A New PR Equalization and MLSD that Enable 400G PAM4 over Band-Limited Channels

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Supporters

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Outline

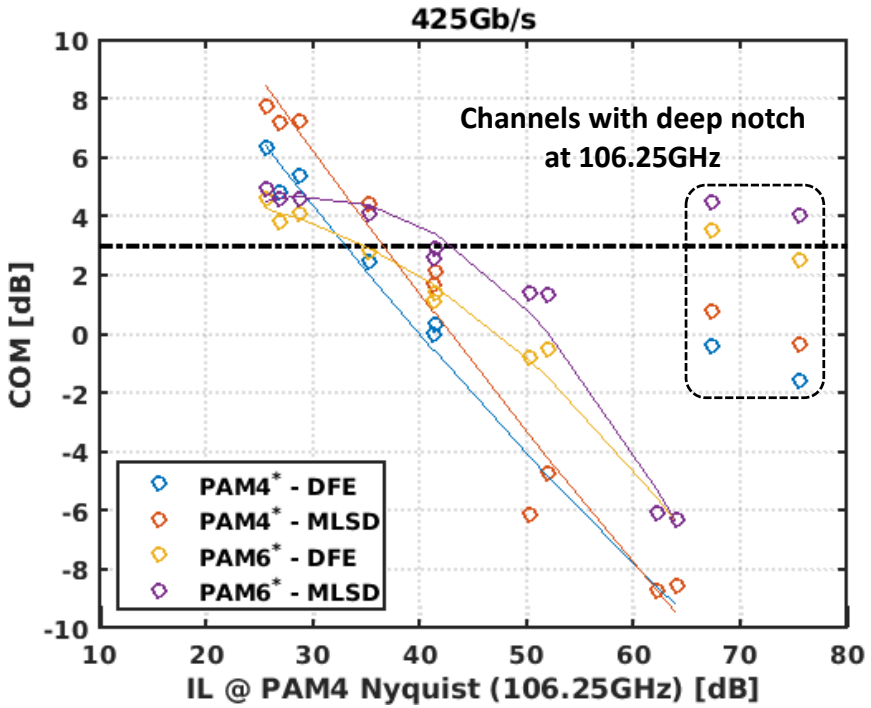
- Introduction and Motivation
- Coding Perspective of Partial-Response Signaling
- Limitations of $1+\alpha D$ Equalization for Higher Rates
- 2^{nd}-Order Partial-Response Equalization
- 2^{nd}-Order $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ Partial Equalization and Maximum-Likelihood Sequence Detection
- Simulation Methodology and Conditions
- 400G Test Channels and Performance Results
- 400G over 200G Legacy Channels
- Next Steps, Summary, and Conclusions
- Backup Slides:
  - Error Events, Error Analysis, Noise Coloring, and Required Updates to COM Flow in Annex 178A.1.10
- Appendix:
  - Channel and COM Info

Introduction

- Full channel equalization with linear equalizers is costly
  - Too much noise amplification, particularly at high rates and for lossy channels, if done in the receiver
  - Signal deemphasize if done in the transmitter
  - Requires at least Nyquist bandwidth, not easy to achieve with readily-available channel technologies and silicon fabrication processes (e.g. 112GHz for 448Gb/s PAM4)
  - Increased jitter sensitivity
- At 200G, reference receiver included FFE to target a partial equalization with only one remaining post-tap ($1+\alpha D$)
- The post-tap was handled by a 1-tap DFE for shorter channels and a 1^{st}-order MLSD for longer channels
- In support of 400G PAM4, an extended partial-response equalization along with its MLSD is suggested and analyzed here
- Backup slides show a summary of error analysis and required COM updates (more details will follow later)
  - Analysis is general and covers PAM-L (e.g. L = 4, 6, …)
- For now, the goal is to start dialogue and consensus building towards adopting the approach in the COM reference receiver for 400G PAM4 over band-limited electrical channels

Motivation

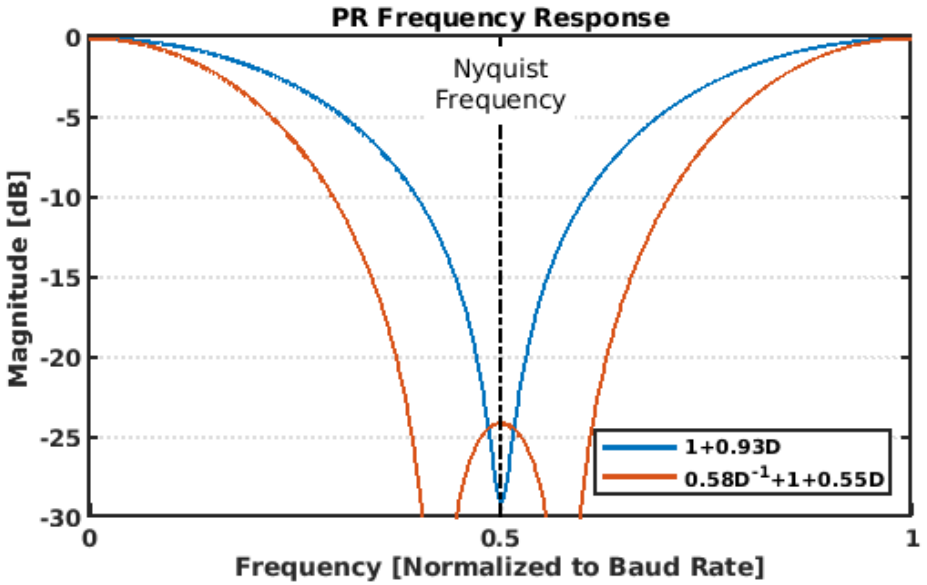
- Consider sample channels 1, 2, 6, 9, 10, 13, 14, 15, 17, 21, 23, 60 (see Appendix)
- At 400G, with the 200G reference receiver architecture and PAM4 modulation, COM performance is not acceptable for majority of feasible channels
  - DFE covers smooth channels with up to ~33dB of D2D IL at 106.25GHz (e.g. channels 60, 10, 14)
  - MLSD extends this to channels with up to ~37dB of D2D IL at 106.25GHz (e.g. channels 60, 10, 14, 13)
- PAM6 modulation is being considered for lossy channels
  - DFE covers:
    - Smooth channels with up to ~35dB of D2D IL at 106.25GHz (~23dB at 85GHz) (e.g. channels 60, 10, 14)
    - Channels with deep notch at PAM4 Nyquist of 106.25GHz (e.g. channel 6)
  - MLSD extends this to:
    - Channels with up to ~42dB of D2D IL at 106.25GHz (~32dB at 85GHz) (e.g. channels 60, 10, 14, 13)
    - Channels with deep notch at PAM4 Nyquist of 106.25GHz (e.g. channels 6, 9)
  - Covers all PAM4 cases, but with less COM margin for short channels and more for long channels



* Curve fit excludes channels with deep notch at ~106.25GHz

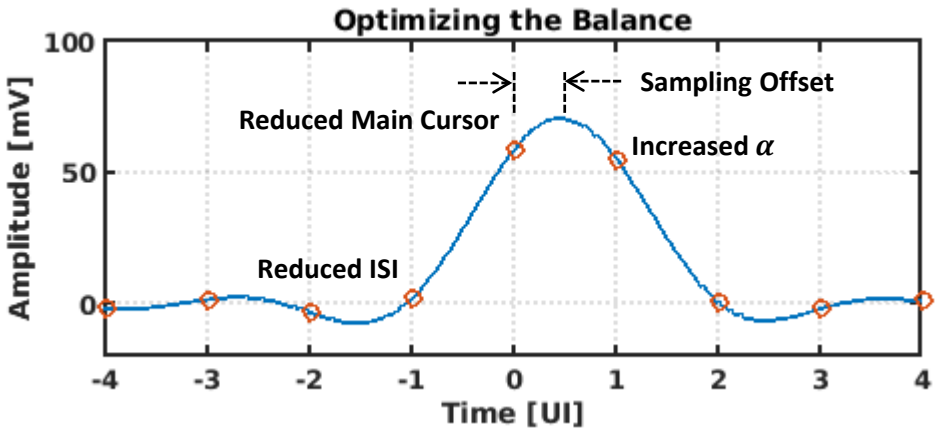
Coding Property and Spectral Shaping of Partial-Response Signaling

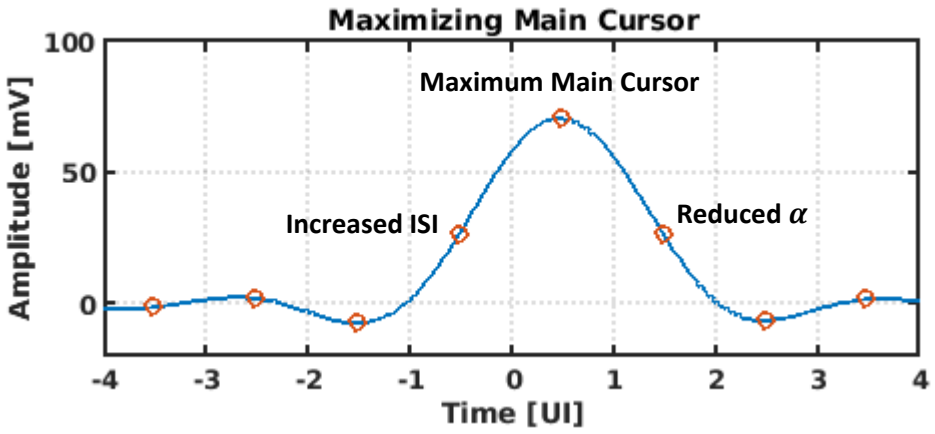
- A PR signaling can be viewed as a level coding scheme
- Coding property is a result of an increase in the number of signal levels and correlation between them
- PR coding spectrally shapes the signal by the PR polynomial frequency response (low-pass in our case)
- In time domain, this corresponds to adding more levels and managing level transitions to avoid large dv/dt
- PR spectral shaping can be partially or entirely applied by the channel or the combination of the channel and linear filters (correlative level coding, multi-level coding, coded modulation, line coding, …)
- Figure shows frequency response of two PR examples
  - 2^{nd}-order PR better fits lower bandwidth channels
  - Less linear equalization
  - Less noise amplification
  - Usually better performance
- MLSD is a technique that implements PR decoding (hence completes equalization)



Limitations of 1+αD Equalization for Higher-Rate Applications

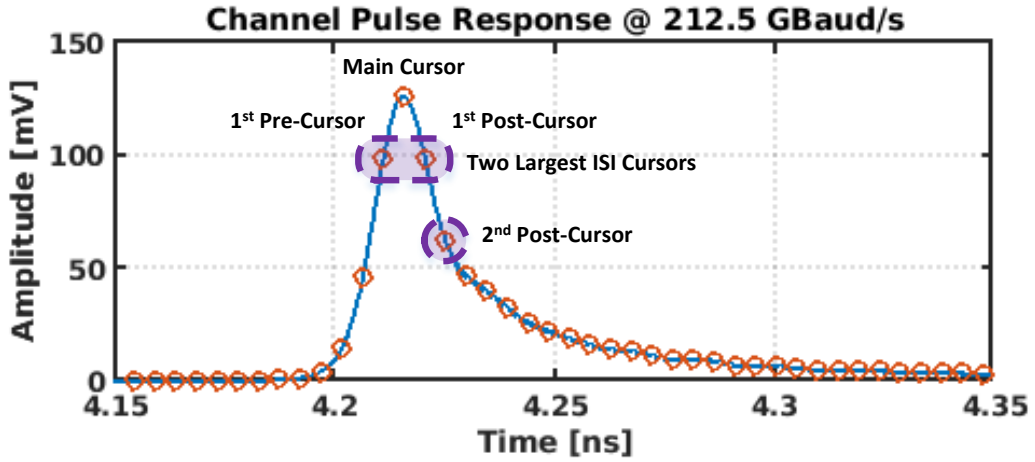
- Leaves only one ISI term for further processing
  - Usually a deliberate choice to minimize implementation complexity and was enough for acceptable performance
- The ISI term is constrained to be post-cursor
  - DFE limitation, also imposed on MLSD as a direct replacement for DFE
- Main cursor value and α cannot be maximized at the same time
  - A result of compromising main cursor for a larger α and reduced residual ISI

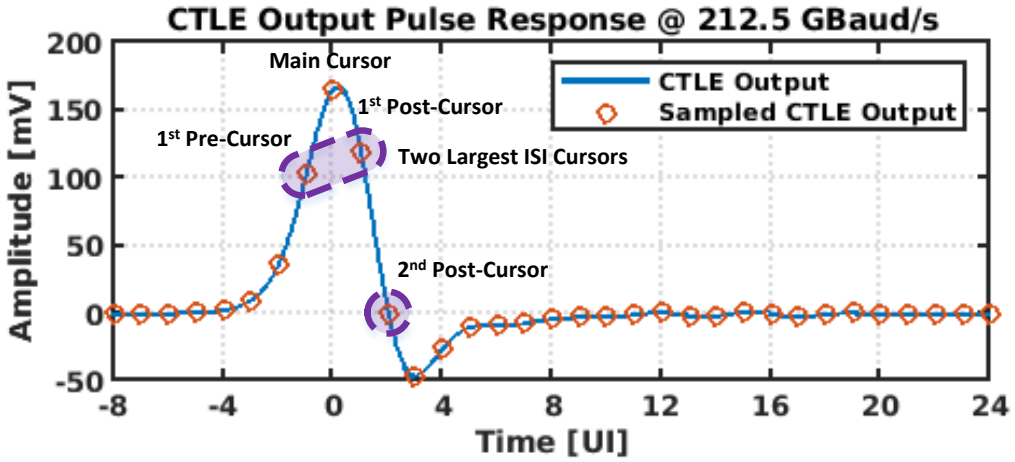




2nd-Order Partial Response Equalization

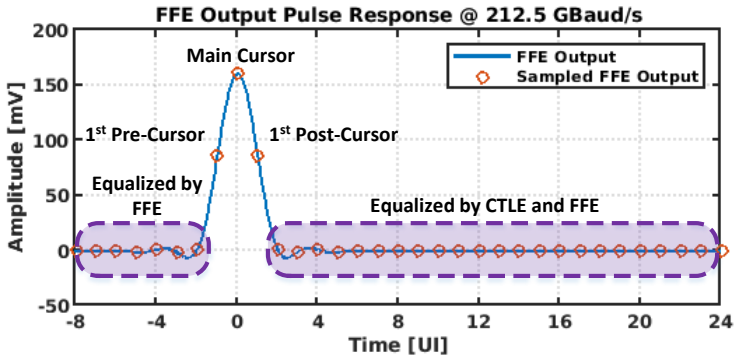
- What if partial-response target is extended to cover two post-cursors ($1+\alpha_1 D+\alpha_2 D^2$)?
  - Both DFE (2-tap) and MLSD (2nd-order) options are available
  - Still suffers from post-cursor limitation
  - Although further widens pulse response and relaxes bandwidth requirement, the relaxation is marginal because post-cursor values usually decrease with index (2nd post-curser < 1st post curser)
  - Is increased complexity a worthwhile trade-off?
- If a 2nd-order partial equalization is an option to consider, target the two largest ISI cursors
  - For our channels these are almost always the first pre and first post cursors

