802.3cd (comments #i-79-81).
Threshold Adjustment Proposal for TDECQ Measurement and SECQ Calibration

Marco Mazzini, Cisco

Frank Chang, Inphi

Mingshan Li, AOI

Mark Heimbuch, Source Photonics

Phil Sun, Credo Semiconductors

Hai-Feng Liu, Intel

Kohichi Tamura, Oclaro

David Leyba, Keysight

Winston Way, NeoPhotonics

Mark Kimber, Semtech

Supporter List

- David Chen (AOI)
- Huanlin Zhang (AOI)
- David Lewis (Lumentum)
- David Li (Hisense)
- Mike Wang (Hisense)
- Scott Schube (Intel)
- Sudeep Bhoja (Inphi)
- Pavel Zivny (Tektronix)
- Jeff Twombly (Credo)
- Karen Liu (Kaiam)
- Alex Tselikov (Kaiam)
- Ed Ulrichs (Source Photonics)
- Zhigang Gong (O-Net)
- David Piehler (Dell EMC)
- Samuel Liu (Nokia)
- Chongjin Xie (Alibaba)
- Earl Parsons (CommScope)
- Atul Gupta (Macom)

Background

- Current TDECQ measurement is based on using SSPRQ data for a reference receiver with:
  - Limited BW (e.g., at Nyquist)
  - 5 T-spaced taps for equalization

The maximum value specified (e.g. 3.4 dB) is also used as SECQ in Rx test.

- There have been a number of contributions on TDECQ measurement
  - way_3bs_01a_0717, way_3bs_01a_0717
  - tamura_3bs_01a_0917, tamura_01a_1017_smf
  - chang_3cd_01a_0917
  - baveja_3cd_01_1117

<u>That raised the issue that many TX units that were able to close the link BER tests with margins might fail TDECQ tests.</u>

- Several ways to relax the TDECQ test were considered including:
  - Adjustment of reference Rx BW
  - Increase the number of FFE taps in reference equalizer
  - Use of different patterns in TDECQ testing
  - Increase the specs for TDECQ max.

but none of them provides a satisfactory resolution to the above issue.

- Recently a proposal to relax the TDECQ test was made by adjusting the thresholds of each sub-eye (mazzini_120617_3cd_adhoc-v2)

Motivation

This presentation is to follow up the proposal to:

1. Review the proposal of adding threshold adjustment into TDECQ measurement
2. Show threshold variation theory and measured TDECQ data with threshold adjustment
3. Recommend the amount of adjustment and the introduction of optical RLM_{min} derived from point 2 above
4. Review the impact of the proposed change on SECQ, so to be able to agree on further steps to ensure TDECQ will improve transmitter yield without breaking receivers.

Review the Proposed Change of Threshold Adjustment

- TDECQ threshold definition background

- The decision thresholds used in current TDECQ method (802.3bs, 121.8.5.3) are equally spaced, with the sub-eye threshold levels Pth1, Pth2, and Pth3 determined by OMAouter and average power (Pave) as defined in Equations (121–1), (121–2), and (121–3).

$$(121\text{–}1)\qquad P_{\text{th1}} = P_{\text{ave}} - \frac{OMA_{\text{outer}}}{3}$$

$$(121\text{–}2)\qquad P_{\text{th2}} = P_{\text{ave}}$$

$$(121\text{–}3)\qquad P_{\text{th3}} = P_{\text{ave}} + \frac{OMA_{\text{outer}}}{3}$$

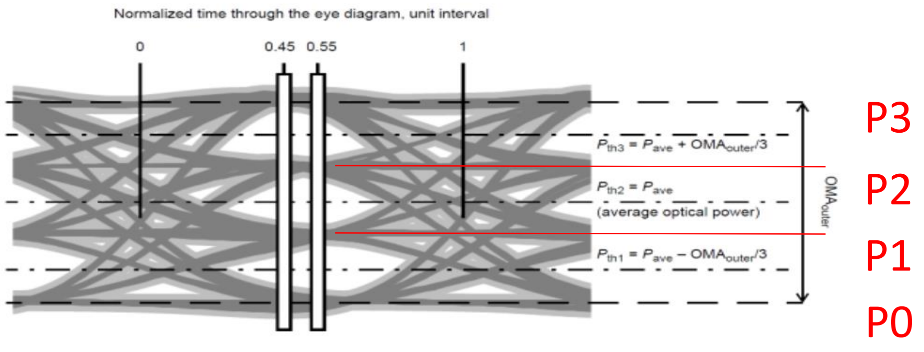


Figure 121–5—Illustration of the TDECQ measurement

- While TDECQ thus defined works fine for linear signals with equal eye amplitude, the thresholds would not be optimum for signals
  - Close to ideal transmitter
  - With unequal eye amplitudes after equalization
  - With different noise levels for different signal levels

Threshold Variations and TDECQ Measurements with Threshold Adjustment Implemented

- PAM4 threshold variation versus filtering (Mark K.)
- $LiNbO_3$ MZM data (mazzini_120617_3cd_adhoc)
- AOI's data on DML
- Data on EML, and VCSEL (chang_011018_3cd_adhoc)

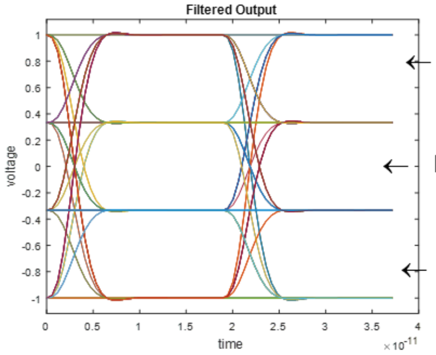
Results achieved with custom Keysight TDECQ algorithm implementing threshold adjustment.

