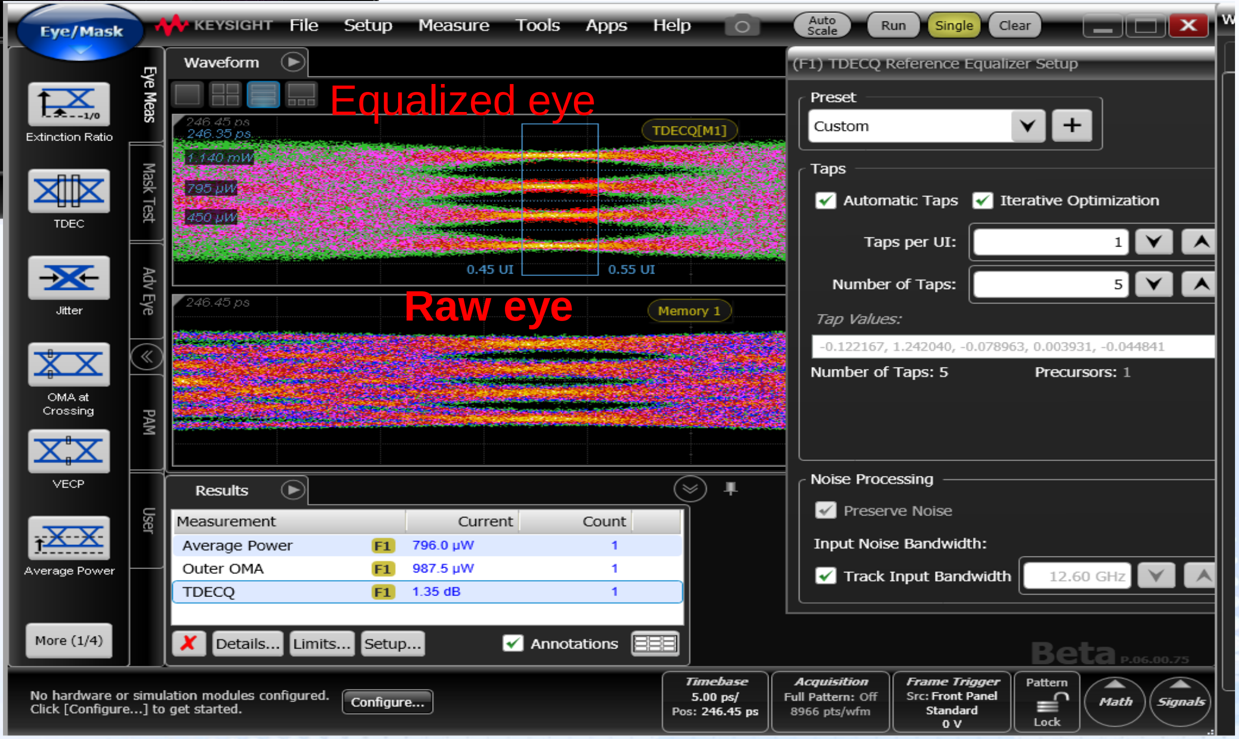
Note: TDECQ/SECQ tests for slides#9-12 are actually SECQ (without test fiber) and based on PRBS15 pattern.

TX eye diagrams: off-optimized condition (D3.1)

Off-optimized case (D3.1) ER=6.2dB
TDECQ/SECQ=1.86dB, RLM=0.966



Off-optimized case D3.1 with threshold Adj
TDECQ/SECQ=1.35dB, Adj~1.% of OMAouter



		Adj	%
Pth3	1130.167	-9.83333	-0.99%
Pavg	796	-1	-0.13%
Pth1	466.8333	-6.83333	-0.69%

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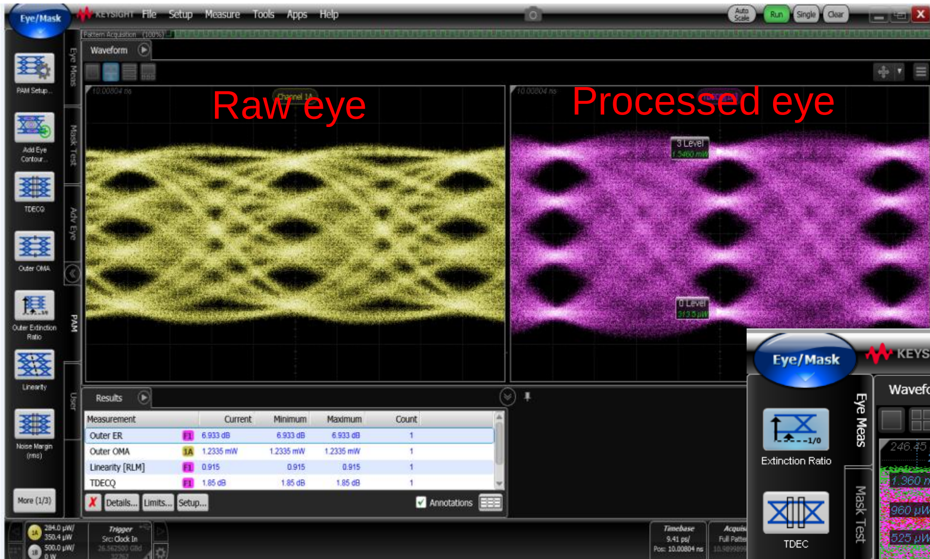
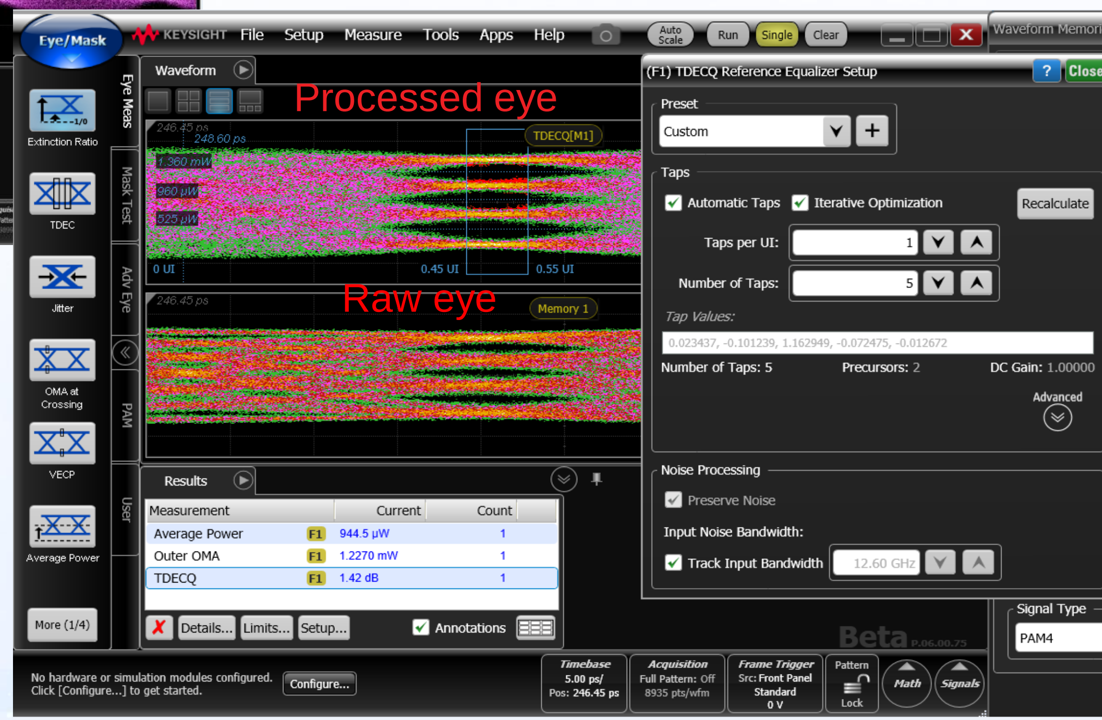
TX eye diagrams: Case1 (D3.1)