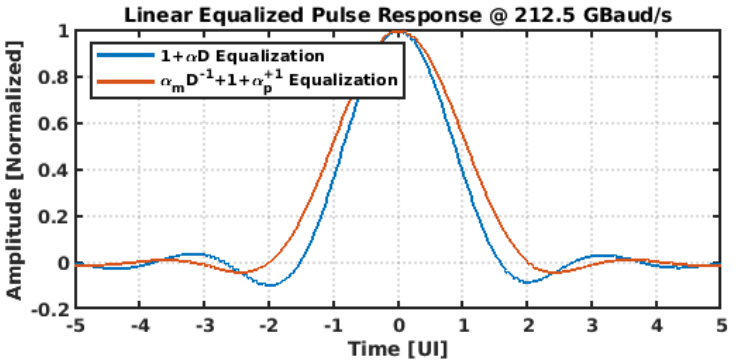


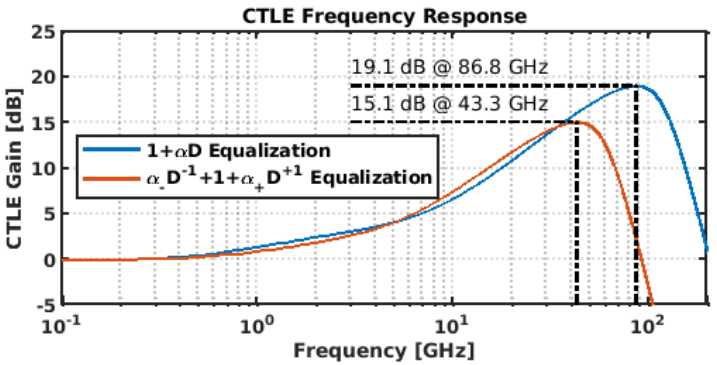


2nd-Order $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ Partial Response Equalization

- The idea is to also move penalty-heavy linear equalization of the (strong) first pre-cursor out of linear equalization chain (in addition to the first post-cursor)
- Target $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ partial equalization
  - Linear equalizer targets equalizing all cursors, except the first pre and first post cursors
- Advantages
  - Improved handling of the dominant pre and post ISI cursors
  - Avoiding to compromise the main cursor (sampling offset, deemphasize)
  - Since target of linear equalizer is an even wider pulse, analog bandwidth requirement is further relaxed
  - CTLE peak gain further reduces (channel is the same)
  - Noise amplification further reduces
  - FFE (Tx and Rx) target is further relaxed
- Disadvantages (?)
  - No DFE option (only MLSD)
  - Increased complexity

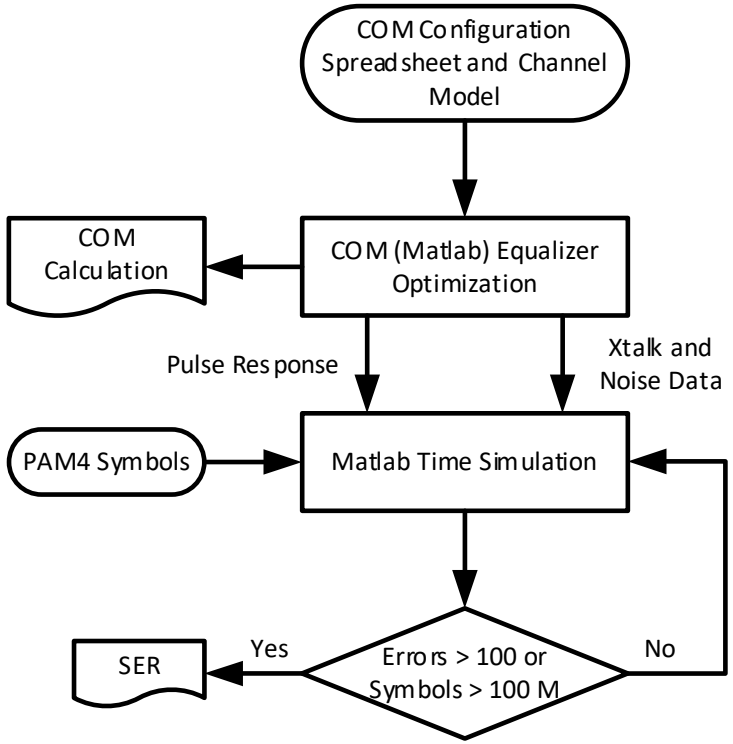






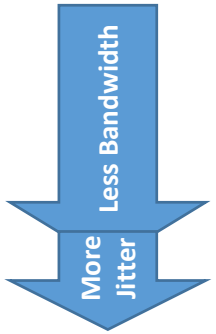
Performance Evaluation and Simulation Methodology

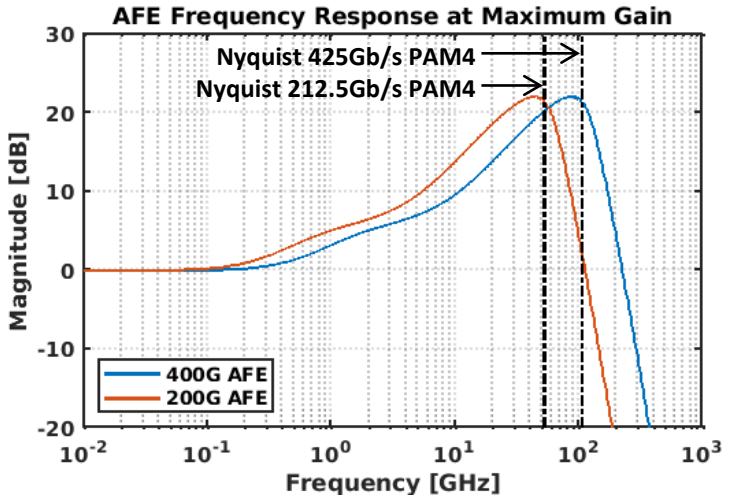
- COM Matlab code version "com_ieee8023_4p15p0" was used
- The code was customized for $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ PR and MLSD operation (com_ieee8023_4p15p0_hs1p0)
  - Modifications to MMSE tap optimization to add a pre-cursor (future contribution)
  - Post processing to calculate COM for the 2nd-order MLSD (future contribution)
  - Includes effect of noise coloring (future contribution)
- The original and customized versions were used to generate signal and crosstalk pulse responses and noise powers and transfer functions for the 1-tap DFE, $1+\alpha D$ MLSD, and $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ MLSD
- Pulse responses were convolved with PAM4 symbols and time-domain noises were generated for the three above cases
- Precoding was enabled
- Simulations ran to the first of 100 detected errors or 100M PAM4 symbols
- Hybrid approach to co-evaluate and verify COM and time-domain results

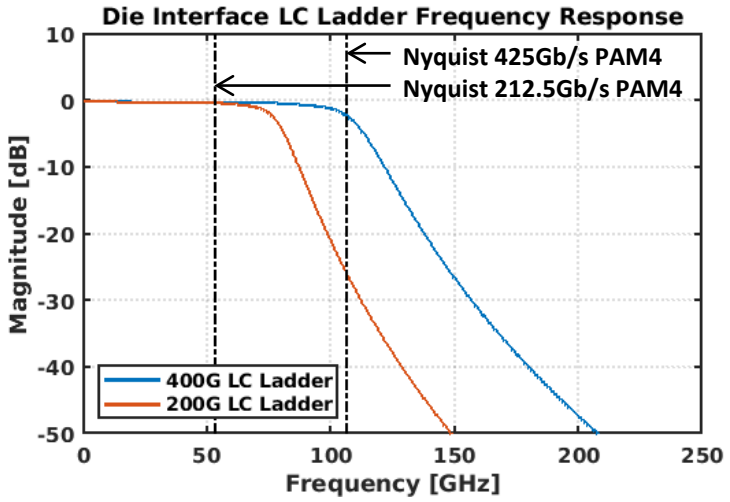


Simulation Conditions

- Simulations were repeated for five bandwidth and jitter conditions:
  1) 400G AFE and 400G die interface bandwidths and 400G jitter
  2) 200G AFE and 400G die interface bandwidths and 400G jitter
  3) 400G AFE and 200G die interface bandwidths and 400G jitter
  4) 200G AFE and 200G die interface bandwidths and 400G jitter
  5) 200G AFE and 200G die interface bandwidths and 200G jitter



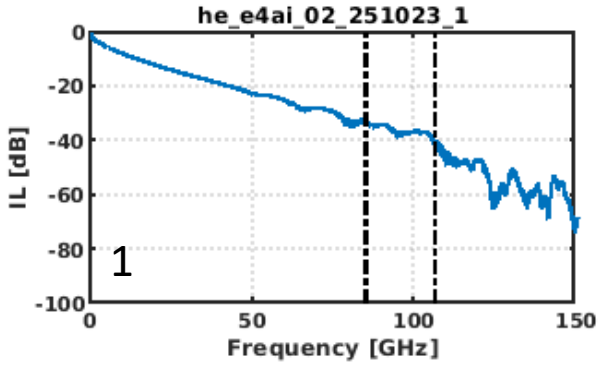


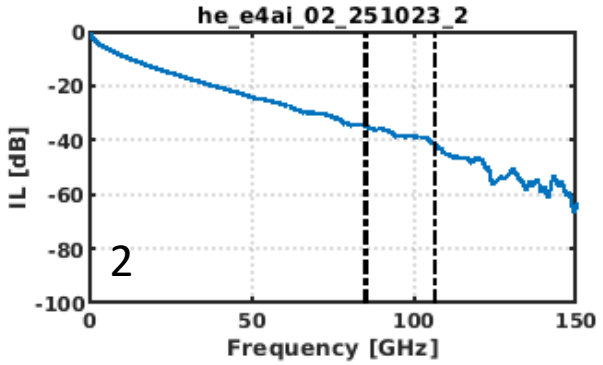


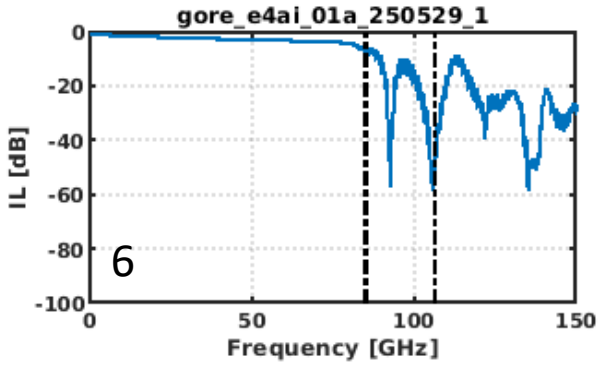
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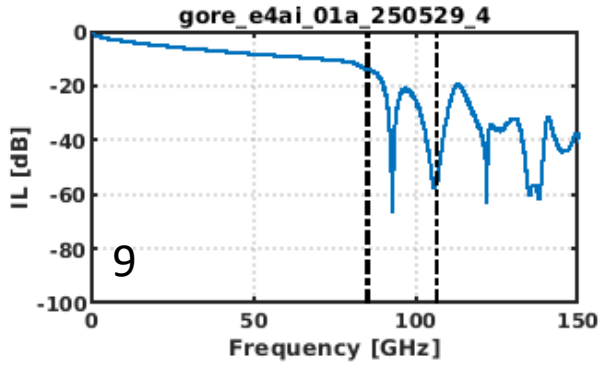
- 200G AFE corresponds to the C2C/C2M 212.5Gb/s filter and CTLE parameters (f_r, f_z, f_p1, and f_p2)
- 400G AFE corresponds to scaling filter and CTLE poles and zeros by a factor of 2 (f_r, f_z, f_p1, and f_p2)
- 200G die interface corresponds to the C2C/C2M 212.5Gb/s LC parameters (C_d, L_s, and C_b)
- 400G die interface corresponds to scaling LC parameters by a factor of 1/1.4 (C_d, L_s, and C_b)
- 200G jitter corresponds to doubling the C2C/C2M 212.5Gb/s jitter parameters (sigma_rj and A_DD (in UI))
- 400G jitter corresponds to the CR/KR 212.5Gb/s jitter parameters (sigma_rj and A_DD (in UI))

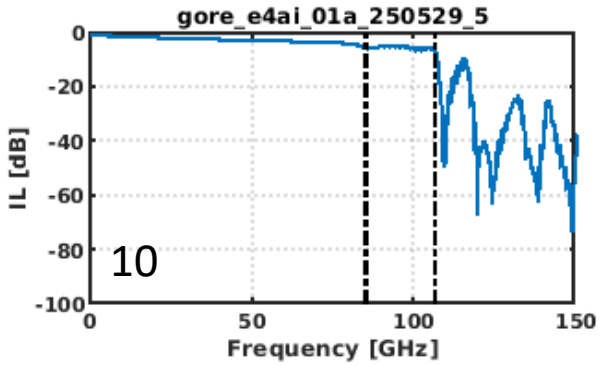
400G Test Channel Sample Responses (Channel Only)

