Optimal Equalization approach to 400ZR analysis with 75G spacing

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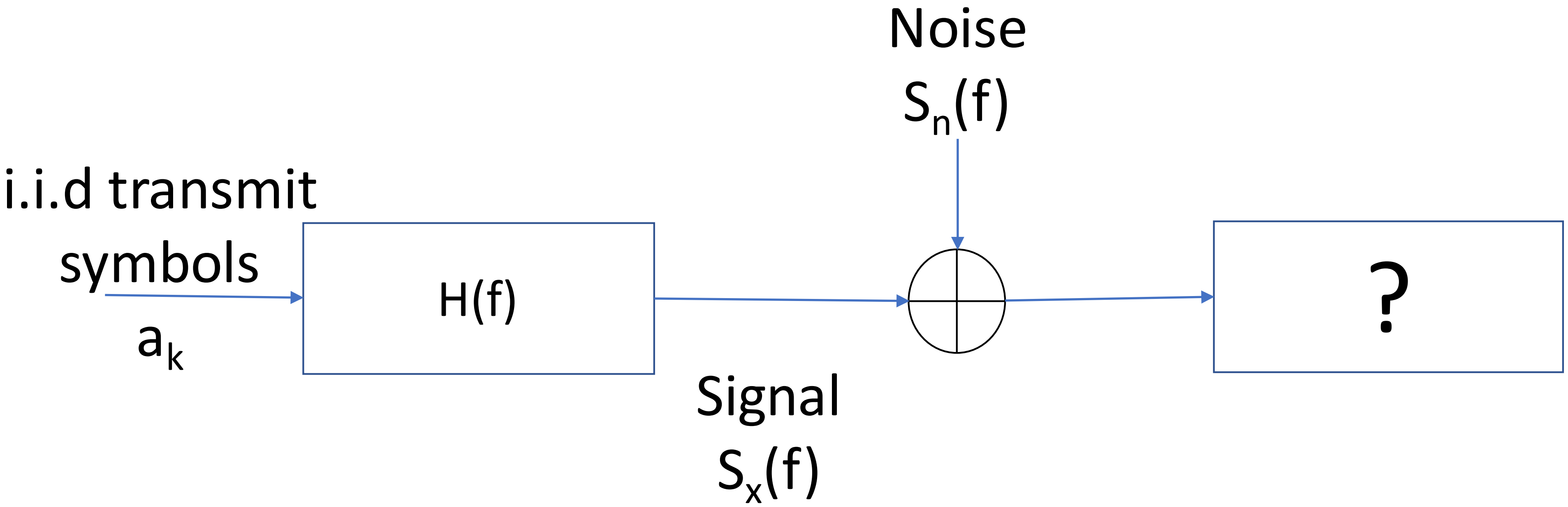
Outline

- Optimal Equalization Theory
- Application to 400ZR analysis
- Proposed framework to derive specifications

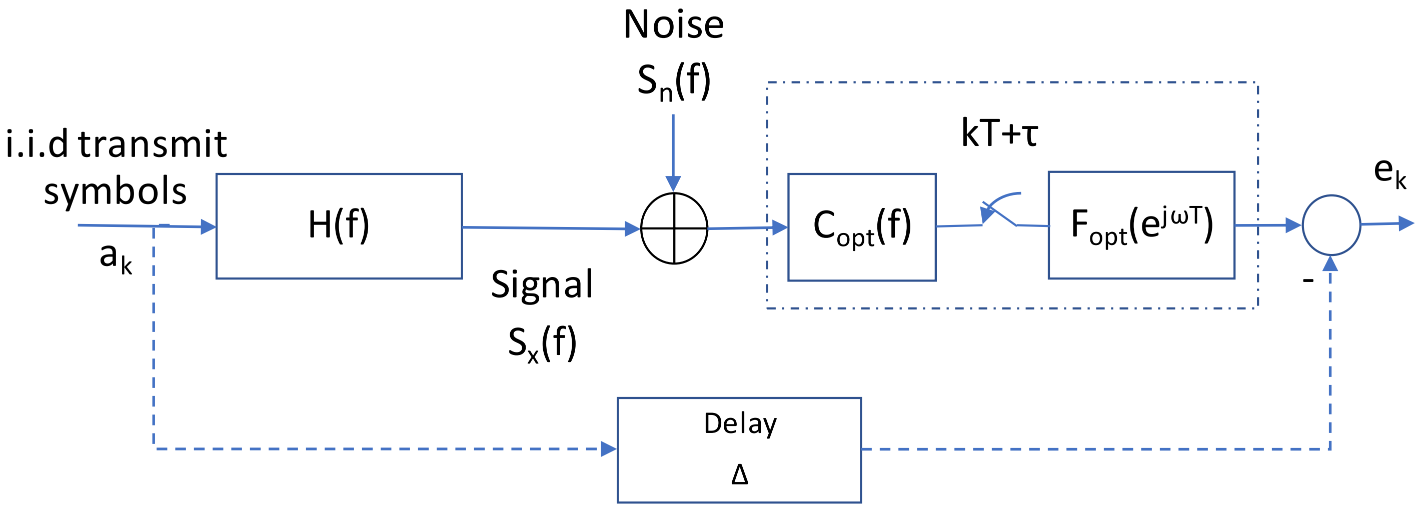
Optimal Equalizer: Problem statement



Digital communication theory provides equations to calculate the performance of an optimal receiver[1]

[1] Lee and Messerschmitt, “Digital Communication”, Second Edition 1994, Chapter 10, Equalization, Equation (10.68)

Optimal Equalizer: Solution



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

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

Eq. 1

A close cousin of this equation called "Salz SNR" was used in 10GBASE-T specifications (802.3-2018, Clause 55)

Comments on the optimal equalizer equation

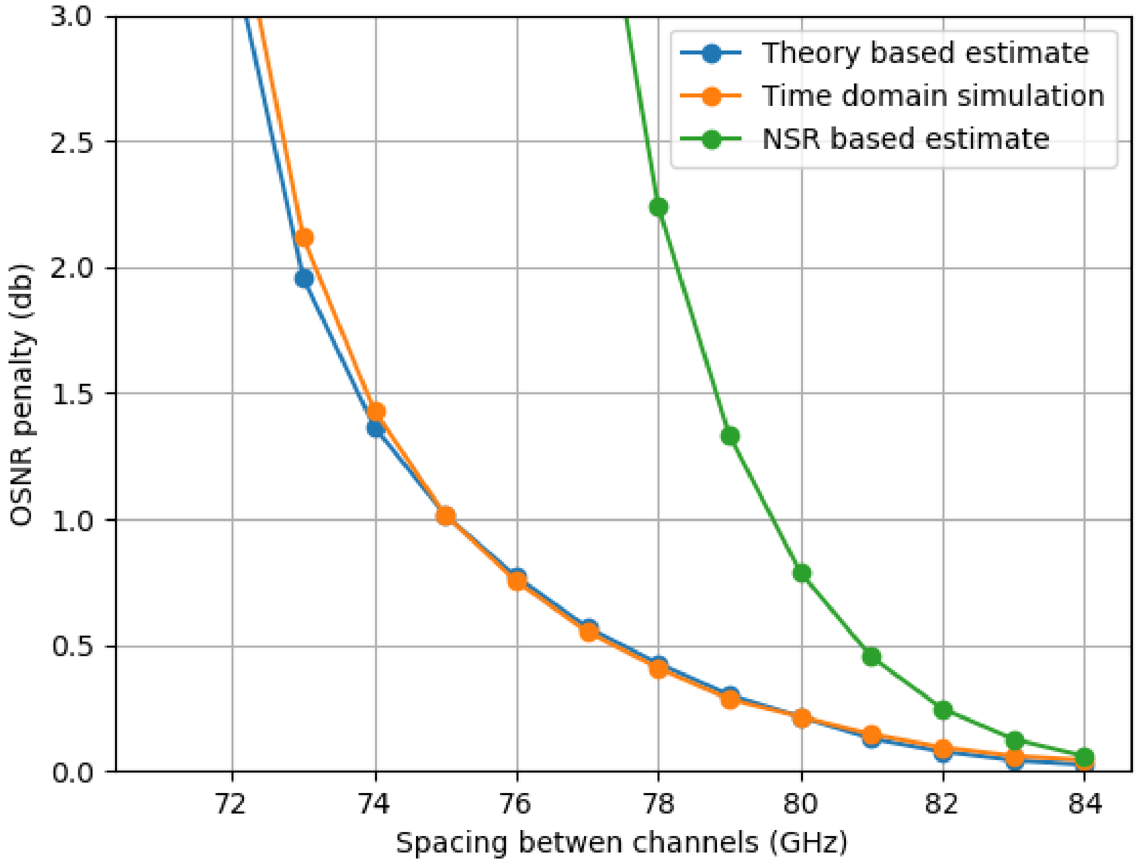
- This equation is applicable for receivers which use **linear equalization**
- The equation represents the bound on achievable performance of a real receiver
- Result can be easily extended to suboptimal analog frontend + oversampled ADC + sufficiently long adaptive linear equalizers
- Comparison of this calculation to some example receiver implementations are included in later slides

