A Salz-Inspired Implementation Allocation Estimate Aiding 400 Gb/s/Lane Channel Objective and Baseline Refinement

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Contents

Background: The 400 GBPL Project

- Electrical channel objectives may still be refined.
- Channels are being designed now and need a loss objective.
- A reference receiver could refine that loss requirement, but even a first pass waits on baselines in the Working Group.
- The purpose for the remainder of this presentation is to propose investigation options and constraints to aid in the devolvement of a loss requirement

Proposed Approach is a SNR based Implementation Allocation Estimate (IAE)

- Explore an Implementation Allocation Estimate (IAE).

  Define: IAE = $SNR_{avail,\mathrm{dB}} - SNR_{req,\mathrm{dB}}$

  - $\mathrm{SNR}_{\mathrm{avail,db}}$ is derived from a Salz analysis with assumed transmitter noise, receiver noise, and channel.
  - $\mathrm{SNR}_{\mathrm{req,db}}$ follows from the target DER and modulation order; implementation penalties are explored separately.
- IAE is the implementation headroom available on a given channel. Use IAE to investigate
  - Whether a channel leaves enough headroom for a realizable receiver.
  - Evaluate the consistency of channel objectives, reference equalizer assumptions, and implementation expectations/limitations.
- Results may help guide future refinement of reference equalizer assumptions, associated penalties, and die-to-die loss objectives.

Salz[1]-Inspired Unbiased Receiver SNR

Rewrite the 2nd equation on slide 12 of Zimmerman[2] for a double-sided folded spectra, using $\chi(\mathrm{f}+\mathrm{kf_b})$ consistent with Annex 178A

$$SNR_{avail} = \exp\left(\frac{1}{f_b}\int_{-f_b/2}^{f_b/2} \ln\left[1+\sum_{\mathrm{k}}\chi(\mathrm{f}+\mathrm{kf_b})\right] df\right)$$

$$\chi(\mathrm{f}) = \frac{\mathrm{S}(f)}{\mathrm{N}(f)}$$

where SNR_{avail} is the channel-limited SNR available to an unbiased Salz reference receiver, $\chi(f)$ is the SNR density, and f_b is the signaling rate.

Because the integration band is limited to $\pm f_b/2$, $\chi(f) = S(f)/N(f)$ is replaced by $\sum_k \chi(f + k\,f_b)$, which folds the out-of-band content back into the band rather than discarding it.

[1] J. SALZ, "Optimum Mean-Square Decision Feedback Equalization", The Bell System Technical Journal Vol. 52, No. 8, October 1973
2 George Zimmerman, " Salz SNR Text and Procedure" IEEE 802.3bz 2.5G/5GBASE-T Task Force – September 2015 Interim – Bonita Springs, FL, USA

Signal *S(f)* Estimation

Start with the pulse response of the channel voltage transfer function $H_{tot}(f)$ similar to Annex 178A, which includes the required transmitter and receiver filters.

$$H_{tot}(f) = \mathrm{A_t sinc}\left({}^{\mathrm{f}}/_{\mathrm{f_b}}\right) H_t(f) H_{21}(f) H_r(f)$$

Derive a collection of sampled pulse responses.

$$\mathrm{h}\,[\mathrm{t}] = \mathcal{F}^{-1}\{H_{tot}(f)\}$$

$$\mathrm{h_{sig}}(\tau, \mathrm{k}) = \mathrm{h}(\tau + \mathrm{kTb}) \,,$$

Where, $\mathrm{T_b} = 1/\mathrm{fb}$, τ is a phase of Tb/M, and M is samples per U

$$\text{use the value } \tau \text{ which maximizes } \sum_{\mathrm{k}} |\mathrm{h_{sig}}(\tau, \mathrm{k})|^2$$

At the selected τ, the FFT over k gives the power spectral response S(f).

$$H_s(\mathrm{f}) = \mathrm{FFT}\{\mathrm{h_{sig}}(\tau, \mathrm{k})\}$$

$$S(f) = \sigma_{\mathrm{x}}^2 \mid H_s(\mathrm{f}) \mid^2$$

Note that this signal includes ISI as signal!

Noise N(f) Estimation

$$N(f) = N_{RN}(f) + N_{TN}(f) + N_{XN}(f) + N_{\mathrm{JN}}(f)$$

Power densities and their variances from Annex 178A

$N_{RN}\,(f)$= receiver noise PSD → σ_{RN}^2 from $\mathrm{SNR_{TX}}$

$N_{TN}\,(f)$= transmitter noise PSD → σ_{TN}^2 from eta0

$N_{XN}\,(f)$= crosstalk noise PSD → σ_{XN}^2 from channel

$N_{\mathrm{JN}}\,(f)$= jitter noise PSD → $\sigma_{\mathrm{JN}}^2$from A_{dd} and σ_{rj}

Define Implementation Allocation Estimate

$$\mathrm{IAE} = SNR_{\mathrm{avail,dB}} - SNR_{\mathrm{req,dB}}$$

Where:

$$\boldsymbol{SNR}_{\mathrm{avail},\boldsymbol{dB}} = 10 * \log10(SNR_{\mathrm{avail}})$$