Unoptimized Case1: ER=6.9dB
TDECQ/SECQ=1.85dB, RLM =0.915



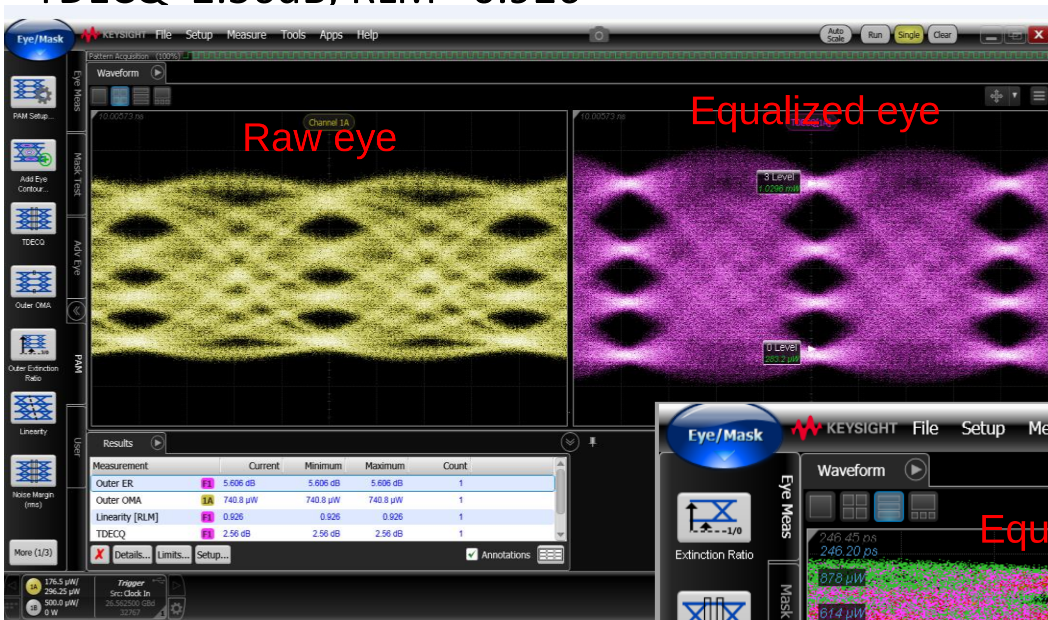
Case1(D3.1 with threshold Adj)
TDECQ/SECQ=1.42dB Adj within +1.95%



		Adj	%
Pth3	1353.5	6.5	0.53%
Pavg	944.5	15.5	1.95%
Pth1	535.5	-10.5	-0.86%

TX eye diagrams: Case2 (D3.1)

Unoptimized case2 ER=5.6dB, TDECQ=2.56dB, RLM =0.926

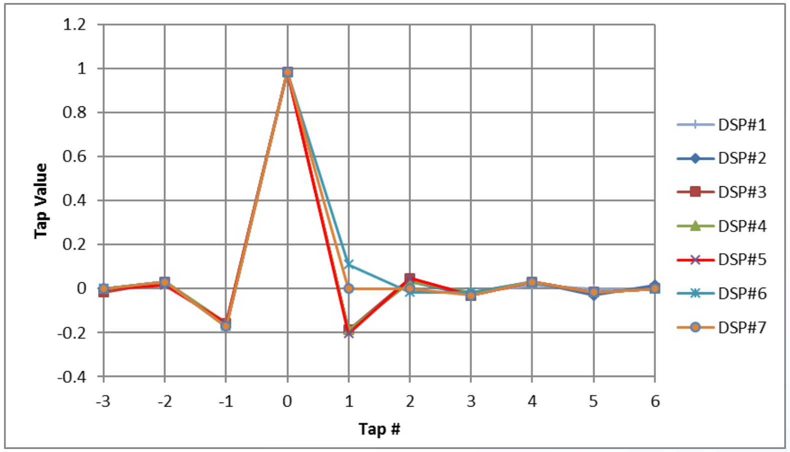


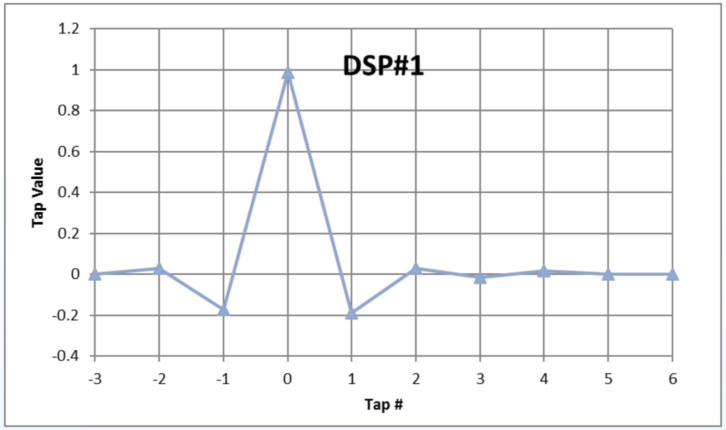
Case2 (D3.1 with threshold Adj) TDECQ=1.68dB, Adj within -1.93%

