400GBASE-ZR 75GHz specification framework and compliance methodology proposal

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P802.3cw/P802.3ct task force

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Outline

- Motivation
- Optimal Receiver Solution
  - Proposed metric: Optimal equalization SNR
  - Comparison to NSR metric and weighted crosstalk
- Applying proposed metric to 400GBASE-ZR at 75GHz spacing
- Proposed framework
  - Parametric simulation analysis: recommended reference tables
  - Examples showing compliance
- Proposed specifications
- Summary

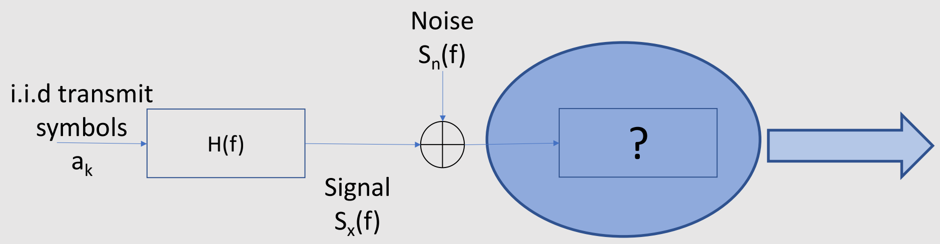
Motivation

- For 400GBASE-ZR 75GHz use case, we are yet to establish a solid system metric with sound theoretical basis.

- A sound *framework* needs to be agreed upon amongst interested parties to foster the development of solid specifications for 400ZR at 75GHz spacing.

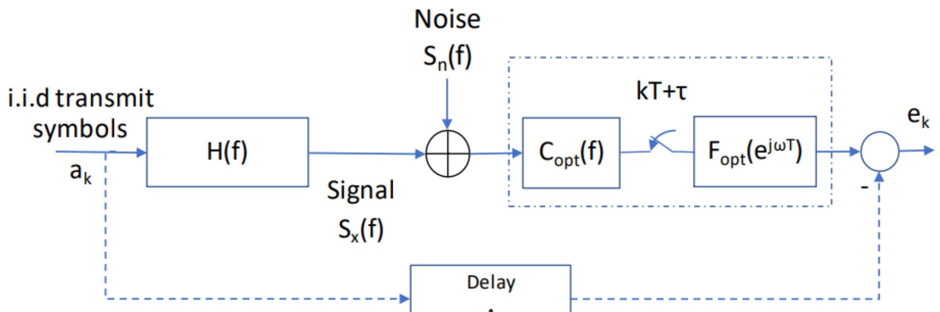
- Independent *compliance* methodologies for Tx, Link and Rx are needed for 400GBASE-ZR 75GHz system and component demarcation. An encapsulating spec (e.g. a figure of merit) is highly preferred for compliance to ensure no *over-specification* of transceivers.

Optimal Receiver Solution



Digital Communication theory provides elegant equations to calculate the performance of an optimal RX [1, 2, 3]

Optimal Equalizer: Solution



- This equation is applicable for receivers which use *linear equalization*
- The equation represents the *bound* on achievable performance of a real receiver
- Result can be conveniently extended to *suboptimal* analog frontend + fractionally-sampled ADC and equalizers

Proposed Metric: Optimal equalization SNR

Definitions:

$$SNR(f) \triangleq \frac{S_x(f)}{S_n(f)}$$

$$SNR\_f(e^{j\omega T}) \triangleq \sum_l SNR\left(j\left(w - \frac{2\pi l}{T}\right)\right)$$

$\langle \quad \rangle_H$ *is harmonic mean over* $[-\pi, \pi]$

Performance of optimal MMSE equalizer

$$\frac{E[a_k^2]}{E[e_k^2]} = \langle 1 + SNR\_f(e^{j\omega T}) \rangle_H \qquad \text{Eq. 1}$$

Ref [1]: Lee and Messerschmitt, "Digital Communication", 2nd Ed. 1994, Ch10

Ref [2]: T. Berger and D. Tufts, "Optimum pulse amplitude modulation--I: Transmitter-receiver design and bounds from information theory," in IEEE Transactions on Information Theory, vol. 13, pp. 196, April 1967.

Ref[3]: J. Salz, "Optimum mean-square decision feedback equalization," in The Bell System Technical Journal, vol. 52, no. 8, pp. 1341-1373, Oct. 1973

Ref [4]: https://www.ieee802.org/3/ct/public/20_09/kota_3cw_01_200921.pdf

Ref [5]: https://www.ieee802.org/3/ct/public/tf_interim/20_1001/kota_3cw_01_201001.pdf

Relationship to Weighted Crosstalk and NSR

- "Weighted crosstalk" metric is defined by M. Filer et.al "Generalized weighted crosstalk for DWDM systems with cascaded wavelength-selective Switches", Optics Express, Vol. 20, No. 16, July 2012
  - Specific weighing function is the *scaled receive signal spectrum*, which is mathematically equivalent to a receiver which implements a filter that matches the *square root of the receive spectrum*

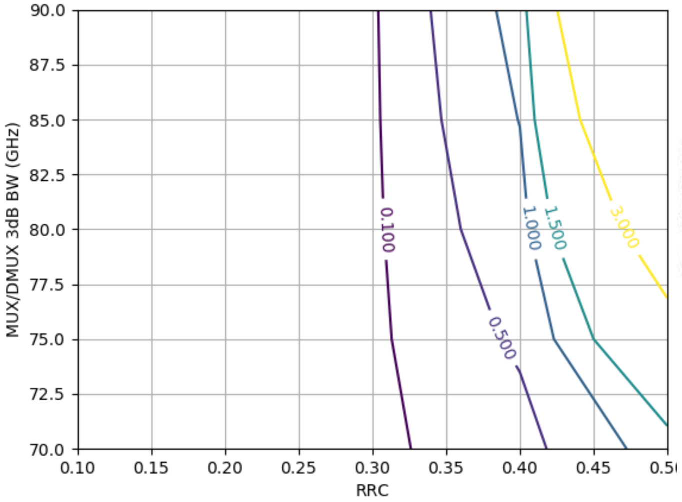
- "NSR" metric defined by S. Kunze et. al. "Impacts of 75GHz Channel Spacing for 400GBASE-ZR", maniloff_3cw_01_200528.pdf, as well as maniloff_3cw_01_200910.pdf
  - Original presentation implied that the receive filter was a *fixed RRC filter*
  - Later presentation implied the filter would *adapt* to Tx spectrum with no further details provided

- Results of these metrics will be similar to the optimal equalization solutions under certain conditions:
  - *C(f) is matched to H(f)*
  - *Folding/Aliasing of the noise and signal spectra has negligible effect*
  - *Ratio of integrated noise and signal power over [-0.5/T,0.5/T] matches the arithmetic mean of 1/SNR_f()*

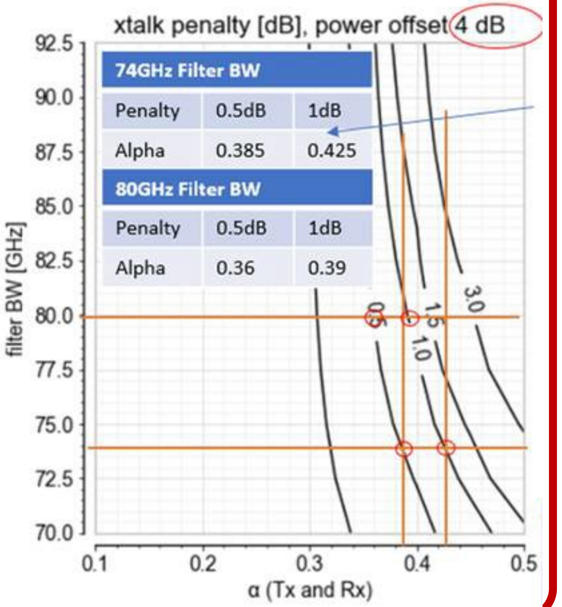
More on NSR and Weighted Crosstalk

Our sim [NSR]

Power offset = 4dB, AWG offset = -4GHz,
laser offset = 1.8GHz

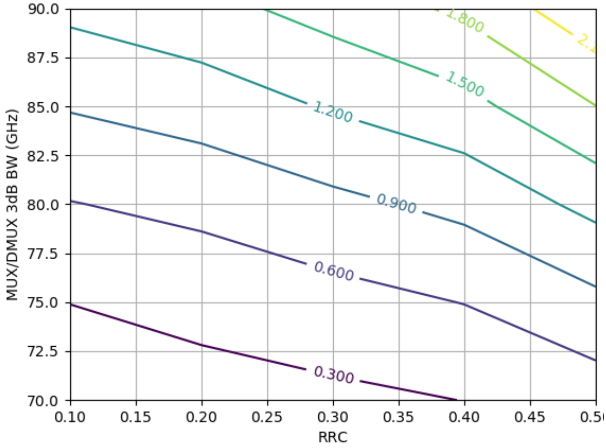


[maniloff_3cw_01_200910.pdf]



