Ceq Definition and Limit
(In support of Comment #237)

Mark Kimber (Semtech)

Laurent Alloin (Ciena)

Eric Maniloff (Ciena)

July 2026

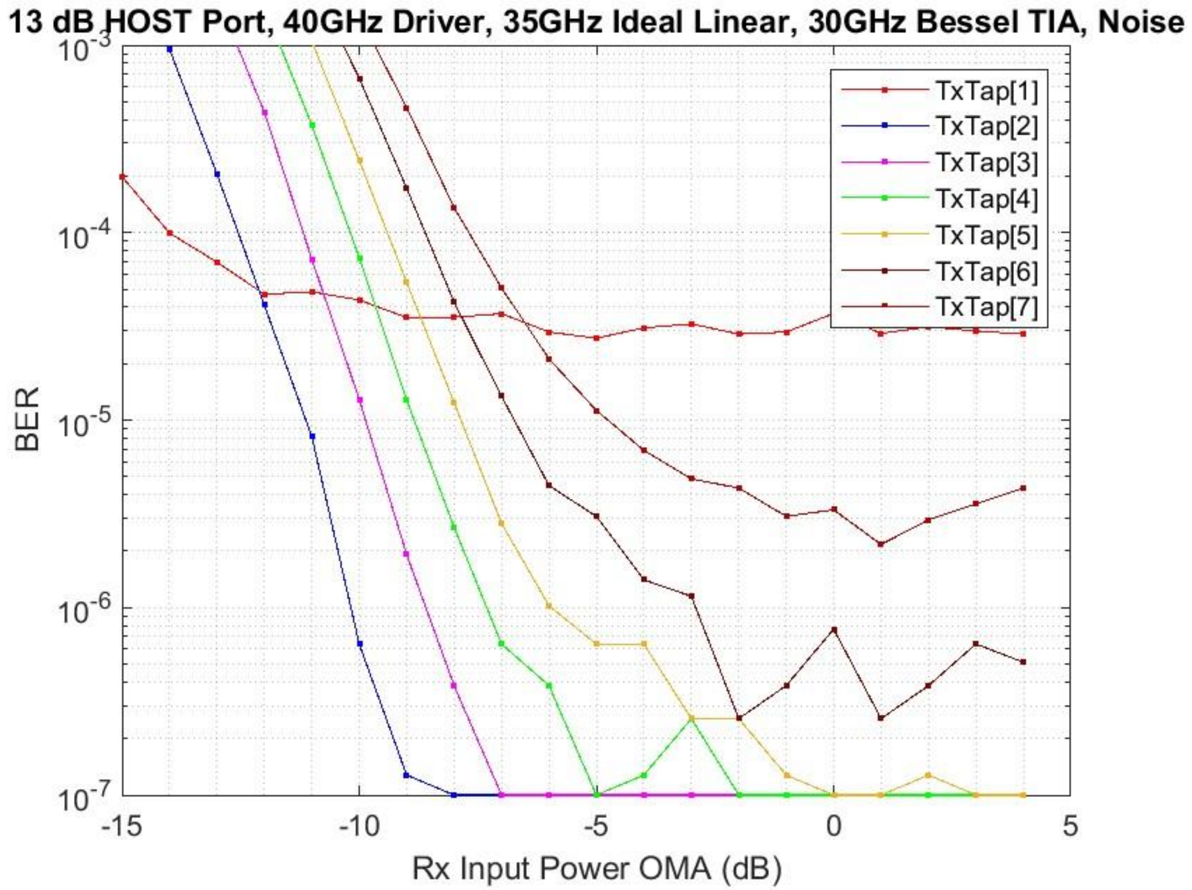
Overview

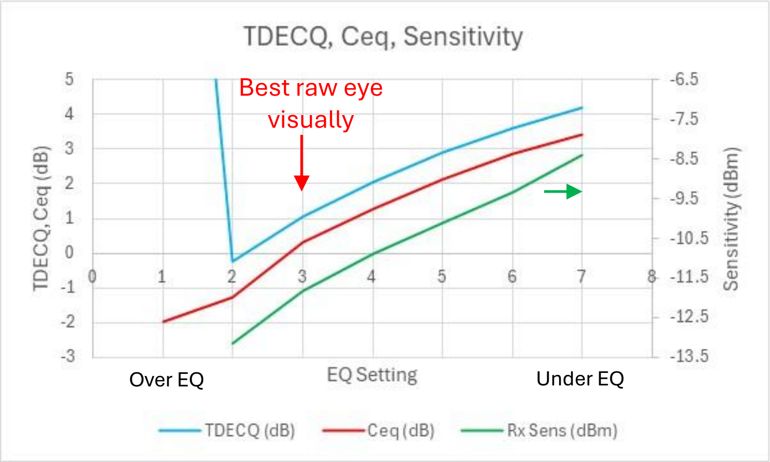
- Previous presentations have shown that over equalization (peaking) in the transmitter is detrimental to BER floor performance
- Optimization of the transmitter for lowest TDECQ results in over equalization of the transmitter
  - Optimization of TDECQ to lowest values improves the Tx SNR as the expense of frequency response
- Keeping Ceq > 1 (0 dB) can help to prevent over equalization
- This presentation is in support of Comment 237

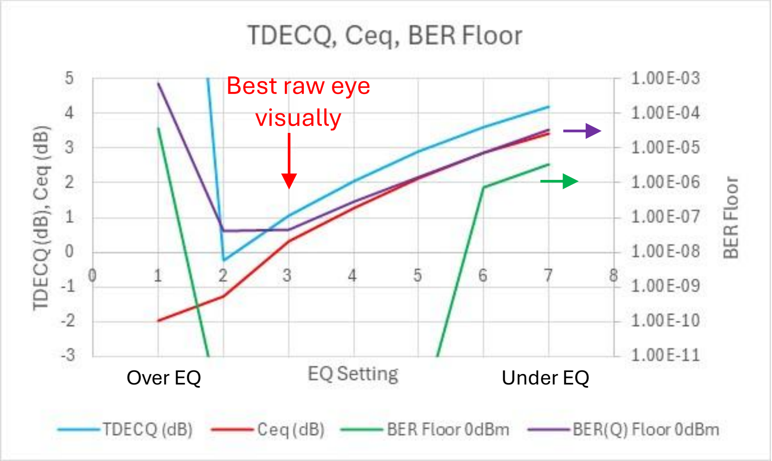
Previously….