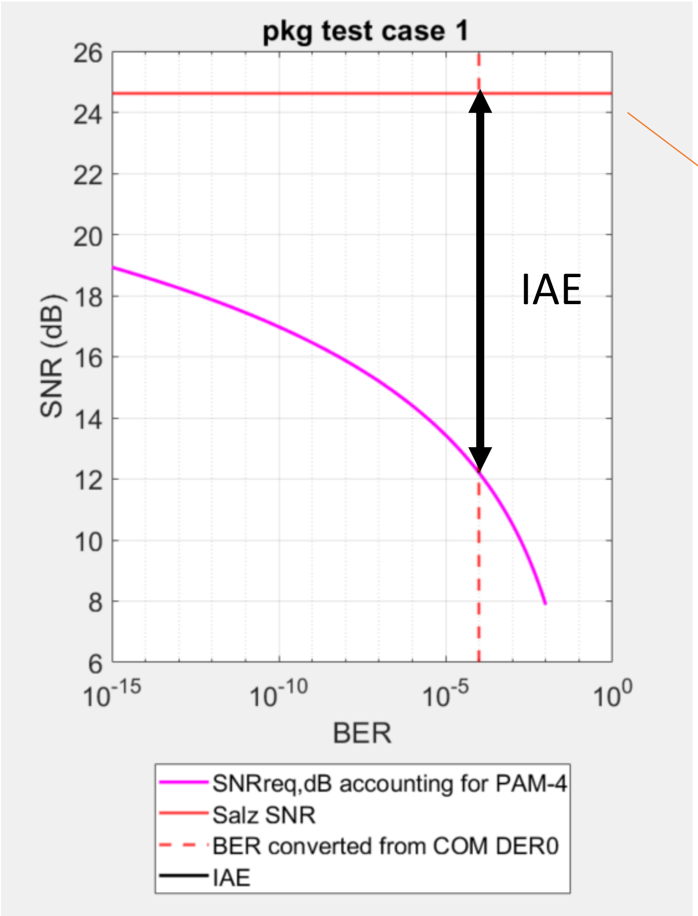
And an SNR required at the detector to meet the target error ratio. Under Gaussian residual noise it follows from the target BER and modulation (L) order alone

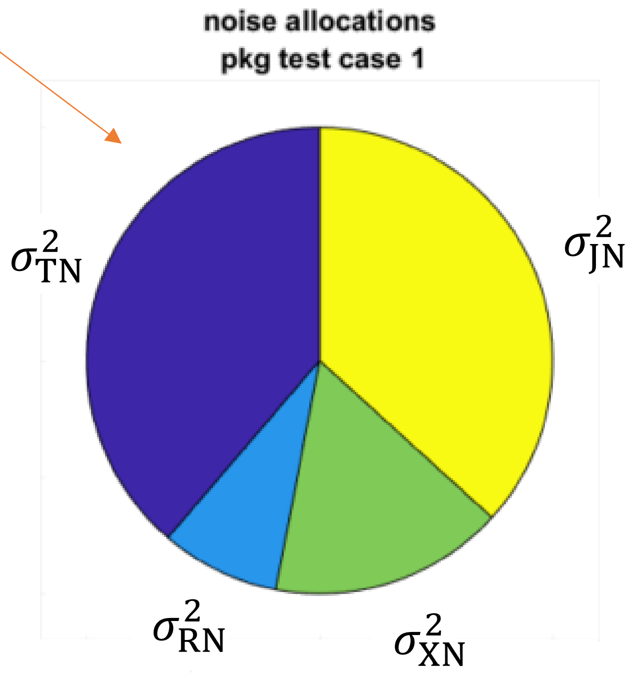
$$\boldsymbol{SNR}_{\mathbf{req},\boldsymbol{dB}} = 10\log_{10}\left(\frac{[Q^{-1}(BER/A)]^2}{\mathrm{B}}\right)$$

$A = \frac{2(L-1)}{L\log_2 L}$, accounts for the average number of nearest neighbor symbol error opportunities

$B = \frac{6\log_2 L}{L^2-1}$, relates the symbol spacing to the required SNR

Illustration of IAE





- ❑ Pie chart shows the relative noise allocation (σ_{TN}^2, σ_{RN}^2, σ_{XN}^2, σ_{JN}^2)
- ❑ Red horizontal line is the $SNR_{avail,dB}$
- ❑ Magenta curve is $SNR_{req,dB}$ versus BER
- ❑ Dashed vertical line is the target error ratio
- ❑ IAE is the gap between them at that target

An Explored Detour: Constraining the Equalizer with Implementation Penalties (Not Retained)

$$\mathrm{IAE}_{\mathrm{pen}} = SNR_{\mathrm{avail,dB}} - SNR_{\mathrm{req,dB}} - SNR_{\mathrm{pen,dB}}$$

Explore a modest set of implementation penalties to determine if it is a better predictor

Consider ISI, RLM, Q, and CTLE penalties. Refinements such at ILD, ACBW[1], common mode, and skew improvements possible for future work.