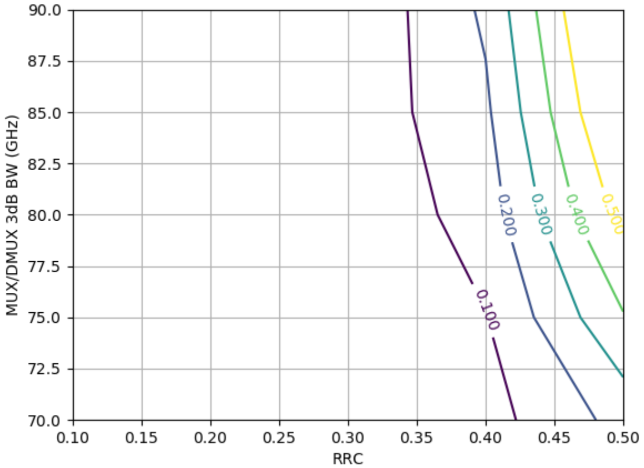
Our sim [suboptimal Rx]

Power offset = 4dB, AWG offset = -4GHz,
laser offset = 1.8GHz, RxOSR=1.2x



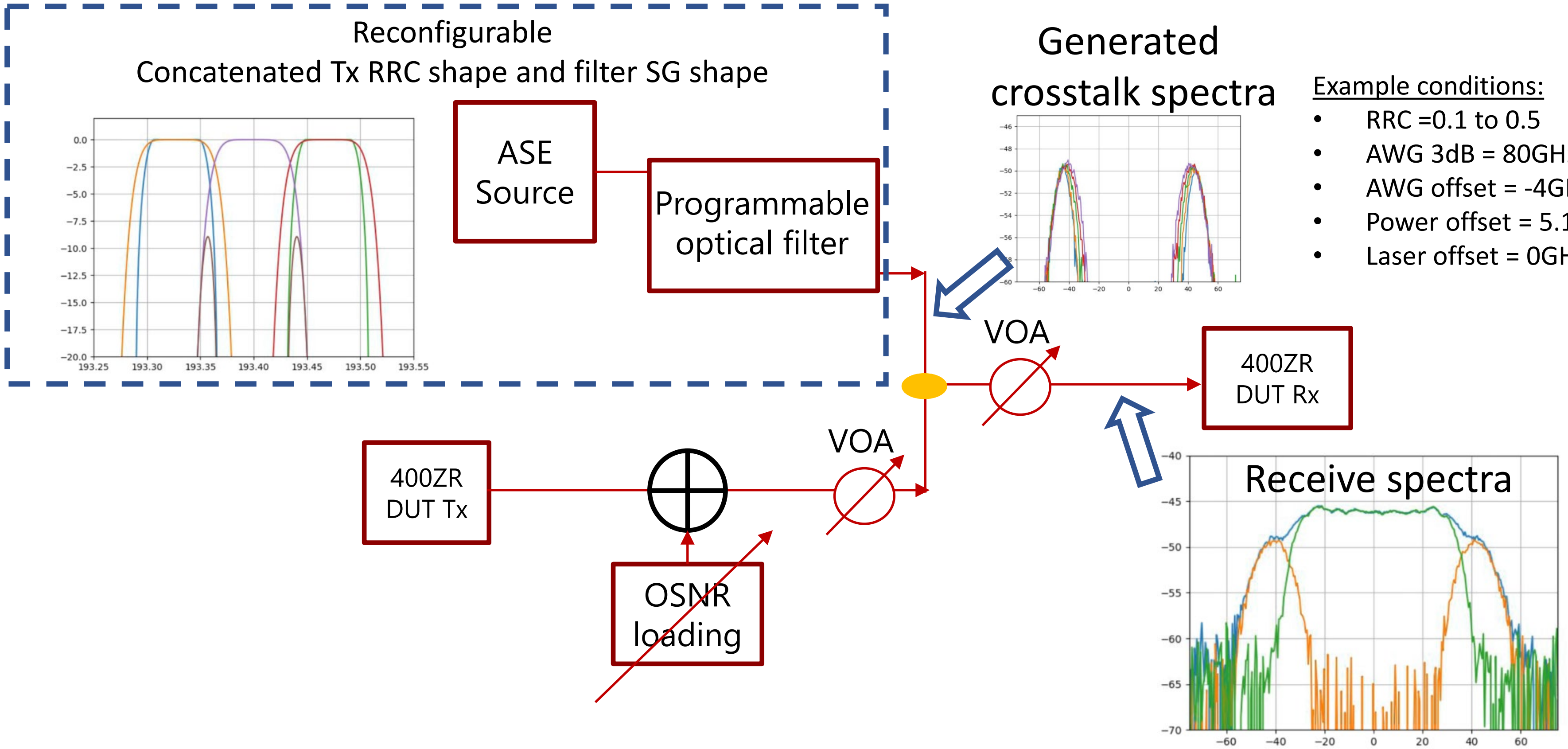
Our sim [optimal Rx]

Power offset = 4dB, AWG offset = -4GHz,
laser offset = 1.8GHz



- We can replicate the NSR results from [maniloff_3cw_01_200910.pdf] (slide 8, bottom right figure)
- However, if we use optimal or suboptimal receiver models, we get much better performance (lower penalty contours)
- This could be explained by the fact that NSR metric has unclear definition of the ‘matched filter’.
- For weighted crosstalk metric, the subtleties lie in the findings of the weighing function.
- The ‘**optimal eq SNR metric**’ does not have the above-mentioned drawbacks as it can ‘auto match’ and produce optimal RX results as well as predicting performance of suboptimal RXs. This flexibility and versatility are important because one does not want the standard to define an unclear ‘matched RX’ which could raise the power and cost of the receivers.

Experimental Setup: Shaped ASE Approach



Example conditions:

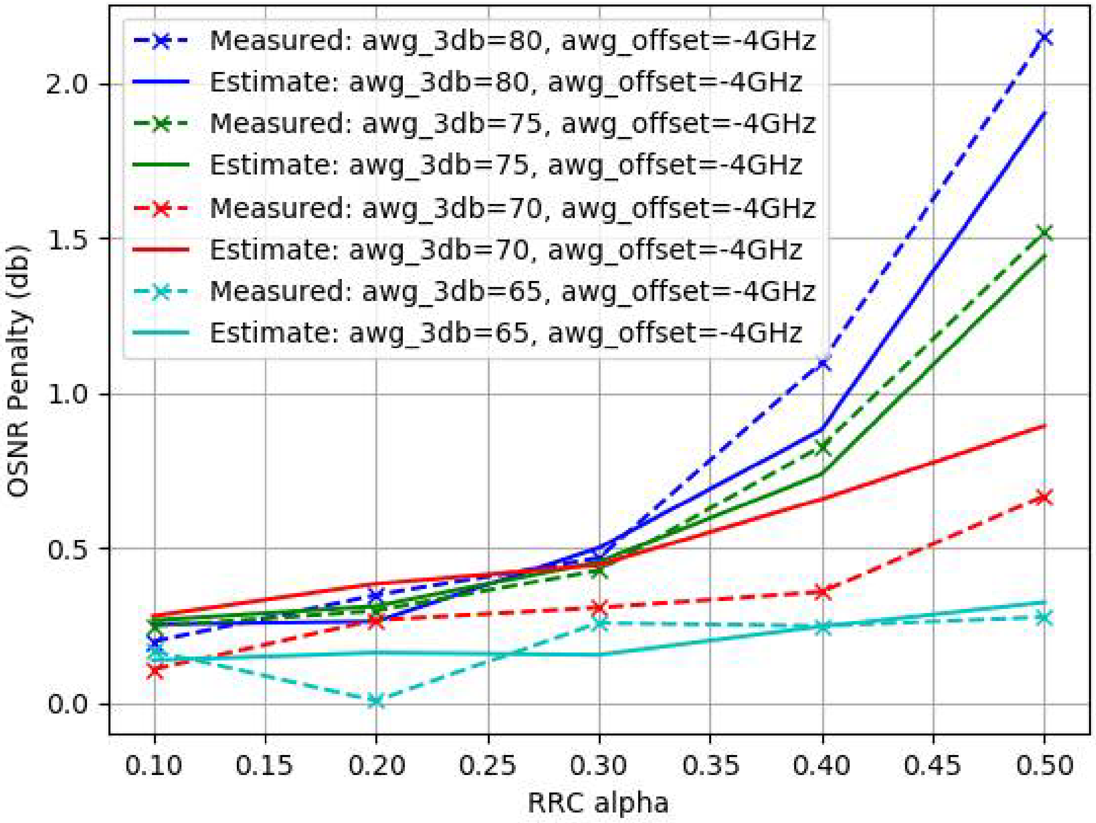
- RRC =0.1 to 0.5
- AWG 3dB = 80GHz
- AWG offset = -4GHz
- Power offset = 5.1dB
- Laser offset = 0GHz

Example conditions:

- RRC =0.5
- AWG 3dB = 80GHz
- AWG offset = -4GHz
- Power offset = 5.1dB
- Laser offset = 0GHz