Relationship to Weighted Crosstalk/NSR

- "Weighted crosstalk" metric 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
- NSR metric defined by S.Kunze et. al. "Impacts of 75GHz Channel Spacing for 400GBASE-ZR: Interchannel Crosstalk/Minimum Excess Bandwidth", May 28 2020 802.3cw conference call https://www.ieee802.org/3/cw/public/tf_interim/20_0528/maniloff_3cw_01_200528.pdf
- Results of these metrics will be similar to the optimal equalizer calculations 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()

Simulation: Comparing crosstalk penalty estimation methods

- Ideal RRC 0.5 spectra (no DAC images)
- No mux/demux
- Aggressor channels 4db higher power
- Penalty to 26db OSNR target
- Time domain simulation parameters:
  - 30GHz 5th order butterworth receive filter
  - 2X oversampling ADC
  - 32-tap T/2 spaced equalizer

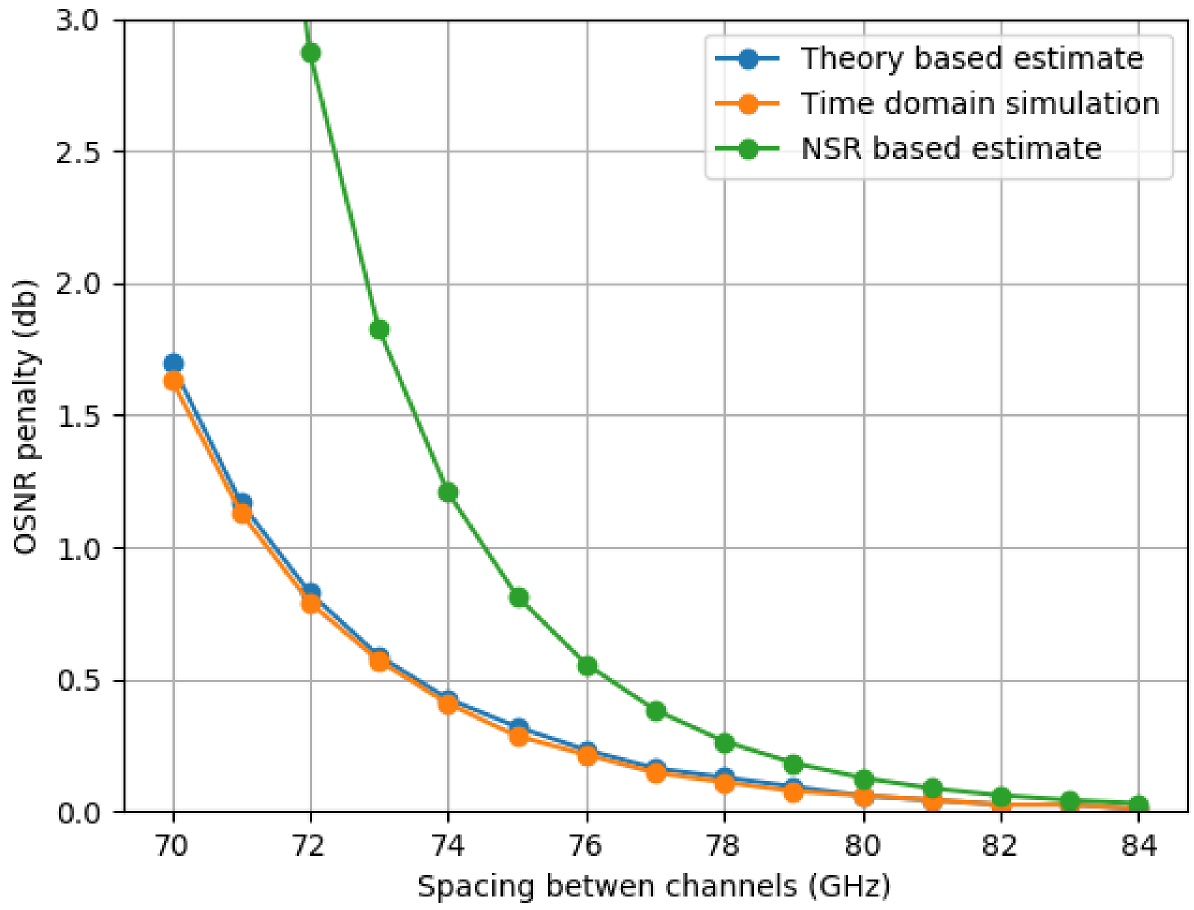


Optimal equalizer based estimate closer to time-domain simulation

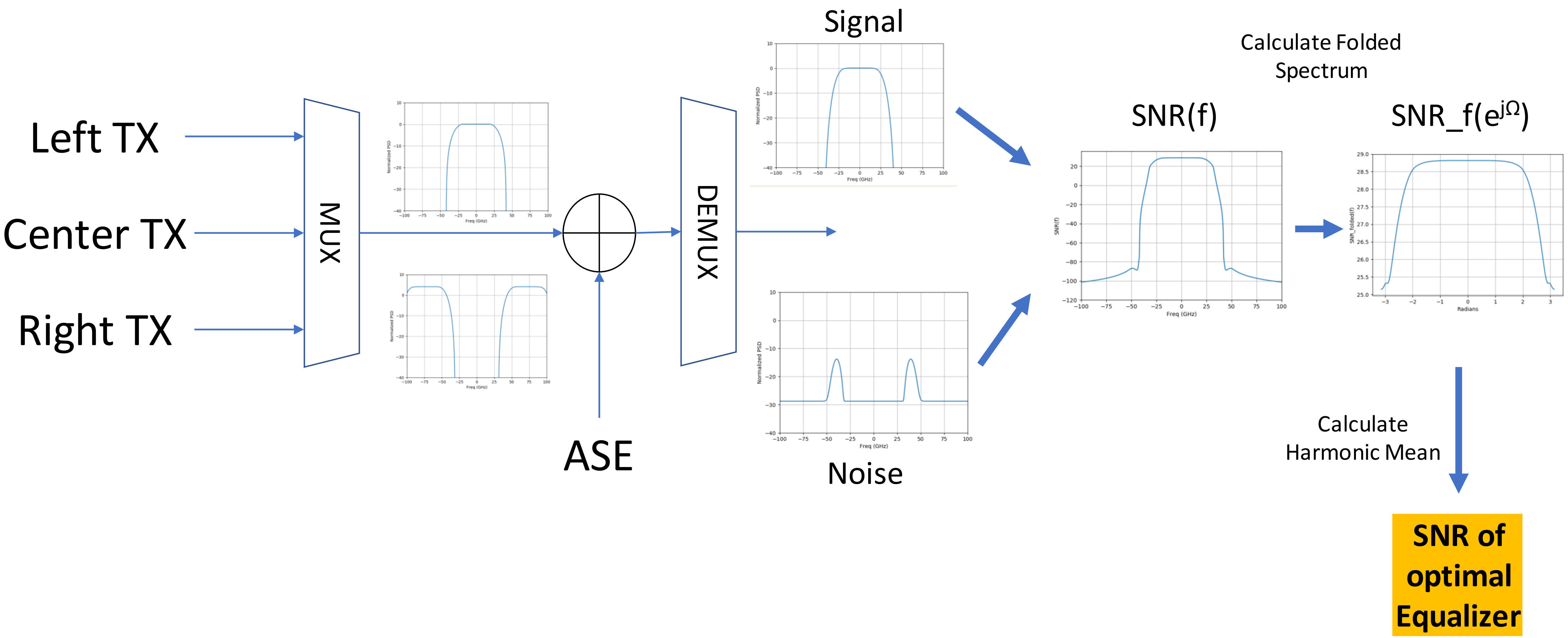
Simulation: Comparing crosstalk penalty estimation methods

- Realistic transmit spectrum
- No mux/demux
- Aggressor channels 4db higher power
- Penalty to 26db OSNR target
- Time domain simulation parameters:
    - 30GHz 5th order butterworth RX filter
    - 2X oversampling ADC
    - 32-tap T/2 spaced equalizer

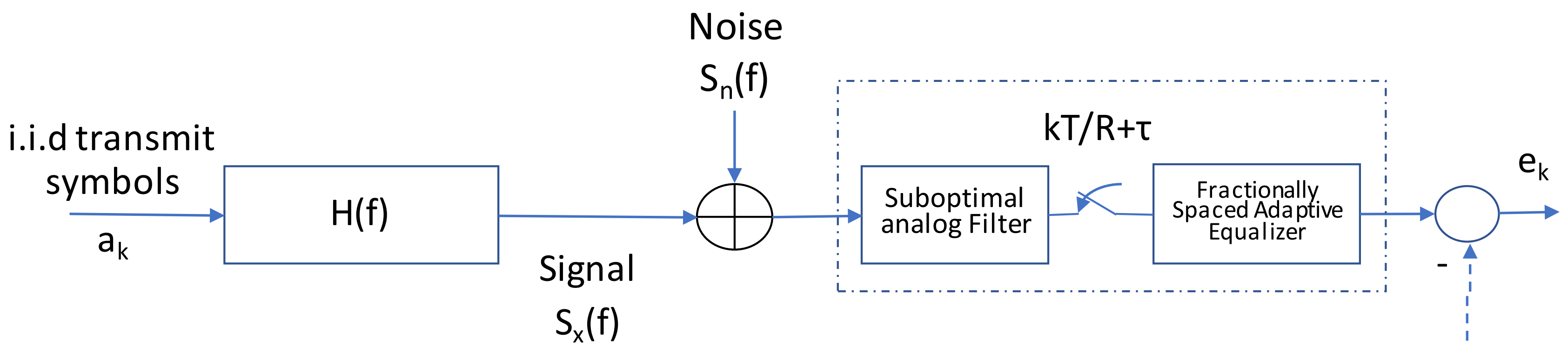
Optimal equalizer based estimate closer to time-domain simulation