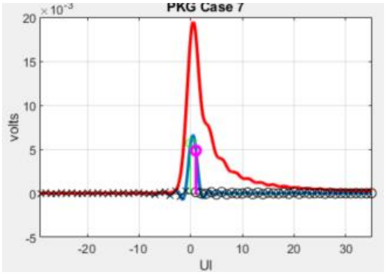
$$\boldsymbol{SNR}_{\mathrm{pen},\boldsymbol{dB}} = \mathrm{P}_{\mathrm{precursor\_isi}} + \mathrm{P}_{\mathrm{Qunatizaion}} + \mathrm{P}_{,\mathrm{RLM}} + \mathrm{P}_{\mathrm{CTLE}}$$

$\mathrm{P}_{\mathrm{precursor\_isi}}$ The receiver cancels postcursor ISI but may have no way to recover power dispersed into the precursor, so it may be considered noise

$\mathrm{P}_{\mathrm{Quantizaion}}$ is the quantization noise power spectral density defined in 178A.1.7.6

$\mathrm{P}_{\mathrm{RLM}} = 10 * \log 10({}^{1}/_{\mathrm{RLM}^2})$ RLM adjustment

$\mathrm{P}_{\mathrm{CTLE}}$ Amplitude/power reduction for a CTLE pulse



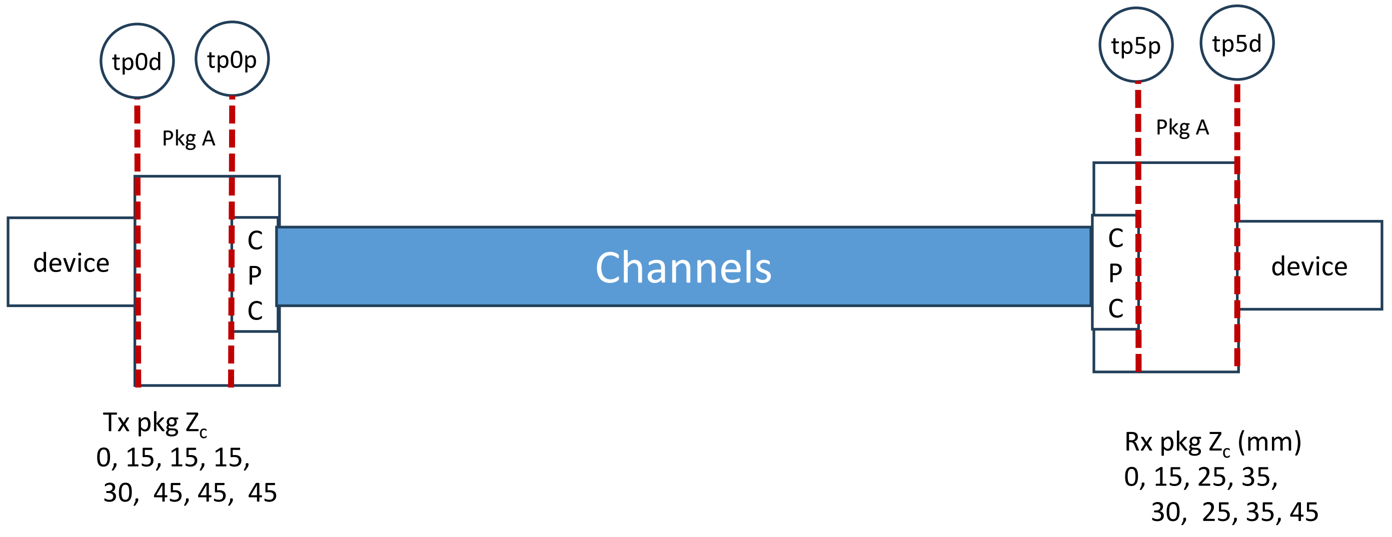
[1] Apparent Channel Bandwidth(ACBW) defined in "400 GBPL Electrical Objective Kaleidoscope: Reach, Loss, Cutoff, Noise, and COM" mellitz_400GPL_01_260730

Context and Next

- Partial channel or component analysis is tangent to this work
- For each modulation, compute and compare COM, IAE, ACBW[1], and $IL_{\text{die-to-die}}$

[1] Apparent Channel Bandwidth(ACBW) defined in "400 GBPL Electrical Objective Kaleidoscope: Reach, Loss, Cutoff, Noise, and COM" mellitz_400GPL_01_260730