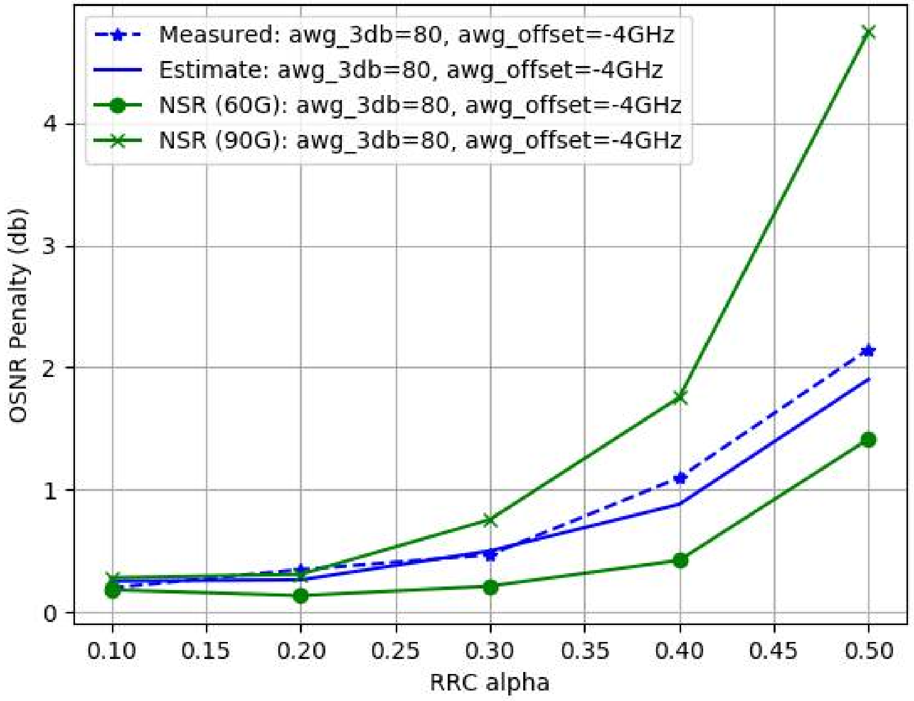
- ASE source followed by programmable optical filter offers flexibility to generate *concatenated* Tx RRC shape and filter Super-Gaussian (SG) shape to mimic the overall response of aggressor channels going through the Mux filter response.
- The above generated left/right aggressor shapes filtered by a response of a Demux centered around the DUT Tx center frequency will form the emulated crosstalk spectra in a reconfigurable manner.
- The crosstalk spectra gets mixed with the DUT signal spectra to form the receive spectra to be detected by the DUT Rx.

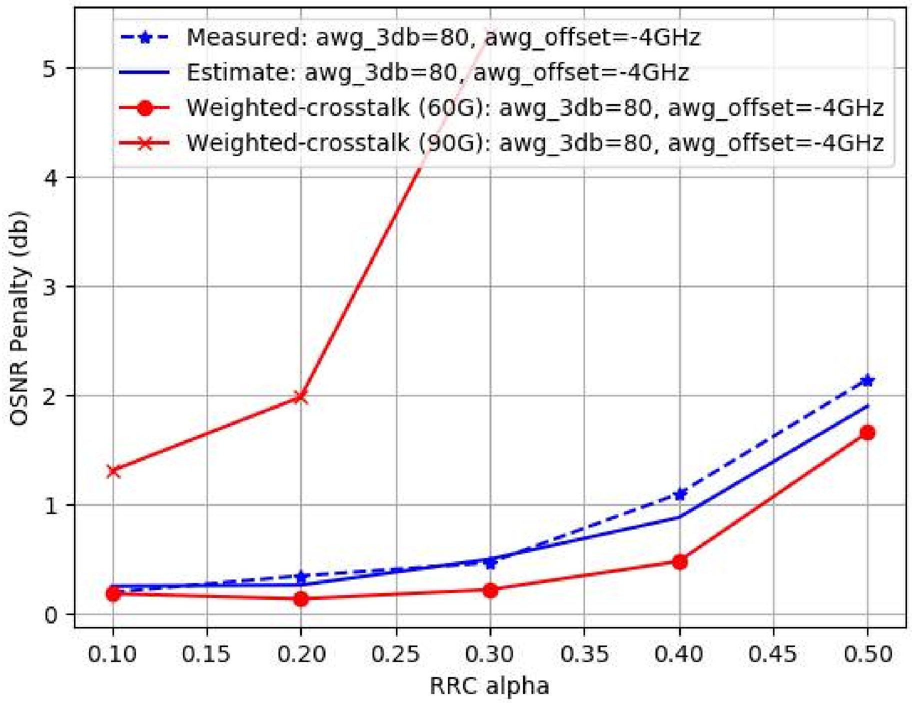
Experimental 400G ZR Results



- The DUT is a realistic 400G ZR DSP based transmitter and receiver implementation in the lab.
- The experimental curves show the rOSNR penalties as a function of RRC w/ a family of emulated AWG 3dBs and offsets.
- The estimated curves are based on the suboptimal RX models taking the DUT signal and crosstalk spectra as the inputs.

More comparison with NSR and Weight Crosstalk





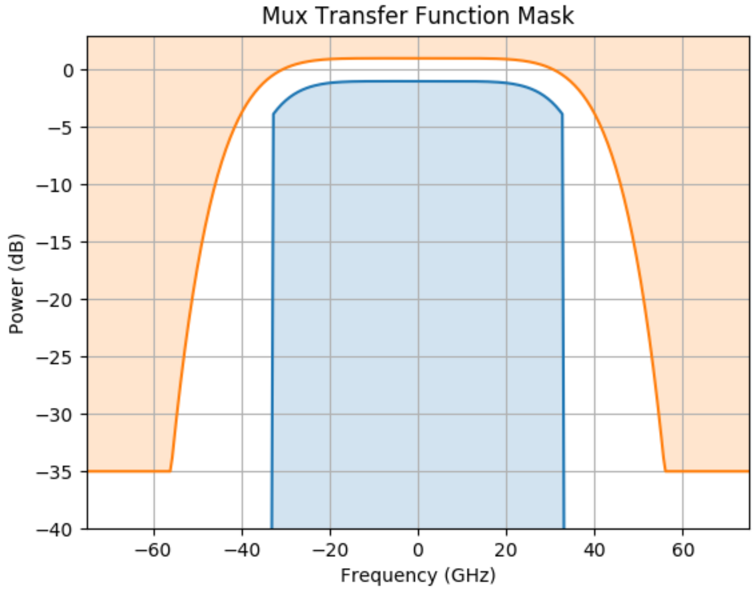
- “NSR” and “weighted crosstalk” on the measured responses with 60 and 90GHz integration window.
- “NSR” metric in this case uses the **same RX filter** as the optimal EQ calculation as the weighting filter.
- “Weighted-crosstalk” uses the **received signal spectrum** as the weighting filter (matches Filer’s paper).
- Strong dependence on the **choice of the integration window** for both NSR and WXTLK metrics are shown.

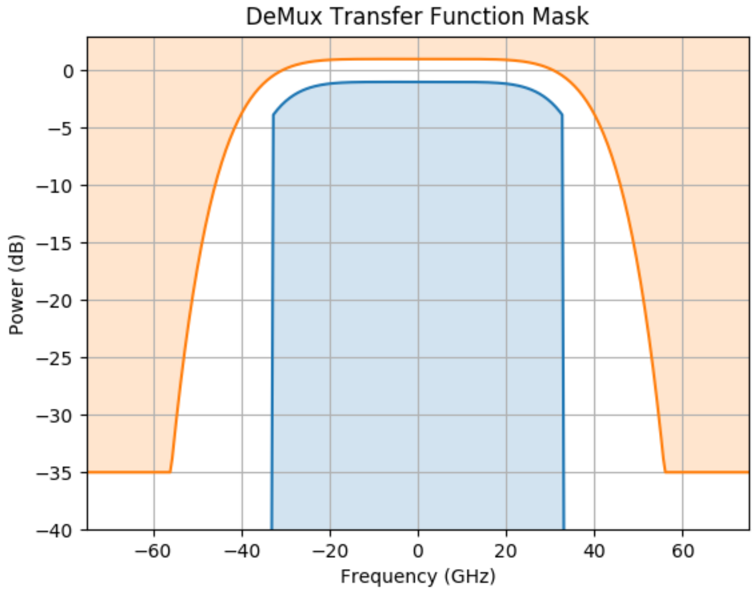
Key Aspects of the Framework

Optimal Eq SNR metric	• A **rigorous** metric that is backed by **digital communication theory** accounts for **arbitrary** signal and noise/crosstalk spectral shapes
Link Compliance Mask	• Defines the **separate transfer function** requirements for the optical Mux and Demux components
TX Center Ch Compliance	• Calculates **a figure of merit** which ensures a compliant TX will produce better receiver SNR than the RX compliance test setup
TX Crosstalk Compliance	• Calculates **a figure of merit** which ensures a compliant TX **does not cause more crosstalk** than the RX compliance test setup
RX Compliance	• Defines a **worst-case setup** specifying the **minimum performance** required from a compliant receiver