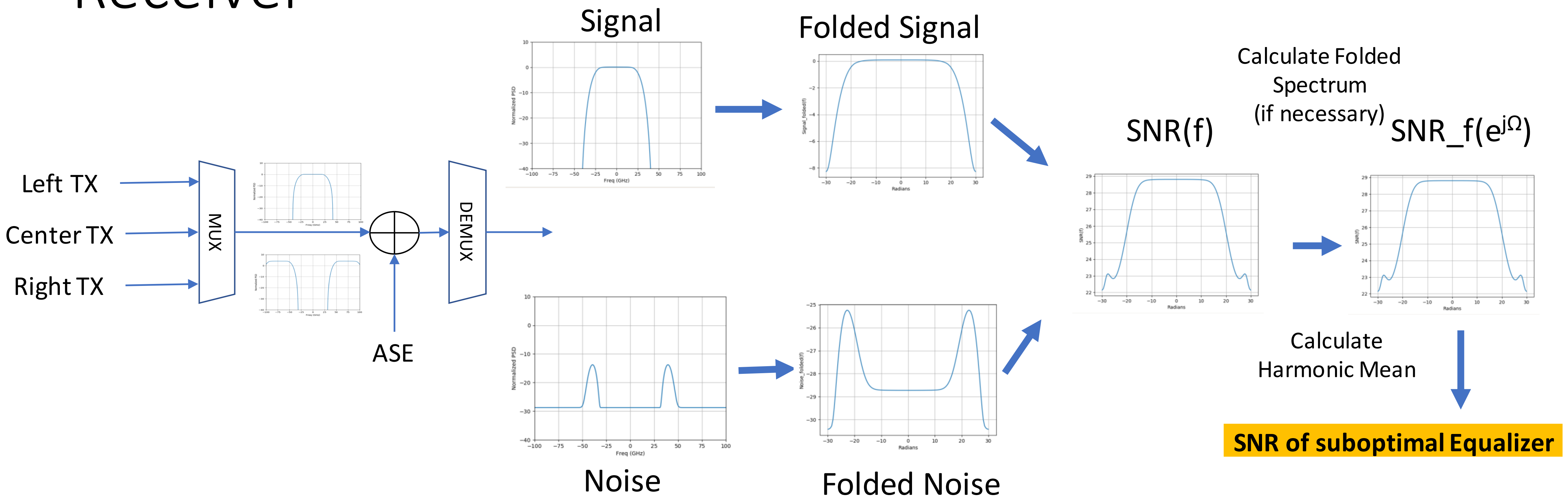


Eq. 1 in pictures



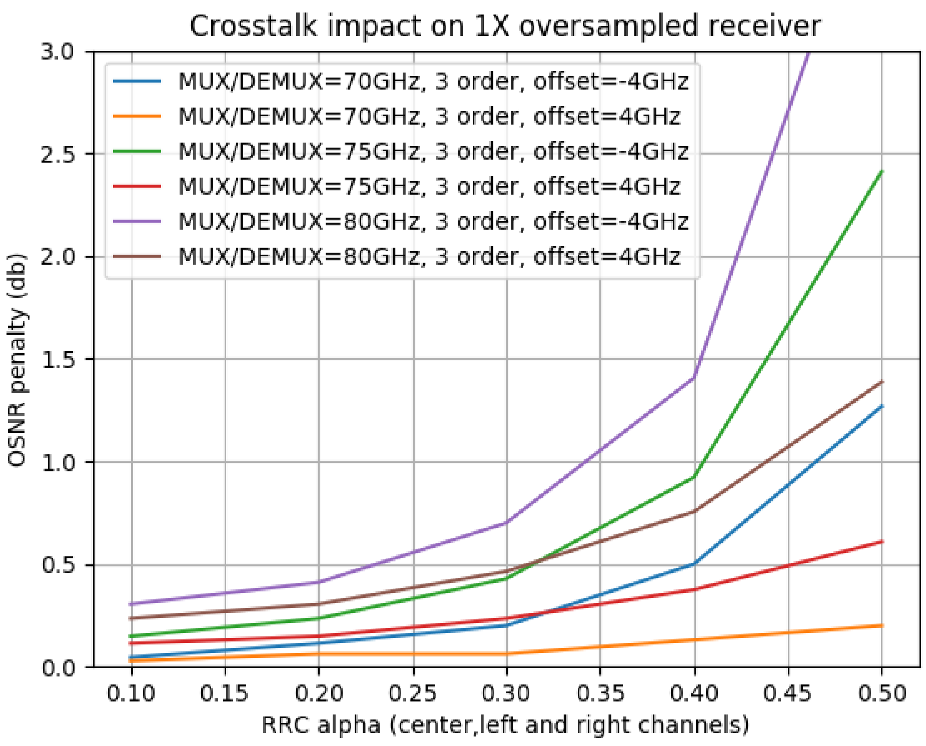
Calculations for a Suboptimal Receiver

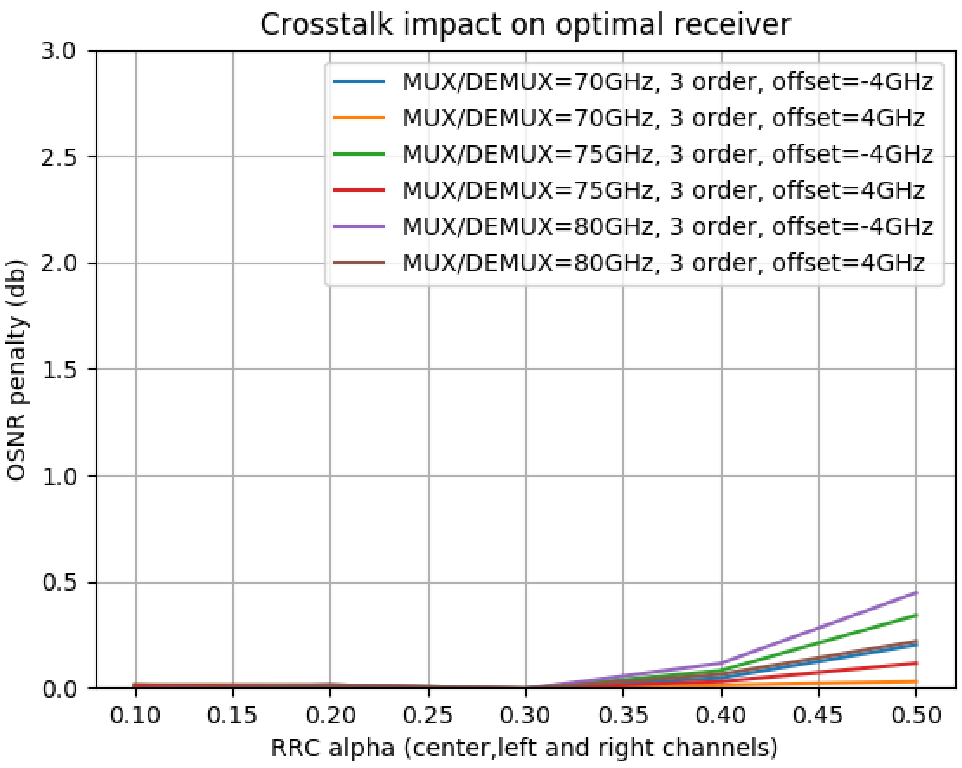




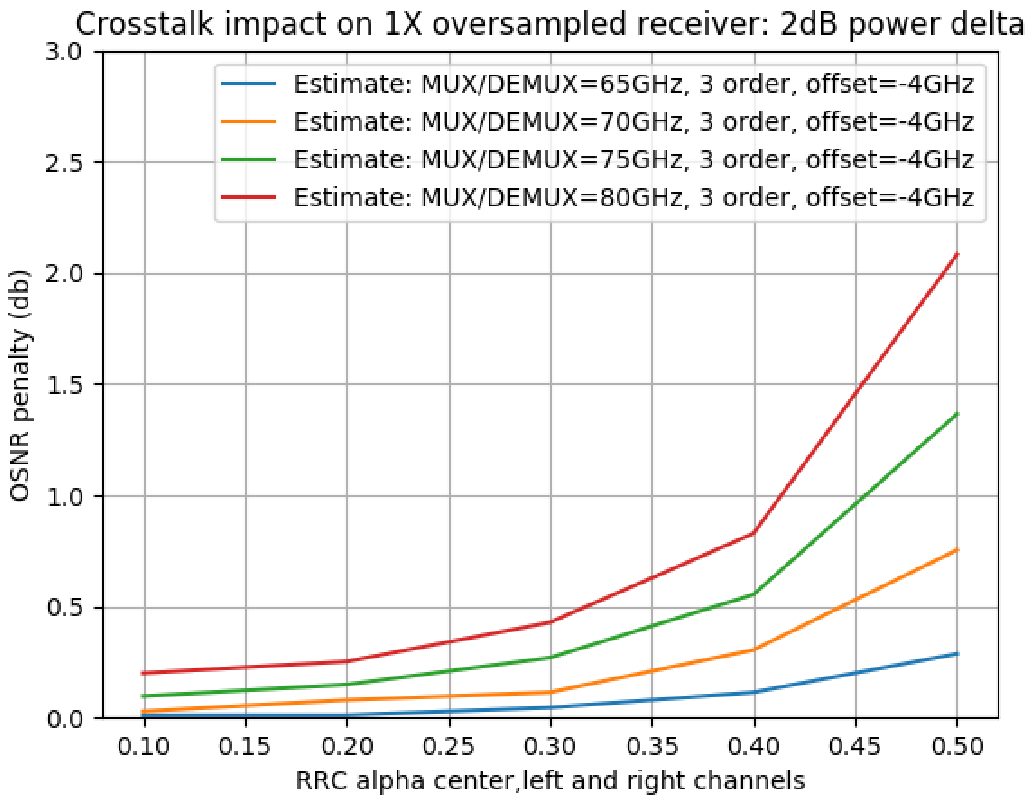
