TDECQ map and interpretation

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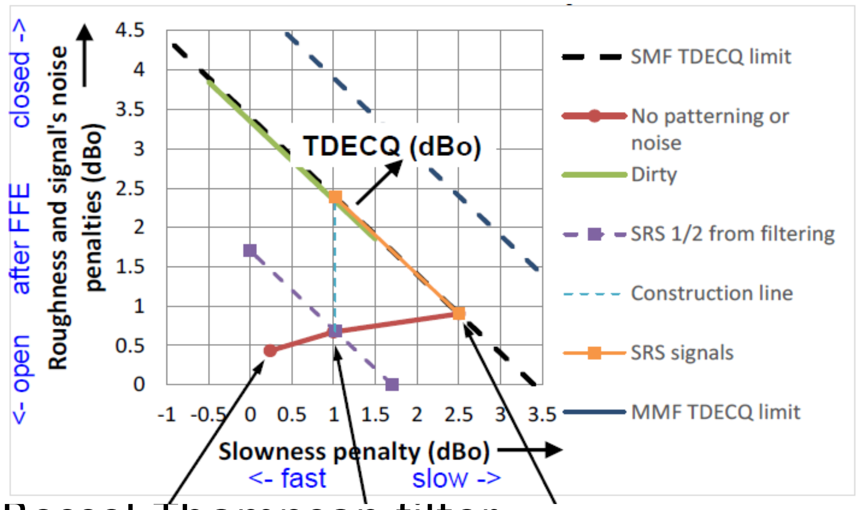
TDECQ map



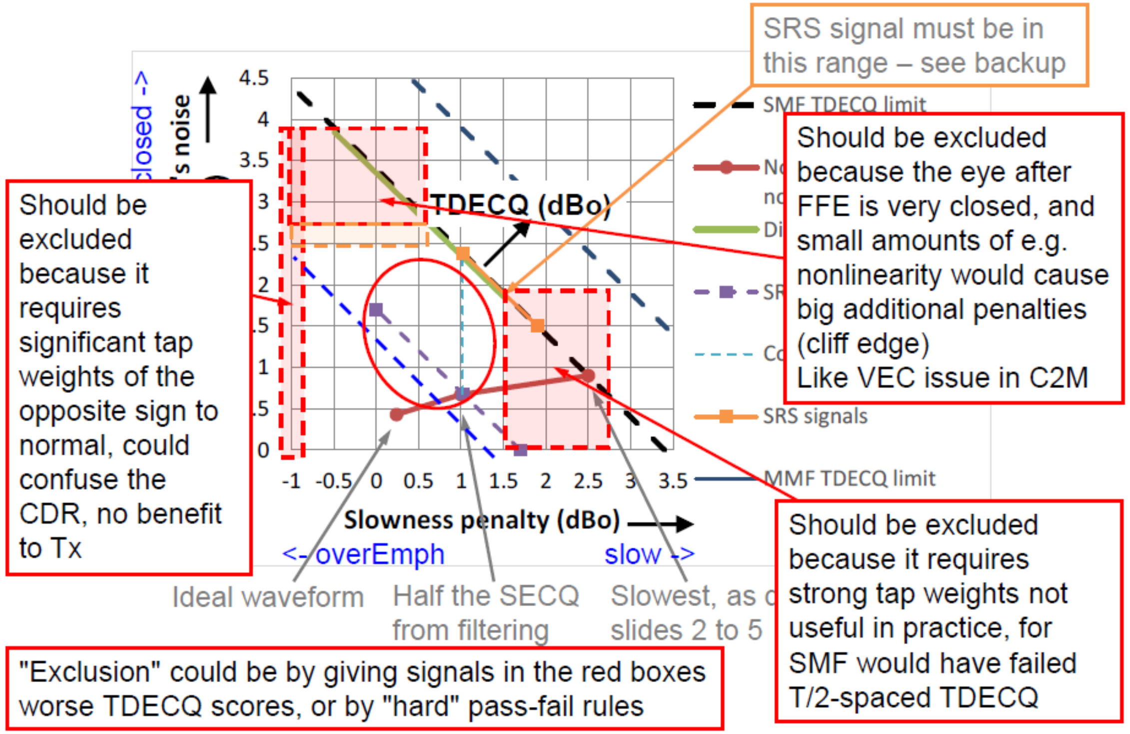
- Plots C_{eq} on horizontal axis
- Plots (TDECQ – C_{eq}) on vertical axis

http://ieee802.org/3/cd/public/Mar18/dawe_3cd_01a_0318.pdf

- C_{eq} is the equalizer's noise enhancement factor
    - for white noise filtered by a 13.28125 GHz fourth-order Bessel-Thompson filter
    - C_{eq} = **1** for signals which are unequalized
    - C_{eq} **>1** for an equalized bandwidth limited signal
    - C_{eq} **<1** for pre-emphasized signals (at TP3), it's equivalent to equalizable noise
  - TDECQ is the dB ratio of the noise that can be added to the Tx signal as compared to an ideal unequalized transmitter
      - It's the sensitivity penalty you'd expect to see for a receiver and reference equalizer combination
      - It's made up of noise multiplication factor C_{eq} and unequalizable signal penalties
- TDECQ – 10.log(C_{eq}) is the unequalizable penalty of the signal
  - It doesn't take into account SNR changes due to noise filtering
- Neither of these tell the whole story of how difficult a signal is to equalize