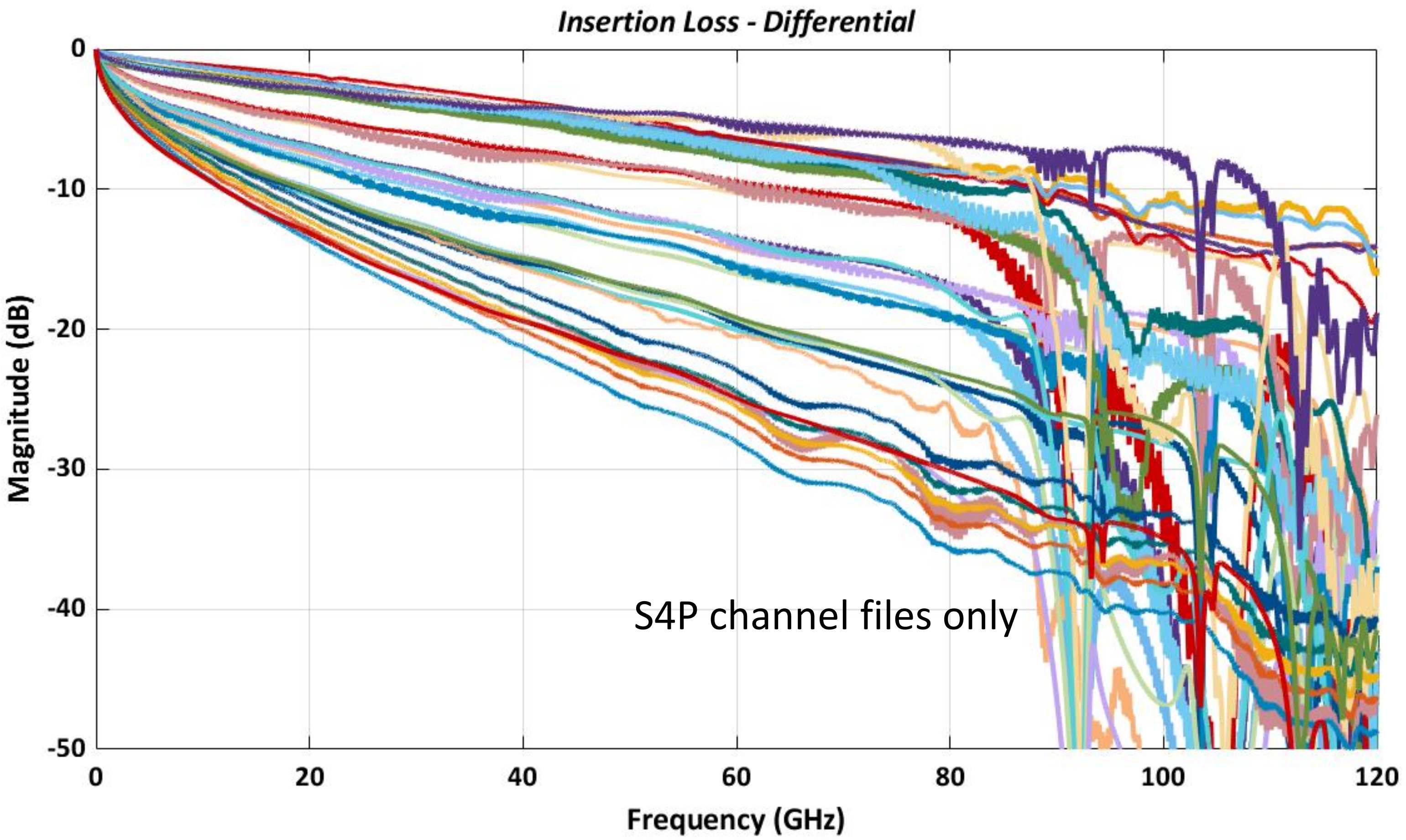
Sweeps for Correlation and Data Mining Analysis using PAM6 (170 Gbaud), PAM6 (180 Gbaud), PAM4 (212.5 Gbaud)



Process

- ❑ Sweep channels and package loadings using
  IEEE802.3 NEA channels, channel used in mellitz_400GPL_01_260730 channels, and other channels included
- ❑ This produces a population of hypothetical channels spanning a broad die-to-die loss range.
- ❑ Compute COM and IAE for those channels
  - For each modulation option
- ❑ Perform correlation and analysis and determine conclusions.

IL Snapshot Shows Selected Files Produce Wide Variations



- ❑ Channels exhibit a broad range of loss and high-frequency behavior
- ❑ Crosstalk used where available
- ❑ Die-to-die loss spans a wide range across the channel configurations with the added package losses:
  - 7 dB to 50 dB @ 85 GHz
  - 7.3 dB to 60 dB @ 90 GHz
  - 9 dB to 92 dB @ 106.25 GHz

COM Noise Parameter Sweeps

Noise assumptions are used both SNR_{avail} and COM,

Noise range sweeps helps correctional analysis (yellow)

- ❑ Sweep receiver noise using η_0 $(3\text{e}9\ \text{v}^2/\text{GHz}$ to $5\text{e}9\ \text{v}^2/\text{GHz})$
- ❑ Sweep transmitter noise using SNR_{TX} (33 dB to 40 dB)

R_LM is 0.93 for PAM-6 and 0.95 for PAM-4

Other noise and jitter parameters

sigma_RJ	0.01	UI
A_DD	0.02	V^2/GHz
eta_0	sweep	dB
SNR_TX	sweep	dB
R_LM	0.95	

170 Gbaud 180 PAM 6 and 212.5 Gbaud PAM 4 COM Filters

PAM 6 170 Gbaud

Table 93A-1 parameters			
Parameter	Setting	Units	Information
data rate	425	Gbit	
PAM N levels selector	6 (26-05-20) 85 GHz	selector	
L	6	use selector	6
f_b	170.00	GBd	85GHz 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	[1 2 3 4 5 6]	[1 2 3 4 5 6]	
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 Eq			
f_r	0.55	*fb	93.5GHz
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)	0.85		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:-15]	[-20:1:-0]	see if 0 is OK
f_z	68.00	GHz	
f_p1	68.00	GHz	
f_p2	170.00	GHz	
g_DC_HP	[-6:1:-0]		see if 0 is OK
f_HP_PZ	1.0625	GHz	