Crosstalk impact for Ideal RRC spectra

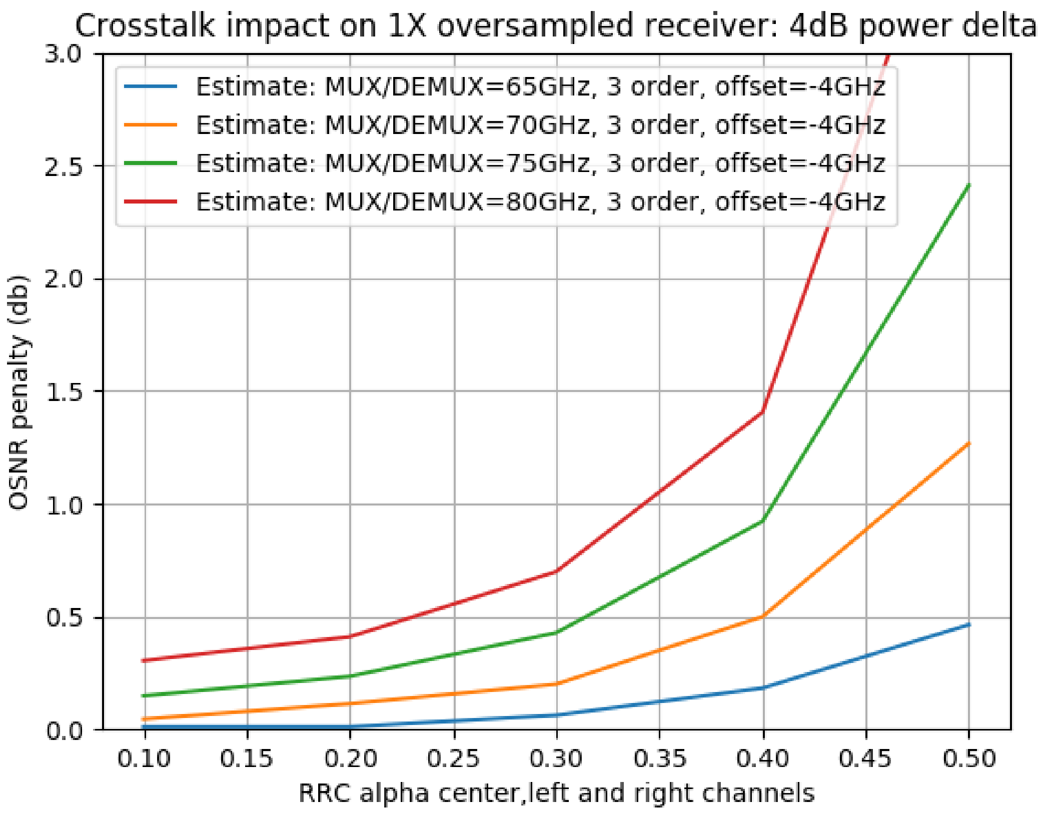
Ideal RRC spectra without DAC images
Left and Right channels are offset 1.8GHz towards center
Left and Right channels 4db higher than center channel