PAM4 Threshold Variation versus Filtering

- Intent is to understand if filtering changes the average threshold value
- Create PAM4 eye
  - PRBSQ15
  - Grey coded
  - 2^{20} bits = 1,048,576 bits
  - -1, -1/3, +1/3, +1 levels
  - 131070 x “0”, 131072 x “1”, 131073 x “2”, 131073 x “3”
  - RLM = 1.0 for these simulations (based on long term 0 and 3 levels)
- Filter waveform
  - 4 pole Bessel or 4 pole Butterworth
- Average samples for each eye region
  - Lower threshold V <= -1/3
  - Middle threshold -1/3 <= V <= 1/3
  - Upper threshold V >= 1/3
- TDECQ thresholds based on OMAouter/3
  - Lower threshold = -0.6667
  - Middle threshold = 0
  - Upper threshold = 0.6667
- NB – Average eye value does not infer optimum threshold

Summary of Different Filtering Cases

100GHz Bessel Filter Eye

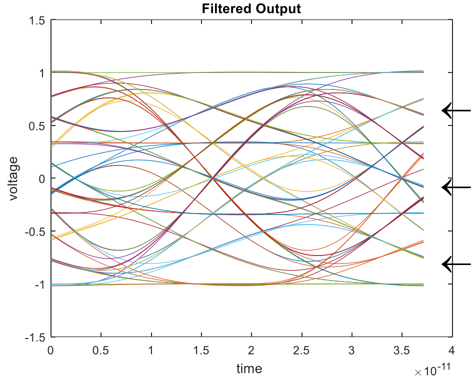


Upper eye average = 0.7570

Middle eye average = 5.6103e-6

Lower eye average = -0.7570

20.0GHz Bessel Filter Eye

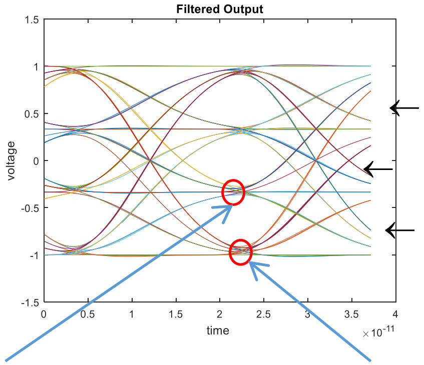


Upper eye average = 0.6774

Middle eye average = -2.1543e-7

Lower eye average = -0.6774

26.6GHz Bessel Filter Eye



Upper eye average = 0.7149

Middle eye average = 1.5147e-5

Lower eye average = -0.7149

With Bessel filter, eye closure is symmetrical about level

With Bessel filter, eye closure is from outer level into eye

For all cases,
Total waveform average = 6.3578e-6

- Changing the filter bandwidth and filter response can change the average eye value
  - Even if the low frequency RLM=1
- To evaluate the optimum threshold requires consideration of added noise and eye opening
  - 5T equalizer will make the threshold closer together, still keeping some residual (see next slide)

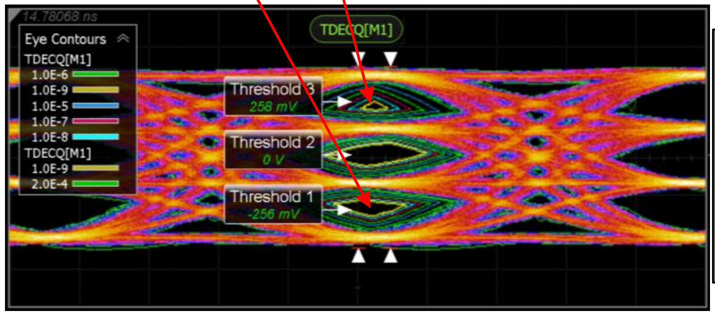
Review the Proposed Change of Threshold Adjustment

- Examples of Average Threshold ≠ Optimized Threshold -

From mazzini_120617_3cd_adhoc

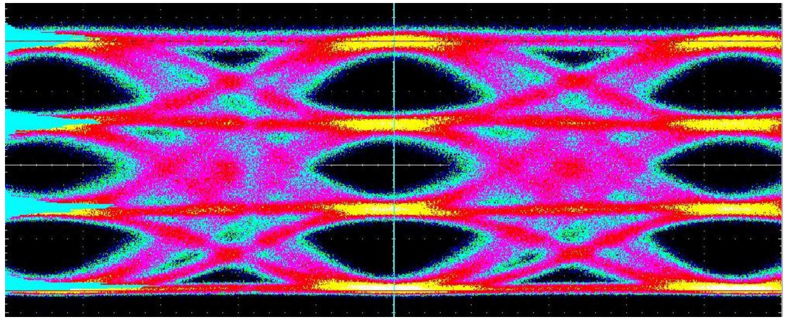
Usually 0/1 & 2/3 optimum thresholds are closer to levels 1 and 2, respectively.

This is true for almost ideal or very clean eye (as per previous slide).



Measurement		Current
TDECQ	M1	1.00 dB
Eye 2/3 Level	F1	258.6 mV
Eye 1/2 Level	F1	-200 µV
Eye 0/1 Level	F1	-253.4 mV
Linearity [RLM]	F1	0.982
TDECQ	F1	0.27 dB
Outer OMA	F1	772.6 mV

Example: clean electrical eye, 773mV VMAouter, @53GBaud, lab-grade equipment, observed BW = 60GHz.



Levels	Mean	StdDev	PkPk
Level3	3.4 mW	44 uW	437 uW
Level2	2.5 mW	36 uW	307 uW
Level1	1.5 mW	26 uW	229 uW
Level0	568 uW	18 uW	181 uW

Global Measurements	
OMA Outer	2.8 mW
Level Mismatch (R_{LM})	0.97

Example: SiP eye, no equalization.

In the optical domain, we also have to consider laser RIN, so expect to have more noise over levels 2 and 3.

Real receivers will implement threshold optimization to get the lowest BER.