- Kimber_3dj_01a_2505 presented simulations and measurements at 106.25 Gb/s showing the impact of Tx over equalization and correlation with Ceq and BER floor

Simulation Results – Ideal Linear Modulator



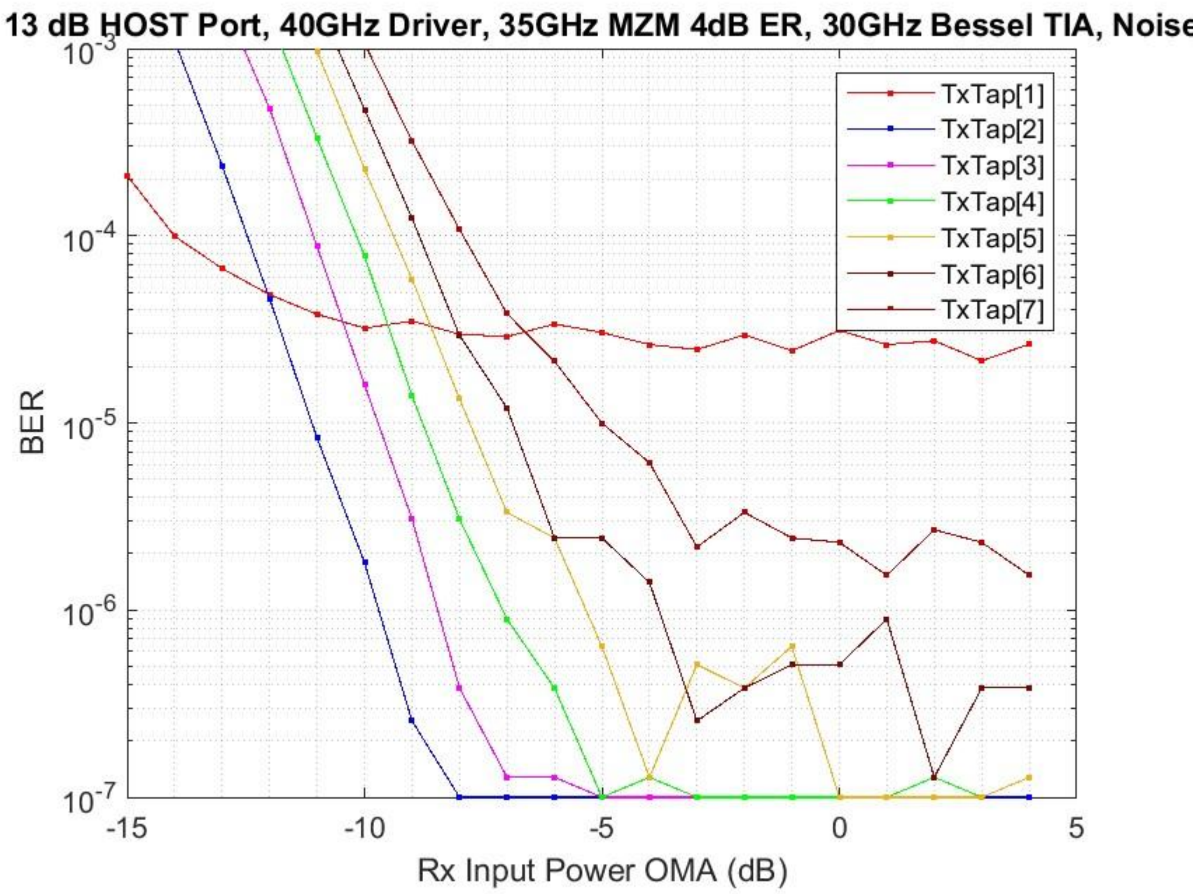


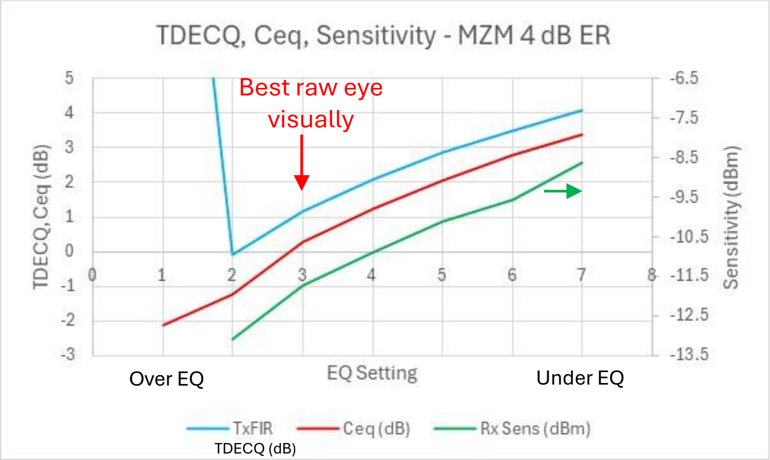