	Adj	%
Pth3	877.3333	0.666667	0.09%
Pavg	629.4	-15.4	-1.93%
Pth1	381.4667	0.533333	0.07%

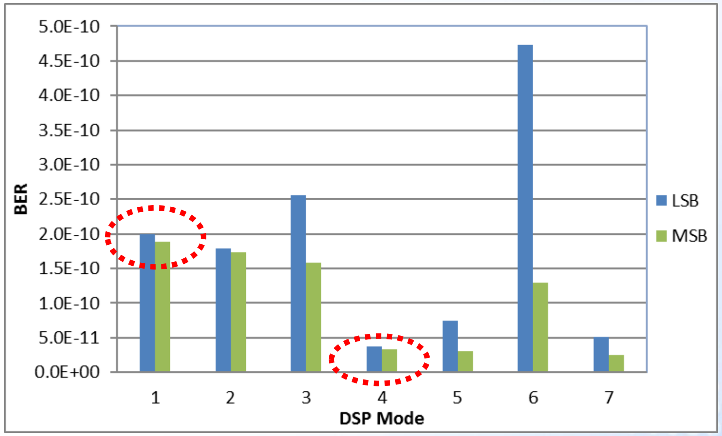
Correlate TDECQ with Rx Sens: how to tackle the analog equalizer non-availability issue

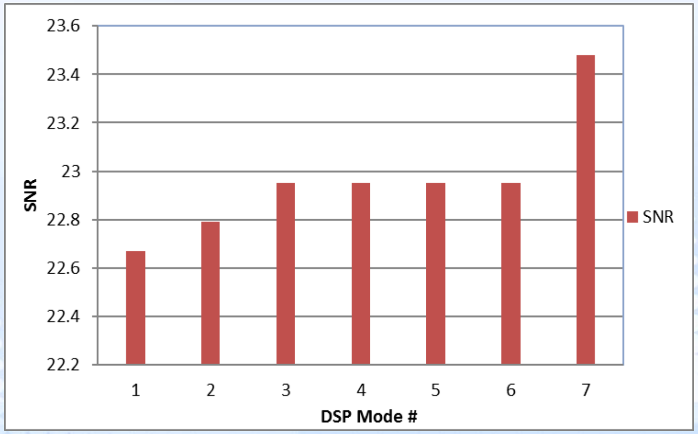
- Emulated low power DSP Mode with closer to Ref 5T equalizers for link BER measurements.





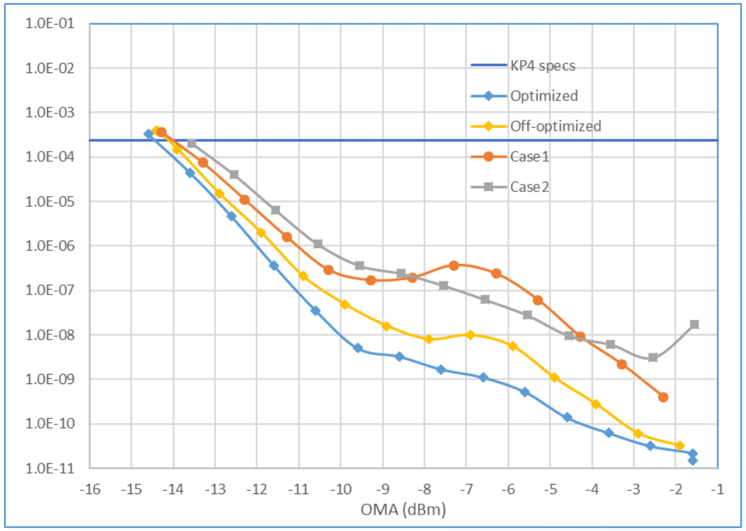
- Comparing performance of various DSP modes (for BER flooring)

