Transmit Quality Metric approach for Coherent Specifications

Supporting Contribution for D1.0 comment 384

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What do we mean by a TQM?

A normative measure of transmitter induced performance penalty in dB relative to an ideal transmitter = TQM

- Tx only RSNR Penalty (TQM) determined using a captured DUT Tx output waveform and a *Reference Rx.* Proposal is developed in this contribution.

TQM is NOT intended as a replacement for individual parametric specifications

- Parametric specifications (worst-case values) are necessary for Rx design

TQM IS intended to bound the overall transmit performance

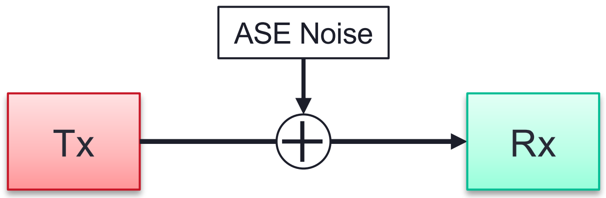
- Allowing all Tx parameters to be at worst case values would be unrealistic and prohibitive on ROSNR
  - Today our coherent ROSNR specifications assume this DOES NOT take place; however, the overall transmit performance bound is not specified. This is a hole in our methodology.
- A compliant Tx would require meeting both parametric and TQM specifications

Adopting a TQM *may* allow the relaxation of some individual parametric specifications

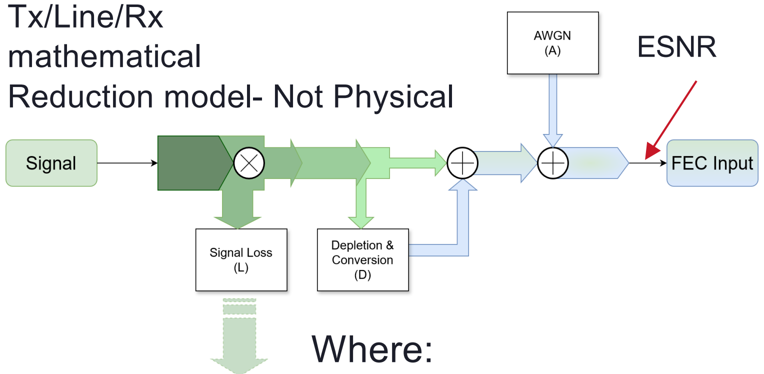
Background Primer on Methodology for Modem Performance Measurement Analysis

Analysis Methodology: ESNR and $ESNR_{ref}$

- **For a basic modem Tx to Rx fiber connection over a patch-cord with optional ASE noise loading:**



the signal-to-noise ratio at the FEC input (ESNR) may be described assuming a noise model which includes signal loss/conversion ahead of noise addition:



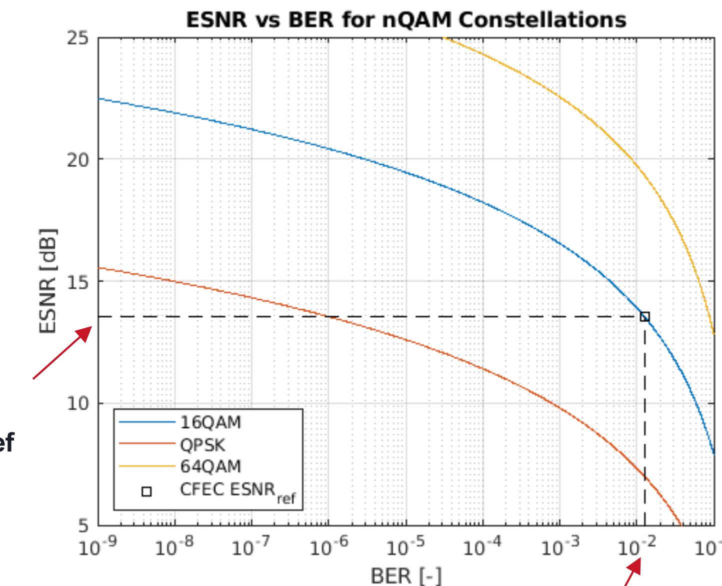
$$ESNR = \frac{EC_{modem}^{-1} \cdot S}{N_{ase} + N_{modem}} = \frac{EC_{modem}^{-1}}{NSR_{ase} + NSR_{modem}}$$