Review the Proposed Change of Threshold Adjustment

- With un-optimized thresholds, the TDECQ test would lead to overestimation of TDECQ penalty for the link if the receivers have the ability to do threshold adjustment.
- We propose to allow the threshold adjustment of the Reference receiver to optimize the TDECQ in a limited range.
- Together we propose to define lower limit for optical signal RLM
- This will certainly help the Tx, and its impact on Rx test will be discussed

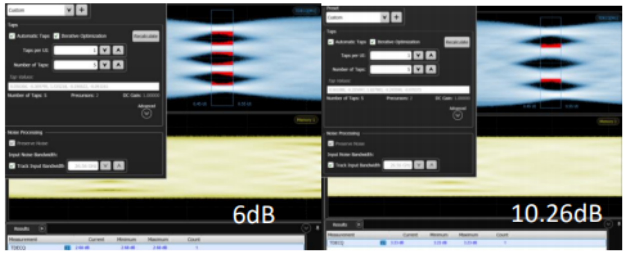
Example 1 – MZM TDECQ Algorithm Tests

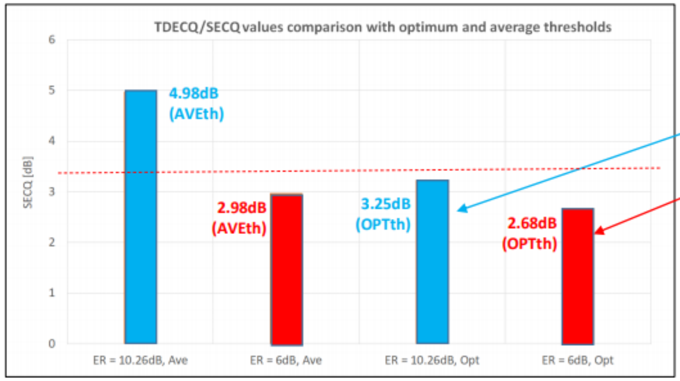
- 53GBaud MZM tests with PRBS20 pattern
  - [mazzini_120617_3cd_adhoc-v2]

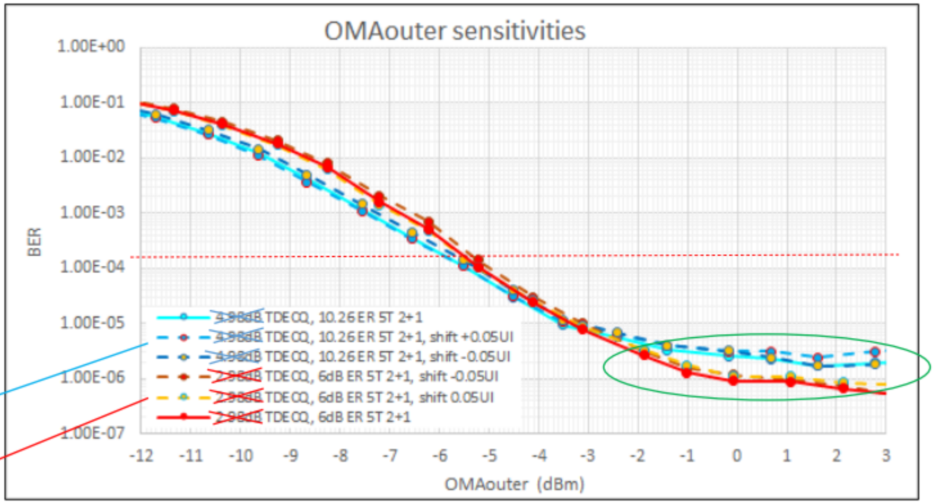
53GBaud PAM 4 TX/RX : sensitivity/TDECQ correlation.

These same PRBS20 waveforms were processed by Keysight by considering:

- Threshold optimization into TDECQ algorithm.
- Equalization is done at 0.5UI sample location, with 0.1UI window applied.