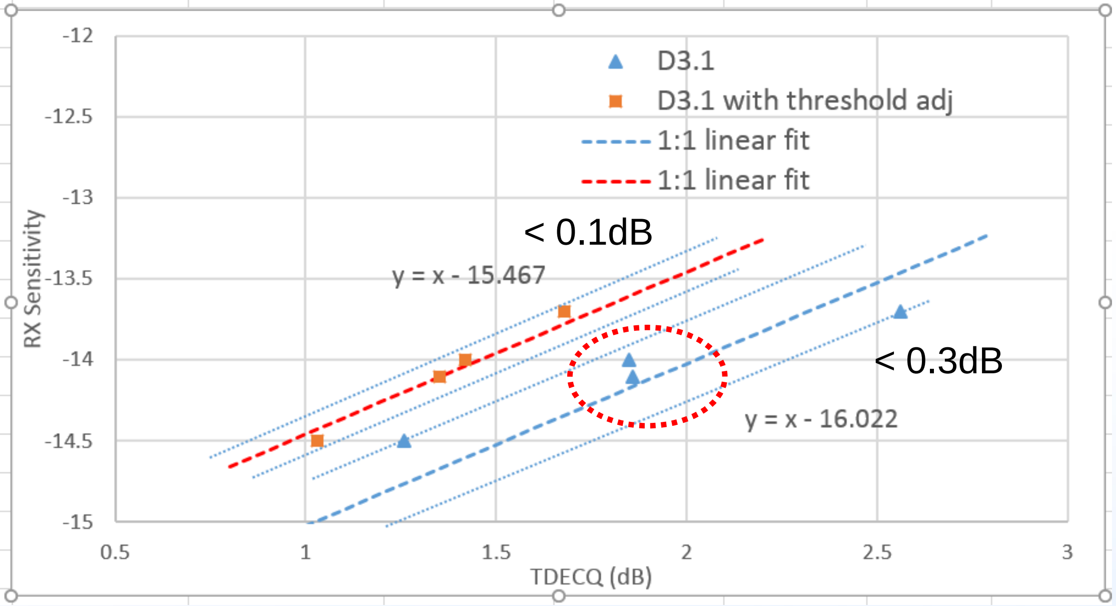




Correlate TDECQ with Rx Sensitivity

- Link BER performance





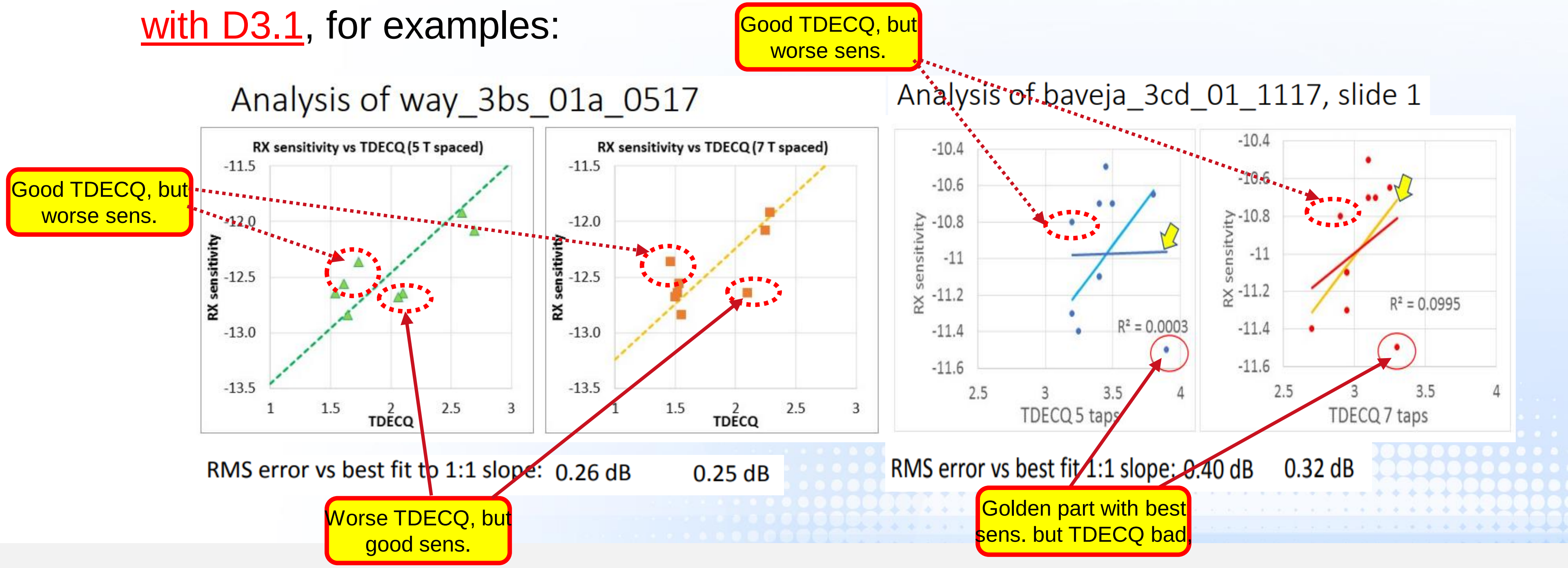
	Full optimized	off-optimized	Case1 <-2%	Case2 <+2%
EML bias	-1.28	-1.26	-1.41	-1.12
ER	6.1	6.2	6.9	5.6
TDECQ (D3.0)	1.26	1.86	1.85	2.56
TDECQ (TH adj	1.03	1.35	1.42	1.68
OMA Sens.	-14.5	-14.1	-14	-13.7

Note: 1:1 linear fit is a better approximation with threshold adjustment than the fixed threshold case which could be argued to be less than 1:1.

Show better correlation with TDECQ and predict well how RX sens. will vary when threshold adjustment is implemented with limits

Correlating TDECQ with Rx Sensitivity (D3.1)

- Some thoughts: All of us who took the data feel this correlation is "poor". Where is the "disconnection" with data analysis by king_3cd_01_0118?
  - The data analysis were good but based on statistics in macro scale with large fitting error of 0.3-0.4dB. If looking into individual TOSAs, there are many exceptions for the situation that good TDECQ values delivers worse RX Sens and vise verse, so simply tough to predict RX sensitivity from TDECQ values with D3.1, for examples:

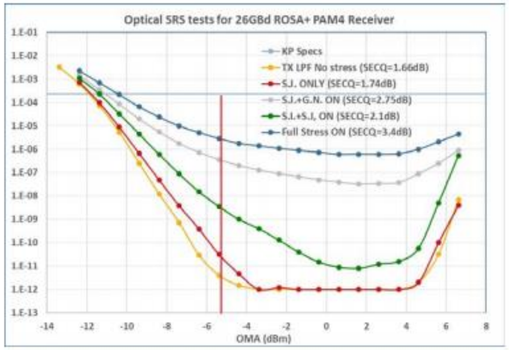


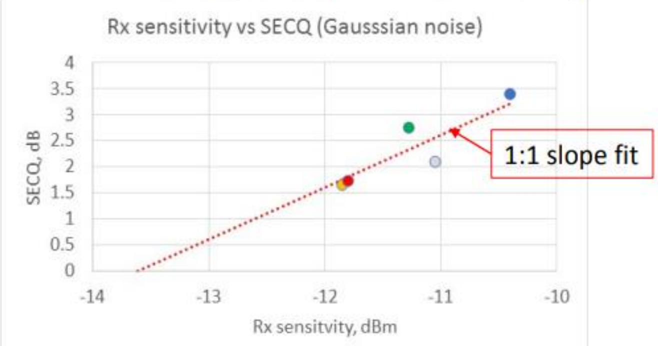
The Impact to RX SECQ (D3.1)

- Recap current analysis with D3.1 by (king_3cd_01_0118)
  - LN MZM TX for instrument testers are well behaved linear devices, and expect to show better correlation.