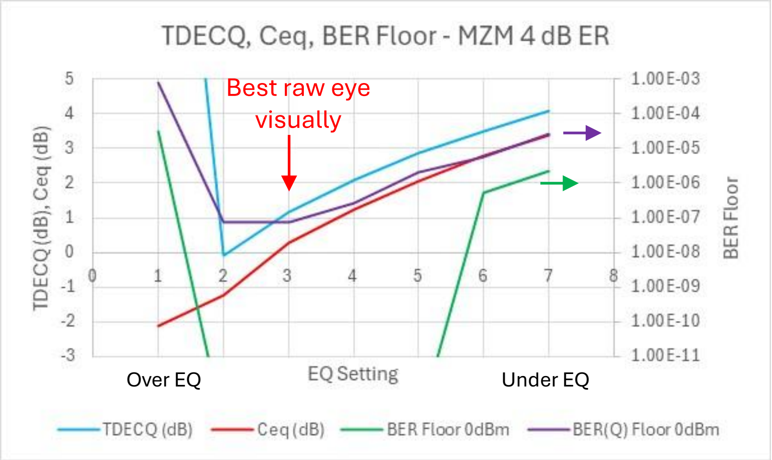
BER(Q) is estimated BER from Q

No non-linearity in the system

Simulation Results – MZM Modulator 4dB ER

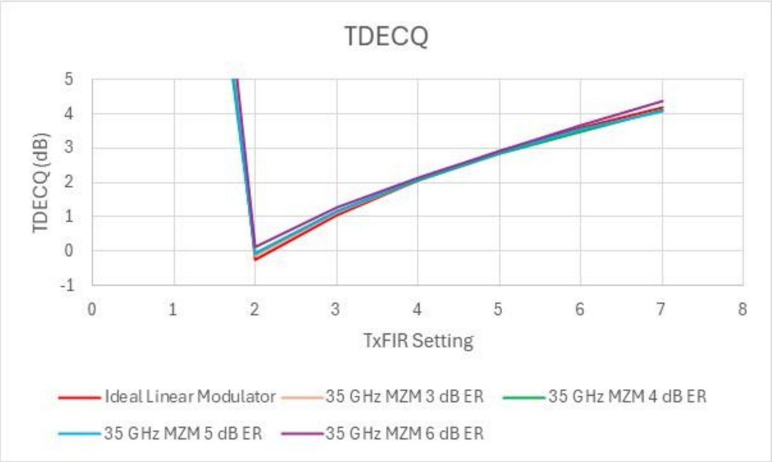


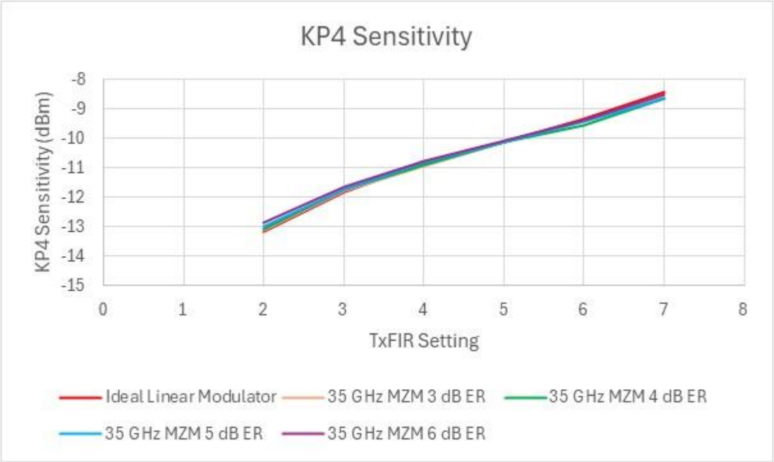


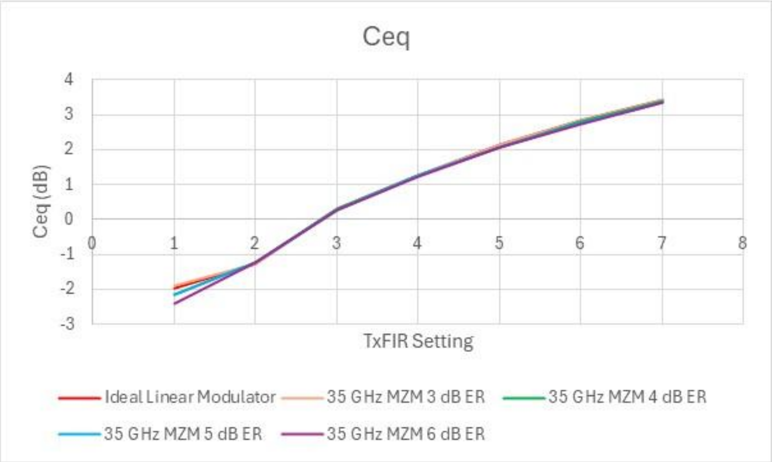