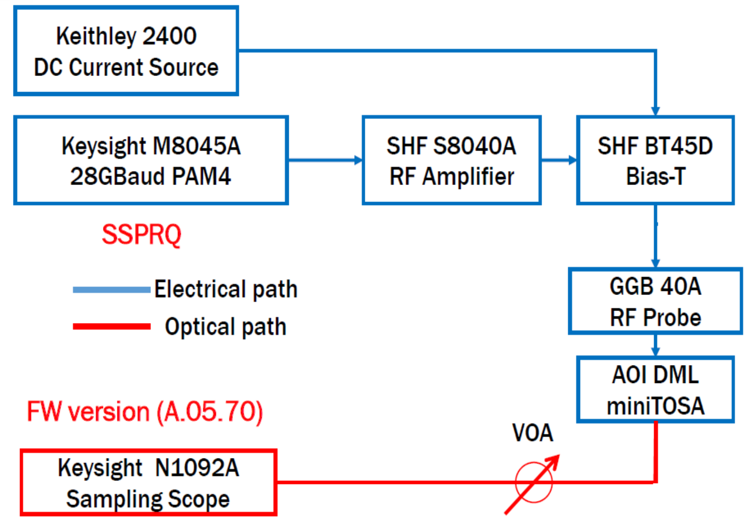


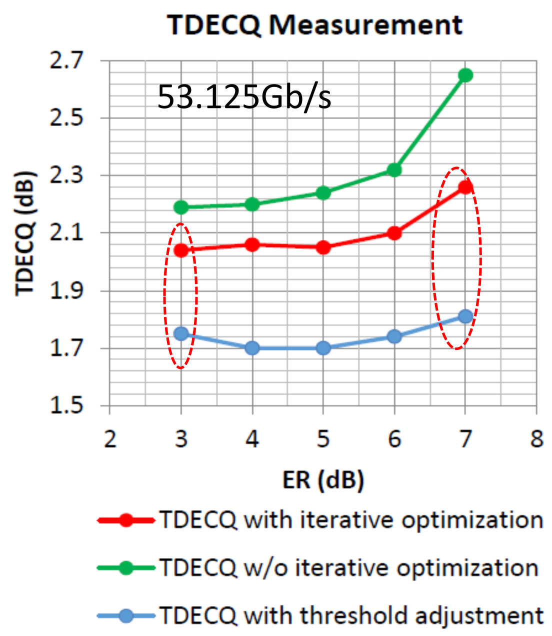


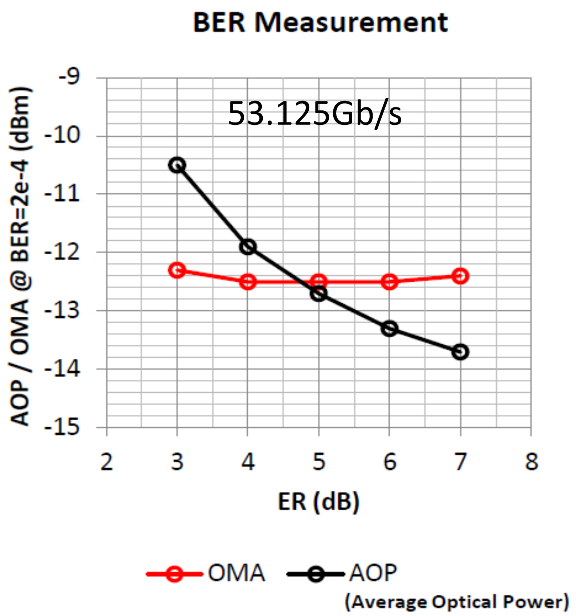
Both TX conditions now pass the 53GBaud SECQ limit of 3.4dB.
This is more in line with the sensitivity results presented into [mazzini_3bs_01_0917], 1dB to 1dB match seems to be at BER floor.

Example 2 - DML TDECQ Tests

- Discrete 56.125Gb/s DML tests with SSPRQ pattern
  - Setup refer to baveja_3cd_01_1117
- Post-processed waveforms with Threshold Adj.
- Improve 0.29 to 0.45dB with ER dependent
  - *Less variation on ER after applying threshold adjustments*
- TDECQ become more consistent with RX OMA Sens
- Observe threshold Adj. helps 106.25Gb/s.
  - TDECQ can’t be measurable at ER=4.5dB



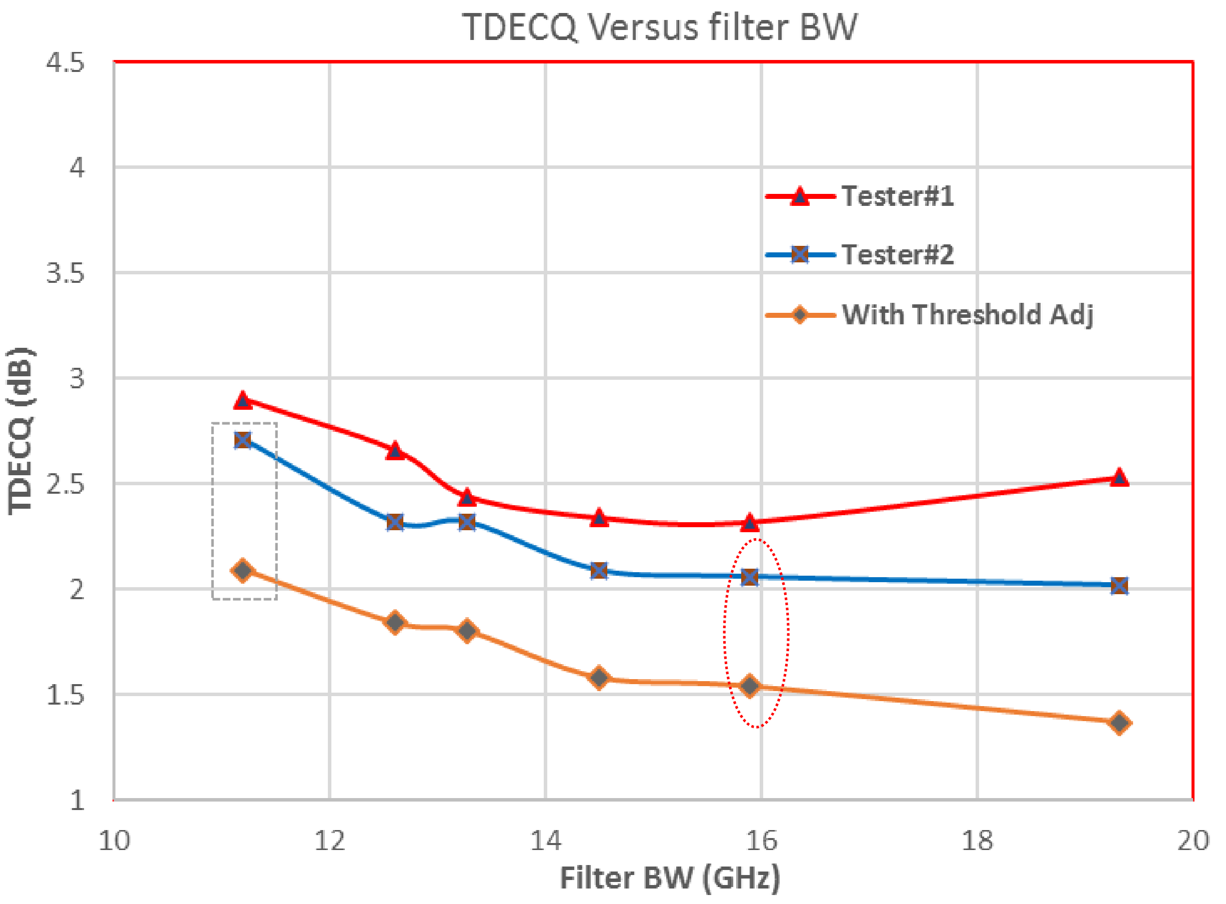




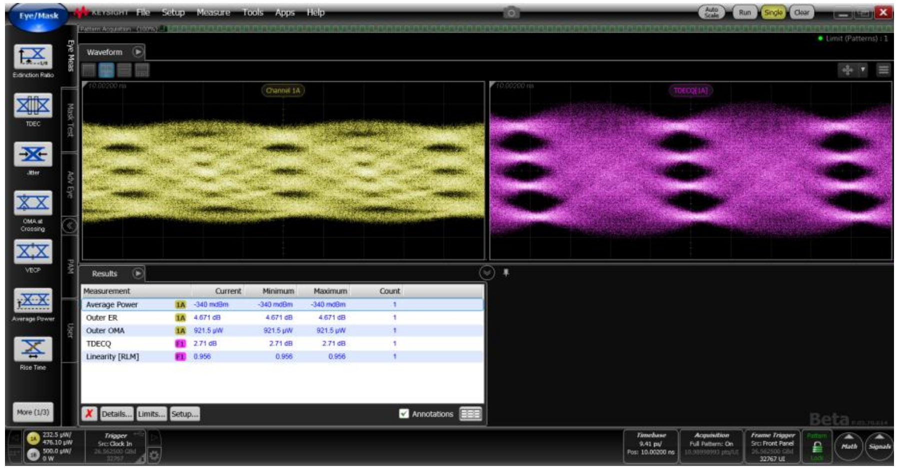
106.25GB/s TDECQ		
ER	w/o threshold adjustment	with threshold adjustment
3.5	4.91	2.41
4.5	--	3.34