Where:

- EC_{modem}: Eye-closure term, representing signal loss
- S: Signal power
- N_{ase}: ASE noise power
- N_{modem}: Modem implementation noise power
- NSR_{ase}: ASE noise-to-signal ratio
- NSR_{modem}: Modem implementation noise-to-signal ratio

- **The noise tolerance of a communication system is determined by the minimum required ESNR at the FEC input, $ESNR_{ref}$. Under AWGN conditions, $ESNR_{ref}$ is only a function of the modulation format and the maximum BER tolerated by the FEC. E.g.**
  - 400ZR, 16QAM
  - CFEC, 1.25E-2 BER FEC threshold
  - RS+BCH 1.1E-2 BER FEC threshold

400ZR $ESNR_{ref}$ = 13.55 dB



400ZR BER_{thresh} = 1.25E-2

Analysis Methodology: $RSNR_{ase}$, $RSNR_{th}$, $\Delta RSNR$

- The (optical) SNR_{ase} at the modem input is defined as
$$SNR_{ase} = \frac{S}{N_{ase}} = \frac{1}{NSR_{ase}}$$
- Furthermore, the performance of an implementation can be characterized by its Required SNR_{ase} ($RSNR_{ase}$) at the modem input
$$RSNR_{ase} = \frac{S}{\overline{N}_{ase}} = \frac{1}{\overline{NSR}_{ase}}$$
- where:
  - $\overline{N}_{ase}$: Maximum ASE noise that can be added before the BER FEC threshold is reached.
  - $\overline{NSR}_{ase}$: Maximum ASE noise-to-signal ratio
- $RSNR_{ase}$ may be measured or can be calculated analytically based on $ESNR_{ref}$:

$$ESNR_{ref} = \frac{EC_{modem}^{-1}}{\overline{NSR}_{ase} + NSR_{modem}}$$

$$\overline{NSR}_{ase} = \left(EC_{modem} \cdot ESNR_{ref}\right)^{-1} - NSR_{modem}$$

$$RSNR_{ase} = \left(\left(EC_{modem} \cdot ESNR_{ref}\right)^{-1} - NSR_{modem}\right)^{-1}$$

- For an ideal modem (NSR_{modem}= 0 and EC_{modem}= 1), the theoretical RSNR, $RSNR_{th}$, is equal to the reference ESNR:

$$RSNR_{th} = \left(\left(1 \cdot ESNR_{ref}\right)^{-1} - 0\right)^{-1} = ESNR_{ref}$$

- For typical modem implementations,
$$RSNR_{ase} > RSNR_{th}$$
- Therefore, the quality of a modem may be quantified by the RSNR Penalty, $\Delta RSNR_{modem}$, due to modem implementation noise and modem eye-closure:

$$\Delta RSNR_{modem} = RSNR_{ase}(EC_{modem}, NSR_{modem})/RSNR_{th}$$

- The analytical calculation of $RSNR_{ase}$ is only feasible if eye-closure and implementation noise are known. These values can be estimated via a noise loading experiment.