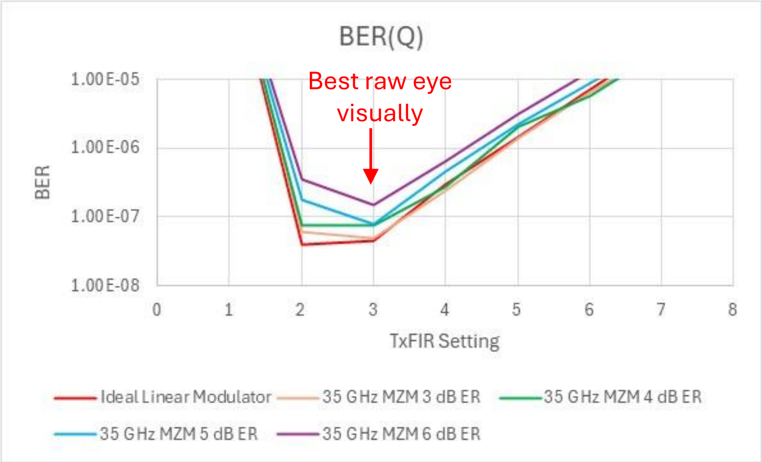
BER(Q) is estimated BER from Q

Simulation Summary



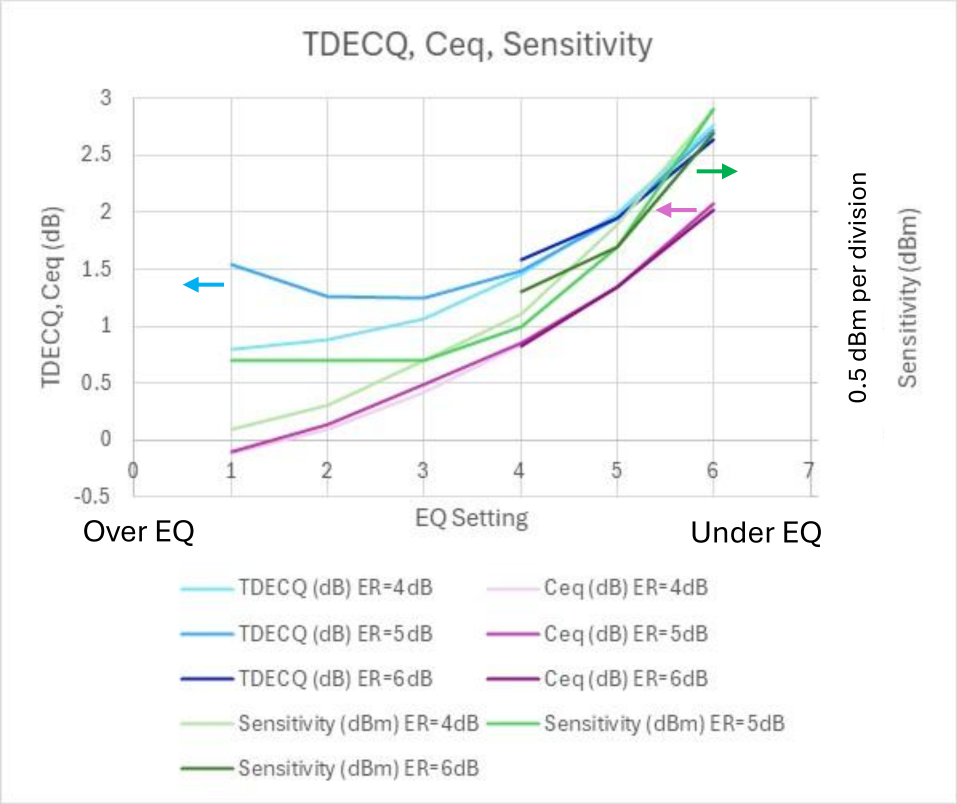


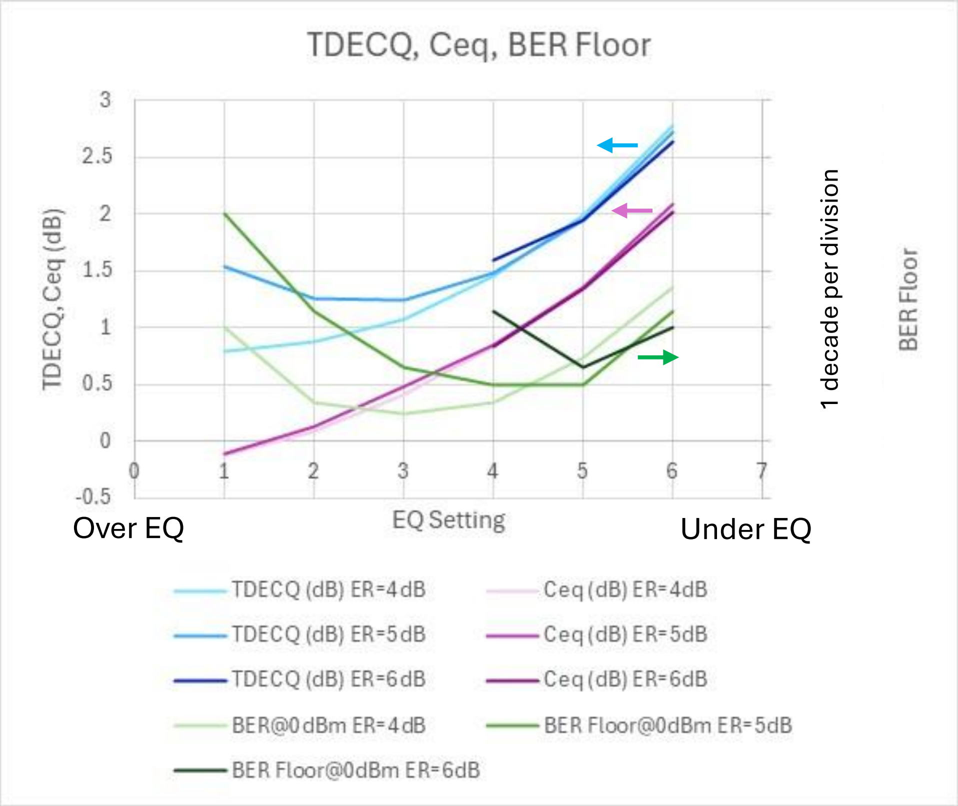




- BER floor is more sensitive to distortion when Ceq < 0dB
- Distortion needs to be limited