Mux frequency offset applied symmetrically to both left and right channels (i.e. -4GHz is 4GHz towards the center channel)



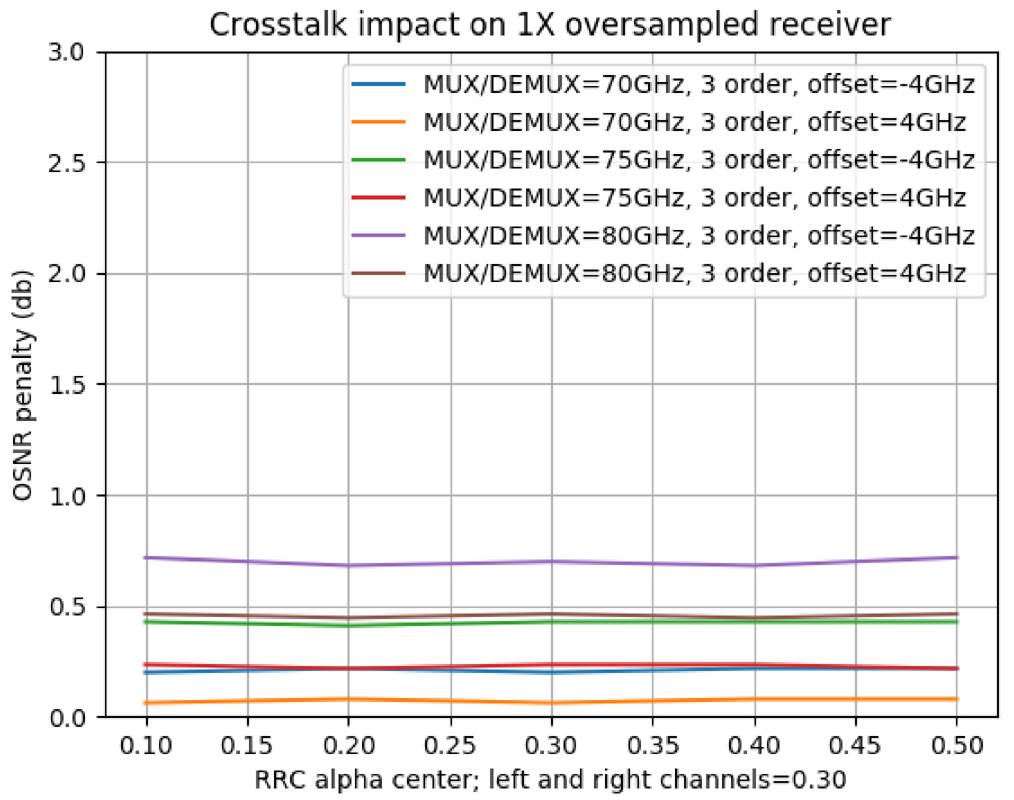


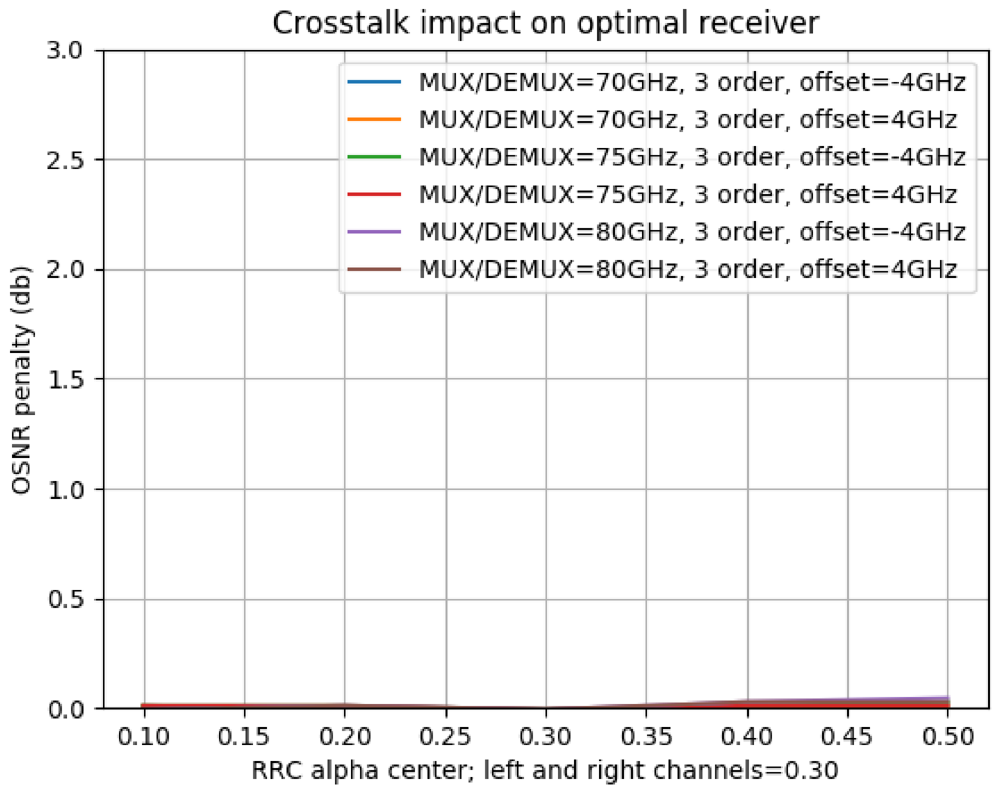
Impact of power delta between center and crosstalk channels