Analysis of chang_cd_01_1117: BER plots vs SECQ (5 tap T-spaced)

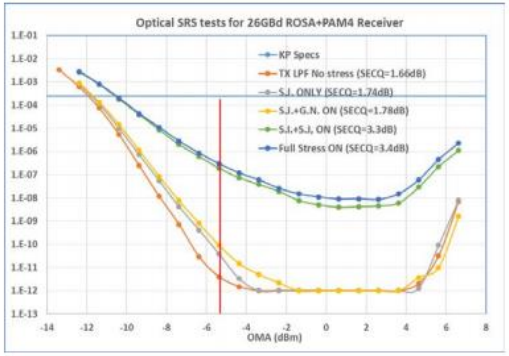
Gaussian noise dominant
RMS error < 0.3 dB

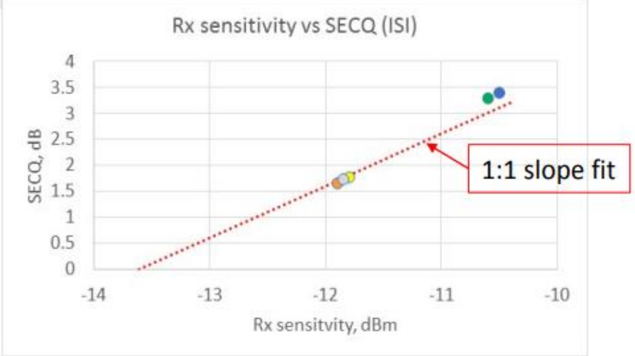




SI dominant
RMS error < 0.2 dB

Very good dB/dB fit for both cases





- *chang_3cd_01_1117* concluded that "*There exists strong interplay between G.N and S.I (with S.J.). G.N. impact most the BER degradation in SRS.*". **But the data shows very good correlation between SECQ and Rx sensitivity for both GN and SI dominant stress (RMS error of <0.3 dB)**

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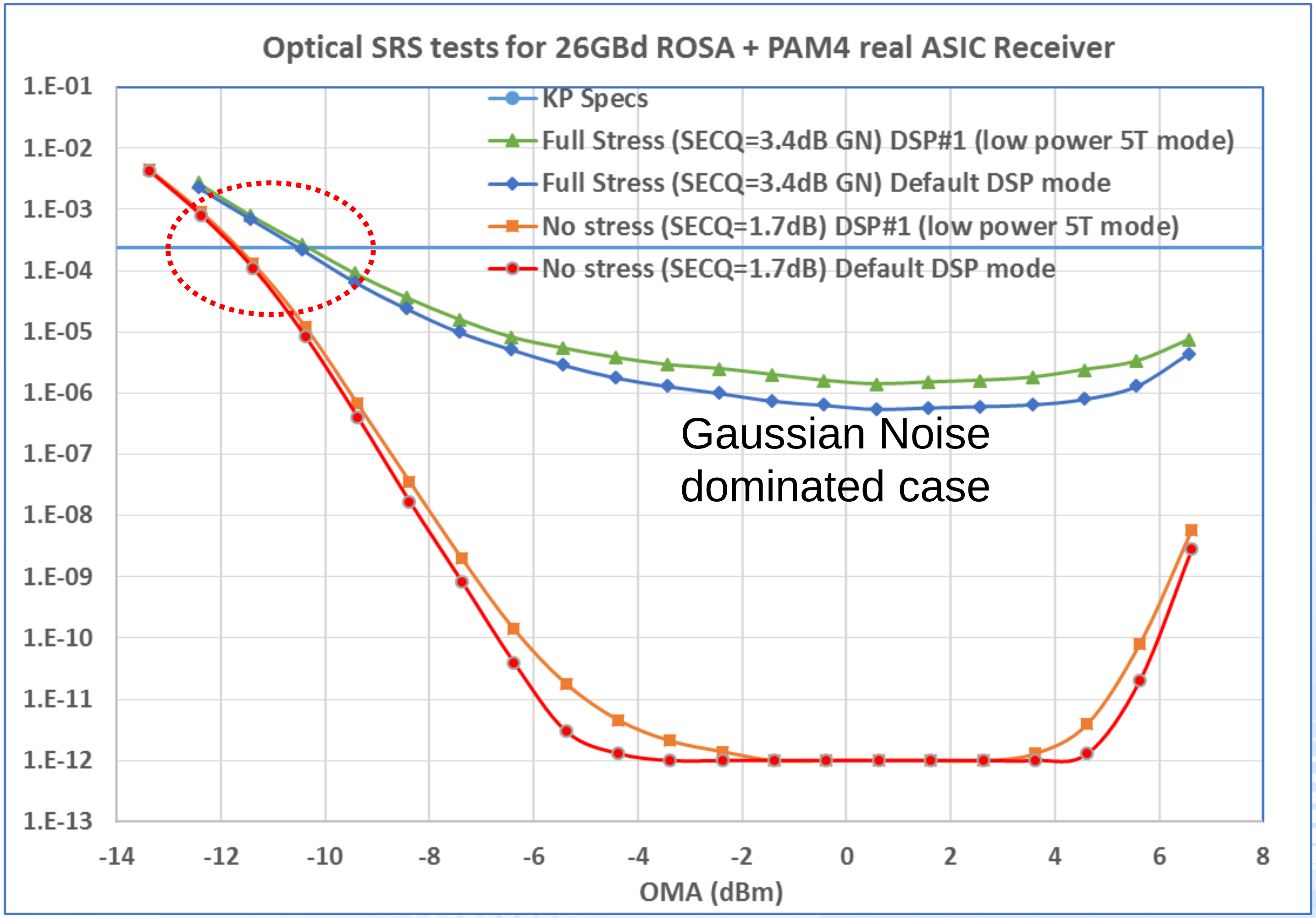
Impact to RX SRS (D3.1) by different DSP modes

- Negligible impact on RX SRS Sensitivity by different DSP modes. (only little degrade on BER flooring) chang_3cd_01_1117