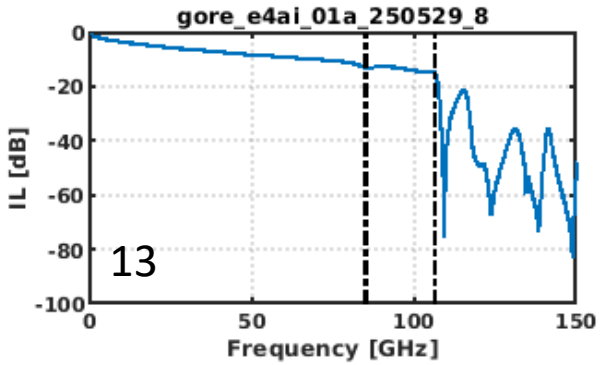


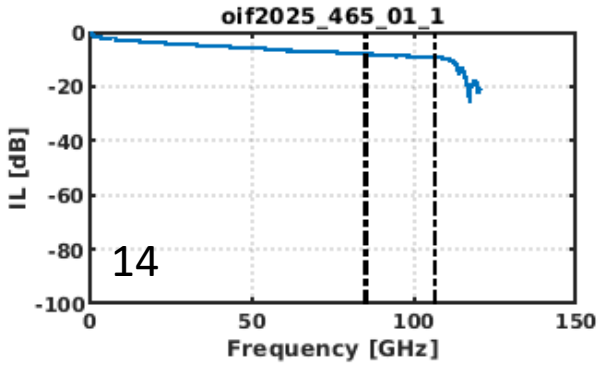


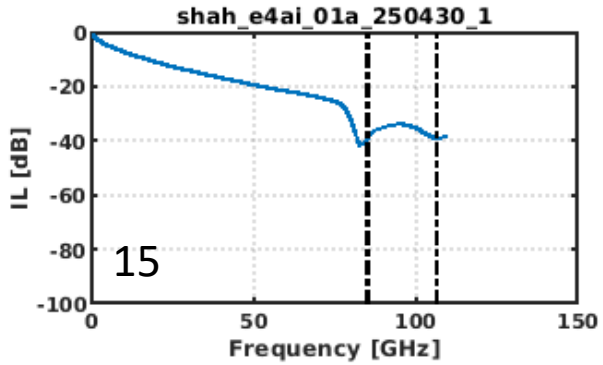


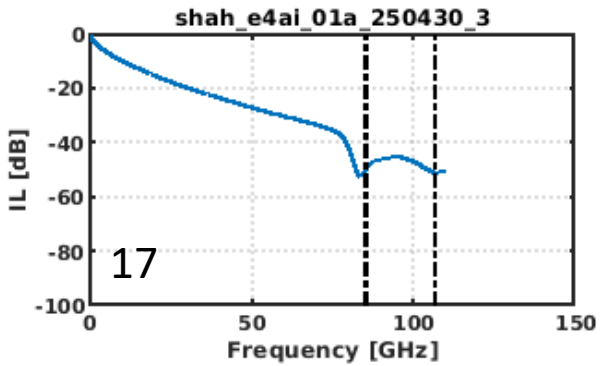


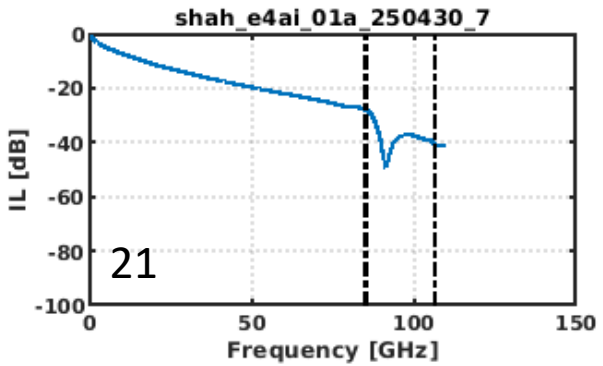


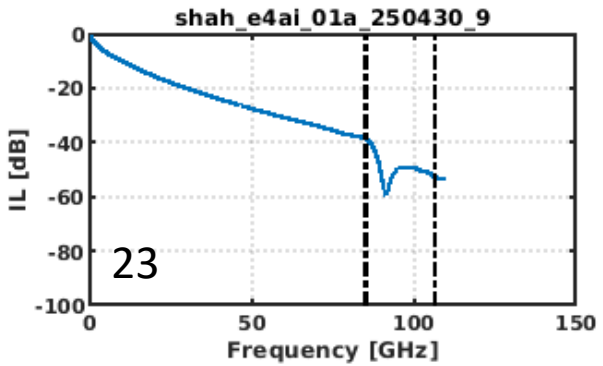


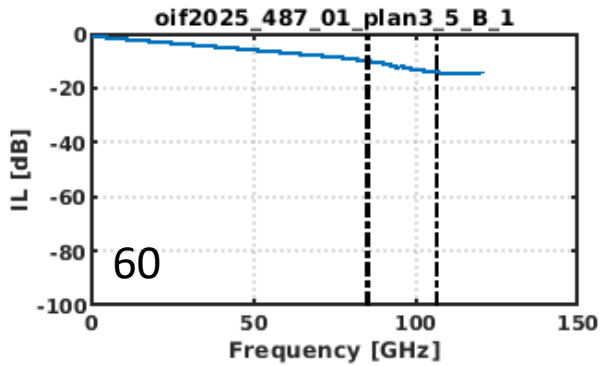




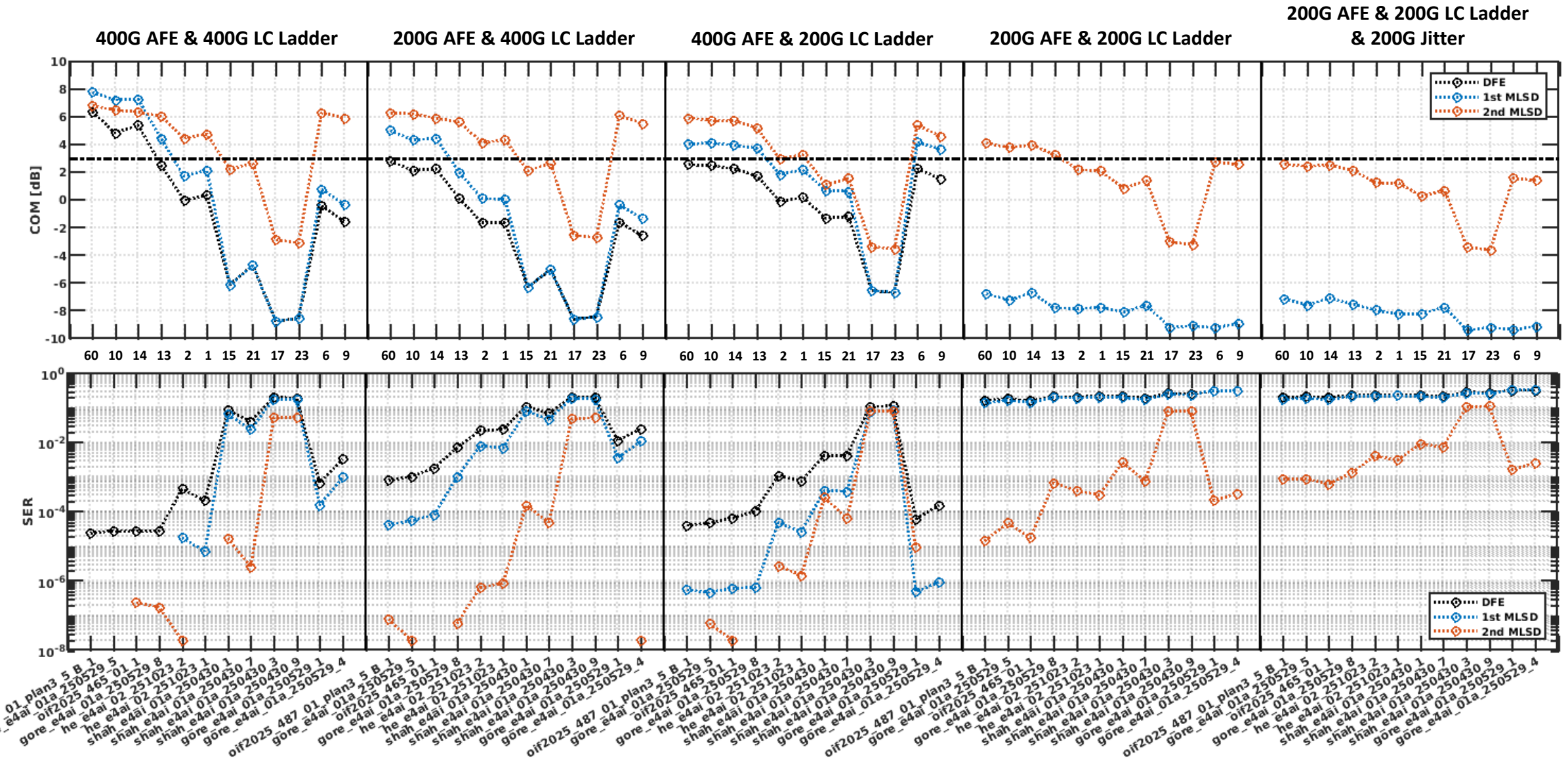






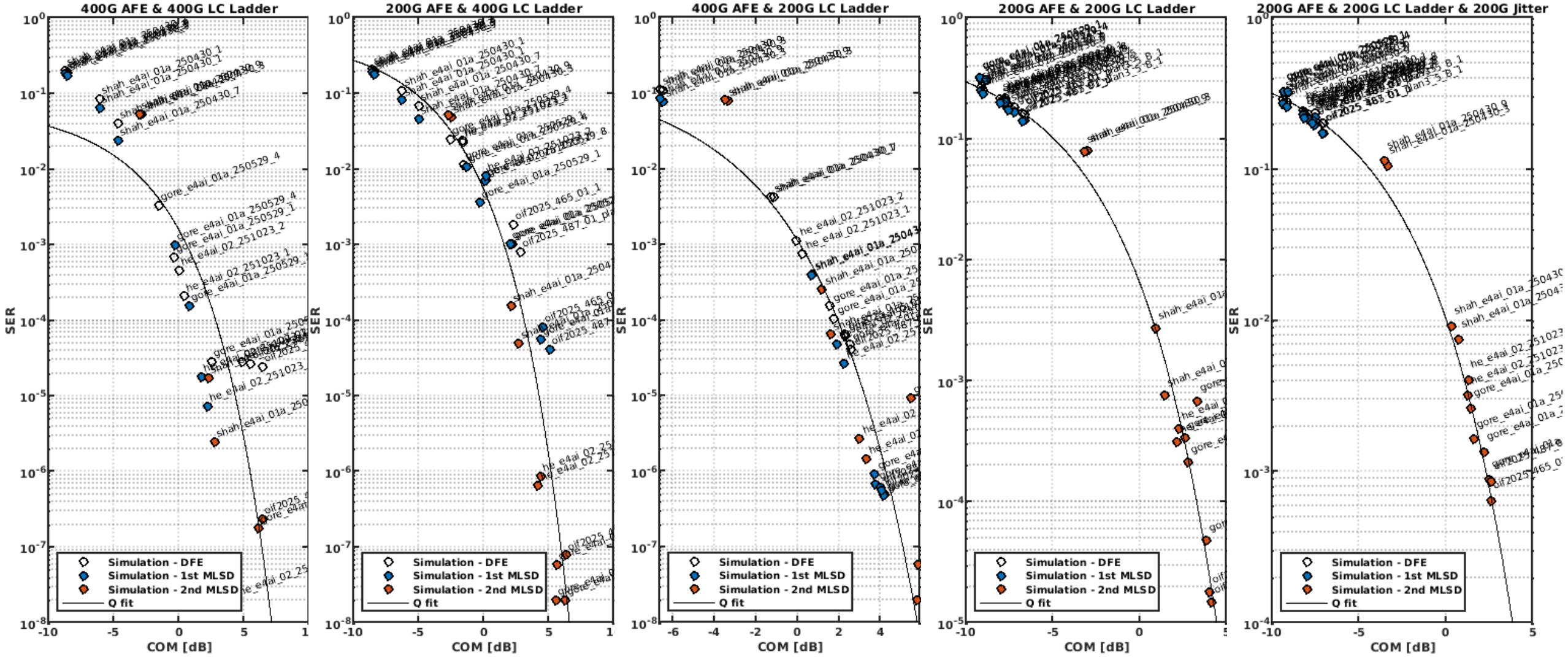


Simulation Results – COM and SER @ 425 Gb/s PAM4



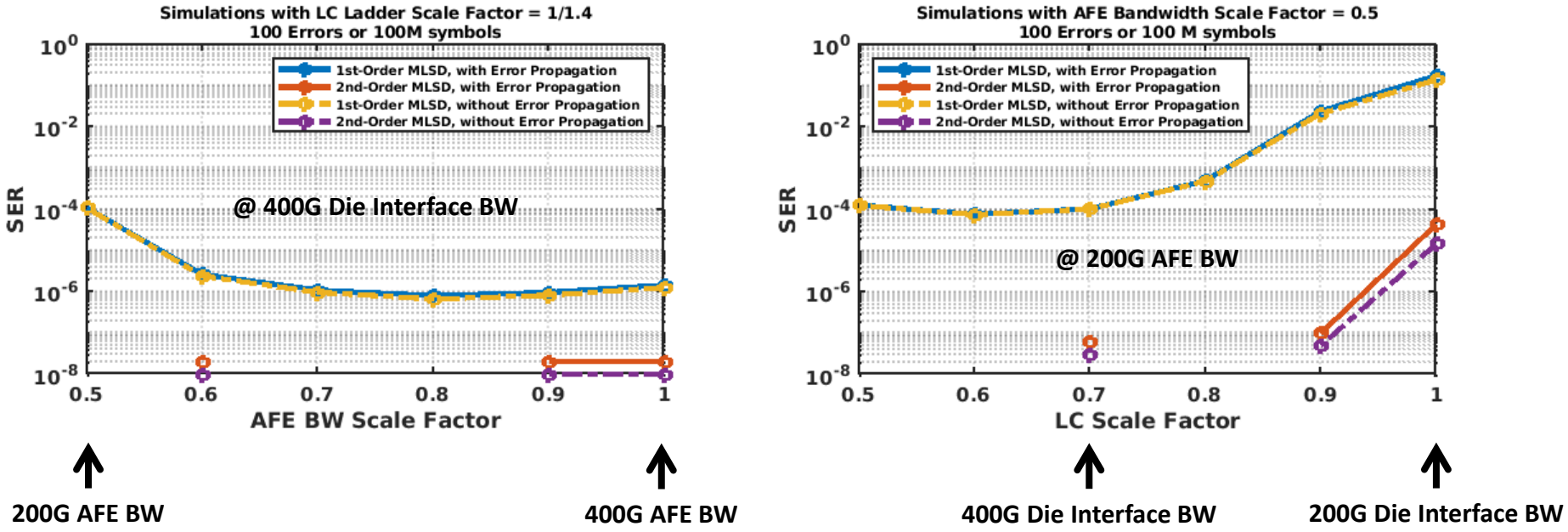
COM and SER Correlation – Q Fit

- Correlation tightens as more noise terms are added and distribution converges to Gaussian