Link Compliance Masks of Mux and Demux

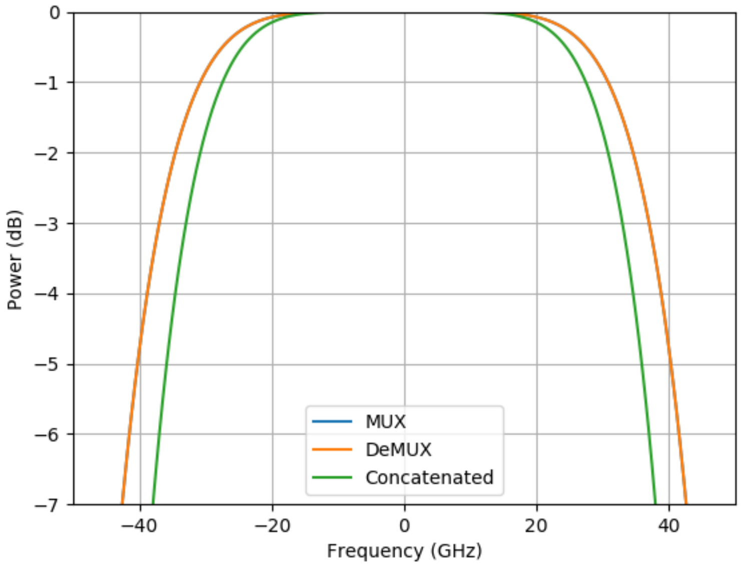
- Defines an allowed compliance transmission mask for each channel
  - Use Super-Gaussian (SG) responses to select allowable range of the links
- Define a reference link based on SG responses for Tx and Rx compliance tests
  - Nominal center frequency (ITU grid with 75G spacing)
  - Minimum order (3rd order)
  - Range of allowable 3dB BW (66GHz to 74GHz)
  - Allowed center frequency variability (-4GHz to 4GHz)





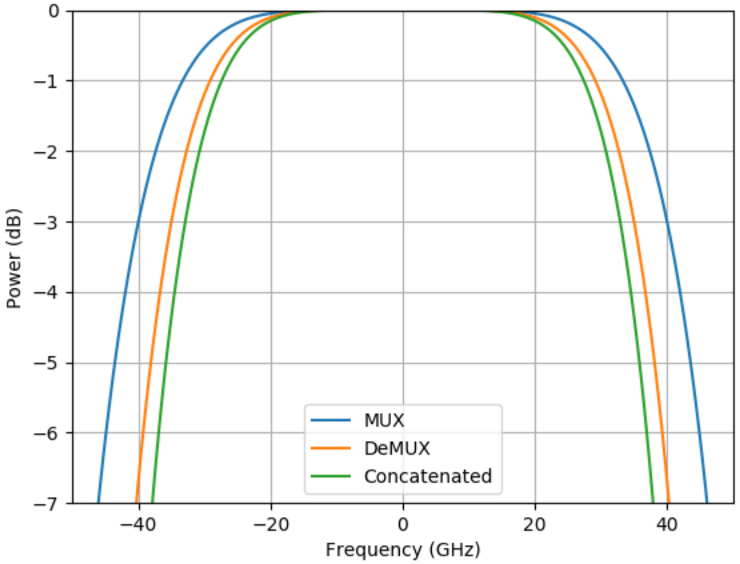
The Problem With a Concatenated link Mask

- Mux = 74GHz
- Demux=74GHz



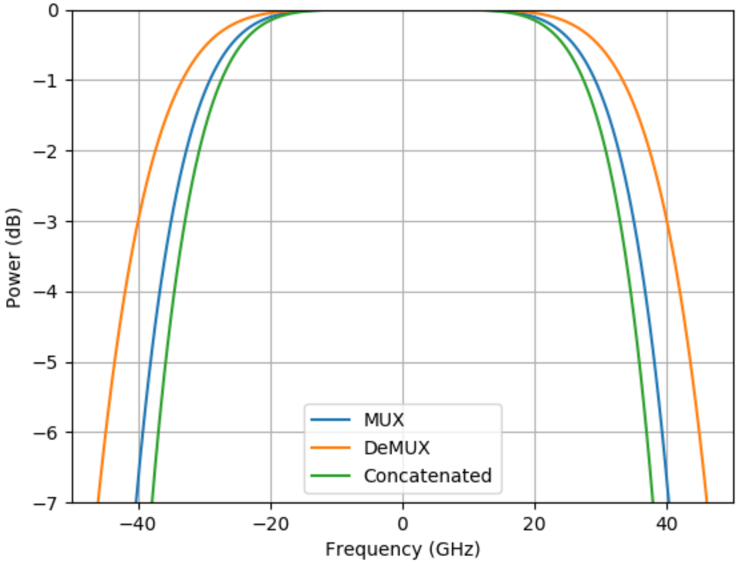
[Left, DUT, Right]	Penalty
[0.4, 0.4, 0.4]	1.78dB
[0.5, 0.5, 0.5]	2.56dB

- Mux = 80GHz
- Demux=70GHz



[Left, DUT, Right]	Penalty
[0.4, 0.4, 0.4]	1.14dB
[0.5, 0.5, 0.5]	1.74dB

- Mux = 70GHz
- Demux=80GHz

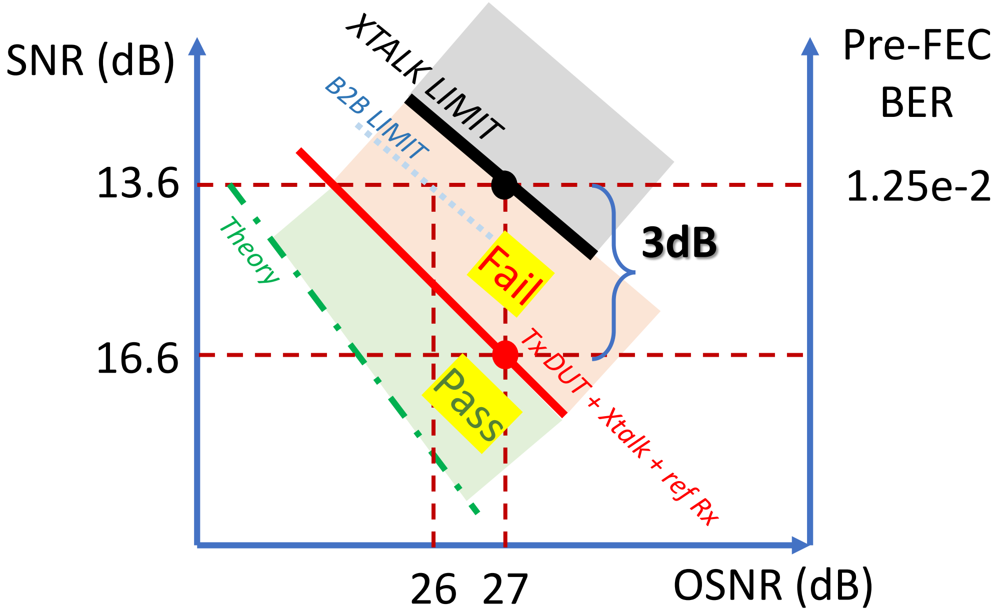


[Left, DUT, Right]	Penalty
[0.4, 0.4, 0.4]	3.23dB
[0.5, 0.5, 0.5]	4.54dB

- Three scenarios all have the same transfer function [Green curve] yet originated from different combinations of Mux/Demux.
- Two cases of Tx RRC vectors [left aggressor, center DUT and right aggressor] generate drastically different penalties under worst case condition detailed in reference table slide (see later slide).
- A concatenated transfer function thus would fail to ensure the different need for Mux and Demux filter characteristics which in turn would generate false positive and break the interoperability.

Operating Margin (OM)

- Margin in dB is the difference between the SNR achieved after equalization and the minimum required SNR at the FEC decoder input
- FEC threshold (t/h) SNR for CFEC is 13.6db
- Operating Margin = 10*log10(EqSNRMin) – 13.6

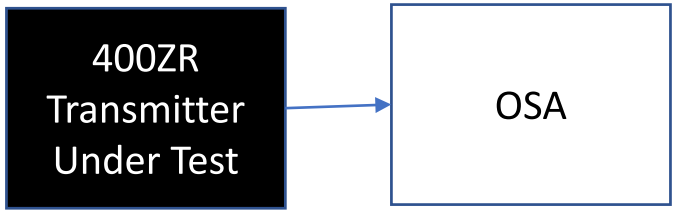


Note: 3dB OM as an illustrative example

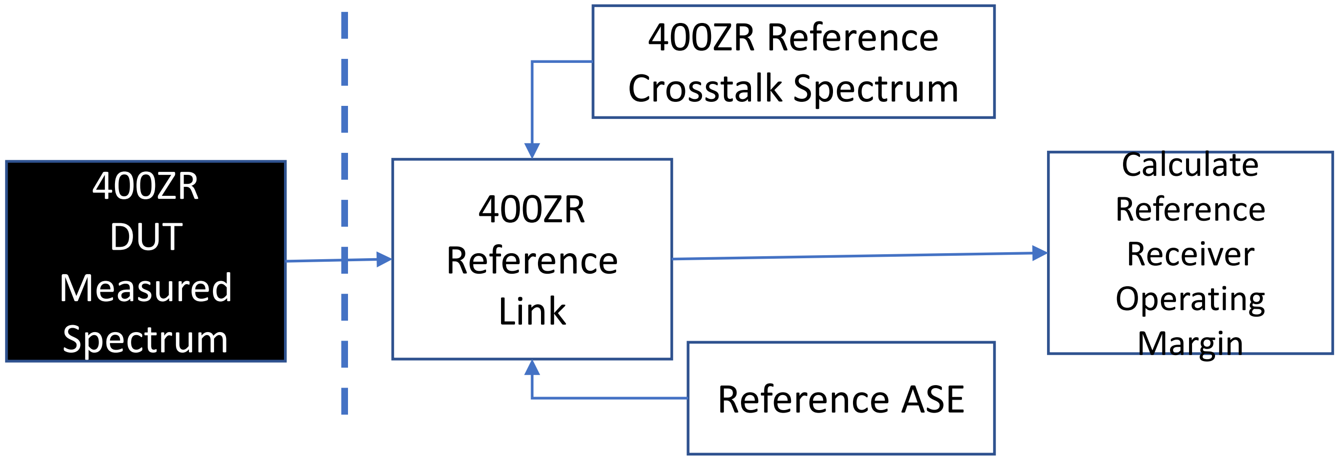
400GBASE-ZR TX Center Channel Compliance Test