LM MZM TX SSPRQ pattern

Compare Rx SRS under different DSP modes for no (B2B) and fully stressed



Impact to RX SRS (D3.1) by different DSP modes

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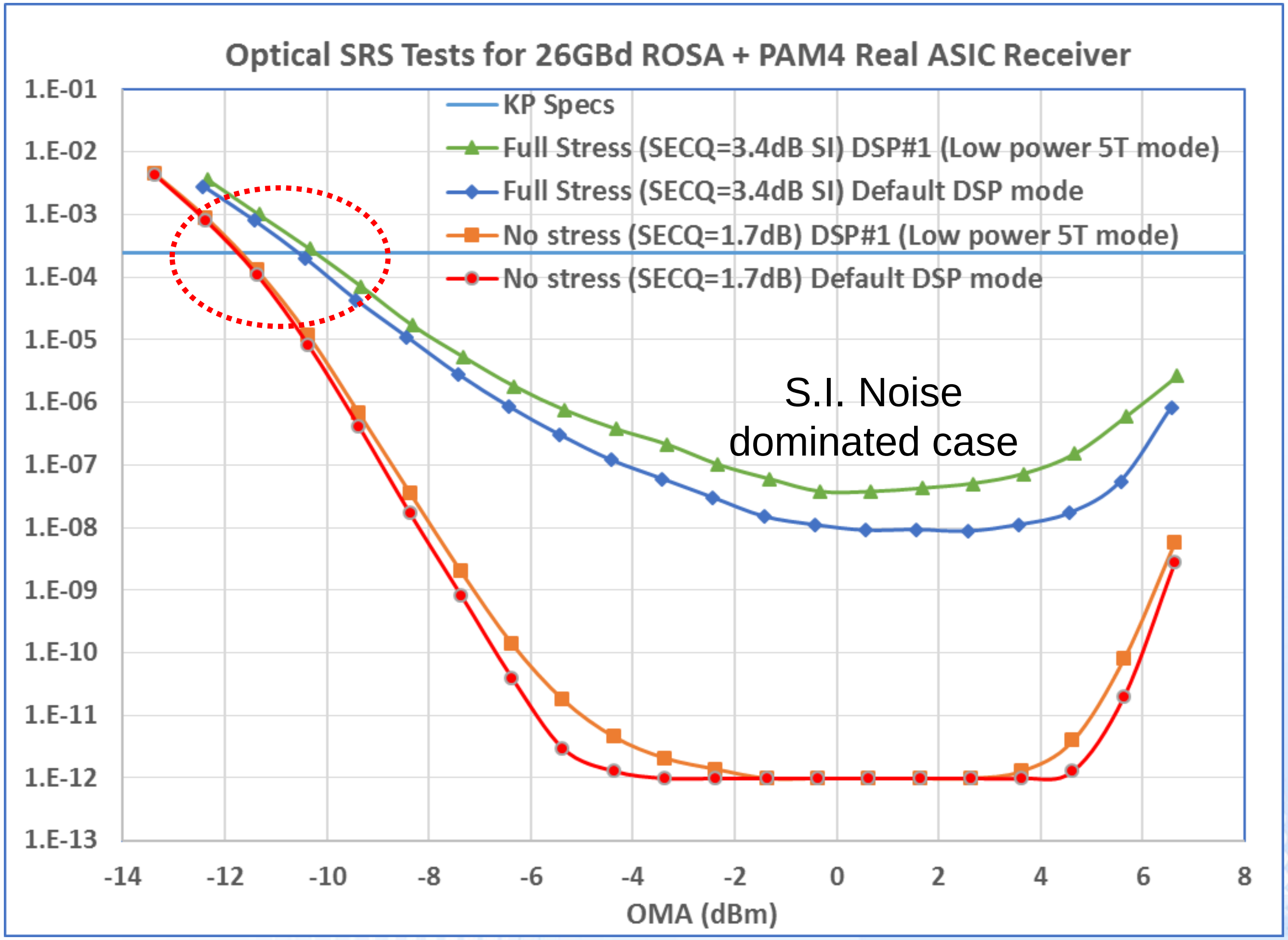
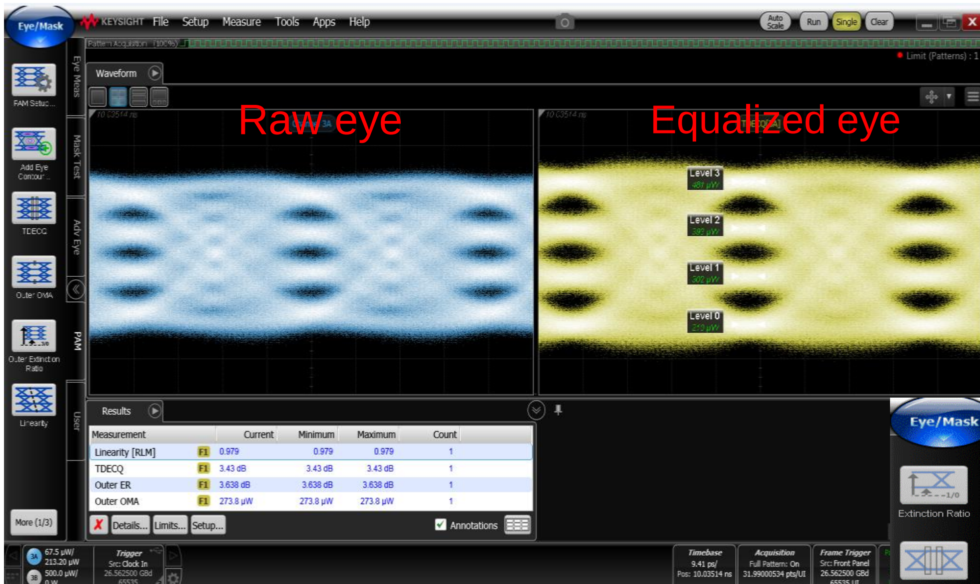
LM MZM TX SSPRQ pattern