Crosstalk impact of Ideal RRC0.3 left/right channels on center channel

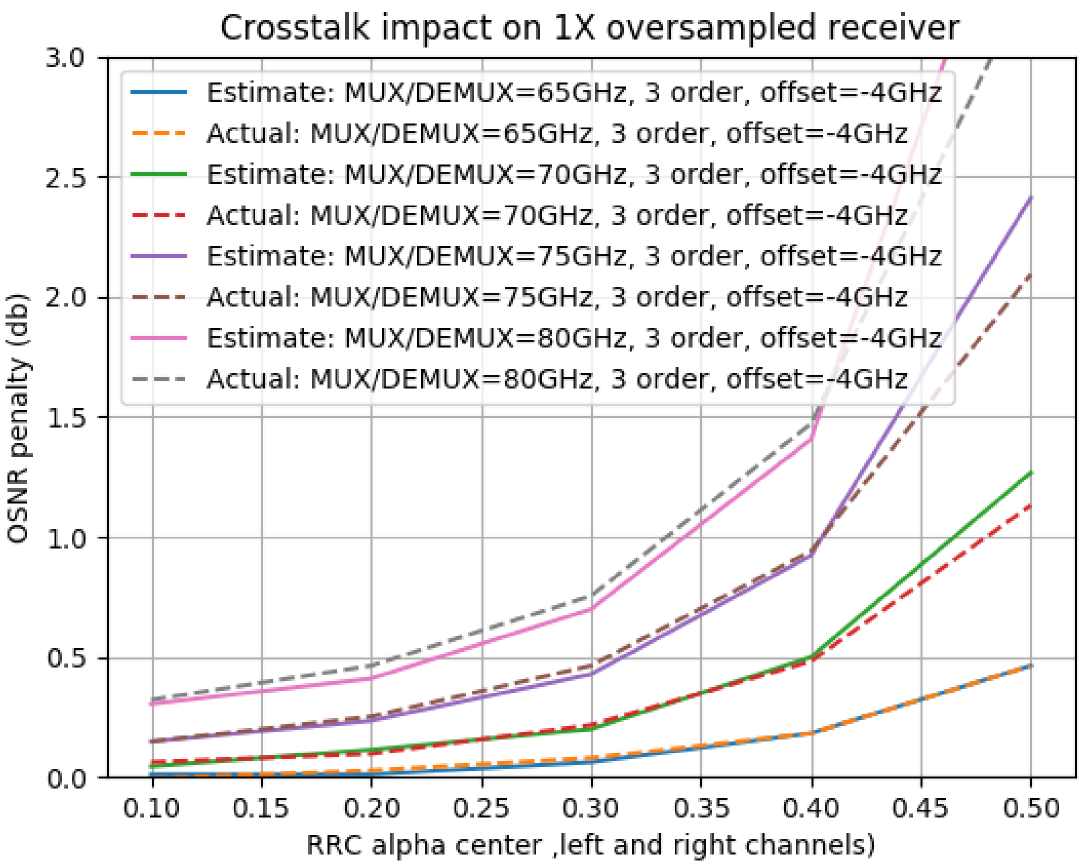




Comparing Estimates to Simulation penalties

Estimates calculated using the procedure for suboptimal receiver

Analog filter is 5th order Butterworth with 30GHz 3dB frequency

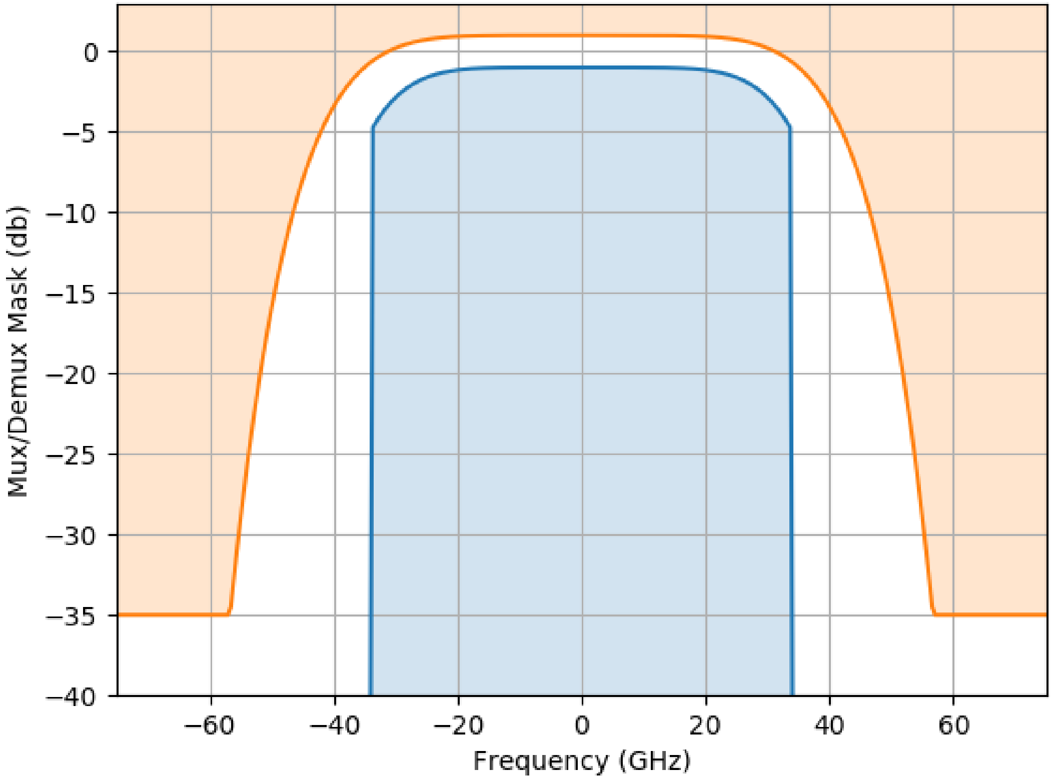


Reference Transmitter/Crosstalk/Link/Receiver

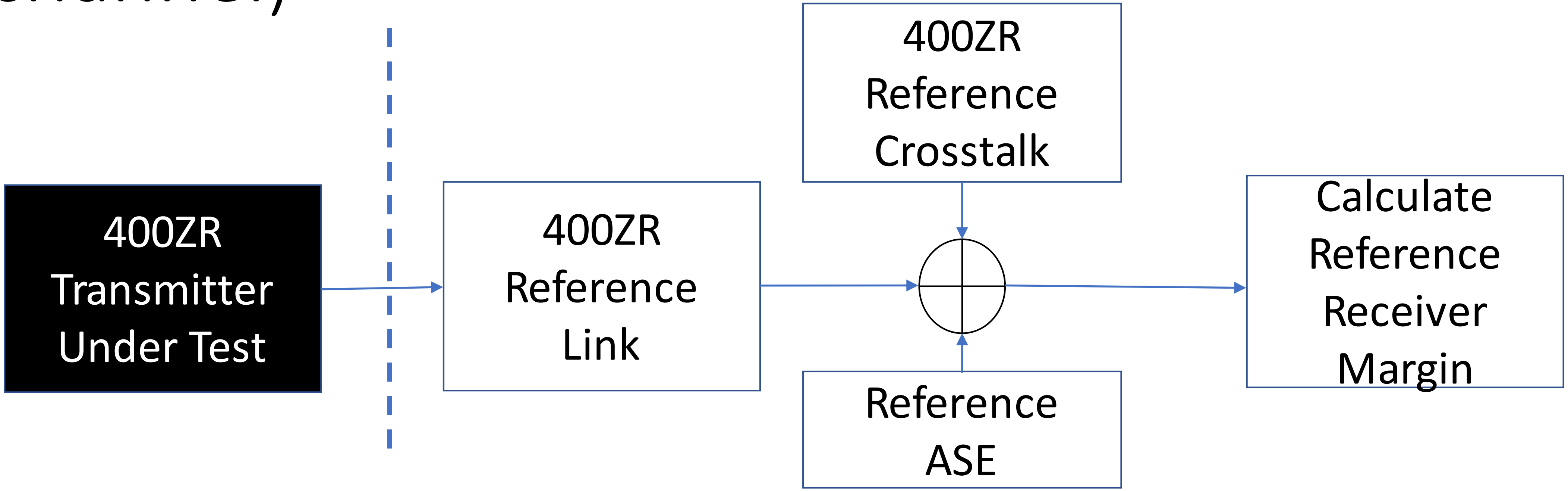
- Transmitter specifications can be tested using a reference link, reference crosstalk and reference receiver
- Link specifications specified independent of transmitter and receiver
- Receiver specifications can be tested using a reference transmitter, reference crosstalk and reference link