TDECQ Map – frequent sightings

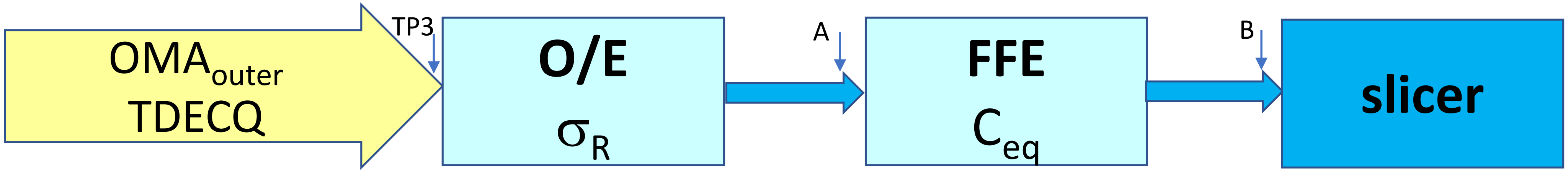
- Usually surrounded by warnings of what is bad for a receiver
  - But without supporting data from real receivers, or analysis to back up the claims



- **Note**: Since Ceq and TDECQ-Ceq sum to TDECQ, the compliant transmitter region is a triangle – which always looks like it could do with trimming at the corners

Analysis of signal and noise amplitude for max TDECQ transmitters

Imagine a PAM4 signal input into a unity gain receiver chain: Noise

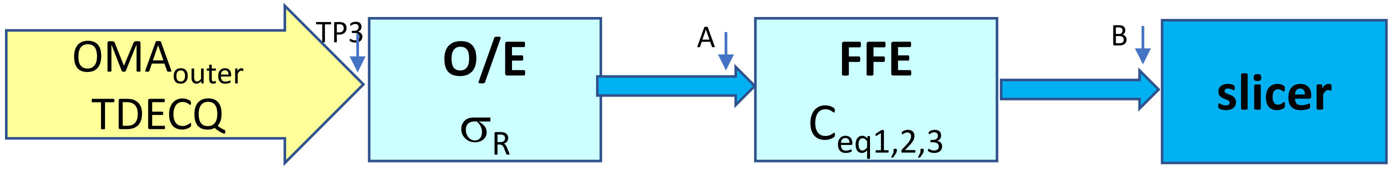


- TDECQ calculates how much noise can be added by an ideal receiver to the signal compared to an ideal (unequalized, noiseless) transmitter
- For an ideal unequalized transmitter, the noise the receiver can add is $\frac{OMA_{outer}}{6.Qt}$
  - where Q_t = 3.414, consistent with a target BER of 2.4×10^{-4} for Gray coded PAM4
- For an equalized transmitter, the noise the receiver can add, σ_R, (ref. point A) is

$$\sigma_R = \frac{OMA_{outer}}{6.Qt} \cdot 10^{-TDECQ/10}$$

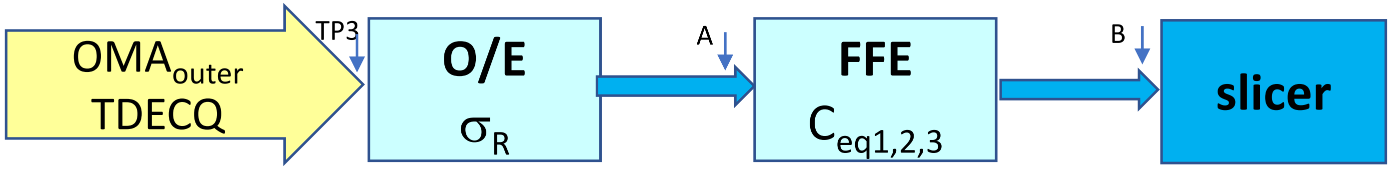
  - Alternatively, the receiver sensitivity, S, in OMA_{outer} , is: $S = 6.Qt.\sigma_R.10^{TDECQ/10}$
- After the equalizer (ref. point B), the noise amplitude is multiplied by C_{eq}
- This *must* be compensated by the EQ, with an equal increase in effective eye-opening, by a factor Ceq (without altering the OMA_{outer})