Compare Rx SRS under different DSP modes for no (B2B) and fully stressed

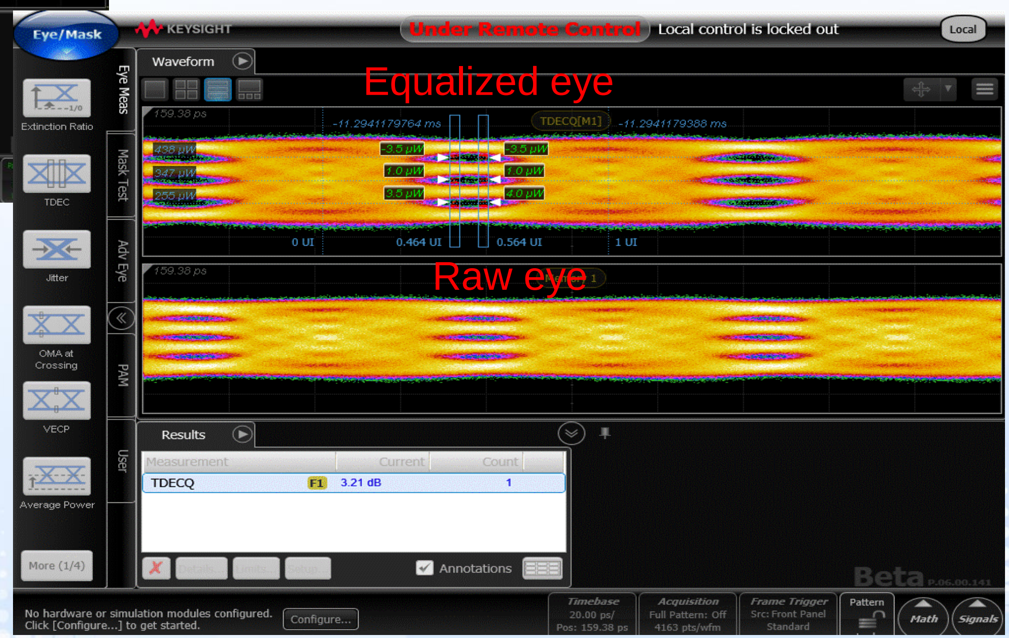


The Impact to RX SECQ

D3.1 Full stressed, RX LPF~13.28GHz
- SECQ=3.43dB, ER=3.6dB



Re-process using new beta FW release with threshold Adj
SECQ=3.21dB, Adj within 1.46%



	uW	Adj (uW)	
Pth3	438	-3.5	-1.28%
Pavg	347	1	0.37%
Pth1	255	4	1.46%
OMAouter	273.8		

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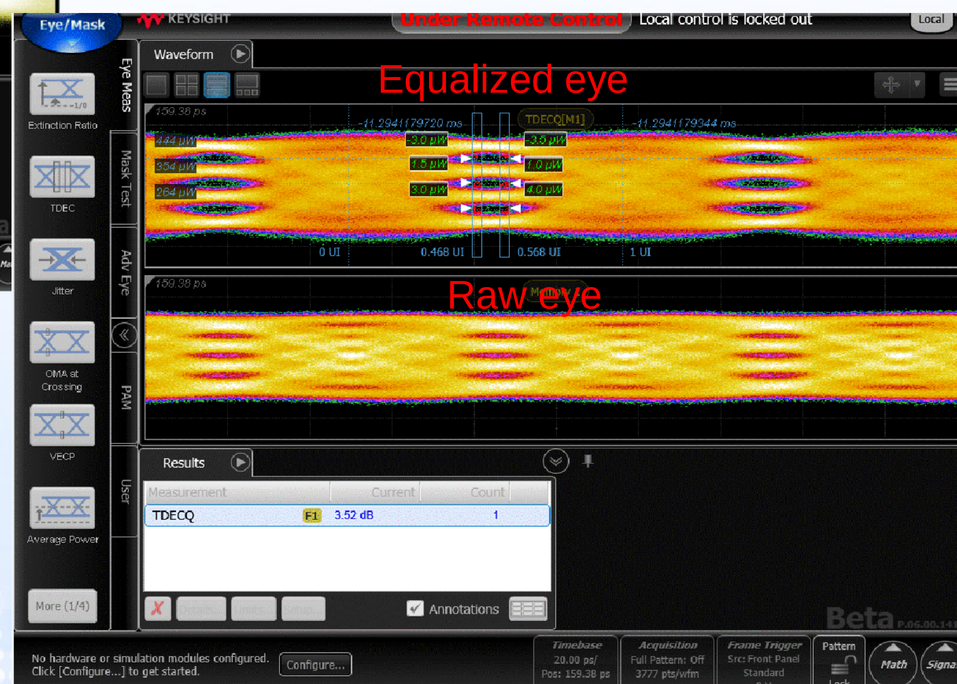
The Impact to RX SECQ

D3.1 over-stressed, RX LPF~13.28GHz
SECQ=3.64dB, ER=3.5dB

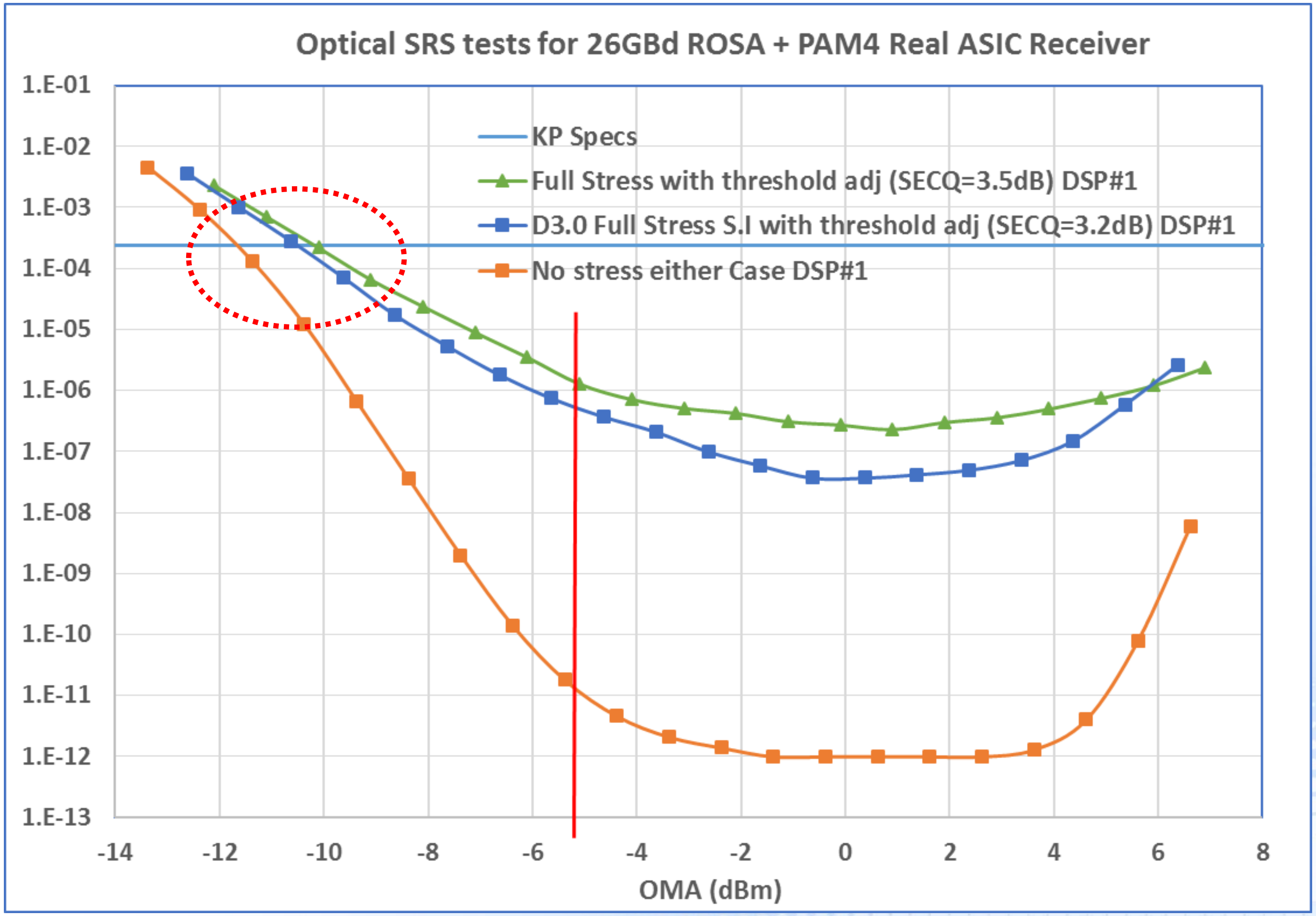
Re-process using new beta FW release with threshold Adj
SECQ=3.52dB, Adj within -0.73%