Example 3 – VCSEL TDECQ Tests vs. Rx filter BW

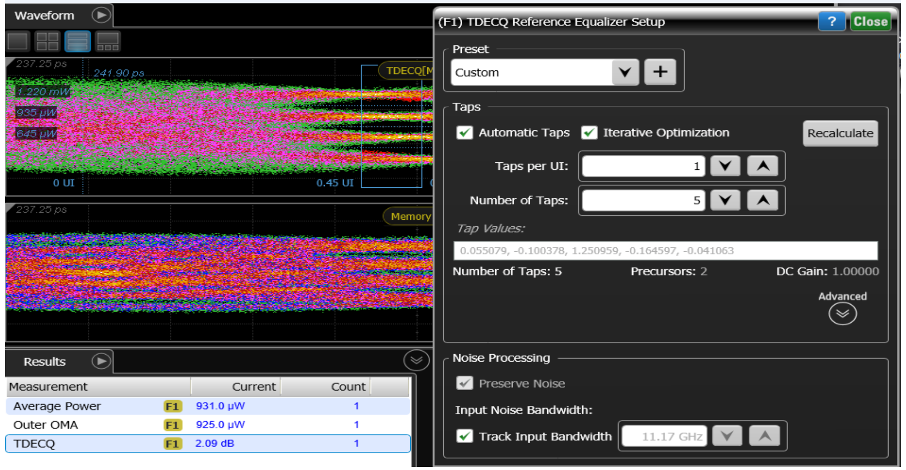
- Discrete 56.125Gb/s VCSEL tests with PRBS15 pattern
  - Measured RLM ranges from 0.94-0.96
  - Show 0.4 – 0.5dB improvements (chang_011018_3cd_01_adhoc-v2)



Without threshold adjustment (RLM=0.956)