PAM 6 180 Gbaud

Table 93A-1 parameters		
Parameter	Setting	Units
data rate	425	Gbit
PAM N levels selector	6 (26-05-20) 90 GHz	selector
L	6	use selector
f_b	180.00	GBd
f_min	0.05	GHz
Delta_f	Setting	GHz
R_0	46.25	s
PKG_NAME	PKG_CPC PKG_CPC	
z_p select	[1 2 3 4 5 6]	[1 2 3 4 5 6]
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
L_s	[0.13 0.15 0.14; 0.13 0.15 0.14]/1.4	nH
C_b	[0.3e-4 0.3e-4]/1.4	nF
filter and Eq		
f_r	0.55	*fb
c(0)	0.55	
c(-1)	0	[-0.34:0.02:0]
c(-2)	0	[0:0.02:0.14]
c(1)	0	[-0.2:0.02:0]
N_b	1	UI
b_max(1)	0.85	
b_max(2..N_b)	0	
b_min(1)	0	
b_min(2..N_b)	0	
g_DC	[-20:1:-15]	[-20:1:-0]
f_z	72.00	GHz
f_p1	72.00	GHz
f_p2	180.00	GHz
g_DC_HP	[-6:1:-0]	
f_HP_PZ	1.125005294	GHz

PAM 4 212.5 Gbaud)

Table 93A-1 parameters		
Parameter	Setting	Units
data rate	425	Gbit
PAM N levels selector	4 (26-08-31)	selector
L	4	use selector
f_b	212.50	GBd
f_min	0.05	GHz
Delta_f	Setting	GHz
R_0	46.25	s
PKG_NAME	PKG_CPC PKG_CPC	
z_p select	[1 2 3 4 5 6]	[1 2 3 4 5 6]
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
L_s	[0.13 0.15 0.14; 0.13 0.15 0.14]/1.4	nH
C_b	[0.3e-4 0.3e-4]/1.4	nF
filter and Eq		
f_r	0.55	*fb
c(0)	0.55	
c(-1)	0	[-0.34:0.02:0]
c(-2)	0	[0:0.02:0.14]
c(1)	0	[-0.2:0.02:0]
N_b	1	UI
b_max(1)	0.85	
b_max(2..N_b)	0	
b_min(1)	0	
b_min(2..N_b)	0	
g_DC	[-20:1:-15]	[-20:1:-0]
f_z	85.00	GHz
f_p1	85.00	GHz
f_p2	212.50	GHz
g_DC_HP	[-6:1:-0]	
f_HP_PZ	1.328125	GHz

Other Configuration Parameters

Other operational parameters include MLSD for this work COM dB is at DER0 of 1e-4 for PAM 4 and 1e-3 for PAM 6

I/O control		
Port Order	0	auto ports
COM_CONTRIBUTION	0	logical
BREAD_CRUMBS	0	logical
Salz_snr	1	logical
DO_NOT_COMPUTE_COM	0	1
SALZ_NOiSE	Tn Rn Jn Xn ISI PEN CTLE PEN	Lexical
ACBW	1	

Rx FFE parameters

Floating Tap Control		
N_bg	2	0 1 2 or 3 groups
N_bf	4	taps per group
N_f	80	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	9	(UI) start of tail taps limit
Filter: Rx FFE		
ffe_pre_tap_len	6	UI
ffe_post_tap_len	8	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	6	like enob