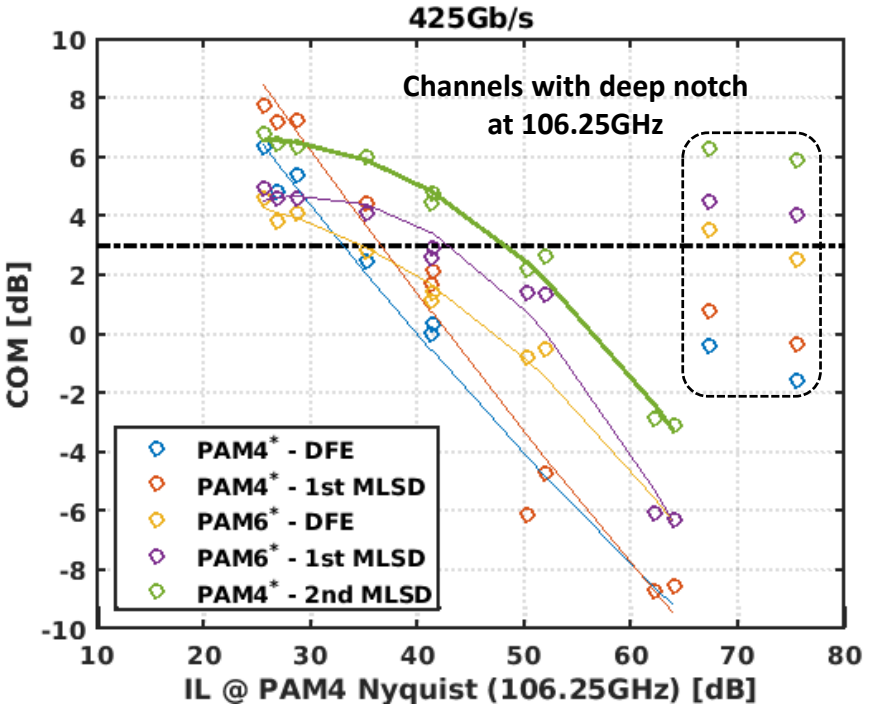
AFE Bandwidth and Die Interface Sweeps

- With a 400G Die Interface (LC Ladder Scale Factor = 1/1.4), AFE Bandwidth Scale Factor is swept from 0.5 (200G bandwidth) to 1 (400G bandwidth)
- With a 200G AFE bandwidth (Bandwidth Scale Factor = 0.5), LC Ladder Scale Factor is swept from 0.5 (> 400G bandwidth) to 1 (200G bandwidth)
- Results demonstrate drastic improvement in SER with the $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ MLSD over the entire range, confirming its successful operation even under severely limited bandwidth conditions



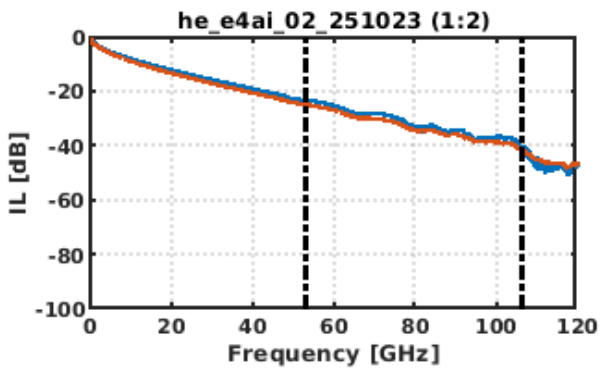
Performance Advantage

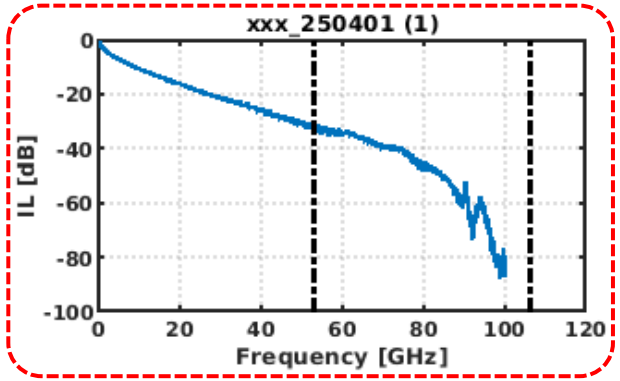
- PAM4 & DFE:
  - Covers smooth channels with up to ~33dB of D2D IL at 106.25GHz (e.g. 60, 10, 14)
- PAM4 & 1+αD MLSD:
  - Covers channels with up to ~37dB of D2D IL at 106.25GHz (e.g. 60, 10, 14, 13)
- PAM6 & DFE:
  - Covers smooth channels with up to ~35dB of D2D IL at 106.25GHz (e.g. 60, 10, 14)
    - All PAM4 cases, but with less margin for short channels and more for long channels
  - Real advantage is it covers channels with deep notches at ~PAM4 Nyquist (e.g. 6)
- PAM6 & 1+αD MLSD:
  - Covers smooth channels with up to ~42dB of D2D IL at 106.25GHz (e.g. 60, 10, 14, 13)
    - All PAM4 cases, but with less margin for short channels and more for long channels
  - Real advantage is it covers channels with deep notches at ~PAM4 Nyquist (e.g. 6, 9)
- **PAM4 & $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ MLSD** extends this to:
  - Channels with up to ~48dB of D2D IL at 106.25GHz (e.g. 60, 10, 14, 13, **2**, **1**)
  - Bonus advantage is it covers channels with deep notches at ~PAM4 Nyquist (e.g. **6**, **9**)
  - Significant increase in COM margin compared to above alternatives

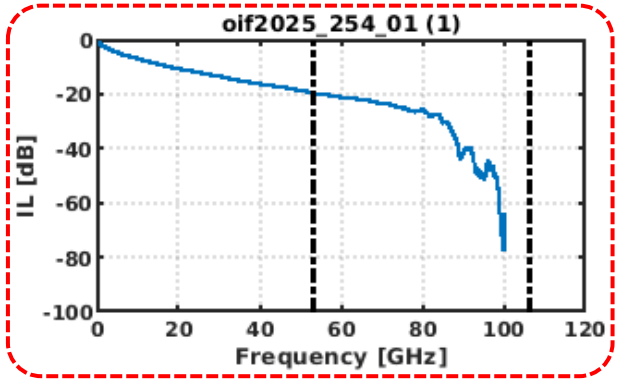


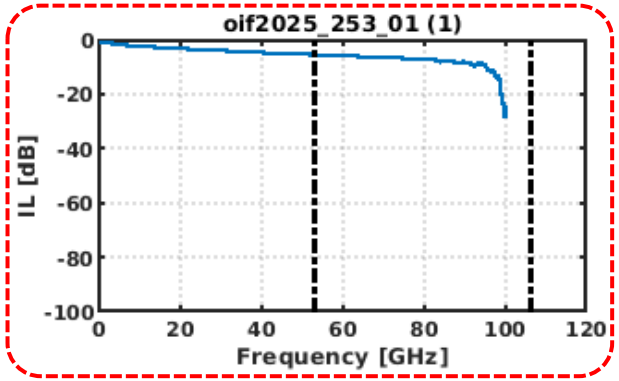
* Curve fit excludes channels with deep notch at ~106.25GHz