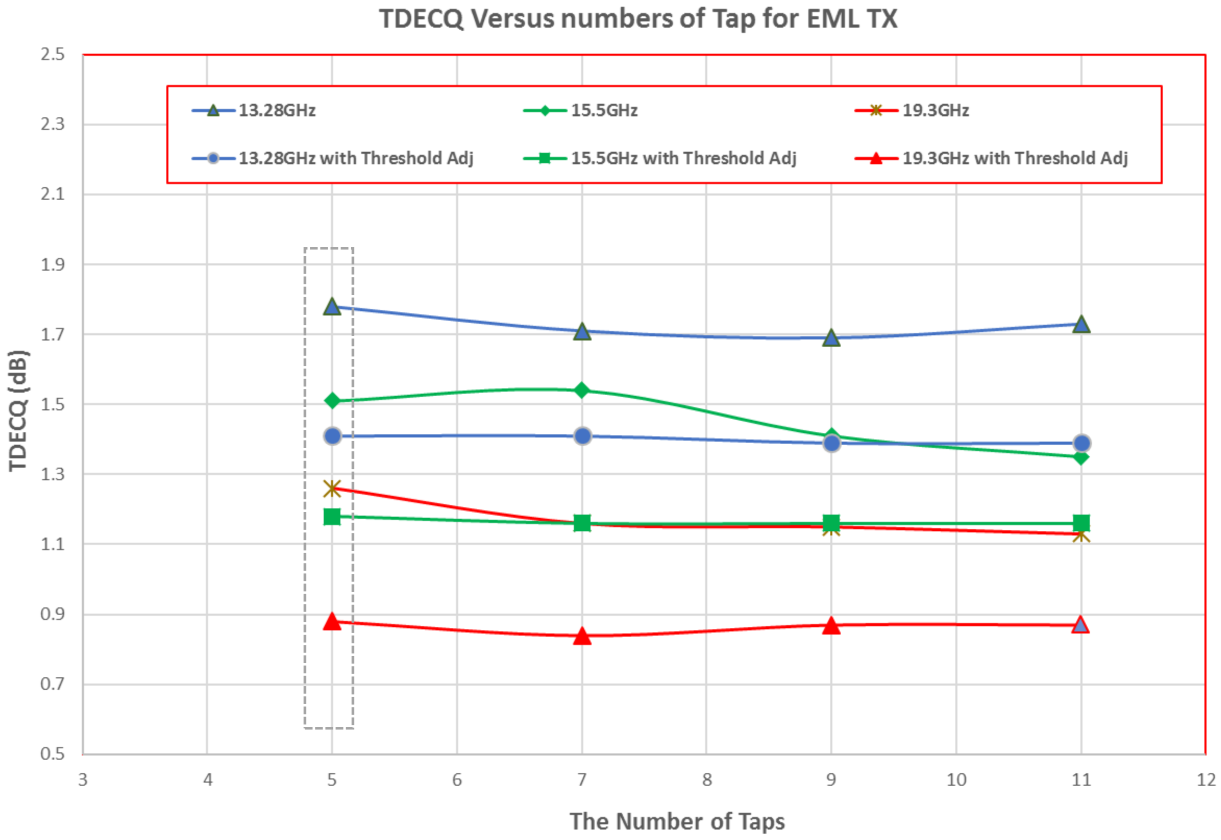


With threshold adjustment

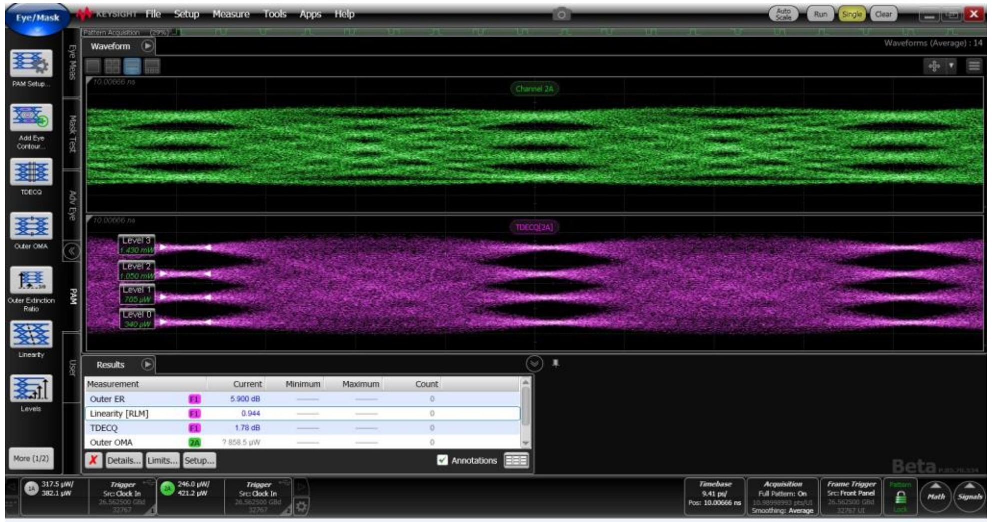


Example 4 – EML TDECQ Tests vs. # of Taps

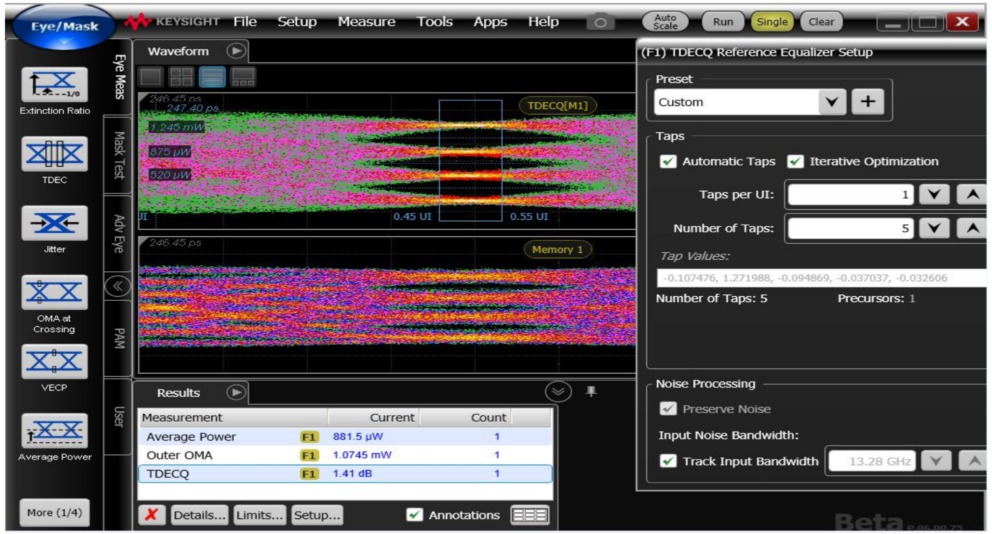
- Discrete 56.125Gb/s EML tests with PRBS15 pattern
  - Threshold adjustment under 3 different RX filter BW
  - Measured RLM ranges from 0.94-0.95
  - Show 0.3 – 0.4dB improvements (chang_011018_3cd_02_adhoc-v2)



Without threshold adjustment (RLM=0.94)



With threshold adjustment



TDECQ Tests Summary

	TDECQ w/o Threshold Adjustment	TDECQ w/ Threshold Adjustment	Signal RLM
53GBd MZM (Cisco) (for ER=6dB)	3 dB	2.7 dB	0.98
53GBd DML (AOI) (for ER=3.5dB)	4.9 dB	2.4 dB	0.97
26GBd DML (AOI) (for ER=4dB)	2.05 dB	1.7 dB	0.98
26GBd VCSEL (Inphi)	2.7 dB	2.1 dB	0.96
26GBd EML (Inphi)	1.8 dB	1.4 dB	0.94
26GBd MZM (Inphi)* (for SRS no stress)	1.7 dB	1.34 dB	0.98

*: refer to chang_011018_3cd_02_adhoc-v2

Based on D3.0 Reference Rx and EQ

TDECQ improvement is seen for all types of Tx.

Amount of Adjustment

Consider a simplified case of only the top eye is compressed by an amount of d, It can be shown (in the backup) the threshold adjustments are given by

$\Delta P_{th3} = d/3$ $\quad\quad$ $\Delta P_{th2} = d/2$ $\quad\quad$ $\Delta P_{th1} = d/6$

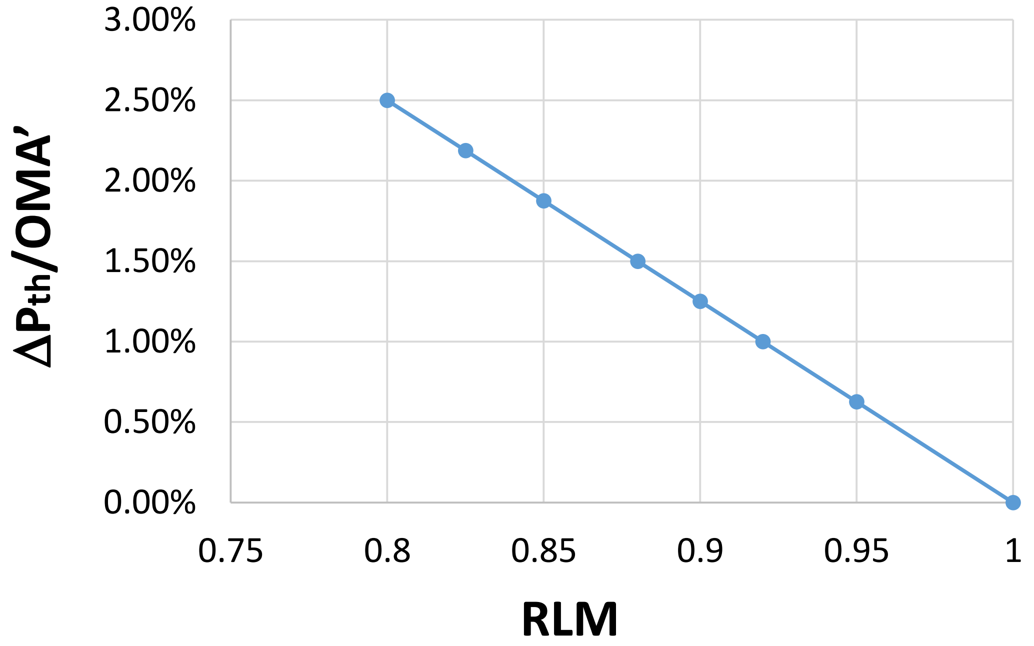
On the other hand, the signal RLM can be shown to depend on d and signal OMA' by