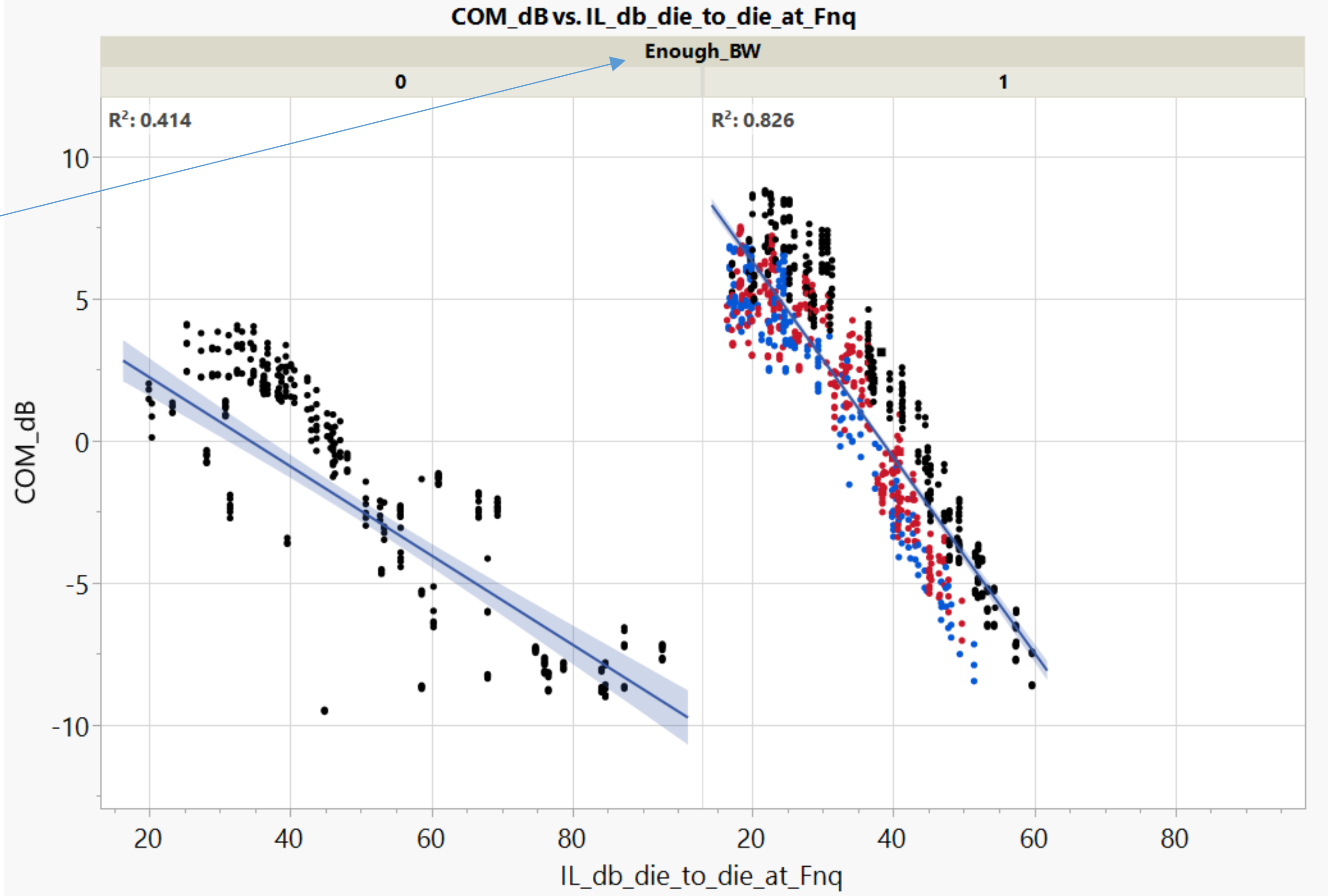
Using .3dj package class A parameters for building loss ranges

.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 0.00089 0.0002]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[87.5 87.5 ; 95 95 ; 100 100; 100 100]	Ohm	[TX RX]
z_p (TX)	[0 15 15 15 30 45 45 45 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[0 15 25 35 30 25 35 45 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[0 15 15 15 30 45 45 45 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0 ;0 0 0 0 0 0 0 0]	mm	[test cases]
z_p (RX)	[0 15 25 35 30 25 35 45 ;0 0 0 0 0 0 0 0 ;0 0 0 0 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			

Operational		
T_r	0.00200	ns
MLSD	1	logical
sample_adjustment	[-24 24]	
num_ui_RXFF_noise	2000	need enough UI to capture pulse delay delay, last FFE tap, and ISI
zero_pad	1	recommended

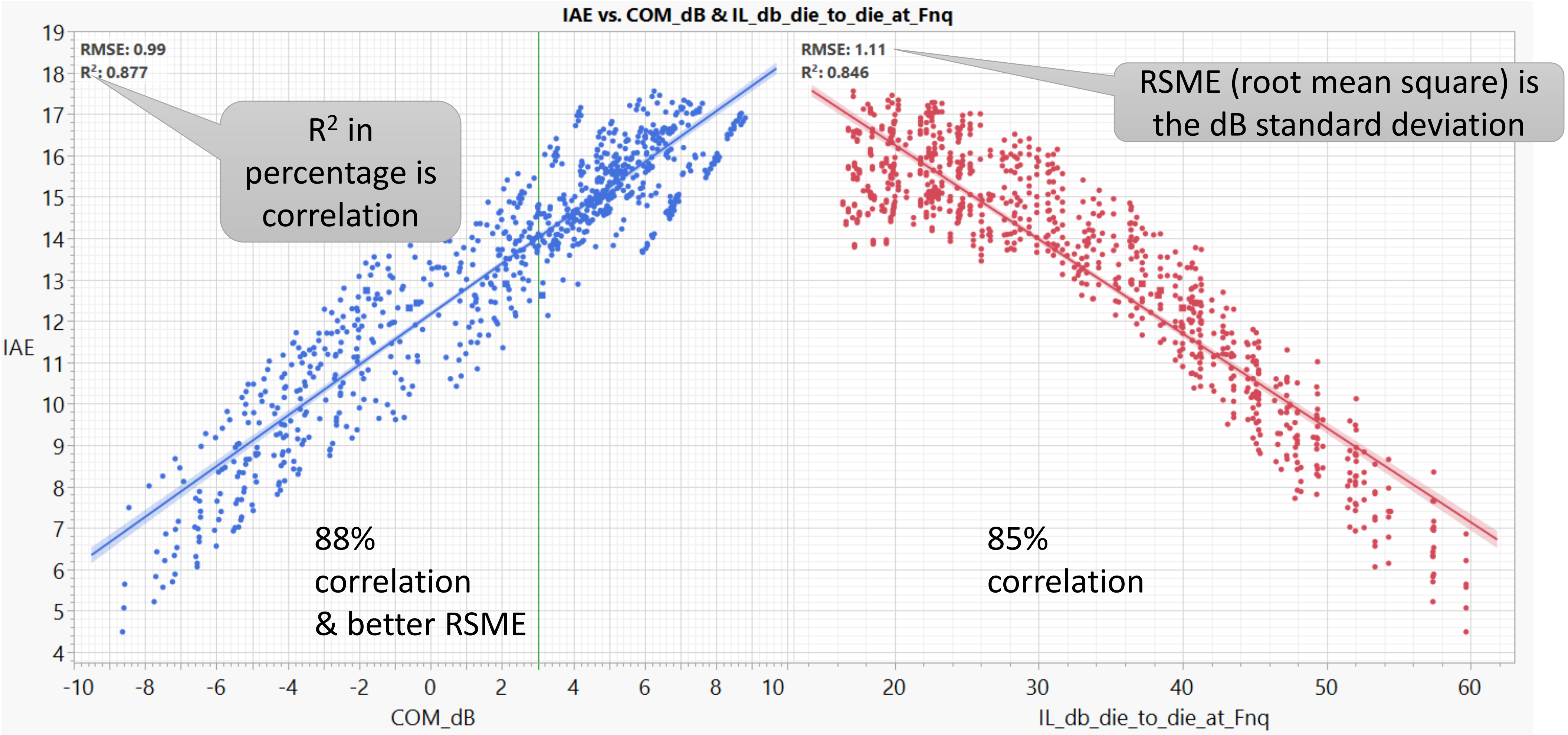
First Step: When Does COM Correlate to Loss?