Imagine a PAM4 signal input into a unity gain receiver chain: Signal



- For an ideal unequalized Tx, the signal amplitude (half the sub-eye OMA) is $\frac{OMA_{outer}}{6}$
- For a transmitter with max TDECQ, the effective signal amplitude after the FFE is $C_{eq}.\frac{OMA_{outer}}{6}.\ 10^{-TDECQ/10}$
  - because the signal amplitude/noise amplitude after the EQ must equal Q_t
- Before the equalizer, the effective signal amplitude is $\frac{OMA_{outer}}{6}.\ 10^{-TDECQ/10}.k_S$
  - k_S is an effective eye closure factor, and may represent equalizable and unequalizable components
    - k_S must be less than 1 if C_{eq} is greater than 1
      - If k_s was 1 for C_{eq} >1, then the signal amplitude/noise amplitude before the EQ would also equal Q_t , and there would be no need for equalization, so C_{eq} would equal 1….
    - k_S must be less than 1 if C_{eq} is less than 1
      - If k_s was 1 for C_{eq} <1, then the signal amplitude/noise amplitude before the EQ would also equal Q_t , and there would be no need for equalization, so C_{eq} would equal 1….
      - If k_s was >1 for C_{eq} <1, then the signal amplitude/noise amplitude before the EQ would exceed Q_t, and theTDECQ of the transmitter could not be at it's maximum value.
      - *Pre-emphasis closes the eye for PAM4 (but makes the FFE work less hard)*
- The equalizer signal gain G_{seq} (improvement in effective eye-opening) is the ratio of the signal before and after the EQ: $G_{seq} = \frac{C_{eq}}{k_s}$, which is greater than C_{eq} when C_{eq}>1 or C_{eq}<1

For a receiver with fixed input referred noise



- Consider three transmitter inputs all with max TDECQ:
  - Tx1 with unequalizable eye closure (C_{eq1}=1)
  - Tx2 with equalizable eye-closure e.g. a low pass response (C_{eq2}>1)
  - Tx3 with higher unequalizable eye closure and some pre-emphasis (C_{eq3}= 0.8)

Right side of Piers map

Left side of Piers map

- After the O/E (point A)
  - For all transmitters Tx1, Tx2, Tx3, the Rx sensitivity is: $S_{Tx1} = S_{Tx2} = S_{Tx3} = 6.\,Q_t.\sigma_R.10^{TDECQ/10}$
  - For DSP based receivers, sampling takes place after the O/E. For all 3 transmitters, receiver degradation due to non-linearity, timing inaccuracy and quantization are all operating with the same OMA_{outer} , and the same receiver noise. The difference between the transmitters stems from the effective eye-closure at this point.
- After the FFE (point B)
  - For the unequalizable Tx1, the noise and signal are the same as before the FFE
  - For the equalizable Tx2, the noise has increased (by C_{eq2}), but the effective eye opening is increased by C_{eq2}/k_{s2}
  - For the unequalizable Tx3 with pre-emphasis, the noise is decreased (multiplied by C_{eq3} which is 0.8), and the effective eye-opening is multiplied by C_{eq3}/k_{s3}, which is greater than C_{eq3}

Summary of signal and noise terms analysis

Comparing transmitters with maximum TDECQ, at the O/E output:

- A transmitter with unequalizable eye closure has a normalized effective eye opening at the receiver of –TDECQ dB
- A transmitter with equalizable eye closure (low pass filtered) has a normalized effective eye opening at the receiver of –TDECQ–10.log.(C_{eq}/k_s) dB
  - It is more closed than the unequalizable Tx, because $C_{eq}>1$, $k_s<1$
- A transmitter with unequalizable eye closure and some pre-emphasis has a normalized effective eye opening at the receiver of –TDECQ–10.log(C_{eq}/k_s)dB
  - It is more closed than the unequalizable Tx, because $C_{eq}<1$ and $k_s<1$; but not as closed as the equalizable Tx for reasonable values of pre-emphasis
- **TDECQ-10.log(Ceq) 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**
- **i.e. Tx with maximum equalizable eye-closure (low pass filtered)**