Analysis Methodology: Experimental noise loading determination of EC_{modem}, NSR_{modem}, and $\Delta RSNR_{modem}$

- The noise loading experiment assumes the previously defined relationship between ESNR and SNR_{ase}:

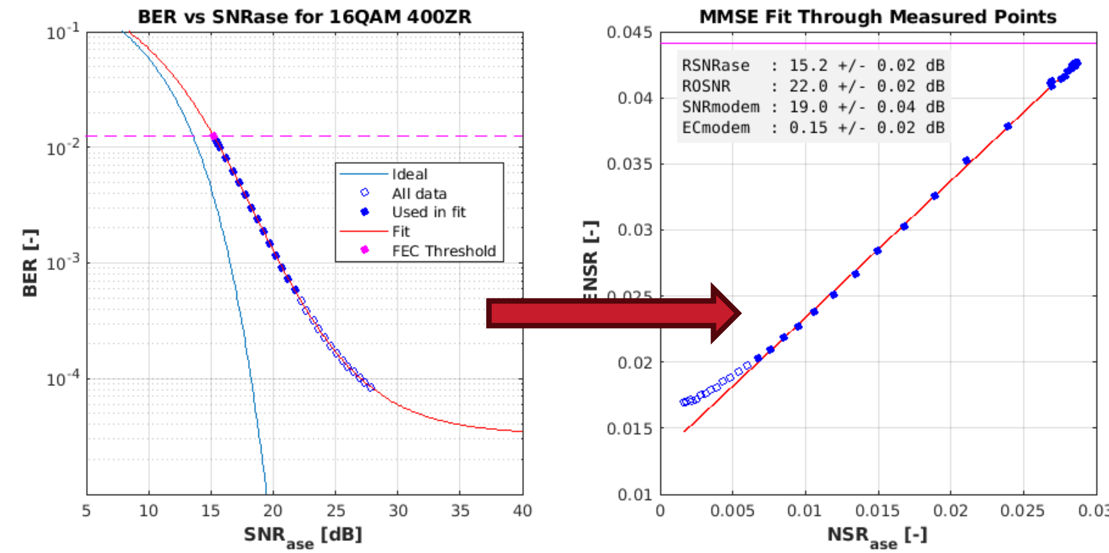
$$ESNR = \frac{EC_{modem}^{-1}}{NSR_{ase} + NSR_{modem}} = \frac{1}{EC_{modem}(NSR_{ase} + NSR_{modem})}$$

$$\begin{aligned} ENSR &= EC_{modem}(NSR_{ase} + NSR_{modem}) \\ &= EC_{modem}NSR_{ase} + EC_{modem}NSR_{modem} \\ &= a \cdot NSR_{ase} + b \end{aligned}$$

- The experiment is conducted as follows:
  1. Increment the ASE noise level at the modem input in steps and measure SNR_{ase} as well as its corresponding BER at the FEC input for each step.

$$\left\{SNR_{ase}^{(1)}, SNR_{ase}^{(2)}, \dots, SNR_{ase}^{(N)}\right\} \leftrightarrow \left\{BER^{(1)}, BER^{(2)}, \dots, BER^{(N)}\right\}$$

  1. Use the known ESNR(BER) relationship (slide 4) and calculate all $ENSR^{(n)}$ and $NSR_{ase}^{(n)}$ points



3. Calculate the 1st order MMSE fit (slope a and offset b) in the vicinity of the FEC threshold over the range where the measured ENSR vs. NSR_{ase} relationship is linear. Then