- **Measurement Setup:** Transmitter under test connected to an optical spectrum analyzer (OSA) to capture the signal spectrum vs frequency
- **Operating Margin (OM) Computation**:
  - Signal spectrum filtered with a reference optical mux and demux (**3rd order** Supergaussian with 3db bandwidth of **74GHz**) centered on channel under test
  - Crosstalk spectrum generated using a reference RRC with power **4dB** higher than transmitter under test
  - Crosstalk channels centered at 75GHz-**1.8GHz** (i.e. worst-case laser offset) to the left and right of channel under test
  - Crosstalk channels filtered with reference mux for left and right channels (3rd order Supergaussian with **74GHz** max bandwidth) centered **75GHz-4GHz** (i.e. max frequency variation of mux center frequency) closer to channel under test
  - Reference ASE **26+1=27dB** OSNR
  - Reference demux (3rd order supergaussian **74GHz** centered on channel under test)
  - Calculate SNR based on a reference suboptimal receiver
  - Calculate Operating Margin
- Figure of Merit: **OM > 2 dB**

Measurement Setup



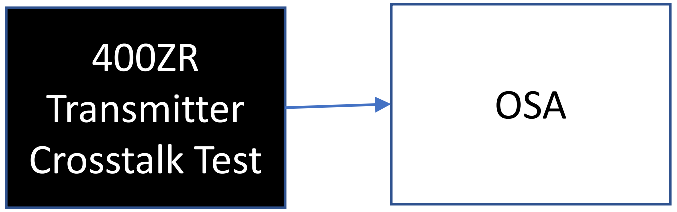
Operating Margin Calculation



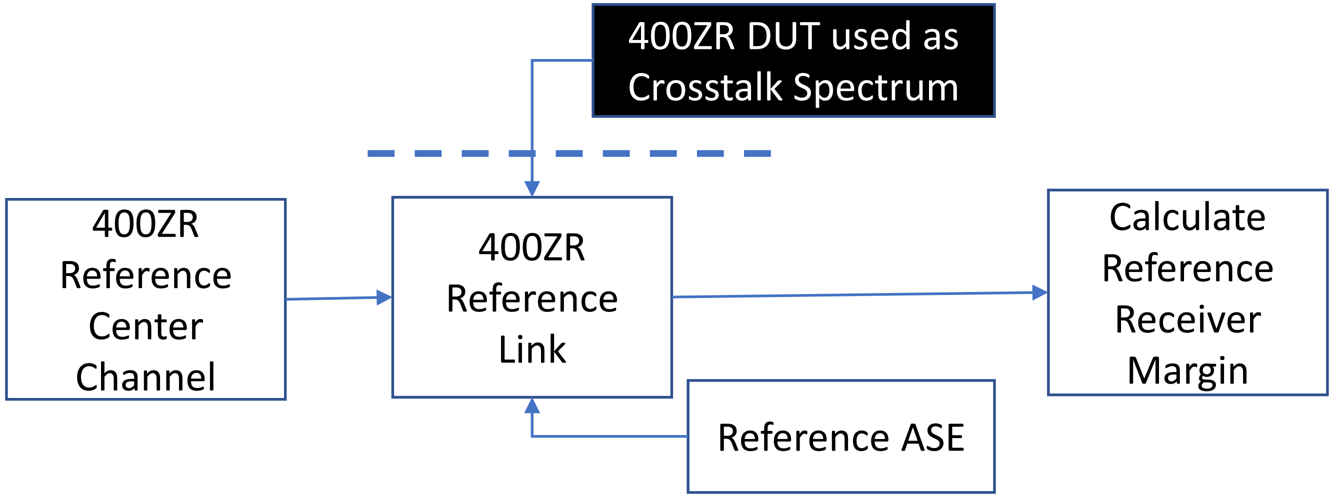
400GBASE-ZR TX Crosstalk Channel Compliance Test

- **Measurement Setup:** Transmitter under test connected to an optical spectrum analyzer (OSA) to capture the signal spectrum vs frequency
- **Operating Margin (OM) Computation**:
  - Reference transmitter used as center channel (RRC with power **4dB** below transmitter under test)
  - Center channel filtered with a reference optical mux and demux (3rd order Supergaussian with 3db bandwidth of **74GHz**) centered on channel under OM calculation
  - Crosstalk spectrum from transmitter under test
  - Crosstalk channels centered at **75GHz-1.8GHz** (i.e. worst-case laser offset) to the left and right of channel under test
  - Crosstalk channels filtered with reference mux for left and right channels (3rd order Supergaussian with **74GHz** max bandwidth) centered **75GHz-4GHz** (i.e. max frequency variation of mux center frequency) closer to channel under test
  - Reference ASE **26dB+1dB** OSNR
  - Reference demux (3rd order supergaussian **74GHz** centered on channel under test)
  - Calculate SNR based on a reference suboptimal receiver
  - Calculate Operating Margin
- Figure of Merit: **OM > 2 dB**

Measurement Setup



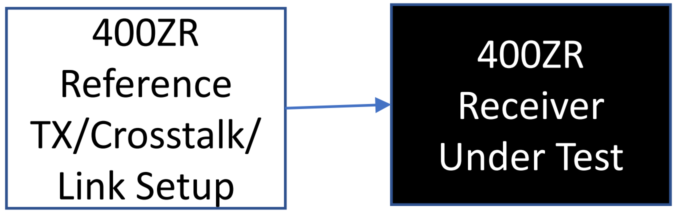
Receiver Margin Calculation



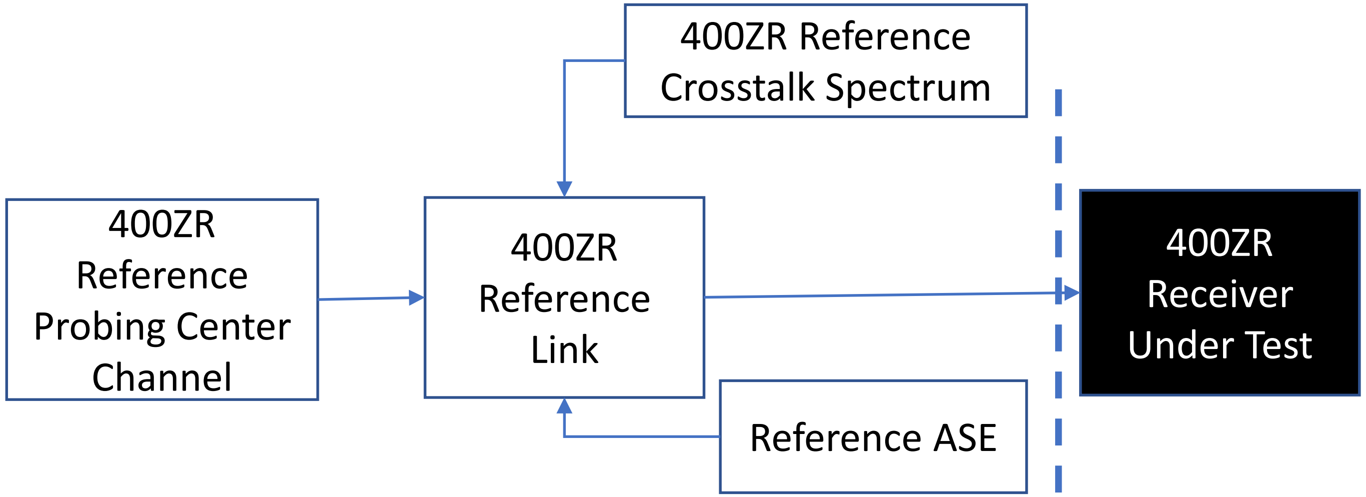
400GBASE-ZR RX Compliance Procedure

- 400ZR Reference setup
  - Probing center channel using reference RRC spectrum with worst case power imbalance lower than aggressor channels.
  - Aggressor left and right channels using reference RRC spectrum with worst case laser offsets
  - Worst case setup for Mux/Demux 3dB bandwidths, center frequency offset
  - Reference ASE **26dB+1dB** OSNR (flat spectrum vs frequency)
- Stressed RX operates with post-FEC BER better than 1e-15