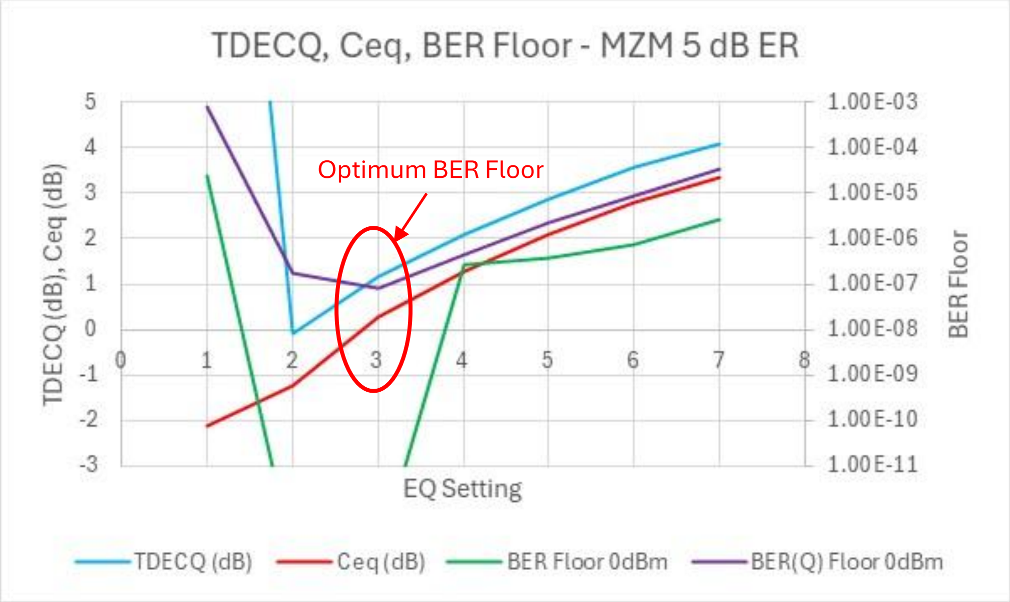
SM Measured Performance - 2



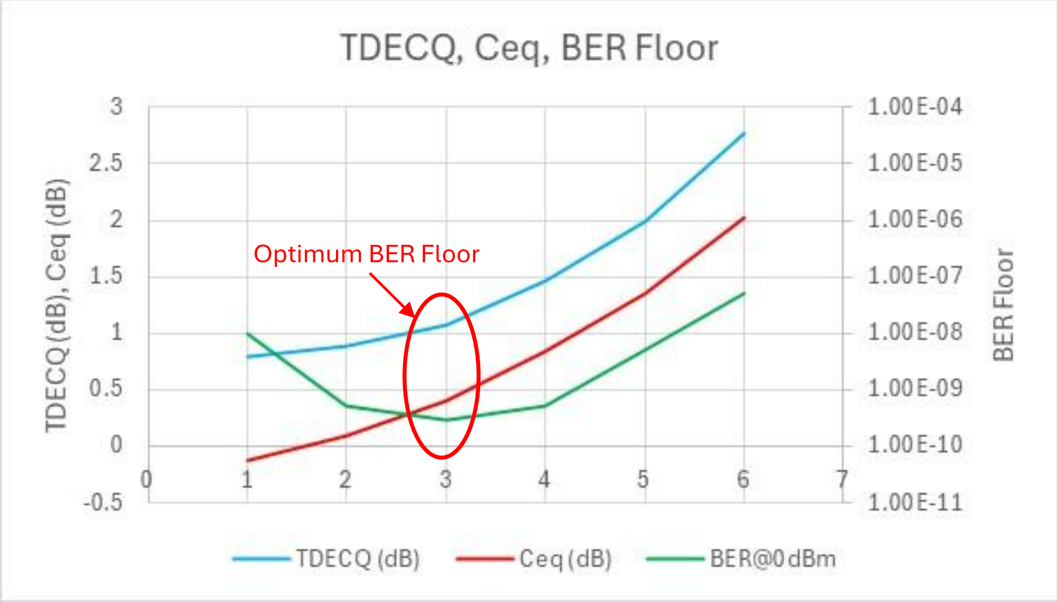


- Ceq doesn't change with ER indicating that the frequency is not changing
- BER Floor is very sensitivity to ER and low Ceq indicating that the high ER has distortion
    - Combination of driver + MZM distortion

Simulation vs Measurement (Single Mode)



Simulated – only MZM THD



Measured (4dB case) – MZM and driver THD

- Good agreement with trends between simulation and measurement
- Both simulation and measurement indicate that Ceq ~0.3-0.5dB for best BER floor with moderate THD levels
- Lowest TDECQ does not align with best BER floor
- Transmitter should be tuned for TDECQ and Ceq limits

Why Ceq can indicate Tx over equalization

- The combination of Tx frequency shape and Rx frequency shape needs to result in a "flat" response (amplitude and phase) for best SNR and best ISI
  - PAM4 is a linear system requiring linear phase and linear amplitude
- If the Tx bandwidth is low, then the Rx bandwidth needs to boost to equalize the link
  - Ceq > 1 and the Rx suffers a noise enhancement penalty
- If the Tx bandwidth is "peaked", then the Rx bandwidth needs to reduce/de-boost the frequency response to equalize the link
  - Ceq < 1