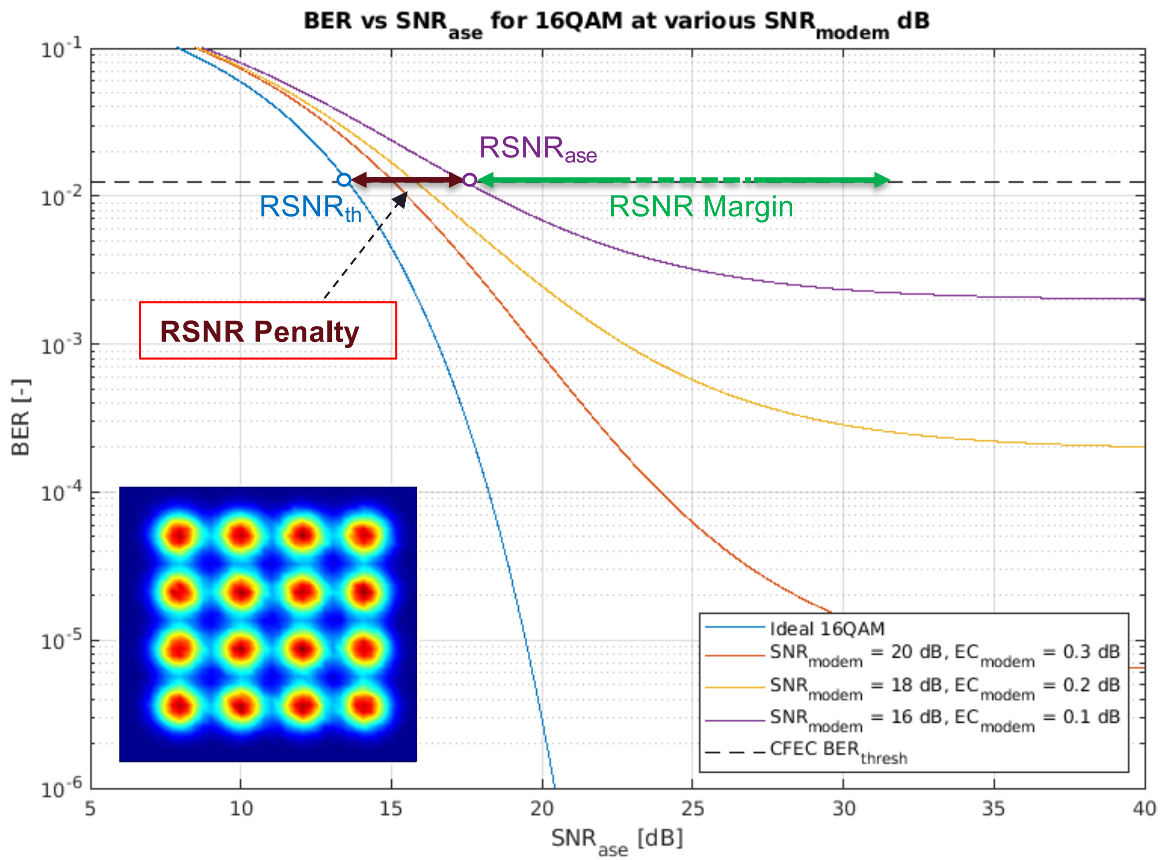
$$\widehat{EC}_{modem} = a$$
$$\widehat{NSR}_{modem} = b/\widehat{EC}_{modem}$$

4. The estimated $RSNR_{ase}$ and the $\Delta RSNR_{modem}$ may be calculated as follows:

$$\widehat{RSNR}_{ase} = \left(\left(\widehat{EC}_{modem} \cdot ESNR_{ref}\right)^{-1} - \widehat{NSR}_{modem}\right)^{-1}$$

$$\Delta RSNR_{modem} = \widehat{RSNR}_{ase}/RSNR_{th}$$

Analysis Methodology: Example of RSNR Penalty in dB and Modem Impairment Allocation



Definitions:

- **$RSNR_{ase}$**: Required signal-to-noise ratio to achieve the required post-FEC Frame Error Ratio.
- **$RSNR_{th}$**: Theoretically required signal-to-noise ratio given an ideal modem.
- **RSNR Penalty**: Difference between $RSNR_{ase}$ and $RSNR_{th}$ in dB
- **RSNR Margin**: Difference between the actual SNR_{ase} and RSNR in dB