Measurement Setup

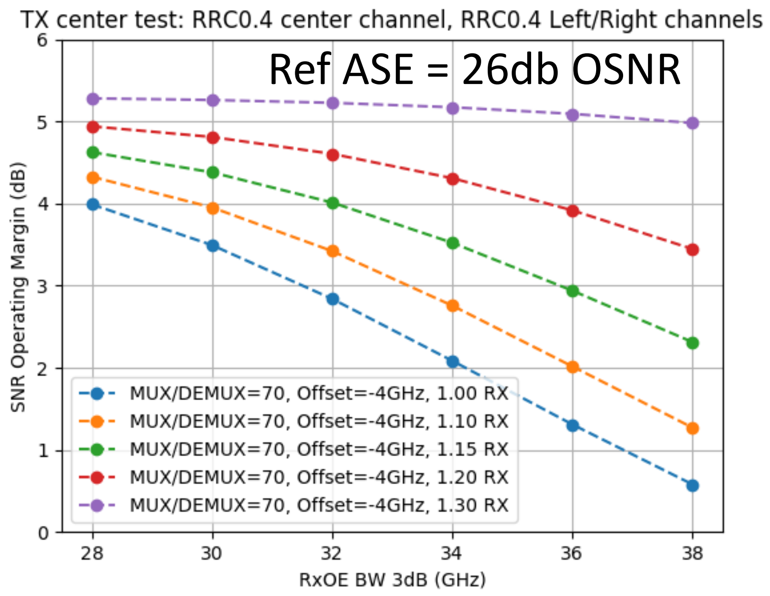


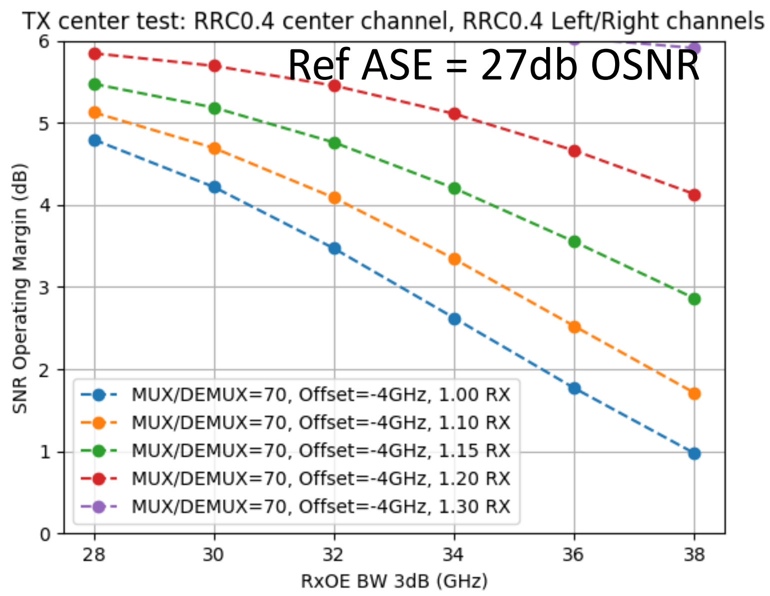
400ZR Reference Setup

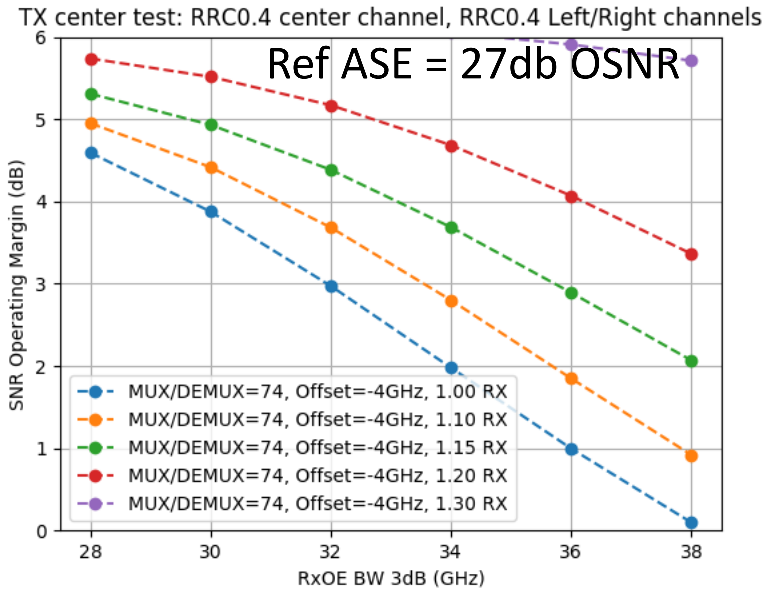


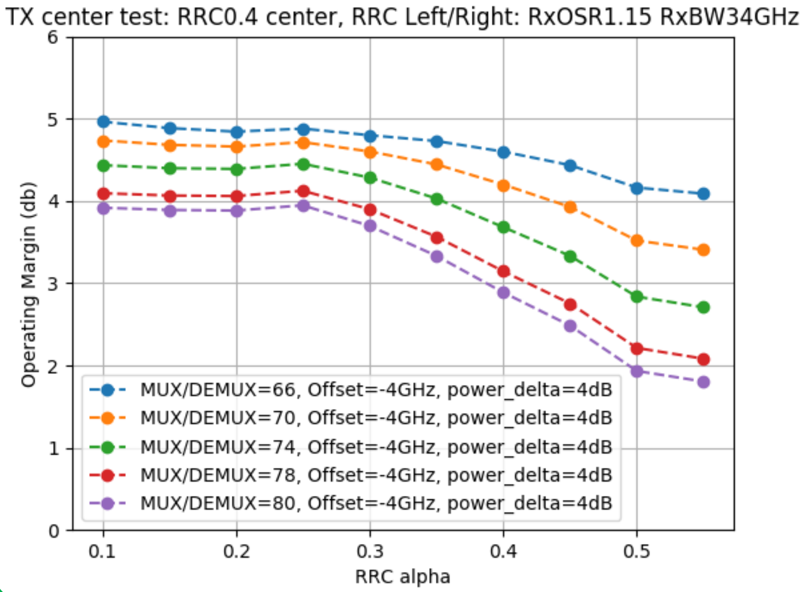
Note: In practice, reference Tx/Crosstalk channels do not need to strictly follow RRC, as long as the setup is calibrated to produce a X dB OM. This can be used as the stimulus to RX under test.

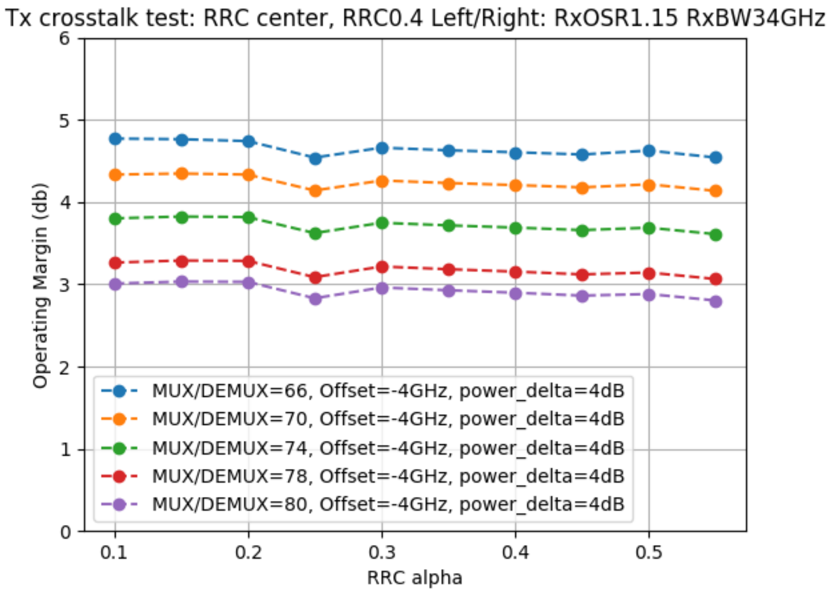
Parametric Analysis

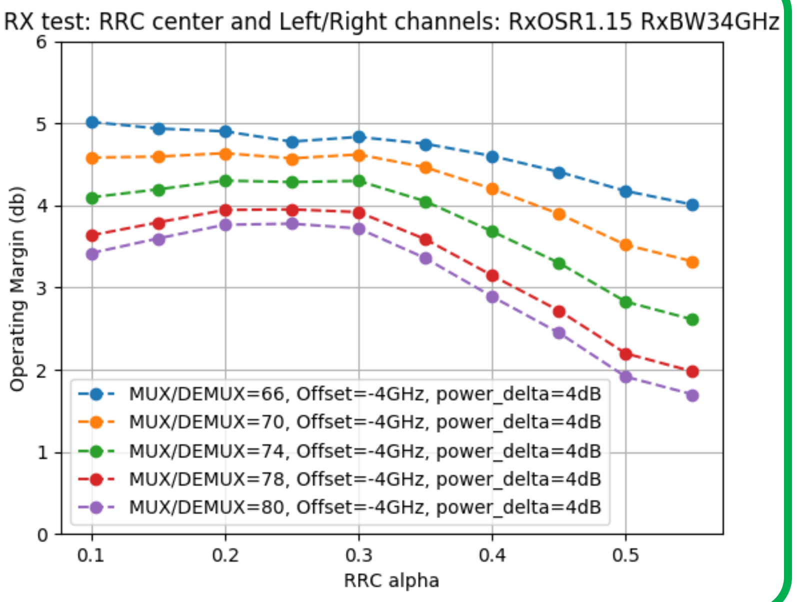












Recommended Reference Tx/Link/Rx Tables

Ref Crosstalk: For Tx/Rx Compliance

Parameter	Value (Unit)
Left Ch. shape	RRC=0.4
Left Ch. power	4dB higher w.r.t. DUT center
Left Ch. freq	-(75-1.8GHz) w.r.t. DUT center
Right Ch. shape	RRC=0.4
Right Ch. power	4dB higher w.r.t. DUT center
Right Ch. freq	(75-1.8GHz) w.r.t. DUT center