From Kimber_3dj_01a_2505

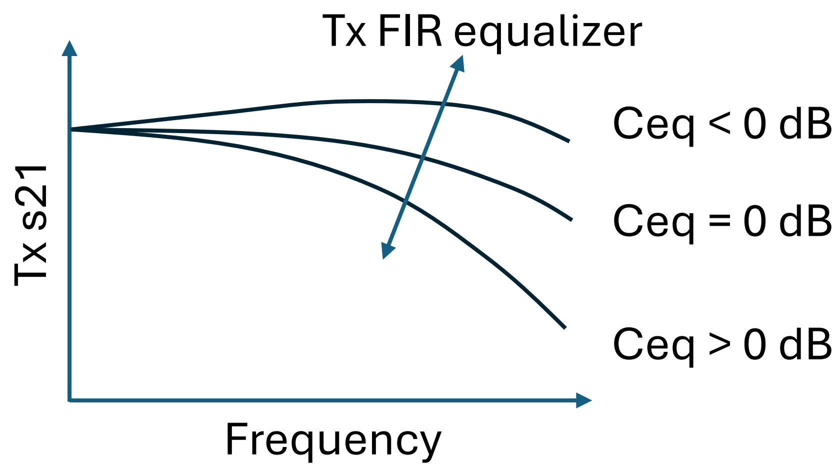
- For a smooth Tx (driver + modulator) frequency response:
  - Ceq is indicating how much equalization is required to equalize (or flatten) the Tx frequency response
  - TDECQ (for Ceq > 0 dB) is giving an indication of link SNR penalty
    - Lower TDECQ = More open Tx eye
      - Better Tx SNR
      - Lower Rx noise amplification due to equalizer

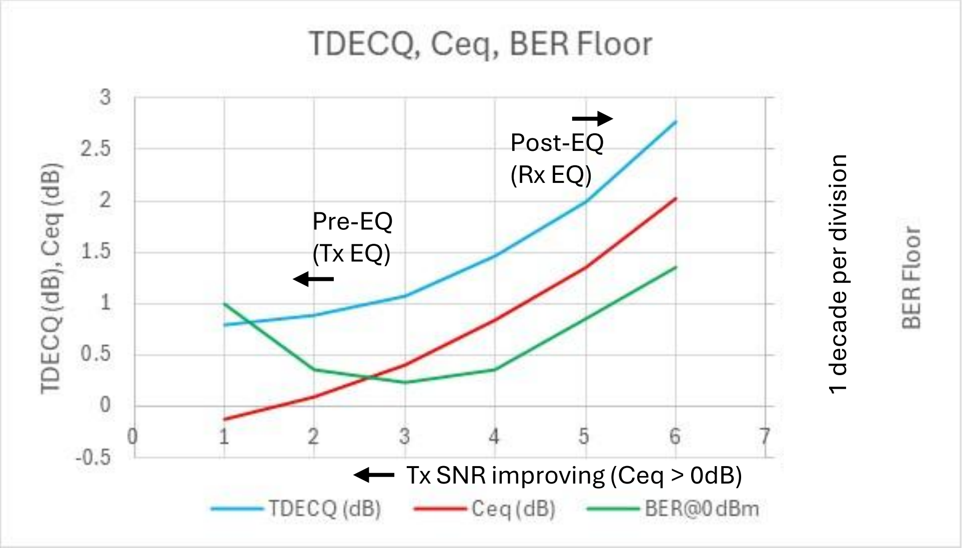
- Simulations and measurements are telling us that Tx peaking is bad
- Ceq is showing when the Tx is starting to be over peaked

- Ceq < 0 dB results in degraded performance
  - 0.5 dB < Ceq < 1 dB tends to be close to optimum for SM optics

- Equalization at the Tx improves
  - Tx SNR (by a small amount)
  - Link SNR (significantly) by reducing noise amplification of Rx EQ
- Equalization of the Tx by the Rx does not improve Tx SNR
  - Degrades link SNR by introducing noise amplification

- These measurements appear to be quite fundamental (i.e. not linked to implementation) and apply widely





Overshoot Simulations

- Overshoot has been proposed as a way of controlling over equalization of the Tx
- Overshoot consists of a number of contributions including:
  - Equalization applied – depends on Tx bandwidth
  - Tx phase response
  - Reflections

Overshoot

- Clause 180.9.9 states Overshoot and Undershoot are measured at the output of the Reference Receiver (i.e. before the equalizer) with a hit ratio of 10^{-4}.