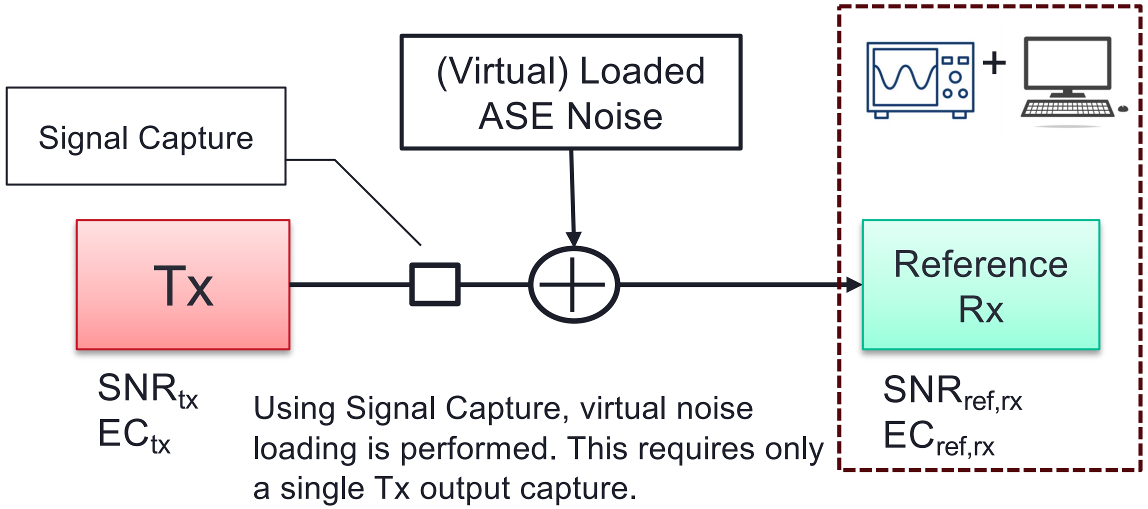
- The combined modem implementation penalty so far defined as NSR_{modem} and EC_{modem}, is a function of Tx and Rx implementations,

$$NSR_{modem} = NSR_{tx} + NSR_{rx}$$
$$EC_{modem} = EC_{tx} \cdot EC_{rx}$$

Reference Rx and TQM

Introducing a Reference Rx

- **For evaluating a Tx only RSNR Penalty TQM, a measurement using a *Reference Rx* is required.**



- Two classes of *Reference Rx* can be considered:
  - **Type 1 -** Golden Rx: Unrealistic complexity, able to fully-compensate Tx impairments. See 4x4MIMO in [1]
  - **Type 2 -** Typical Rx: Representative of a typical performance. See 2x2MIMO in [1]

[1] Q. Fan et al, ITU-T WD06-33, Berlin

- For a TQM implementation intended to bound the overall Tx performance, a **Type 2 Rx is required**
  - Equalizer provides realistic compensation of Tx distortion vs. Tx noise.
  - Appropriate Rx clock recovery and carrier recovery bandwidths for the signal defined
  - **OE front must be characterized and its implementation penalty ($SNR_{ref,rx}$, $EC_{ref,rx}$) must be calibrated.**
- Applying the analysis methodology developed in the previous Section on the collected data from the *Reference Rx* measurement we can extract,

$$NSR_{DUT,ref} = NSR_{tx} + NSR_{ref,rx}$$
$$EC_{DUT,ref} = EC_{tx} \cdot EC_{ref,rx}$$

where $NSR_{modem} \rightarrow NSR_{DUT,ref}$ and $EC_{modem} \rightarrow EC_{DUT,ref}$

Note: NSR_{tx} and $NSR_{ref,rx}$ are often defined, spec'd, or referred to in terms of their inverse, SNR_{tx} and $SNR_{ref,rx}$, respectively. SNR is typically preferred when dB units are used to avoid the negative sign.