RLM = (OMA' - 4d)/OMA' (liu_011018_3cd_adhoc-v2)

If RLM = 0.9, the maximum amount threshold adjustment is

$\Delta P_{th} = d/2 = OMA'/80$

$\Rightarrow$ 1.25% signal OMA

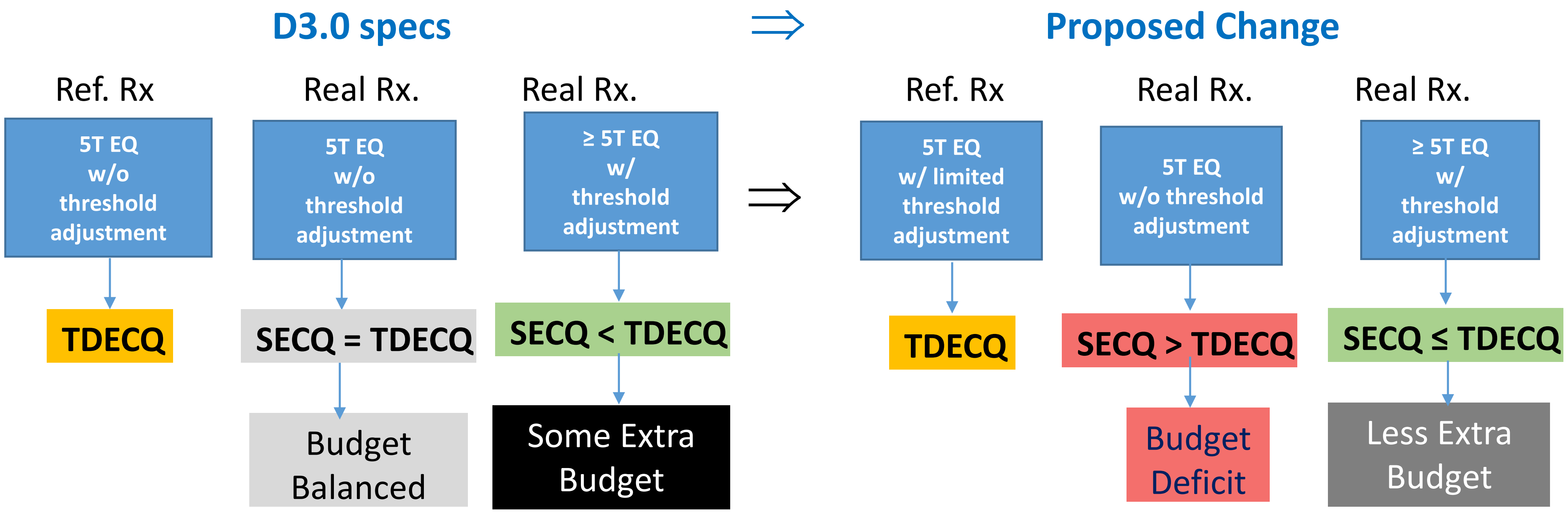


Amount of Adjustment Recommendation

- It is recommended to limit the amount of threshold adjustment to 2.5% of signal OMA.
  - Very low bandwidth transmitters are also excluded
  - Keep receiver threshold adjustment range for receiver bandwidth effects, DC wander caused by LF coupling, and other effects.

- As poor level setting (linearity) could affect the jitter and clock recovery performance, it is also recommended to introduce RLM limit (RLM > 0.9) so that
  - High bandwidth transmitters with poor level setting are excluded

Impact of Proposed Change on SECQ



- For receivers with > 5T EQ and > 2.5% threshold adjustment, no impact to Rx testing is expected
- For receivers without sufficient threshold adjustment, the proposed change will cause margin erosion.

If sufficient threshold adjustment will be implemented in receivers (as many IC vendors suggested), no issue on real receiver in terms of margin erosion is expected.
However there'll be further work to address comments received during ad-hoc calls.

Further Tests to Assess the Impacts on Rx

Main comments (in our records) received on threshold adjustement proposal given were during Jan 10th ad-hoc call.

In the direction to ensure the RX will not hit trouble with this change:

1. Verify that a SECQ calibration done with (such partially) 2.5% optimized thresholds at the receiver will not break the link of such receivers that were demostrated to pass.
2. For real implementations, if the Real RX BW < Nyquist (currently defined for TDECQ/SECQ), the 'effective' optimum threshold should be closer to inner eye (01 th closer to 1 and 23 th closer to 2) than for the Nyquist case -> a such low BW receiver can have more problem to pass whenever the optimum threshold that will be defined in the method will be out of its actual settable range.
    - Basically means that <u>the margin eroded to the RX can be actually higher than the benefit on the TX</u> (indeed the SECQ tester calibrated with e.g. 2.5% optimal threshold variation using the scope and the Nyquist filter can become e.g. 4-5% whenever the Real RX BW < Nyquist, so in principle an actual receiver implementing threshold optimization will have more trouble to pass SRS if its own BW is lower than Nyquist).

Still partially addressed by the fact that there are clear limits in the amount of threshold variation, there are plans to address both comments with experiments to show that:

1. SECQ calibrated with average thresholds (current draft) pass with some margins over a certain amount of real receivers.
2. The same amount of receivers tested with SECQ calibrated using threshold adjustment (so an effective higher stress), still pass.
3. Quantify the margin reduction over the tested population.