400ZR Link Specification

- Define an allowed compliance transmission mask for each channel
  - Use super-gaussian responses to select allowable range of links
- Define a reference link based on super-gaussian responses for TX and RX compliance tests
  - Nominal center frequency (ITU grid with 75G spacing or 0.6nm spacing)
  - Minimum order (for eg.. 3rd order)
  - Range of allowable 3db bandwidth (for e.g. 65-75G)
  - Allowed variability of center frequency (for e.g. [-4,4]GHz)

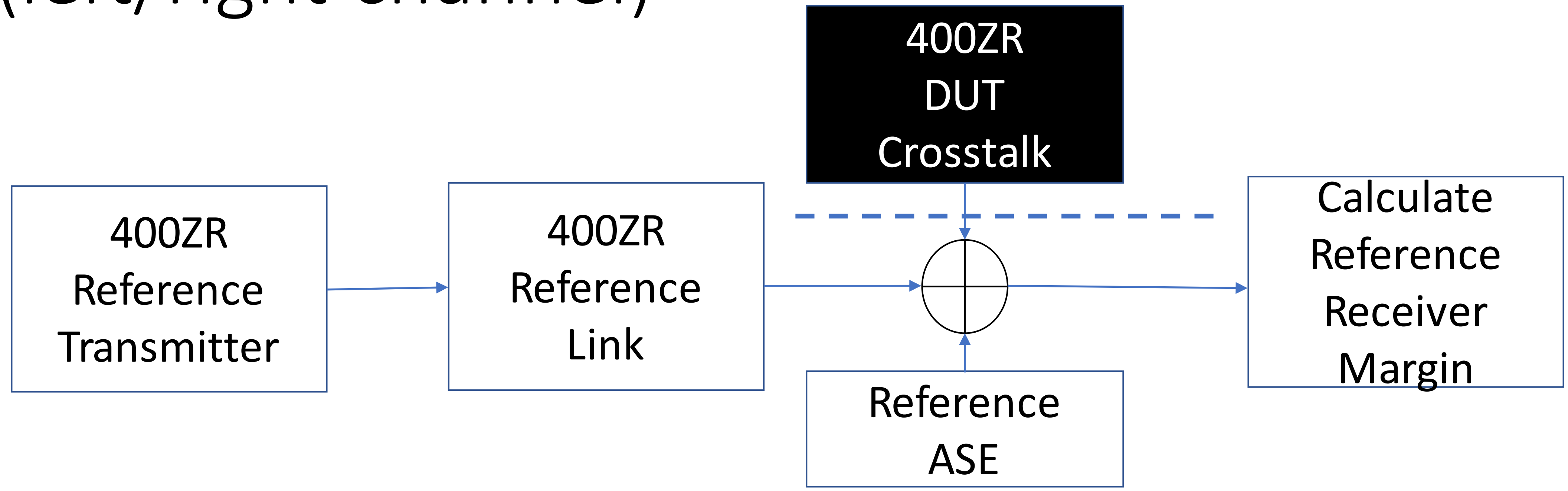


400ZR Transmitter Compliance Testing (center channel)



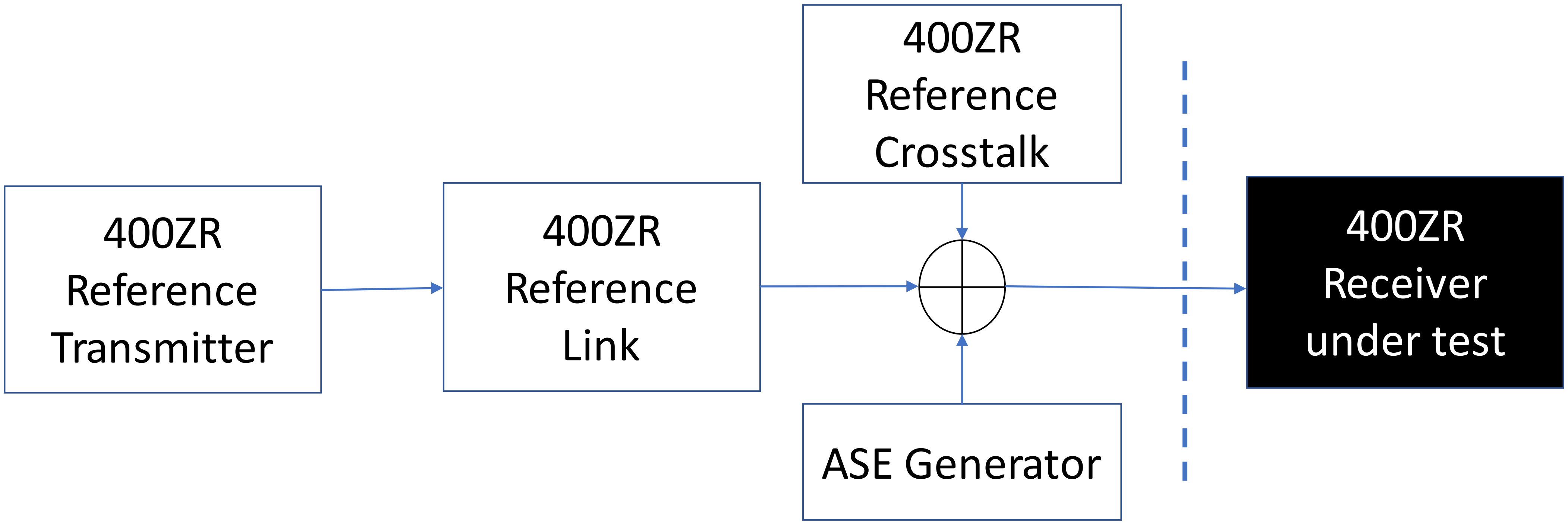
- 400ZR transmitter under test needs to achieve >Xdb of margin to threshold with reference link and a reference receiver
- Eq. 1 (or suboptimal variant) can be used to calculate this margin
- 400ZR reference mux/demux would be supergaussian for e.g. -4GHz offset, 80G bandwidth and 3rd order supergaussian roll-off
- Reference crosstalk generators with be RRC. For e.g. alpha=0.3, 4db higher transmit power
- Reference ASE based on 26db OSNR

400ZR Transmitter Compliance Testing (left/right channel)



- 400ZR reference transmitter for center channel. For e.g. RRC alpha=0.3
- DUT used as crosstalk channels
- Needs to achieve >Xdb of margin to threshold with reference link and a reference receiver
- Eq. 1 (or something similar) can be used to calculate this margin
- 400ZR reference mux/demux would be supergaussian for e.g. -4GHz offset, 80G bandwidth and 3rd order supergaussian roll-off
- Reference ASE based on 26db OSNR