OMA$_{outer}$ and ER$_{outer}$ are also measured after the Ref Rx

Reference Rx BW ~ 53.125 GHz

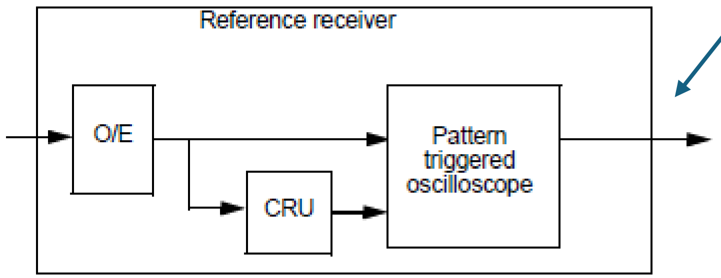


Figure 180–7—Reference receiver block diagram

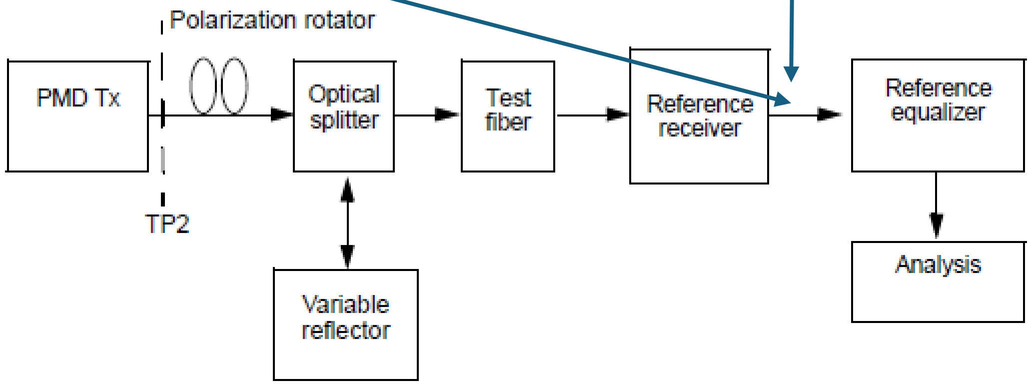
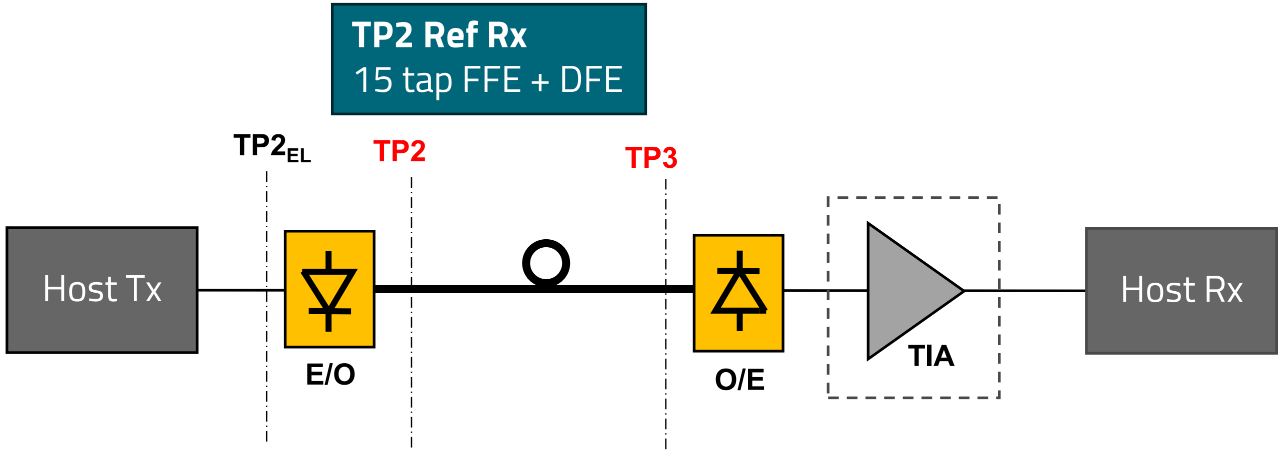


Figure 180–9—TDECQ conformance test block diagram

NB. This means that the overshoot and undershoot are measured on a filtered raw eye and not the TECQ or TDECQ eye.

Simulation Setup



System
TP2 – PRBS15Q
BER – 50 frames PRBS15Q
(1.638 M symbols)

5-tap FIR
1 Vppd
60 GHz Bessel BW
106.25 GBd

Modulator
60 GHz Bessel Filter
Vpi = 6 V
Zero chirp
RIN = -150 dB/Hz

PD + TIA
Responsivity = 0.7 A/W
60 GHz Bessel filter
Tz = 3 kohms max
Noise = 15 pA/rtHz
Output equalizer
Rx Xtalk ~ -40 dB

DSP Rx
FFE - 30 taps (4 pre)
DFE – 1 tap
No MLSE

AGC is used to keep the ER reasonably constant at TP2

Simulation Summary

Fully equalized using TxFIR

Tx FIR (rounded)	MZM BW (GHz)	TDECQ (dB)	DFE	Ceq_equiv	Ceq (FFE only)	Over/Under shoot
[0.03 -0.14 0.63 -0.17 0.05]	40	0.885	0.005	1.0318	1.0355	[20.1, 18.9]
[0.01 -0.11 0.74 -0.12 0.02]	60	0.482	0.025	1.0097	1.0009	[15.3, 15.4]
[0.01 -0.09 0.78 -0.11 0.02]	80	0.481	0.008	1.0116	1.0135	[12.9, 12.4]

TxFIR adjusted to under/over equalize

Tx FIR (rounded)	MZM BW (GHz)	TDECQ (dB)	DFE	Ceq_equiv	Ceq (FFE only)	Over/Under shoot
[0.01 -0.05 0.86 -0.06 0.02]	60	0.683	0.145	1.2388	1.228	[5.2, 3.8]
[0.01 -0.09 0.78 -0.10 0.02]	60	0.577	0.067	1.0864	1.0821	[10.5, 10.3]
[0.01 -0.11 0.74 -0.12 0.02]	60	0.482	0.025	1.0097	1.0009	[15.3, 15.4]
[0.01 -0.13 0.70 -0.14 0.02]	60	0.449	-0.035	0.9170	0.937	[23.5, 22.7]
[0.01 -0.15 0.66 -0.16 0.02]	60	0.375	-0.132	0.8388	0.862	[33.0, 31.5]