AND/OR

1. Consider reference stressor calibrated with SECQ as per current draft.
2. Quantify optimum threshold values and variations
3. Change the receiver BW from Nyquist to lower/higher.
4. Quantify the threshold variation and SECQ with respect point 2.

These activities were delayed due to the general availabilty of TDECQ FW with adjustable threshold algorithm.

Summary

- Proposed to allow threshold adjustment in TDECQ measurement as a solution to address the high Tx yield loss issue.
- Validated the improvements in measured TDECQ values by implementing the threshold adjustment for DML, EML, MZM and VCSEL based Tx.
- Recommended to limit the amount of adjustment to < 2.5% of the signal OMA and signal RLM to > 0.9.
- Reviewed the impacts to Rx stressed testing
  - No impact is expected for Rx with sufficient threshold adjustment
  - For Rx without threshold adjustment, the gain from TDECQ improvement will cause extra stress on Rx side
- Recommended further tests to further assess the impacts on Rx.

THANK YOU

Backup

RLM Definition from 802.3bs-2017 and rationale to optical domain definition

$$V_{mid} = \frac{V_0 + V_3}{2} \quad (120D\text{–}3)$$

$$ES1 = \frac{V_1 - V_{mid}}{V_0 - V_{mid}} \quad (120D\text{–}4)$$

$$ES2 = \frac{V_2 - V_{mid}}{V_3 - V_{mid}} \quad (120D\text{–}5)$$

The level separation mismatch ratio R_{LM} is defined by Equation (120D–6).

$$R_{LM} = \min((3 \times ES1), (3 \times ES2), (2 - 3 \times ES1), (2 - 3 \times ES2)) \quad (120D\text{–}6)$$

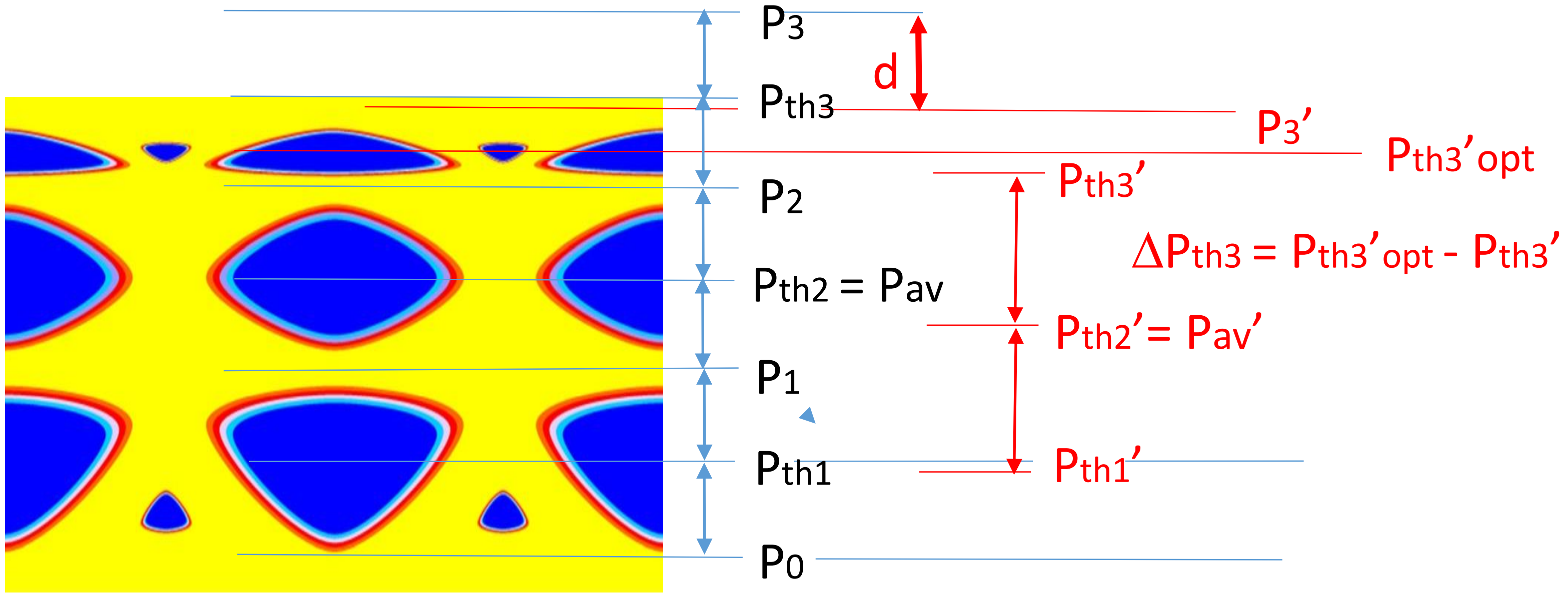
We think there’s need to define RLMmin in case of high bandwidth eye, because with allowed ~2.5% threshold variation then the allowable RLM is lower than 0.9.

To summarise, a little bit of Threshold Variation to cope with lower bandwidth Tx’s and RLM to protect against excessive Level non-linearity that could be passed with high bandwidth transmitters.

Recommend the Amount of Adjustment

– Signal Distortion vs. Threshold Adjustment (I)

Consider a simplified case with only the top eye compressed (by an amount of d)



In this case
$P_3' = P_3 - d$,
$P_2' = P_2$, $P_1' = P_1$, $P_0' = P_0$
$P_{av}' = (P_3' + P_0)/2 = P_{av} - d/2$
$OMA' = P_3' - P_0' = OMA - d$

With the initial thresholds at Pth3’ = Pav’ + OMA’/3, Pth2’ = Pav’ and Pth1’ = Pav’ – OMA’/3, it can be shown the threshold changes to the optimum positions are

$$\Delta P_{th3} = P_{th3} - d/2 - (P_{av}' + OMA'/3) = d/3$$
$$\Delta P_{th2} = P_{av} - P_{av}' = d/2$$
$$\Delta P_{th1} = P_{th1} - (P_{av}' - OMA'/3) = d/6$$

Amount of adjustment can be related to the amount of compression