400ZR Receiver Compliance Testing



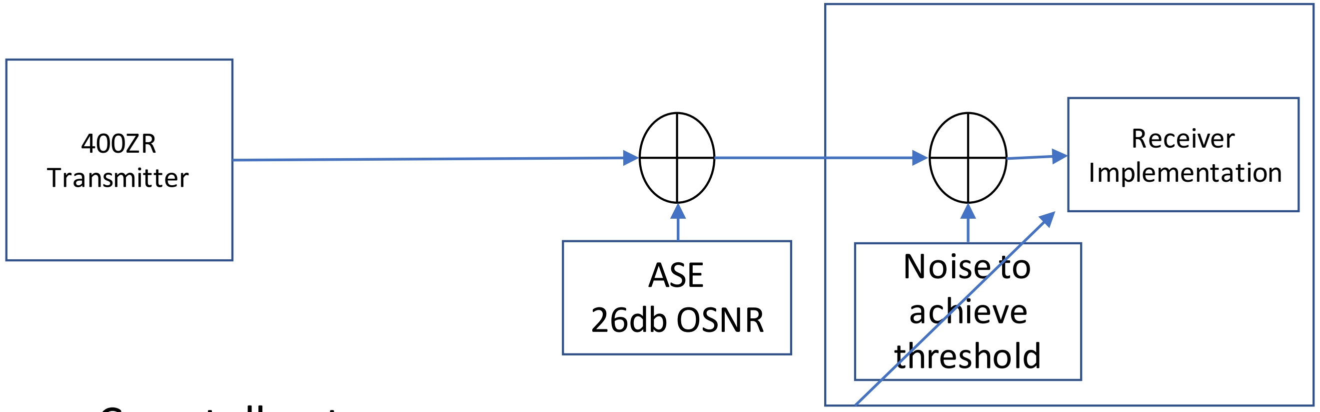
- 400ZR receiver under test needs to achieve < X db penalty with reference transmitter, reference link, reference crosstalk and reference ASE

Backup Slides

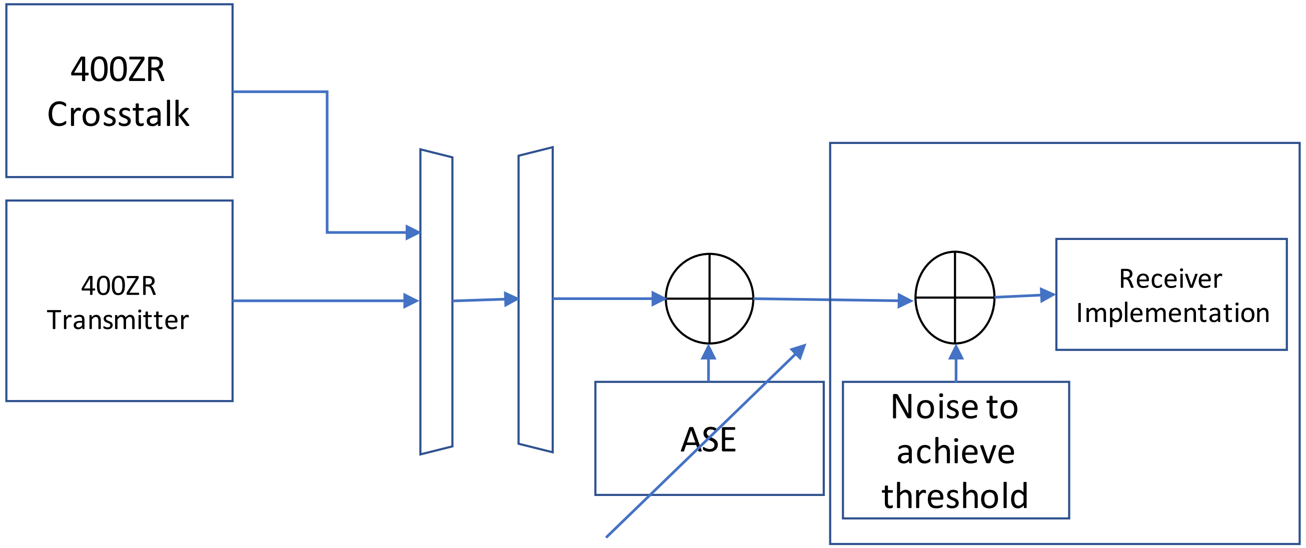
Simulation Setup/Procedure

- Transmitters (channel and crosstalk)
  - Root-Raised Cosine shapes (alpha=0.1 to 0.5)
  - Other non-RRC shapes
  - Crosstalk channels either 2db or 4db higher power
- Channel Spacing
  - Varied from 75G±1.8G
- MUX/DEMUX
  - Supergaussian 3rd order filters
  - 3db varied from 65G to 85G
  - Center frequency from -4 to +4 GHz from nominal
- Receivers
  - Weighted Crosstalk/NSR based calculation of receiver penalty
  - Optimal equalizer equation based penalty calculation
  - Suboptimal receiver using modified Eq. 1
  - Time-domain receiver implementation
- Baseline implementation penalty
  - Baseline setup used to calculate additional noise to achieve FEC threshold
- Crosstalk setup uses implementation penalty
- Penalties calculated relative to reference OSNR=26db

Baseline setup

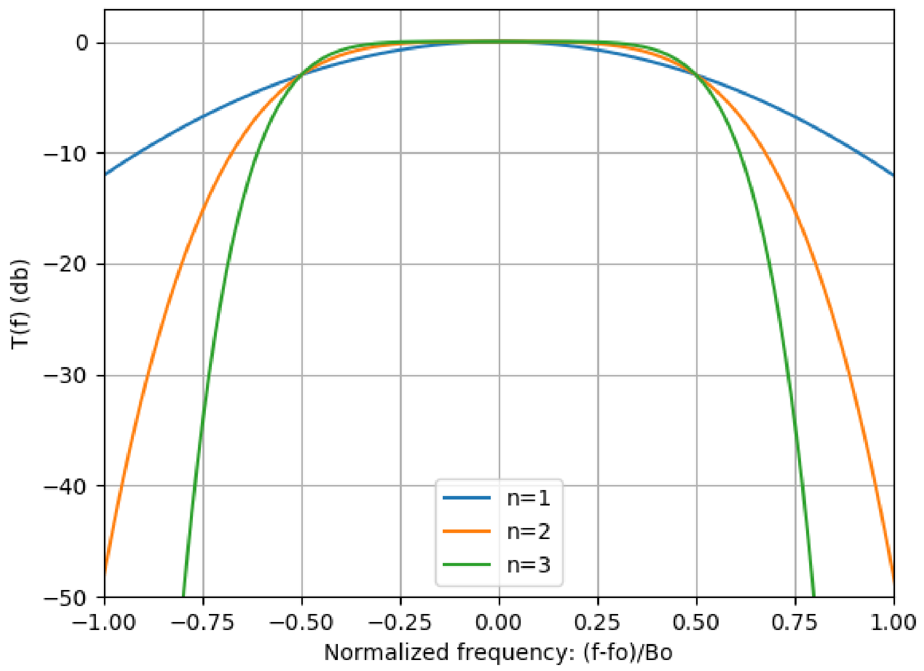


Crosstalk setup



Supergaussian Equation

$$T(f) = e^{-\ln(2)\left(\frac{2(f-f_o)}{B_o}\right)^{2n}}$$



- T(f) is the <u>power</u> transfer function
- B_o is the 3dB bandwidth of super-gaussian filter
- n is the order of the filter
- f_o is the filter center frequency

M. Pfennigbauer and P. J. Winzer, "Choice of MUX/DEMUX filter characteristics for NRZ, RZ, and CSRZ DWDM systems," in Journal of Lightwave Technology, vol. 24, no. 4, pp. 1689-1696, April 2006, doi: 10.1109/JLT.2006.870972.