Recommendations

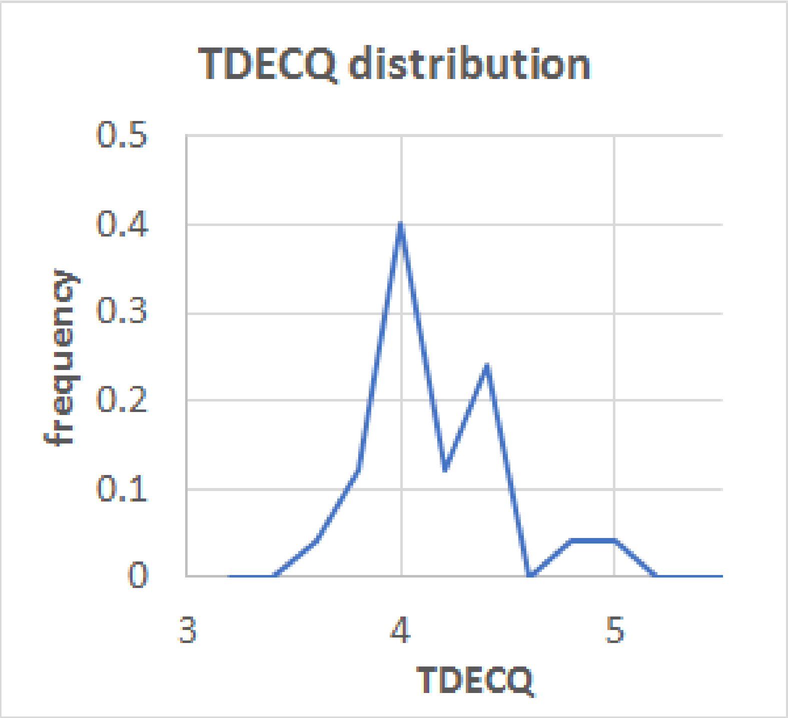
- The toughest receiver test condition is for a low pass filtered test source
  - as specified in 802.3cd D3.3
  - Suggests we should keep the current SRS test point
- The constraint on minimum main tap value of 0.8, limits the amount of pre-emphasis that gets TDECQ credit to ~1 dB
- This means that max TDECQ pre-emphasized transmitter has a bigger effective eye opening than the max TDECQ low-pass filtered test source.
- There is no value in adding a TDECQ-10.log(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

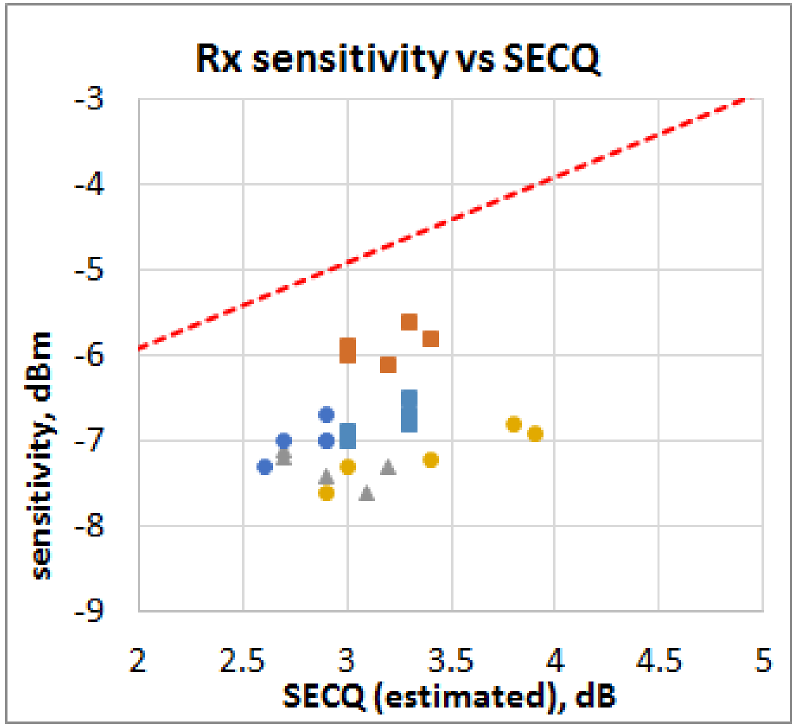
Back up

Reference equalizer noise multiplication

- Assuming least mean square convergence, sum of taps = 1
  - The OMA outer will remain constant
  - The sequence that corresponds to the most closed eye before equalization will get an increase in it's eye opening equal to the sum of the absolute tap coefficients.
  - The noise multiplication factor is: Ceq < $\sqrt{\sum_{1}^{5}(tap\ coefficient)^2}$
    - Noise is distributed over a spectrum:
      - For low frequencies (<< Nyquist) are substantially correlated across the EQ time span and so see no noise multiplication (i.e. the EQ gain is 1 at low frequencies)
      - For high frequencies (>Nyquist) the noise is uncorrelated between taps and the RSS of the taps gives the noise multiplication factor
      - In between, it's complicated

A few more VCSEL results: TDECQ and sensitivity





- TDECQ centered around 4 dB (consistent with previous results)
- Rx sensitivity vs SECQ is a plot of transmitters looped back to their own receivers – thus represents performance of several receivers