Analysis Methodology: Tx only RSNR Penalty Extraction

- Based on the measurements using the reference Rx and with virtual noise loading (SNR_{vase}) and the Reference Rx calibration data, the Tx only RSNR Penalty, $\Delta RSNR_{tx}$, can be therefore be calculated:

$$RSNR_{vase} = \left(\left(EC_{tx} \cdot ESNR_{ref}\right)^{-1} - NSR_{tx}\right)^{-1}$$

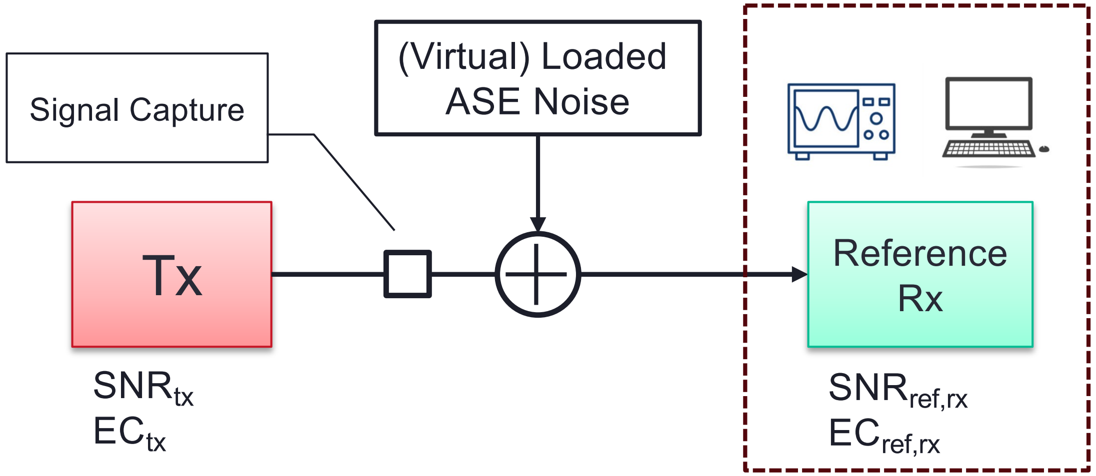
$$\boldsymbol{\Delta RSNR_{tx} = RSNR_{vase} / RSNR_{th}}$$

- Where:

$$NSR_{tx} = \widehat{NSR}_{DUT,ref} - NSR_{ref,rx}$$
$$EC_{tx} = \widehat{EC}_{DUT,ref} / EC_{ref,rx}$$

Conclusion: TQM Proposal

- Define a normative *Reference Rx* (Type 2) which will provide:
  - Pre-FEC BER
  - SNR at the FEC input (aka ESNR)
  - $SNR_{ref,rx}$, $EC_{ref,rx}$
- Conduct (virtual) noise loading experiment using a captured DUT Tx output waveform and a *Reference Rx* to extract:
  - Tx only RSNR penalty, **$\Delta RSNR_{tx}$**, in dB.
  - SNR_{tx}, EC_{tx}

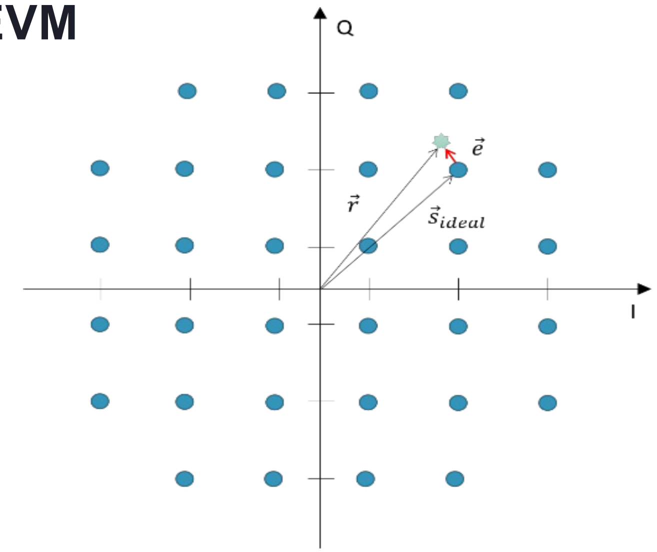


Using Signal Capture, virtual noise loading is performed.
This requires only a single Tx output capture.