- Define enough bandwidth (BW)
  - 1 when ACBW[1] >= $f_b/2$
  - 0 when ACBW < $f_b/2$
- This includes all cases of PAM and sweeps
- Correlation with enough BW is 82.6% (R^2 = 0.826) and without is 41%
- **The following analysis will use channels with enough bandwidth**

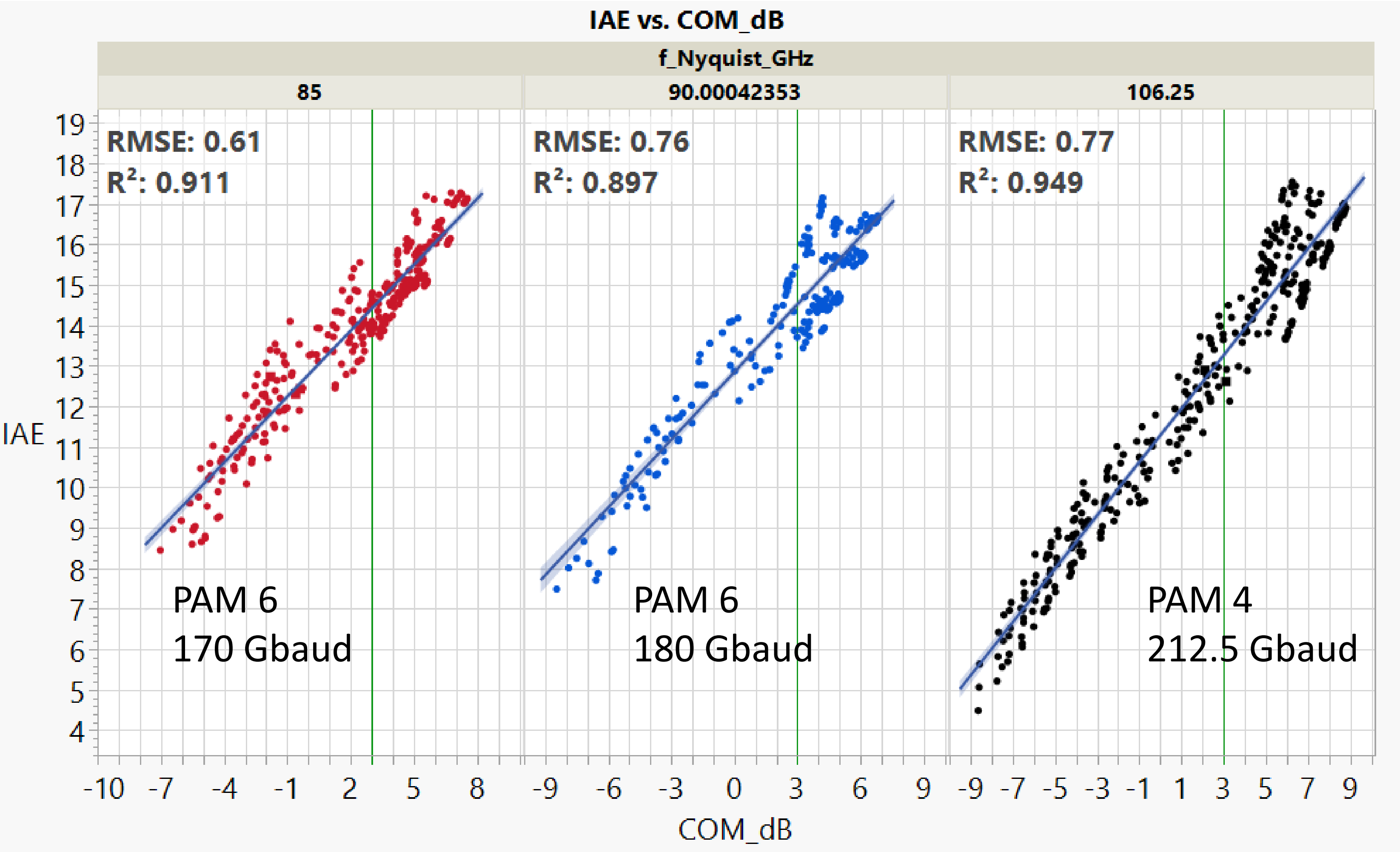


[1] Apparent Channel Bandwidth(ACBW) defined in "400 GBPL Electrical Objective Kaleidoscope: Reach, Loss, Cutoff, Noise, and COM" [mellitz_400GPL_01_260730]