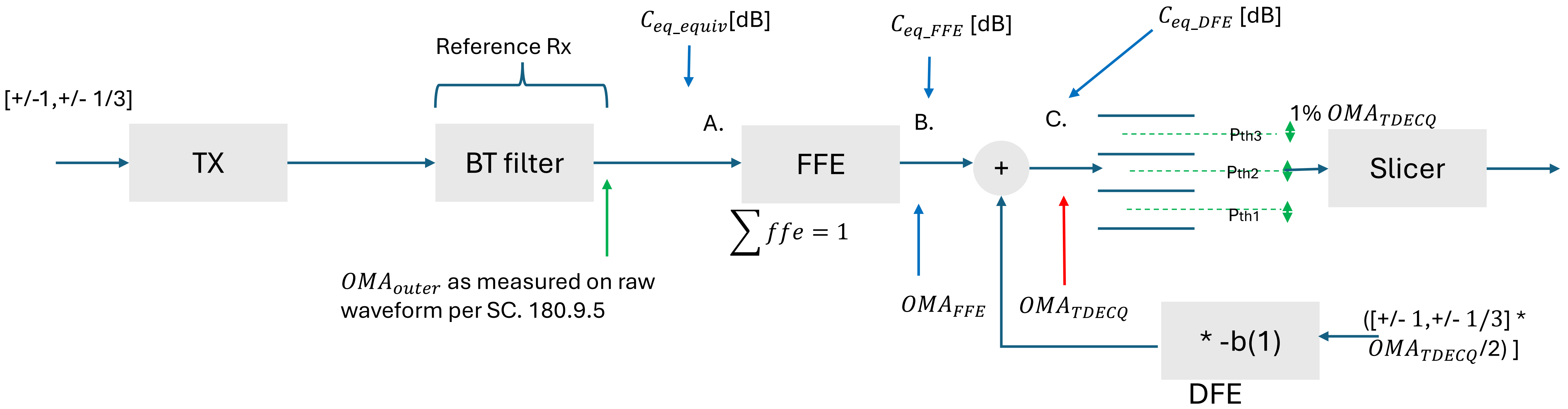
How to calculate a normalized C_{eq_equiv} metric from a TDECQ-DFE measurement?

- In IEEE802.3dj, a DFE tap has been added to the TDECQ equalizer
- The DFE tap changes the meaning of C_{eq} for the FFE due to the DFE doing some of the post cursor 1 equalization
- Need to account for the effect of the DFE tap on the FFE to calculate C_{eq}
- A method has been proposed by Laurent Alloin to account for the impact of the DFE tap on the FFE equalizer and to avoid impact of reflections (cfr. https://www.ieee802.org/3/dj/public/26_05/alloin_3dj_03_2605.pdf)
- The normalized noise enhancement factor is:

$$C_{eq\_equiv} = 10.log_{10}(C_{eq}) + 10.log_{10}(OMA_{outer}) - 10.log_{10}(OMA_{TDECQ}) - 10.log_{10}((1+b)(1-b))$$

- This represents the equivalent noise enhancement that an FFE only TDECQ measurement would have

Various Ceq [dB] quantities @ reference receiver



1. OMA_{outer} as measured per SC 180.9.5 $\neq OMA_{FFE}$

2. OMA_{FFE} tracks the low frequency level signal and varied with reflection type , while OMA_{outer} does not

3. OMA_{FFE}=OMA_{TDECQ} $*$ (1+b)

with $$C_{eq} = \sqrt{\int_f N(f) \times |H_{eq}(f)|^2 df}$$

@ C: C_{eq_DFE} [dB]= $10log10(C_{eq})$ + $10log10(OMA_{outer})$ – $10log10\left(OMA_{TDECQ}\right)$

@ B: C_{eq_FFE} [dB] = C_{eq_DFE} -10*log10(1+b)

@ A: C_{eq_equiv}[dB] = C_{eq_FFE} [dB] -10*log10(1-b)

Proposed edits to D3.1

Appending to table 180-7 p471, the following new parameter:

Normalized Noise Enhancement Factor C_{eq_equiv}[dB]

Description	Reference	200GBASE-DR1 400GBASE-DR2 800GBASE-DR4 1.6TBASE-DR8	Unit
Normalized Noise Enhancement Factor C_{eq_equiv} (min)	180.9.6	0	dB

Also in Clauses 181 and 182

Table 180–7—200GBASE-DR1, 400GBASE-DR2, 800GBASE-DR4, and 1.6TBASE-DR8 transmit characteristics

Description	Reference	200GBASE-DR1	400GBASE-DR2 800GBASE-DR4 1.6TBASE-DR8	Unit
Signaling rate, each lane (range)	—	106.25 ± 50 ppm		GBd
Modulation format	—	PAM4		—
Lane wavelength (range)	180.9.3	1304.5 to 1317.5		nm
Side-mode suppression ratio (SMSR), each lane (min)	180.9.3	30		dB
Average launch power, each lane (max)	180.9.4	4		dBm
Average launch power, each lane[a] (min)	180.9.4	–3.1[b]		dBm
Outer optical modulation amplitude (OMA_{outer}), each lane (max)	180.9.5	4.2		dBm
Outer optical modulation amplitude (OMA_{outer}), each lane (min) for max(TECQ, TDECQ) < 0.9 dB for 0.9 dB ≤ max(TECQ, TDECQ) ≤ 3.4 dB	180.9.5	 –0.1 –1 + max(TECQ, TDECQ)		 dBm dBm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	180.9.6	3.4		dB
Transmitter eye closure for PAM4 (TECQ), each lane (max)	180.9.7	3.4		dB
|TDECQ – TECQ|, each lane (max)	—	2.5		dB
Transmitter functional symbol error histogram, each lane (max)	180.9.8	See Table 180–17		—
Transmitter overshoot and undershoot, each lane (max)	180.9.9	27		%
Transmitter power excursion, each lane (max)	180.9.10	2.3		dBm

Proposed edits to D3.1

and can be calculated according to Equation (180–16)

$$Q_t = \sqrt{2}\,\mathrm{erfc}^{-1}\left(\frac{4}{3}SER_{\mathrm{target}}\right) \tag{180–16}$$

TDECQ is the minimum value of TDECQ(ϕ_0) calculated over the range of ϕ_0.

In subclause 180.9.6, appending to TDECQ definition at line 25, p487, the following new metric definition

"$C_{eq\_equiv} = 10log10(C_{eq})$ + $10log10(OMA_{outer})$ – $10log10\left(OMA_{TDECQ}\right)$ -10*log10((1+b)*(1-b))

C_{eq_equiv}[dB] is the normalized noise enhancement factor

Also in Clauses 181 and 182