Ref Tx: for Tx Xtalk/Rx compliance

Parameter	Value (Unit)
Center Ch. shape	RRC=0.4
Center Ch. power	4dB lower w.r.t. Left and Right
Center Ch. freq	+1.8 or -1.8GHz

Ref Link

Parameter	Value (Unit)
MUX 3dB	74GHz centered @ DUT
MUX shape	3rd order SG
MUX offset	[-71, ±4, 71] GHz
DEMUX 3dB	74GHz centered @ DUT
DEMUX shape	3rd order SG
DEMUX offset	±4 GHz

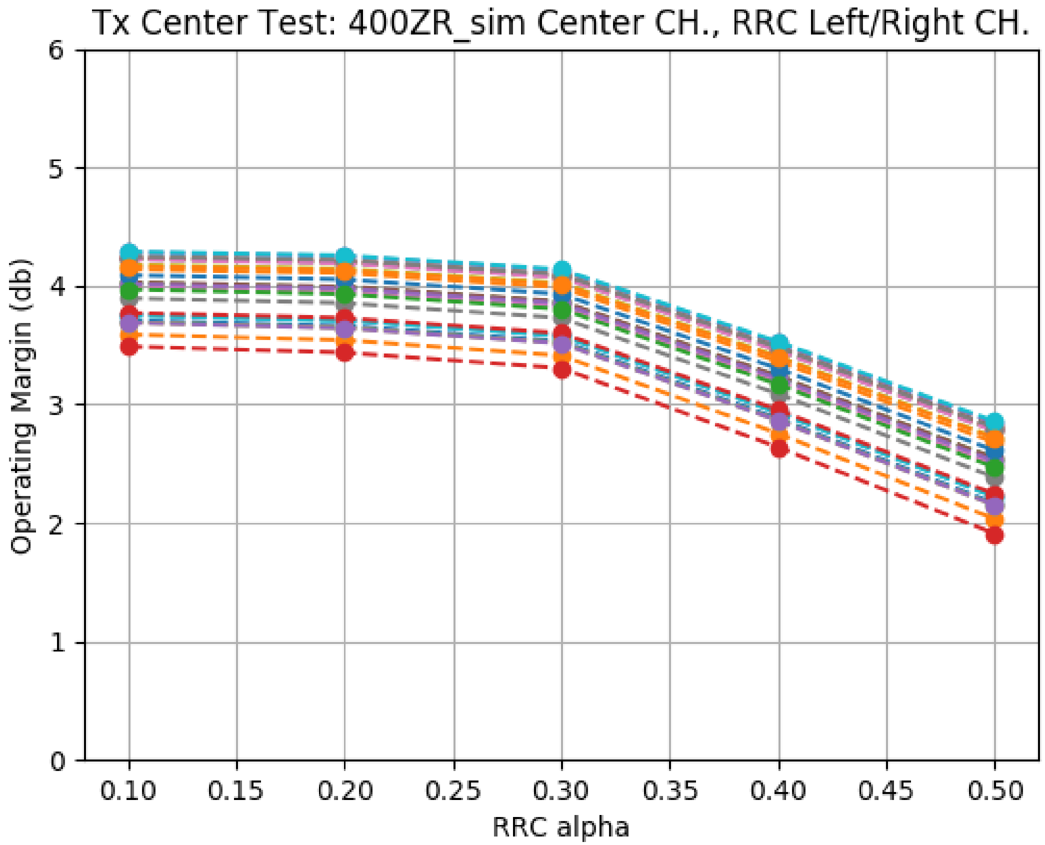
Recommended ref Rx

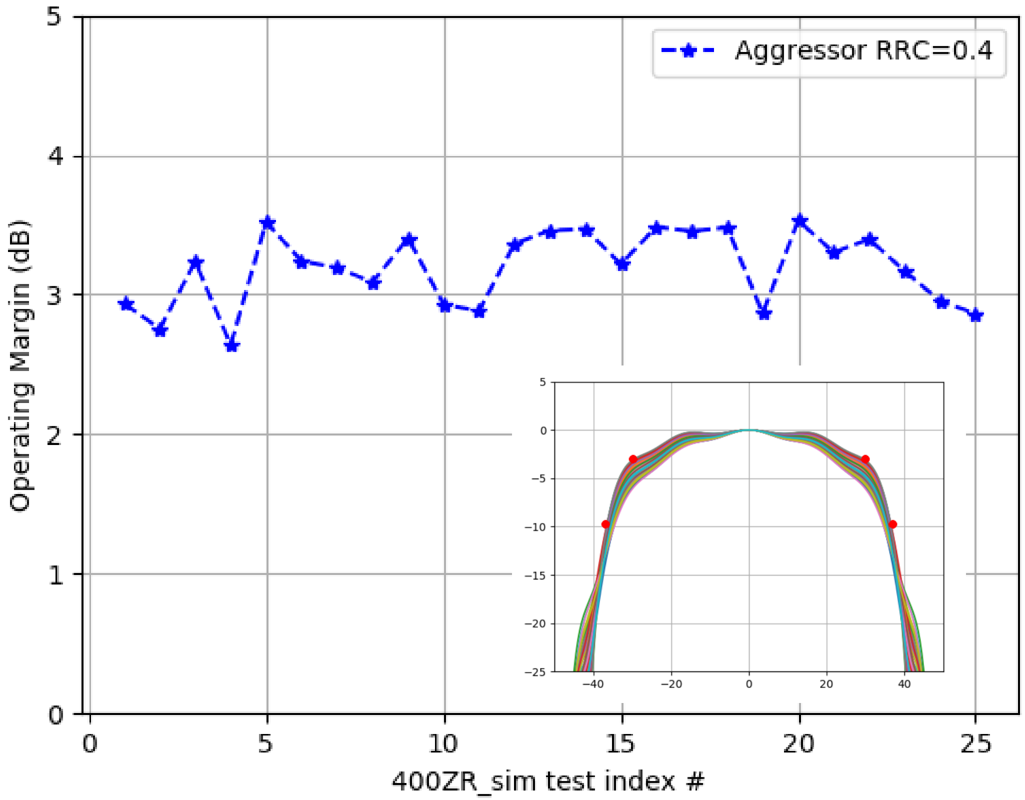
Parameter	Value (Unit)
Rx OSR	1.15 Sam/Sym.
Rx OE 3dB BW	34 GHz
Rx OE Shape	5th Butterworth

Operating Margin condition

Parameter	Value (Unit)
Ref ASE	27dB OSNR
SNR t/h (CFEC)	13.6dB
Margin pass/fail	> X dB / <X dB