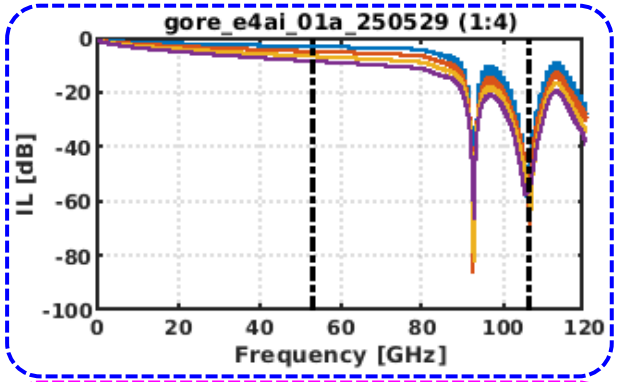
More 400G Channels

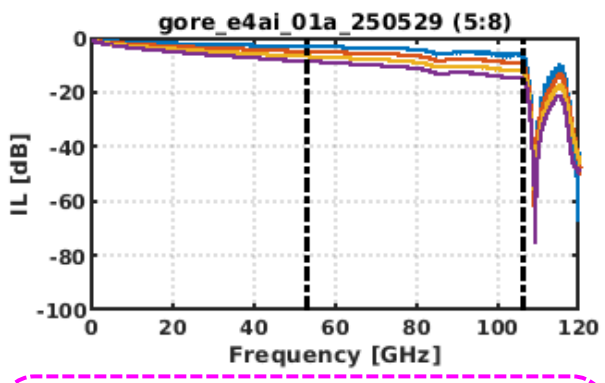


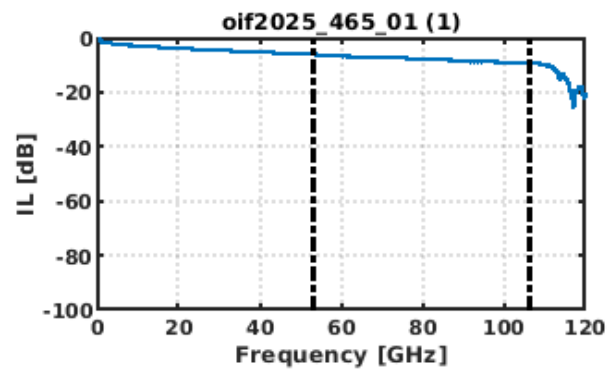


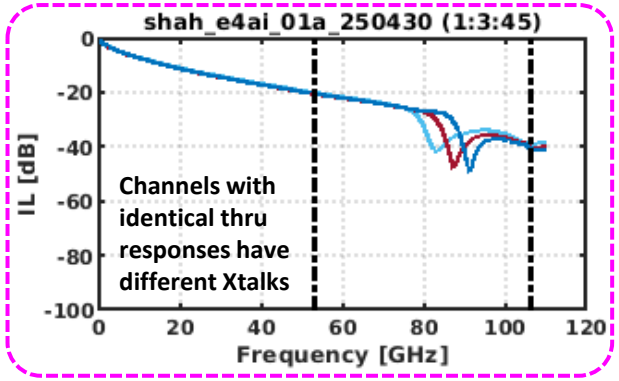


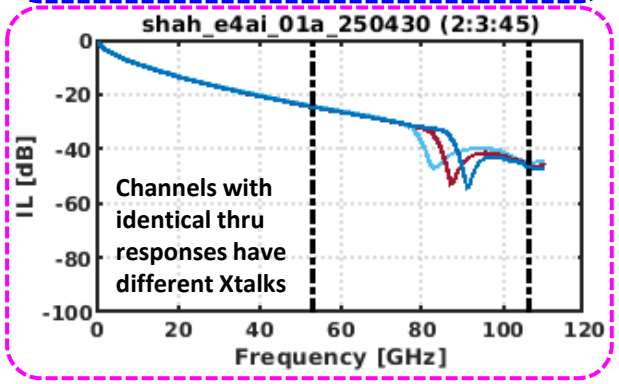


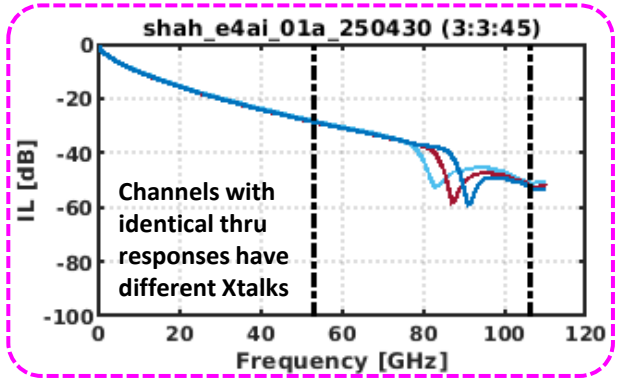


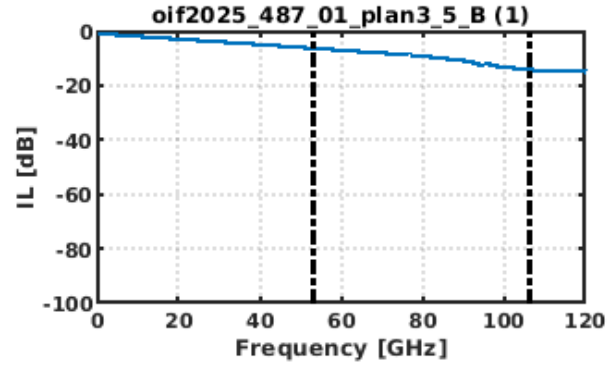






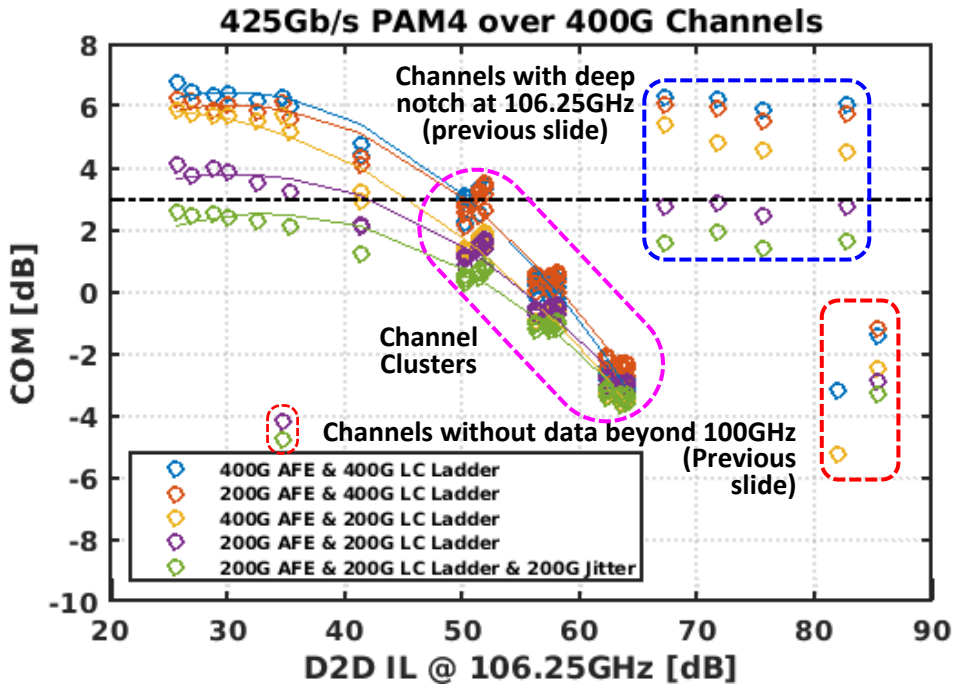




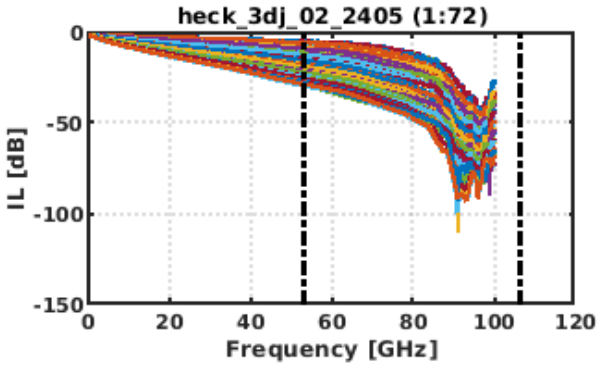


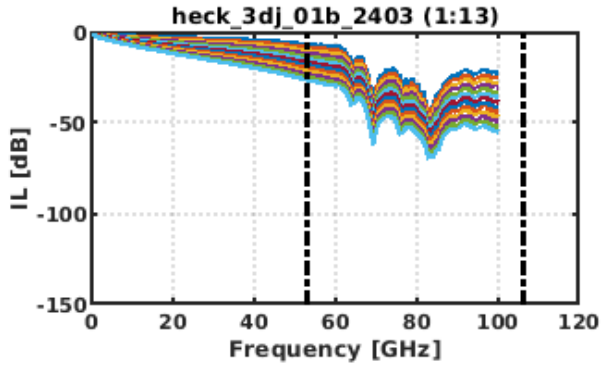
COM Results of All 400G Channels

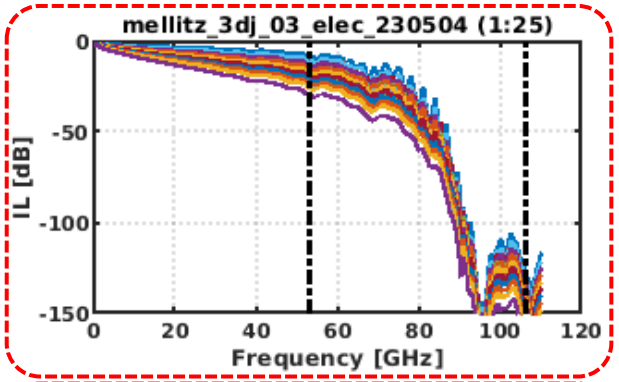
- A total of 60 400G channels (see Appendix)
- All available channels at the time, although not a good representation due to large bias from clusters
- Insignificant difference between 400G AFE and 200G AFE results
  - Passing cases only drop from 23 to 21
- More noticeable difference between 400G LC ladder and 200G LC Ladder results
  - Passing cases drop from 23 to 12
- Combination of bandwidth drops in AFE and LC ladder starts to cut in-band
  - Passing cases drop from 23 to 6
- Impact of up to 2X bandwidth reduction is not catastrophic
- Impact of 2X jitter increase is not catastrophic
- 3 channel clusters around ~51dB, , ~57dB, and ~63dB contain 9 channels with different thru loss profiles, and each with 5 different levels of PS Xtalk (previous slide)
- Channels with deep notches at Nyquist show strong COM results

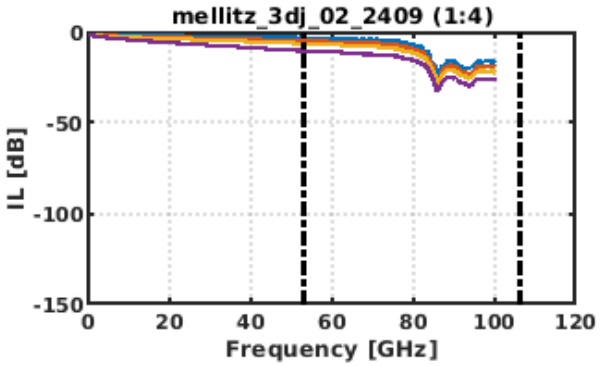


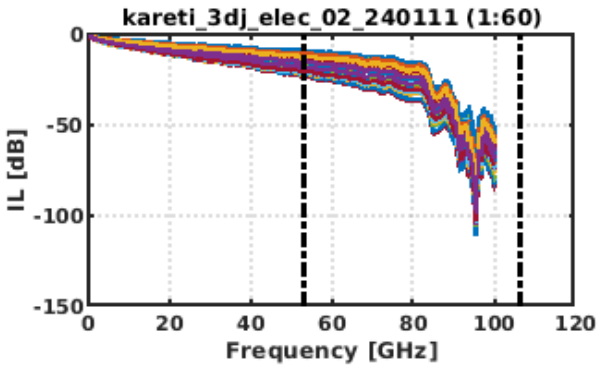
200G Legacy Channels

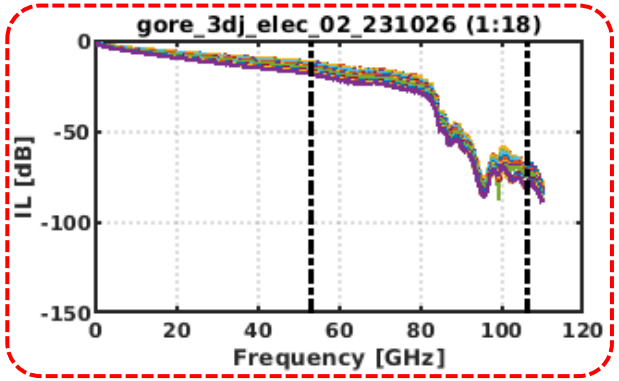


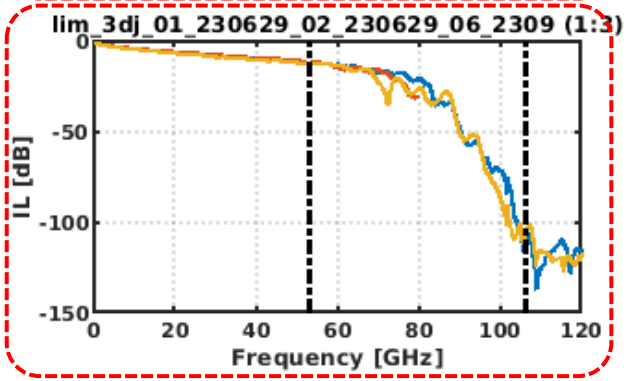


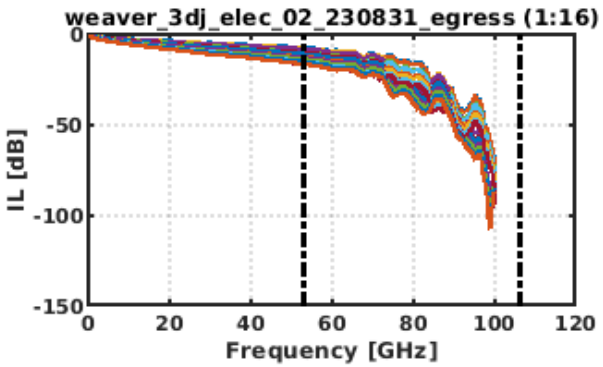


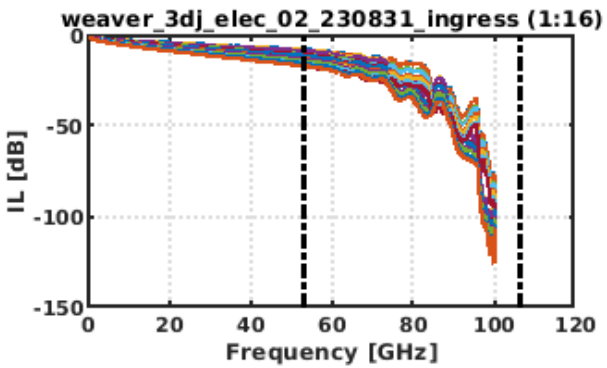


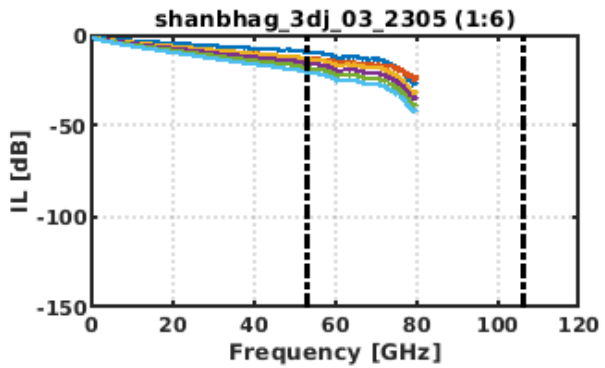


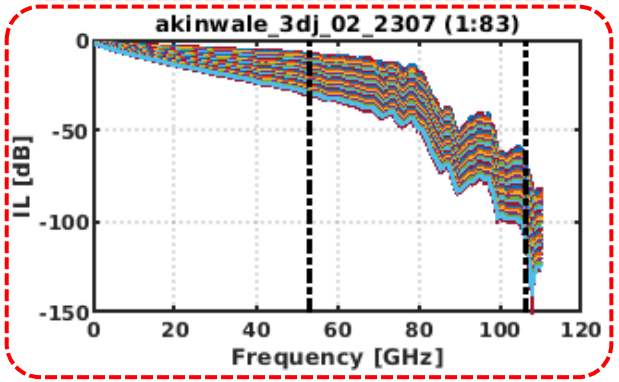


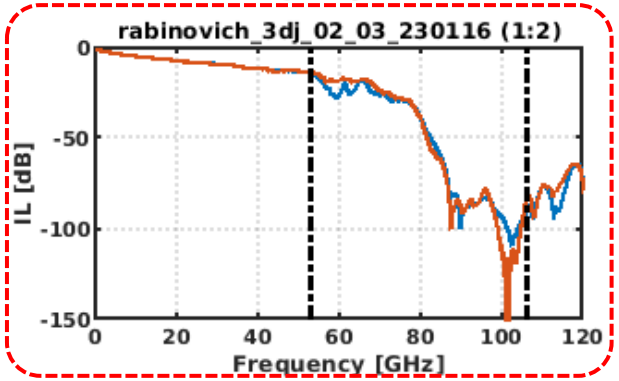






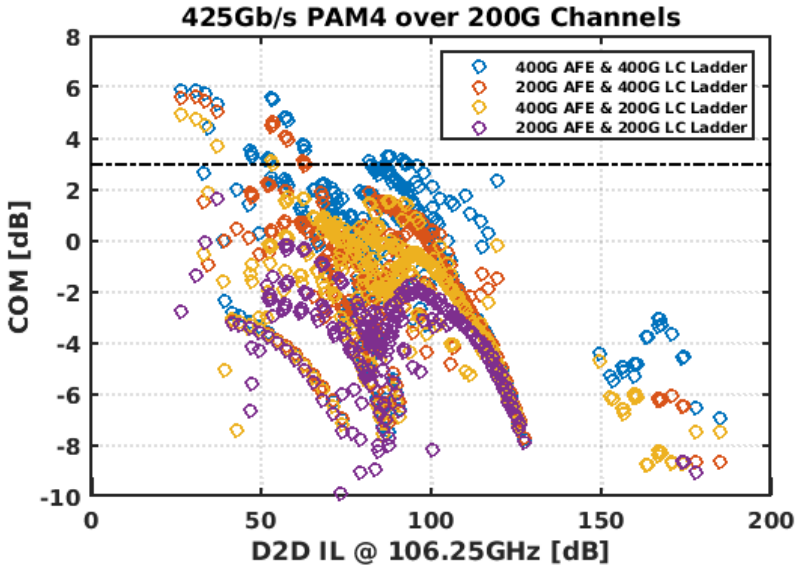


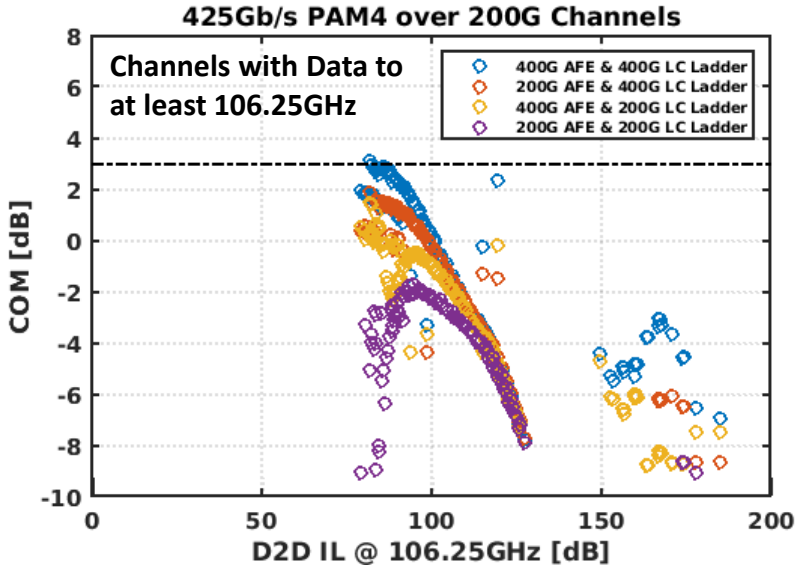




COM Results of 200G Channels

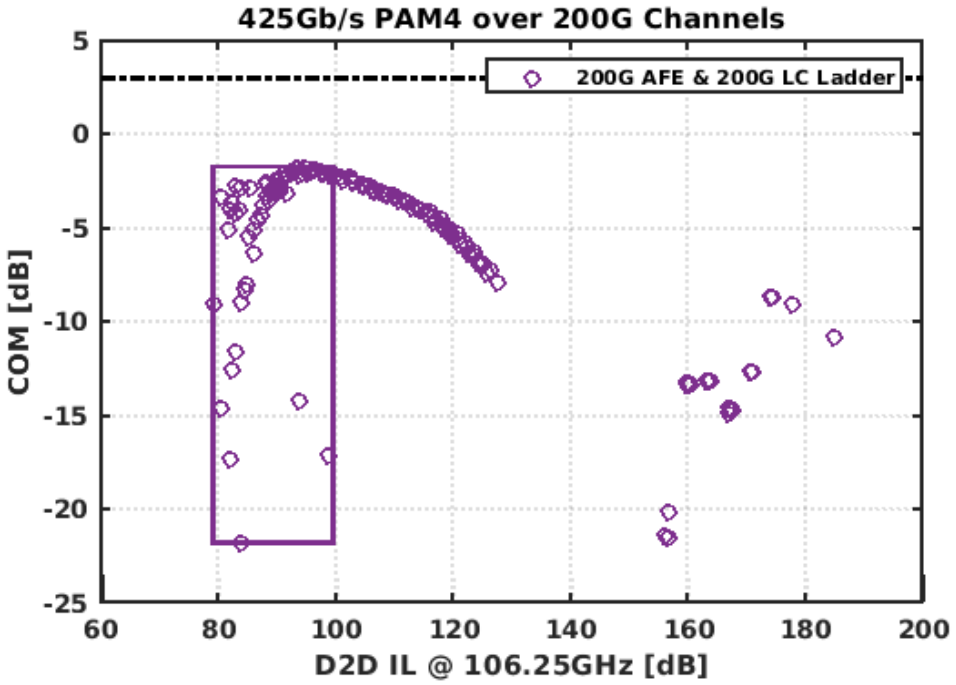
- Consider this an exploration exercise for lesson learning and not a suggestion for using 200G channels at 400G rate in a general sense
- A total of 318 200G C2M and C2C channels (see Appendix)
- For four bandwidth condition cases:
  - 400G AFE and 400G LC ladder → 27 passing cases
  - 200G AFE and 400G LC ladder → 12 passing cases
  - 400G AFE and 200G LC ladder → 7 passing cases
  - 200G AFE and 200G LC ladder → 0 passing cases
- Combination of 200G channels with 200G AFE and 200G LC ladder represents too much bandwidth limitation
- 130 channels with data to at least 106.25GHz (see previous slide)
  - Tightens the spread
  - Does not necessarily role out other channels