	uW	Adj (uW)	
Pth3	446	-2	-0.73%
Pavg	354	1	0.37%
Pth1	263	1.5	0.55%
OMAouter	274.7		

The Impact to RX SRS Sensitivity

- The impact on the Rx SRS is <0.2dB.
  - The real ASIC has threshold adjustment implemented.



Concluding Remarks (1)

- Adding threshold adjustment will minimize the need for guard banding and over temperature testing during manufacturing as well as aging, thus reduced test, higher yield and lower cost.
- Measured link BER with an emulate 5T equalizers by operating at low power DSP mode.
  - Eliminate the dilemma due to the non-availability of analog equalizers usable for such kinds of tests.
- Threshold adjustment measurements show an improved correlation with receiver sensitivity (<0.1dBrms) and closer to 1:1 fit (as requested)
- The stress on RX SRS tests falls well within 0.1-0.2dB (or less). It seems much less than what we originally thought after setting the limits to the adjustable range.

Concluding Remarks (2)

- Minimum risks to add threshold adjustment into TDECQ algorithm.
  - Unless real receiver have threshold adjustment, the transmitter environmental variations and aging will result in TDECQ degradation requiring increased TDECQ guard banding in manufacturing (increased test, lower yield, higher cost).
  - Real receivers will implement threshold adjustment to cope with temperature and aging variations. Using a **small** part of the adjustment range will allow for improved yield and lower cost.
  - Real receivers optimize the decision thresholds, so the TDECQ reference receiver can also be allowed to optimize thresholds. If the adjustment range for each threshold is much smaller than that of real receivers, the receiver specifications can remain unchanged.
- This will make significant improvement over D3.1
  - Lower risk for compliance test in manufacturing.

Proposed Change: 138.8.5

Insert the text shown below in red to the list of exceptions

138.8.5 Transmitter and dispersion eye closure - quaternary (TDECQ)

TDECQ is a measure of each optical transmitter's vertical eye closure as measured through an optical to electrical converter (O/E) with a bandwidth equivalent to a combined reference receiver and worst case optical channel, and equalized with the reference equalizer specified in 138.8.5.1. Table 138–9 specifies the test pattern to be used for measurement of TDECQ.

TDECQ of each lane shall be within the limits given in Table 138–8 if measured using the methods specified in 121.8.5, with the following exceptions:

— The polarization rotator and test fiber shown in Figure 121–4 are not used

— The optical channel requirements in 121.8.5.2 do not apply

— The combination of the O/E and the oscilloscope used to measure the optical waveform has a fourth-order Bessel-Thomson filter response with a bandwidth of 11.2 GHz.

— The reference equalizer to be used for TDECQ for 50GBASE-SR, 100GBASE-SR2, and 200GBASE-SR4 is specified in 138.8.5.1.

--- P_{th1}, P_{th2}, and P_{th3} may be varied by up to 2% of OMA_{outer}.

Proposed Change: 139.7.5.3

Change the text as shown below in red.

139.7.5.3 TDECQ measurement method

~~TDECQ for 50GBASE-FR and 50GBASE-LR is measured as described in 121.8.5.3 with the exception that the reference equalizer is as specified in 139.7.5.4.~~

TDECQ for 50GBASE-FR and 50GBASE-LR is measured as described in 121.8.5.3 with the following exceptions:

- The reference equalizer is as specified in 139.7.5.4
- P_{th1}, P_{th2}, and P_{th3} may be varied by up to 2% of OMA_{outer}

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Proposed Change: 140.7.5

Insert the text shown below in red to the list of exceptions

140.7.5 Transmitter and dispersion eye closure for PAM4 (TDECQ)

The TDECQ shall be within the limits given in Table 140–6 if measured using the methods specified in 121.8.5.1, 121.8.5.2, and 121.8.5.3 using a reference equalizer as described in 140.7.5.1, with the following exceptions:

— The optical return loss of the transmitter compliance channel is 15.5 dB.

— The signaling rate of the test pattern generator is as given in Table 140–6 and uses a test pattern specified for TDECQ in Table 140–10.

— There are no interfering optical lanes and therefore the delay requirement of at least 31 UI between test pattern on one lane and any other lane, as specified in 121.8.5.1, is redundant.

— The combination of the O/E converter and the oscilloscope has a fourth-order Bessel-Thomson filter response with a bandwidth of approximately 26.5625 GHz.

— The normalized noise power density spectrum, *N*(*f*) in Equation (121–9), is equivalent to white noise filtered by a fourth-order Bessel-Thomson response filter with a bandwidth of 26.5625 GHz.

--- P_{th1}, P_{th2}, and P_{th3} may be varied by up to 2% of OMA_{outer}.

Thank You