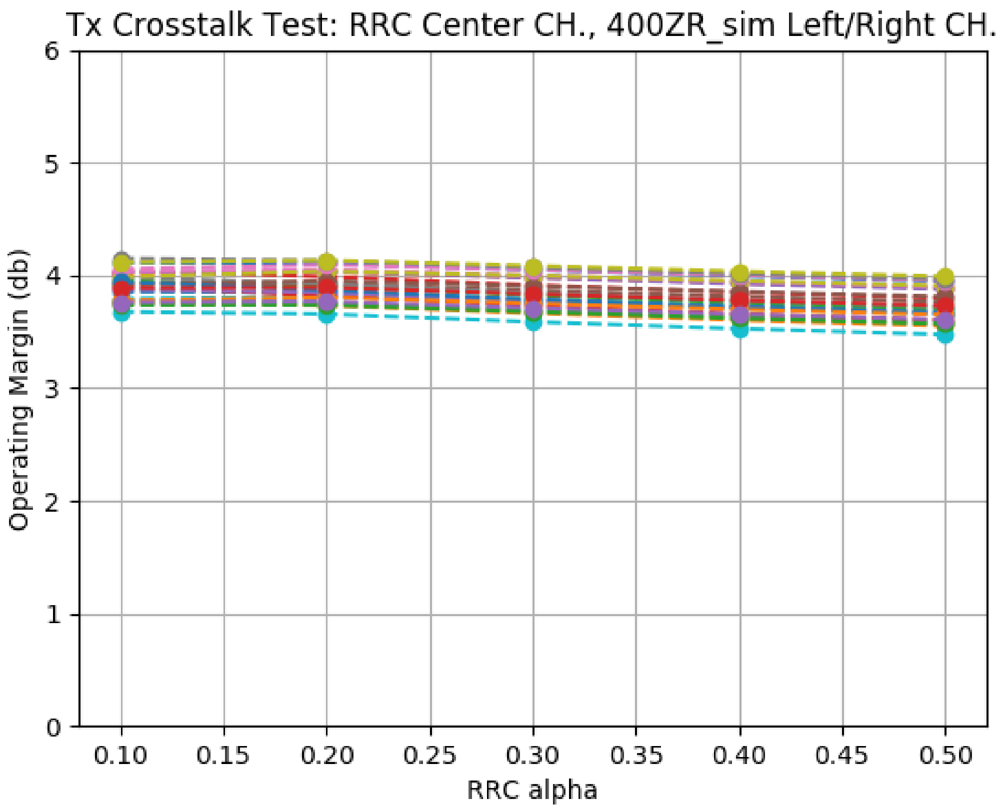
Tx Center Channel Compliance Example

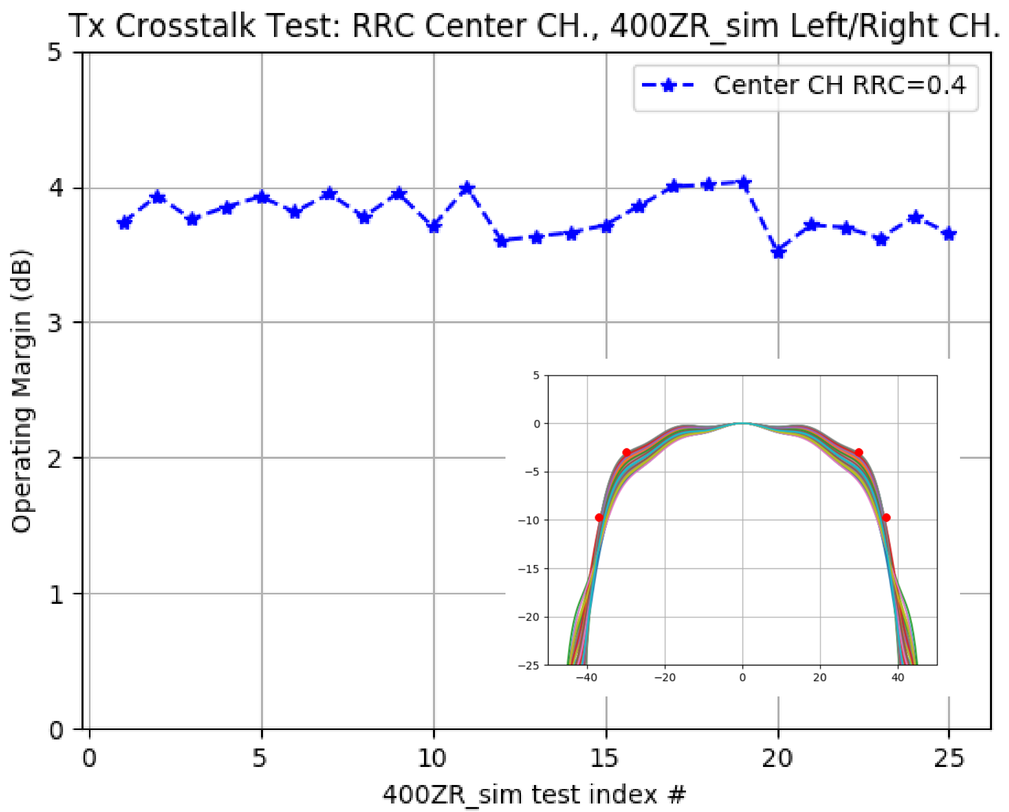




- Twenty-five generated 400ZR simulated TX spectra are input to the Tx compliance calculator one at a time to examined each Tx performance against the TX victim operating margin (OM) metric.
- With aggressor channels (left and right) at to RRC=0.4, and reference Mux/Demux filter and reference ASEs set according to the reference table, all data sets on Tx victim channel show OM above 2dB threshold.

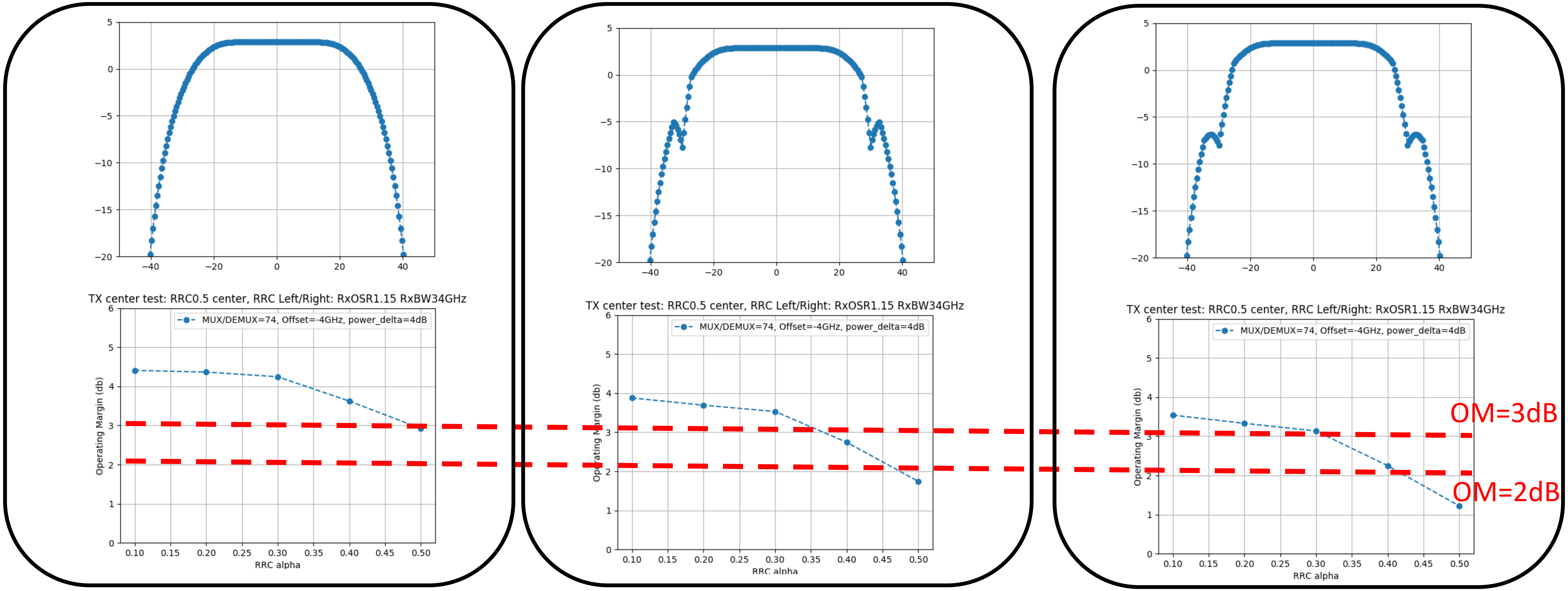
Tx Crosstalk Channel Compliance Example





- Twenty-five generated 400ZR simulated TX spectra are input to the Tx compliance calculator one at a time to examined each Tx performance against the TX as aggressors operating margin (OM) metric.
- With center probing channels set at RRC=0.4, and reference Mux/Demux filter and reference ASEs set according to the reference tables, all data sets on center probing victim channel (impacted by the Tx aggressor channels) show OM above 3dB threshold.

Meeting Tx Mask, but failing Tx OM spec



- All three Tx spectrum examples meet the hypothesized Tx mask, assuming RRC shape with selected discrete points on the RRC curve (e.g., -3dB down and -10dB down).
- The 2[nd] case has a notch at Nyquist frequency with 3GHz window, and the 3[rd] case at Nyquist with 5GHz window.
- However, for the same Tx aggressors and Link filter condition (RRC=0.4 or RRC=0.5), the first case is passing the OM spec yet the second and third case are failing the Tx OM spec.

Proposed New Specifications for 75GHz Use Case

Table XXX-X —400GBASE-ZR transmit characteristics		
Description	Value	Unit
75GHz-induced Tx operating margin (min)	X	dB

Table XXX-X —400GBASE-ZR receive characteristics		
Description	Value	Unit
75GHz-induced Rx Post-FEC BER (max)	1E-15	

Table XXX-X —400GBASE-ZR black link characteristics		
Description	Value	Unit
Mux filter 3dB bandwidth [min, max]	[66, 74]	GHz
Mux filter frequency offset (max)	+/- 4	GHz
Mux filter shape (min)	3rd	Order (Super-Gaussian)
Demux filter 3dB bandwidth [min, max]	[66, 74]	GHz
Demux filter frequency offset (max)	+/- 4	GHz
Mux filter shape (min)	3rd	Order (Super-Gaussian)

Summary

- An optimal equalization SNR metric is introduced and compared with the NSR and weighted crosstalk metrics.

- A framework for Tx/Link/Rx spec development and compliance procedures are detailed, with supporting data from both simulation and experiment. Reference tables with details on each Tx/Link/Rx parameters are recommended (see Slide 19).

- New Tx, Link and Rx specs for 400GBASE-ZR operating at 75GHz channel spacing are proposed (see Slide 23).
    - OM spec can be further refined with contributions from multiple parties after agreement with this proposal