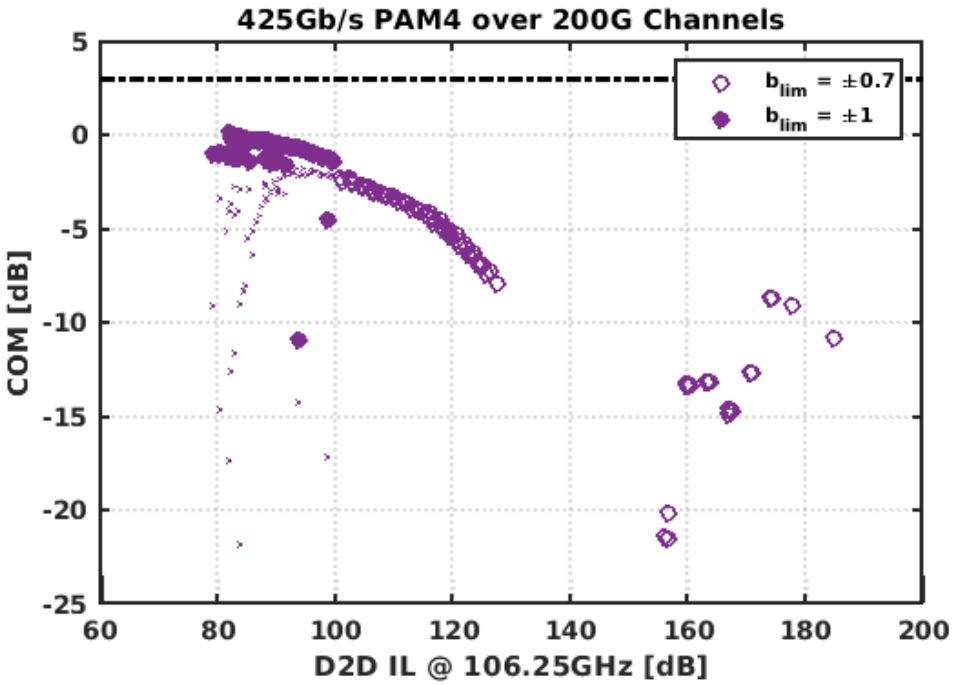




COM Results of 200G Channels – Observation 1

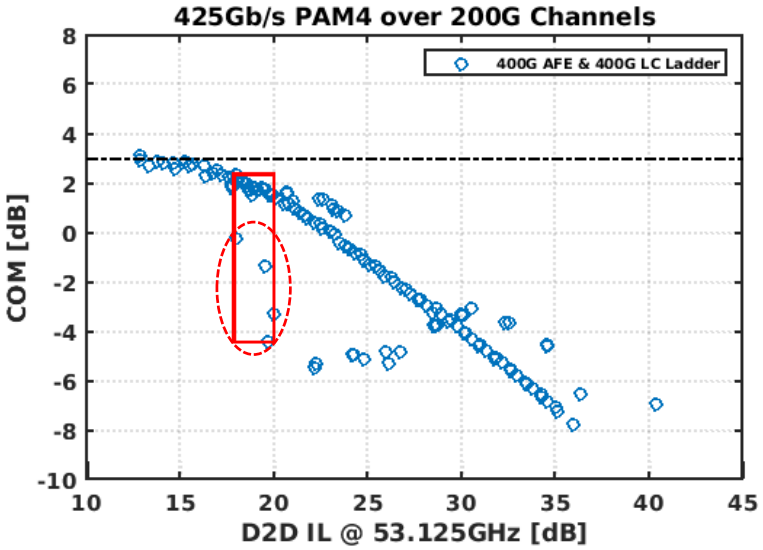
- Low COM for low loss channels under severely limited bandwidth
- A total of 56 cases with IL < 100dB @ 106.25GHz
- Combination of low loss in-band and sharp roll-off out-band is difficult to equalize
- It was indeed observed that many of the FFE taps saturated to their limit of ±0.7 for these cases
- Extending this limit to ±1 empowers the FFE and puts 54 out of 56 cases back on the trend line

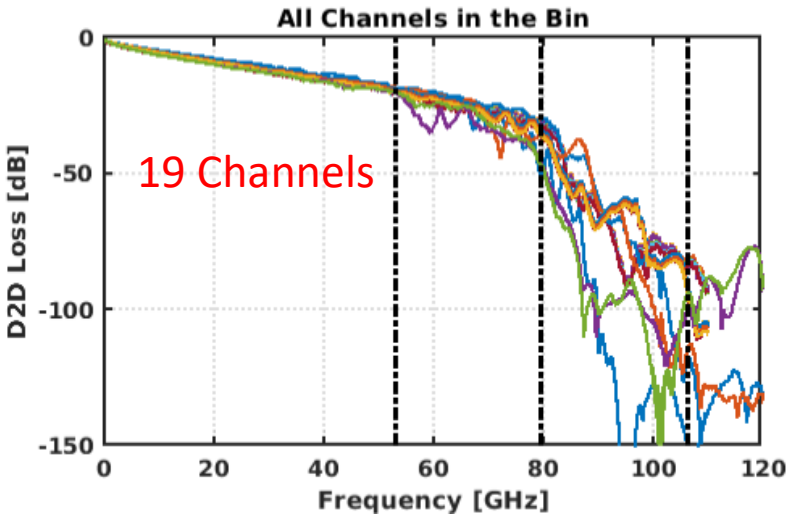


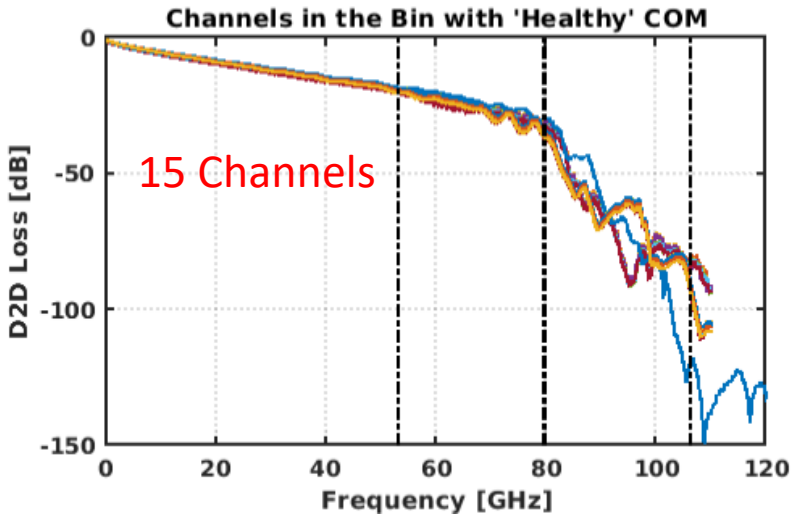


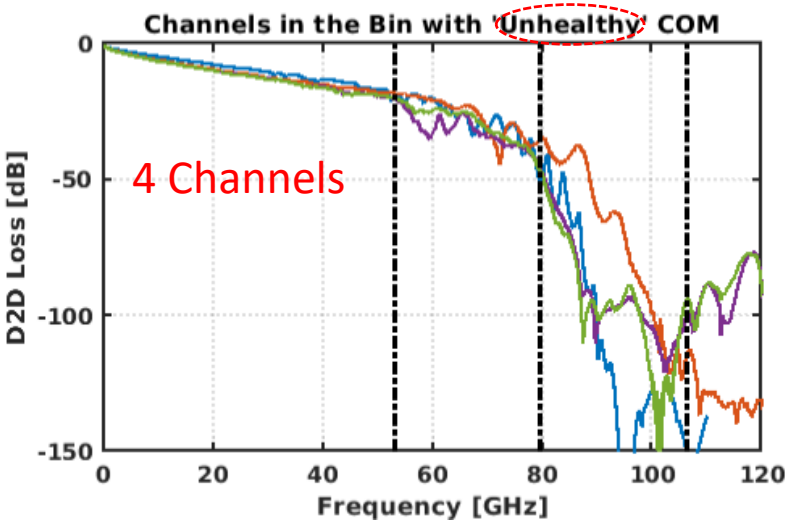
COM Results of 200G Channels – Observation 2

- A total of 19 200G channels in the red bin
- All channels were designed to have healthy responses to 53.125GHz
- All channels have similar average frequency response profiles up to ~80GHz
- Channels with 'Unhealthy' COM have significant ILD in the ~50-80GHz range
- ILD passed ~80GHz does not seem to make a big difference
- Loss passed ~80GHz starts to become a non-issue and certainly not an issue in a wide range around 106.25GHz (80GHz ≈ ¾ Nyquist Frequency)









Next Steps

- In case of interest and positive feedback the following future contributions will follow:
  - Detailed error analysis (A summary is provided in the backup slides)
  - Effect of noise coloring (A summary is provided in the backup slides)
  - Detailed COM flow and required updates to Annex 178A.1.10 (A summary is provided in the backup slides)
  - Error propagation analysis (Sample results are provided in the backup slides)
  - Updated COM Matlab code (COM ad hoc)
  - Any other topic of interest
- A customized version COM code is available that supports both MLSDs
  - Set COM parameter MLSE/MLSD = 1 for $1+\alpha D$ MLSD and MLSE/MLSD = 2 for $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ MLSD
  - This version also includes the effect of noise coloring (for both MLSDs)
  - Already sent to few interested parties (feedback appreciated)
- Depending on further discussions, due diligence, and consensus building intend to propose to replace and/or compliment $1+\alpha D$ with $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ PR and MLSD for various 400G channel classes in COM verification flow

Summary and Conclusions

- Limitation of 1+aD for its extension to higher rates was explained
- A new 2nd-order $\alpha_{-}D^{-1}+1+\alpha_{+}D^{+1}$ MLSD was proposed for 400G PAM4
  - Extendable to PAM6, … if need be (at the moment unlikely)
- Feasibility data in the forms of theoretical analysis, COM simulation, and time-domain simulation were presented
- Analysis and simulation results demonstrate much improved performance (in COM and SER metrics) with PAM4 modulation at 400G over current versions of 400G channels with already-available and/or reasonably-achievable technologies and several 200G legacy channels
- Backward compatible/friendly with current and previous generations of link architecture
  - No change to modulation and FEC
  - So far, no need for additional inner encoding
  - No change to transmitter
  - Minimum change to receiver (repurposing FFE target and swapping MLSD)
  - Can operate over most in-development and some legacy channels
- A series of future steps were suggested
- High potential for consideration as a viable proposal for reference receivers in COM verification flow at 400G

Thank You ☺

Hossein Shakiba
Huawei Technologies Canada

Backup Slides

Minimum-Distance Error Events

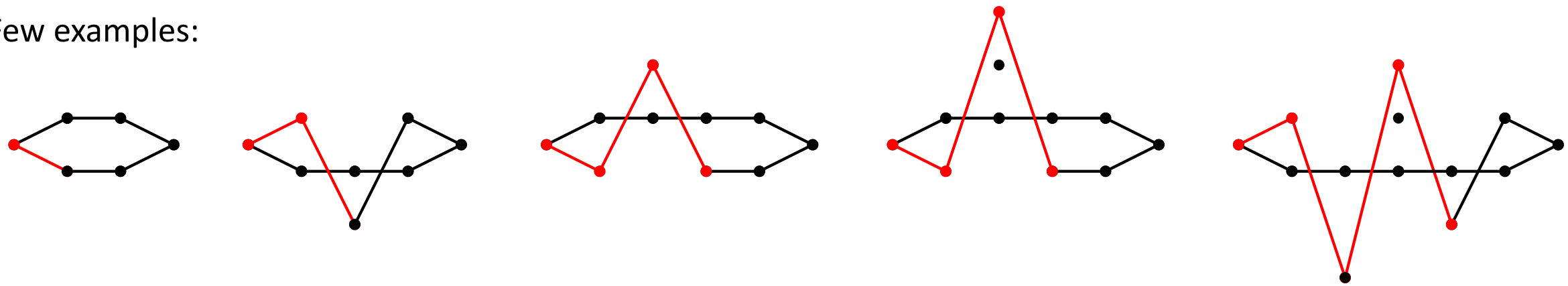
Error Analysis

Noise Coloring

Required Updates to COM Flow in Annex 178A.1.10

Error Analysis – Dominant Error Events

- Error event analysis shows events with alternating errors dominate the error performance (minimum distance)
- This is similar to the 1st-order MLSD, but not necessarily limited to alternating ±1 pattern
- Depending on the values of α_- and α_+, alternating ±2 and ±3 patterns are also possible
- Alternating ±2 pattern could be as likely as alternating ±1
- Alternating ±3 pattern is extremely unlikely
- Nevertheless, all error events start and end with ±1
- Let mEEn denote an error event containing m errors (burst of length m) and a total event length of m+2 with an alternating error pattern of ±n (n = 1, 2, 3), sandwiched between two starting and ending errors of ±1
- Few examples:



1EE1: [-1] 2EE1: [+1 -1] 3EE1: [-1 +1 -1] 3EE2: [-1 +2 -1] 4EE2: [+1 -2 +2 -1]

Error Analysis – PAM-L

- MLSE makes a wrong decision if the accumulated MSE of the error path is less than that of the correct path

$$\sum_{i=1}^{j+1} B_{i,E} < \sum_{i=1}^{j+1} B_{i,C}$$

- Using branch metrics calculated from the PR polynomial, this condition translates to the following expressions for three types of alternating error events:

$$\begin{cases} \alpha_- n_0 + n_1 + \alpha_+ n_2 > A_s(\alpha_-^2 + 1 + \alpha_+^2) & ,j = 1 \\ \alpha_- n_0 + (1-\alpha_-)n_1 - (1-\alpha_- - \alpha_+)\sum_{i=2}^{j-1}(-1)^i n_i - (-1)^j(1-\alpha_+)n_j + (-1)^{j+1}\alpha_+ n_{j+1} > A_s(\alpha_-^2 + (1-\alpha_-)^2 + (j-2)(1-\alpha_- - \alpha_+)^2 + (1-\alpha_+)^2 + \alpha_+^2) & ,j \geq 2 \end{cases} \quad ,jEE1$$

$$\begin{cases} \alpha_- n_0 + (1-2\alpha_-)n_1 - (2-\alpha_- - \alpha_+)n_2 + (1-2\alpha_+)n_3 + \alpha_+ n_4 > A_s(\alpha_-^2 + (1-2\alpha_-)^2 + (2-\alpha_- - \alpha_+)^2 + (1-2\alpha_+)^2 + \alpha_+^2) & ,j = 3 \\ \alpha_- n_0 + (1-2\alpha_-)n_1 - (2-2\alpha_- - \alpha_+)n_2 - (2-2\alpha_- - 2\alpha_+)\sum_{i=3}^{j-2}(-1)^i n_i - (-1)^{j-1}(2-\alpha_- - 2\alpha_+)n_{j-1} - (-1)^j(1-2\alpha_+)n_j + (-1)^{j+1}\alpha_+ n_{j+1} > A_s(\alpha_-^2 + (1-2\alpha_-)^2 + (2-2\alpha_- - \alpha_+)^2 + (j-4)(2-2\alpha_- - 2\alpha_+)^2 + (2-\alpha_- - 2\alpha_+)^2 + (1-2\alpha_+)^2 + \alpha_+^2) & ,j \geq 4 \end{cases} \quad ,jEE2$$

$$\begin{cases} \alpha_- n_0 + (1-3\alpha_-)n_1 - (3-\alpha_- - \alpha_+)n_2 + (1-3\alpha_+)n_3 + \alpha_+ n_4 > A_s(\alpha_-^2 + (1-3\alpha_-)^2 + (3-\alpha_- - \alpha_+)^2 + (1-3\alpha_+)^2 + \alpha_+^2) & ,j = 3 \\ \alpha_- n_0 + (1-3\alpha_-)n_1 - (3-3\alpha_- - \alpha_+)n_2 - (3-3\alpha_- - 3\alpha_+)\sum_{i=3}^{j-2}(-1)^i n_i - (-1)^{j-1}(3-\alpha_- - 3\alpha_+)n_{j-1} - (-1)^j(1-3\alpha_+)n_j + (-1)^{j+1}\alpha_+ n_{j+1} > A_s(\alpha_-^2 + (1-3\alpha_-)^2 + (3-3\alpha_- - \alpha_+)^2 + (j-4)(3-3\alpha_- - 3\alpha_+)^2 + (3-\alpha_- - 3\alpha_+)^2 + (1-3\alpha_+)^2 + \alpha_+^2) & ,j \geq 4 \end{cases} \quad ,jEE3$$

- LHS of the above expressions are the MLSD sequence noise and are linear combinations of $j + 2$ samples of noise taken at consecutive UI-spaced intervals
- In the above expression signal scaling is applied to obtain a PAM level separation of $2A_s$, consistent with the definition used in the COM flow
- In case of white noise, noise samples are identically distributed and independent random variables and will be weighted and power summed

Error Analysis – Effect of Noise Coloring

- Similar to the 1st-order MLSD, we define the noise sequence coefficient vector from the previous expressions:

$$u_j = \begin{cases} u_{jEE1} = \begin{cases} [\alpha_- \quad 1 \quad \alpha_+]^T & ,j=1 \\ [\alpha_- \quad (1-\alpha_-) \quad -(1-\alpha_- -\alpha_+) \quad +(1-\alpha_- -\alpha_+) \quad \cdots \quad -(-1)^{j-1}(1-\alpha_- -\alpha_+) \quad -(-1)^j(1-\alpha_+) \quad (-1)^{j+1}\alpha_+]^T & ,j\geq 2 \end{cases} & ,jEE1 \\ u_{jEE2} = \begin{cases} [\alpha_- \quad (1-2\alpha_-) \quad -(2-\alpha_- -\alpha_+) \quad (1-2\alpha_+) \quad \alpha_+]^T & ,j=3 \\ [\alpha_- \quad (1-2\alpha_-) \quad -(2-2\alpha_- -\alpha_+) \quad +(2-2\alpha_- -2\alpha_+) \quad -(2-2\alpha_- -2\alpha_+) \quad \cdots \quad -(-1)^{j-2}(2-2\alpha_- -2\alpha_+) \quad -(-1)^{j-1}(2-\alpha_- -2\alpha_+) \quad -(-1)^j(1-2\alpha_+) \quad (-1)^{j+1}\alpha_+]^T & ,j\geq 4 \end{cases} & ,jEE2 \\ u_{jEE3} = \begin{cases} [\alpha_- \quad (1-2\alpha_-) \quad -(2-\alpha_- -\alpha_+) \quad (1-2\alpha_+) \quad \alpha_+]^T & ,j=3 \\ [\alpha_- \quad (1-3\alpha_-) \quad -(3-3\alpha_- -\alpha_+) \quad +(3-3\alpha_- -3\alpha_+) \quad -(3-3\alpha_- -3\alpha_+) \quad \cdots \quad -(-1)^{j-2}(3-3\alpha_- -3\alpha_+) \quad -(-1)^{j-1}(3-\alpha_- -3\alpha_+) \quad -(-1)^j(1-3\alpha_+) \quad (-1)^{j+1}\alpha_+]^T & ,j\geq 4 \end{cases} & ,jEE3 \end{cases}$$

- Using this notation, the MLSD wrong decision condition becomes:

$$\sum_{i=1}^{j+1} B_{i,E} < \sum_{i=1}^{j+1} B_{i,C} \quad \rightarrow \quad MLSD\ Noise\ Sequence > A_s \times u_j^T u_j$$

- To include the effect of noise coloring, noise autocorrelation matrix is needed:

$$V_j = \begin{bmatrix} 1 & \rho_1 & \cdots & \rho_j & \rho_{j+1} \\ \rho_1 & 1 & \cdots & \rho_{j-1} & \rho_j \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \rho_j & \rho_{j-1} & \cdots & 1 & \rho_1 \\ \rho_{j+1} & \rho_j & \cdots & \rho_1 & 1 \end{bmatrix}$$

- Given the length of the error event, V_j is a truncated $(j+2)\times(j+2)$ matrix for every j and for all error patterns

Error Analysis – Required Updates to Annex 178A.1.10

- Now we can follow the derivations in "shakiba_3dj_elec_01a_230504.pdf" that led to the procedure outlined in section 178A.1.10 of Annex 178A:

1) Use coefficients vector to calculate convolution of scaled noise PDFs to approximate PDF of the MLSD sequence noise:

$$PDF_{noise,jEE}(x) \approx \mathrm{conv}_{i=1}^{j+2} \frac{1}{u_j(i)} PDF_{noise}\left(u_j(i) \times x\right)$$

2) Calculate the white and colored noise powers from the coefficients vector and noise autocorrelation matrix:

$$\sigma^2_{noise,jEE,white} = u_j^T u_j \quad and \quad \sigma^2_{noise,jEE,colored} = u_j^T V_j u_j$$

3) Calculate probability of each error event by scaling the MLSD sequence noise CDF argument with square root of the ratio of the white noise power to the colored noise power:

$$P_{jEEk} = CDF_{noise,jEE}\left(-A_s \times u_{jEEk}^T \times u_{jEEk} \times \sqrt{\frac{u_{jEEk}^T \times u_{jEEk}}{u_{jEEk}^T \times V_j \times u_{jEEk}}}\right) = CDF_{noise,jEE}\left(-A_s \frac{\left(u_{jEEk}^T \times u_{jEEk}\right)^{3/2}}{\left(u_{jEEk}^T \times V_j \times u_{jEEk}\right)^{1/2}}\right) \quad , k = 1, 2, 3$$

4) Consider error event trellis traverse factor:

$$\begin{cases} 2\left(\frac{L-1}{L}\right)^j & , jEE1 \\ 2\left(\frac{L-1}{L}\right)^2\left(\frac{L-2}{L}\right)^{j-2} & , jEE2 \\ 2\left(\frac{L-1}{L}\right)^2\left(\frac{L-3}{L}\right)^{j-2} & , jEE3 \end{cases}$$

, where L = 4 for PAM4

Error Analysis – Required Updates to Annex 178A.1.10

5) Calculate event error ratio (EER aka SER_1 in several previous contributions):

$$SER_1 = EER = EER_{jEE1} + EER_{jEE2} + EER_{jEE3} \approx \sum_{j=1}^{\infty} 2\left(\frac{L-1}{L}\right)^j P_{jEE1} + \sum_{j=3}^{\infty} 2\left(\frac{L-1}{L}\right)^2 \left(\frac{L-2}{L}\right)^{j-2} P_{jEE2} + \sum_{j=3}^{\infty} 2\left(\frac{L-1}{L}\right)^2 \left(\frac{L-3}{L}\right)^{j-2} P_{jEE3}$$

6) Calculate DER from its legacy relationship to SER_1 from before MLSD was introduced (same relationship was also used for the 1st-order MLSD):

$$DER = \frac{L}{2(L-1)} SER_1$$

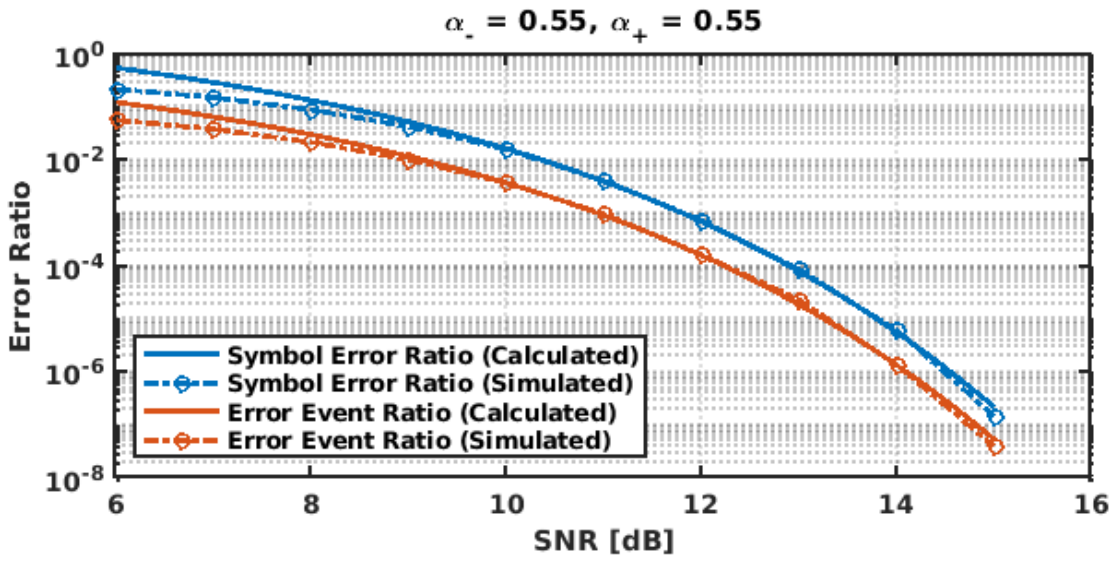
$$DER = DER_{jEE1} + DER_{jEE2} + DER_{jEE3} \approx \sum_{j=1}^{\infty} \left(\frac{L-1}{L}\right)^{j-1} P_{jEE1} + \sum_{j=3}^{\infty} \left(\frac{L-1}{L}\right)\left(\frac{L-2}{L}\right)^{j-2} P_{jEE2} + \sum_{j=3}^{\infty} \left(\frac{L-1}{L}\right)\left(\frac{L-3}{L}\right)^{j-2} P_{jEE3}$$

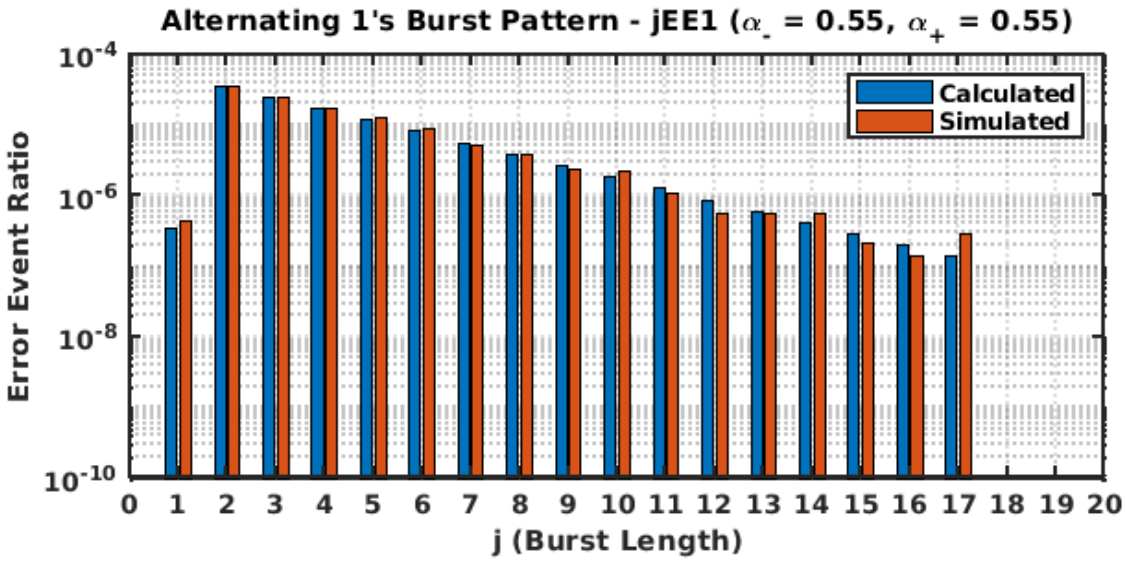
7) Optionally, the overall symbol-error ratio (SER) can also be calculated:

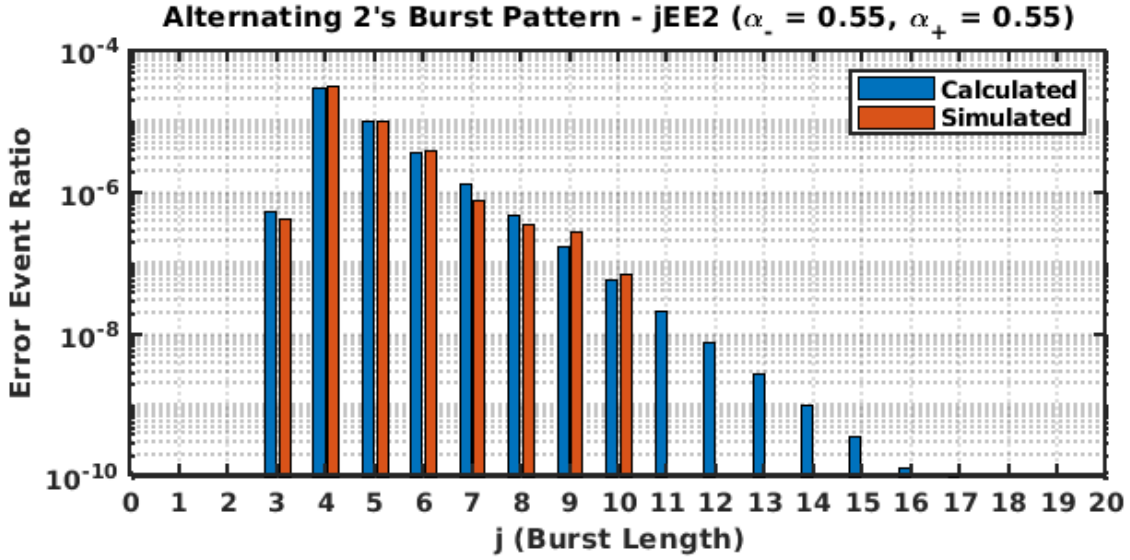
$$SER \approx \sum_{j=1}^{\infty} 2j\left(\frac{L-1}{L}\right)^j P_{jEE1} + \sum_{j=3}^{\infty} 2j\left(\frac{L-1}{L}\right)^2 \left(\frac{L-2}{L}\right)^{j-2} P_{jEE2} + \sum_{j=3}^{\infty} 2j\left(\frac{L-1}{L}\right)^2 \left(\frac{L-3}{L}\right)^{j-2} P_{jEE3}$$

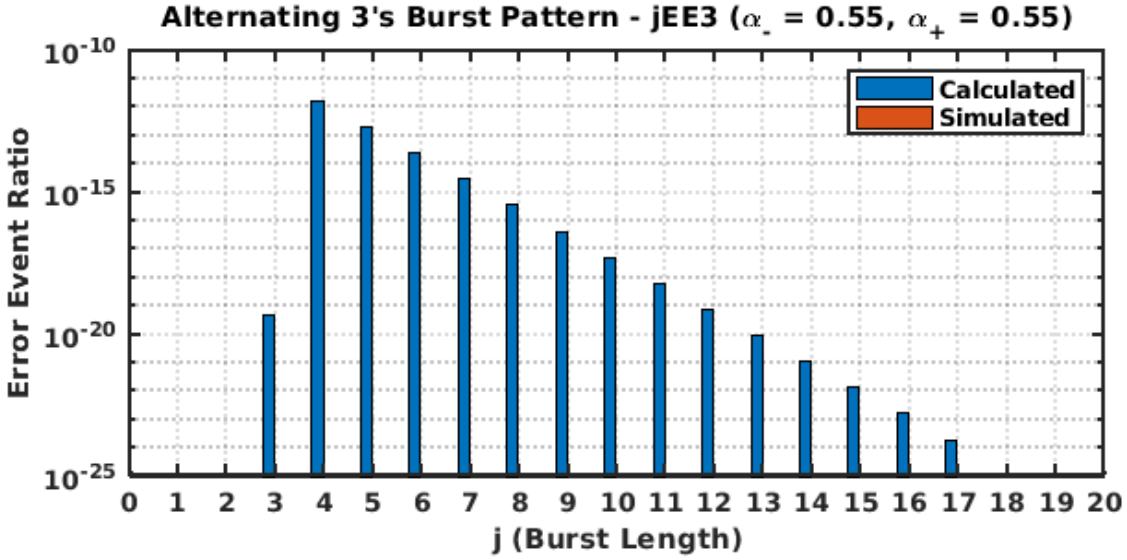
- Note that based on very low likelihood of error events jEE3 for practical range of α_- and α_+, their corresponding terms in the above expressions may be ignored
- Although the original concept of COM and ΔCOM starts to collapse, an effort to develop a methodology for defining an equivalent COM was made and results were used and demonstrated throughout this presentation
- A future contribution will explain the details

Sanity Check – AWGN – w/o Precoding









Appendix

Channel and COM Info

400G Test Channels

Channel #	Channel Name and Link to s4p File	Package
1-2	he_e4ai_02_251023	Included
3	xxx_250401_01	Included
4	oif2025_254_01	Not included, added in COM
5	oif2025_253_01	Not included, added in COM
6-13	gore_e4ai_02_250529	Not included, added in COM
14	oif2025_465_01	Not included, added in COM
15-59	shah_e4ai_01a_250430	Not included, added in COM
60	oif2025_178_01_PLAN3_5_B	Not included, added in COM

200G Test Channels

- C2C:

Channel #	Channel Name and Link to s4p File	Package
1 – 72	https://www.ieee802.org/3/dj/public/tools/c2c/heck_3dj_02_2405.zip	Not included, added in COM
73 – 85	https://www.ieee802.org/3/dj/public/tools/c2c/heck_3dj_02_2403.zip	Not included, added in COM
86 – 110	https://www.ieee802.org/3/dj/public/tools/c2c/mellitz_3dj_03_elec_230504.zip	Not included, added in COM

- C2M:

Channel #	Channel Name and Link to s4p File	Package
1 – 4	https://www.ieee802.org/3/dj/public/tools/c2m/mellitz_3dj_02_2409.zip	Not included, added in COM
5 – 64	https://www.ieee802.org/3/dj/public/tools/c2m/kareti_3dj_elec_02_240111.zip	Not included, added in COM
65 – 82	https://www.ieee802.org/3/dj/public/tools/c2m/gore_3dj_elec_02_231026.zip	Not included, added in COM
83 – 85	https://www.ieee802.org/3/dj/public/tools/c2m/lim_3dj_01_230629.zip https://www.ieee802.org/3/dj/public/tools/c2m/lim_3dj_02_230629.zip https://www.ieee802.org/3/dj/public/tools/c2m/lim_3dj_06_2309.zip	Not included, added in COM
86 – 101	https://www.ieee802.org/3/dj/public/tools/c2m/weaver_3dj_elec_02_230831.zip	Not included, added in COM
102 – 117		Not included, added in COM
118 – 123	https://www.ieee802.org/3/dj/public/tools/c2m/shanbhag_3dj_03_2305.zip	Not included, added in COM
124 – 206	https://www.ieee802.org/3/dj/public/tools/c2m/akinwale_3dj_02_2307.zip https://www.ieee802.org/3/dj/public/tools/c2m/akinwale_3dj_03_2307.zip https://www.ieee802.org/3/dj/public/tools/c2m/akinwale_3dj_04_2307.zip	Not included, added in COM
207 - 208	https://www.ieee802.org/3/dj/public/tools/c2m/rabinovich_3dj_02_230116.zip https://www.ieee802.org/3/dj/public/tools/c2m/rabinovich_3dj_03_230116.zip	Not included, added in COM

COM Parameters – C2C with 400G AFE & 400G Die Interface Case

Set to [1] for channels that include package

Change to PKG_CPC PKG_Module for C2M Channels

Change to 1.4 to 1 for 200G Die Interface

Table 93A-1 parameters			
Parameter	**Setting**	**Units**	**Information**
data rate	425	Gbit	
PAM N levels selector	**4-aggressive**	**selector**	
L	4	**use selector**	
f_b	212.50	GBd	106.25GHz Fnq
f_min	0.05	GHz	
Delta_f	Setting	GHz	
R_0	46.25	s	
PKG_NAME	PKG_CPC PKG_CPC		TX RX
z_p select	[3]		
M	32		
C_d	[0.4e-4 0.9e-4 1.1e-4 ;0.4e-4 0.9e-4 1.1e-4]/1.4	nF	[TX RX]
L_s	[0.13 0.15 0.14; 0.13 0.15 0.14]/1.4	nH	[TX RX]
C_b	[0.3e-4 0.3e-4]/1.4	nF	[TX RX]
filter and Eg			
f_r	0.55	*fb	116.88GHz
c(0)	0.55		[min:step:max]
c(-1)	0	[-0.34:0.02:0]	see if 0 is OK
c(-2)	0	[0:0.02:0.14]	see if 0 is OK
c(1)	0	[-0.2:0.02:0]	see if 0 is OK
N_b	1	UI	As/dffe1
b_max(1)	1		As/dfe2..N_b
b_max(2..N_b)	0		NA
b_min(1)	0		As/dfe2..N_b
b_min(2..N_b)	0		NA
g_DC	[-20:1:0]	[-20:1:-0]	see if 0 is OK
f_z	85.00	GHz	
f_p1	85.00	GHz	
f_p2	212.50	GHz	
g_DC_HP	[-6:1:0]		see if 0 is OK
f_HP_PZ	1.328125	GHz	
bw_scale	1		
add_rx_noise	0		

I/O control		
DIAGNOSTICS	0	logical
DISPLAY_WINDOW	0	logical
CSV_REPORT	0	logical
RESULT_DIR	\results\cpc400G_host_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 3 2 4]	
RUNTAG	Test_CPC400G_pam4_120G_stop_	
COM_CONTRIBUTION	0	logical
BREAD_CRUMBS	1	logical
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	ns
TR_TDR	0.002	
N	10000	logical
TDR_Butterworth	1	
beta_x	0	
rho_x	0.618	
TDR_W_TXPKG	1	UI
N_bx	39	
fixture delay time	[0 0]	
Tukey_Window	1	
Z_t	46.25	ohm
P_peak	1.00E-07	
Noise, jitter		UI
sigma_RJ	0.01	UI
A_DD	0.02	V^2/GHz
eta_0	5.00E-09	dB
SNR_TX	33.5	
R_LM	0.95	
Txpskew	0	
Txnskew	0	
Rxpskew	0	
Rxnskew	0	

Floating Tap Control		
N_bg	3	0 1 2 or 3 groups
N_bf	6	taps per group
N_f	160	UI span for floating taps
bmaxg	0.05	max DFE value for floating taps
B_float_RSS_MAX	0.1	rss tail tap limit (not used)
N_tail_start	22	(UI) start of tail taps limit
Filter: Rx FFE		
ffe_pre_tap_len	8	UI
ffe_post_tap_len	21	UI
ffe_main_cursor_min	1	
ffe_pre_tap1_max	0.7	
ffe_post_tap1_max	0.7	
ffe_tapn_max	0.7	
N_qb	7	like enob
P_qc	1.00E-07	changed for 2.2
Operational		
ERL Pass threshold	7.3	dB
COM Pass threshold	3	db
DER_0	2.00E-04	
T_r	0.00200	ns
FORCE_TR	1	logical
PMD_type	C2C	
EW	0	
MLSD	1	logical
ts_anchor	1	
sample_adjustment	[-24 24]	
num_ui_RXFF_noise	2500	need enough UI to capture pulse delay del
zero_pad	1	recommended
flim	120.0E+9	Hz
zero_pad_tukey_window_in_fb	0.2	fb
Local Search	0	use to get a handle on where the ts and ct
TS_SRCH_MODE	middle	not used if local search = 0

Divide by 2 for 200G AFE

Multiply by 2 for 200G Jitter

COM Parameters – C2C & C2M Package Models

.START	PKG_CPC	[2.8 5.6 6.7 9.4] db	tp0p or Tp5p
Parameter	**Setting**	**Units**	
R_d	[46.25 46.25]	Ohm	[TX RX]
package_tl_gamma0_a1_a2	[0.0005 0.00065 0.000293]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[87.5 87.5 ; 95 95 ; 100 100; 78 78]	Ohm	[TX RX]
z_p (TX)	[0 10 30 45 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[0 10 30 45 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[0 10 30 45 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (RX)	[0 10 30 45 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
C_p	[0 0]	nF	[TX RX]
A_v	0.385	V	Vf=0.400
A_fe	0.385	V	Vf=0.399
A_ne	0.481	V	Vf=0.400
.END			

.START	PKG_Module		
Parameter	**Setting**	**Units**	Information
package_tl_gamma0_a1_a2	[0.0005 0.00089 0.0002]/1.4		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[87.5 87.5 ; 92.5 92.5 ; 100 100; 100 100]	Ohm	
R_d	[46.25 46.25]	Ohm	[TX RX]
z_p (TX)	[0 4 10 33 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[0 4 10 33 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[0 4 10 33 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (RX)	[0 4 10 33 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
C_p	[0 0]	nF	[TX RX]
A_v	0.385	V	Vf=0.400
A_fe	0.385	V	Vf=0.399
A_ne	0.481	V	Vf=0.400
.END			

C2C Channel

PKG_CPC	CPC Channel without Package	PKG_CPC

C2M Channel

PKG_CPC	C2M Channel without Package	PKG_Module