- **Our proposal is to capture in 802.3dj coherent clauses:**
  - **$TQM = \Delta RSNR_{tx}$** = Tx only RSNR penalty in dB (*normative* with a maximum spec)
  - SNR_{tx}, EC_{tx} in dB (*informative*)

EVM & TCC

EVM



$$EVM(dB) = 10 \cdot \log_{10}\left(\frac{P_{error}}{P_{max}}\right)$$

EVM provides a measure of SNR based on deviations of measured symbols from theoretical symbols

TCC

$$TCC(dB) = 10\log_{10}\left(\frac{\sigma_{ideal}^2}{\sigma_{TUT}^2 + \sigma_S^2}\right) + 10\log_{10}\left(\frac{p_{unfiltered}}{p_{filtered}}\right)$$

TCC provides a comparison of the SNR margin between a perfect transmitter and a transmitter under test, as measured by a reference receiver

See: Q. Fan & X. Liu, TH2A.26, OFC 2024

Aside: Tx only RSNR Penalty vs TCC

- Tx only RSNR Penalty is related to TCC as follows:

$$\Delta RSNR_{tx} = \frac{RSNR_{ase}}{RSNR_{th}} = \frac{\left(\left(EC_{tx} \cdot ESNR_{ref}\right)^{-1} - NSR_{tx}\right)^{-1}}{RSNR_{th}}$$

$$= \frac{RNSR_{th}}{\left(\left(EC_{tx} \cdot ESNR_{ref}\right)^{-1} - NSR_{tx}\right)}$$

$$= \frac{EC_{tx} \cdot RNSR_{th}}{(RNSR_{th} - EC_{tx} \cdot NSR_{tx})}$$

$$= \frac{EC_{tx} \cdot \sigma_{th}^2}{(\sigma_{th}^2 - EC_{tx} \cdot \sigma_{tx}^2)}$$

- Assuming no eye-closure, i.e. $EC_{tx} = 1$,

$$\Delta RSNR_{tx} = \frac{\sigma_{th}^2}{\sigma_{th}^2 - \sigma_{tx}^2} = \frac{\sigma_{th}^2}{\left(\sigma_{tx}^2 + \bar{\sigma}_{ase}^2 + \sigma_{ref,rx}^2\right) - \sigma_{tx}^2}$$

$$= \frac{\sigma_{th}^2}{\left(\sigma_{tx}^2 + \bar{\sigma}_{ase}^2 + \sigma_{ref,rx}^2\right) - \sigma_{tx}^2} = \frac{\sigma_{th}^2}{\bar{\sigma}_{ase}^2 + \sigma_{ref,rx}^2}$$

- Comparing the noise loading component of TCC to Tx only RSNR Penalty with $EC_{tx} = 1$:

$$\frac{\sigma_{th}^2}{\bar{\sigma}_{ase}^2 + \sigma_{ref,rx}^2} = \frac{\sigma_{ideal}^2}{\sigma_{TUT}^2 + \sigma_s^2}$$

Reference: OFC2024, TH2a.26

- Where:
  - $\sigma_{th}^2, \sigma_{ideal}^2$: Theoretical noise variance at the FEC threshold
  - σ_{tx}^2: Tx implementation noise variance
  - $\sigma_{ref,rx}^2$: Reference Rx implementation noise variance
  - $\bar{\sigma}_{ase}^2, \sigma_{TUT}^2$: Maximum tolerated (virtual) ASE noise variance at the input of the (Reference) Rx
  - $\sigma_{th}^2 = \sigma_{tx}^2 + \bar{\sigma}_{ase}^2 + \sigma_{ref,rx}^2$: The total noise variance at the FEC threshold in a (virtual) noise loading experiment is the sum of all the implementation- and (ASE) loading noise variances.

Thanks!