Both COM and IL Correlate Well to IAE

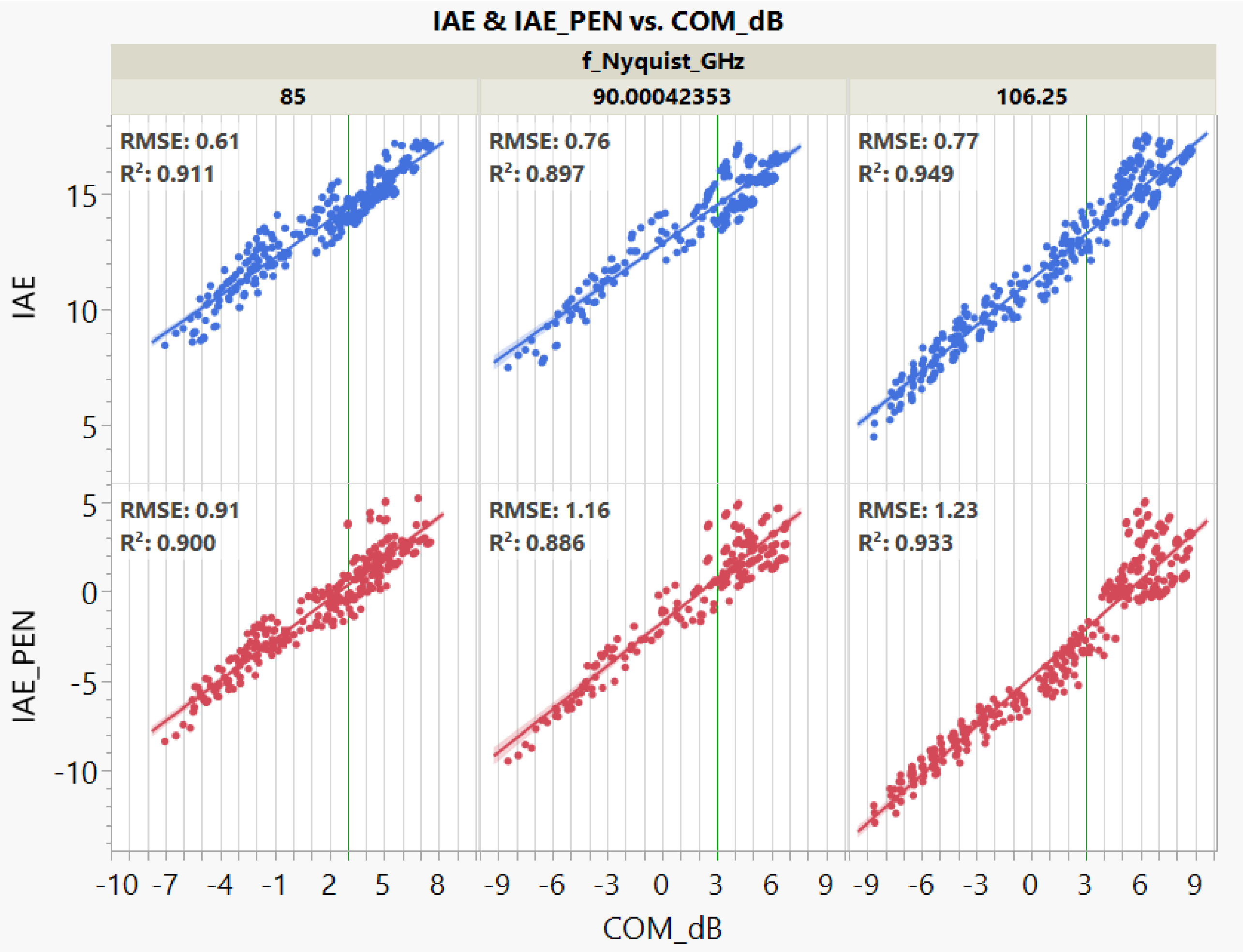


Correlation Improves to Over 90% When Baud Rate and PAM Levels Are Considered



- ❑ IAE is positive for these channels
- ❑ Positive IAE means room remains for noise and a receiver
- ❑ Negative IAE would mean no room to operate
- ❑ Different DER0 for PAM 4 and PAM 6 is what aligns IAE and COM.

IAE$_{PEN}$ Does Not Improve Correlation

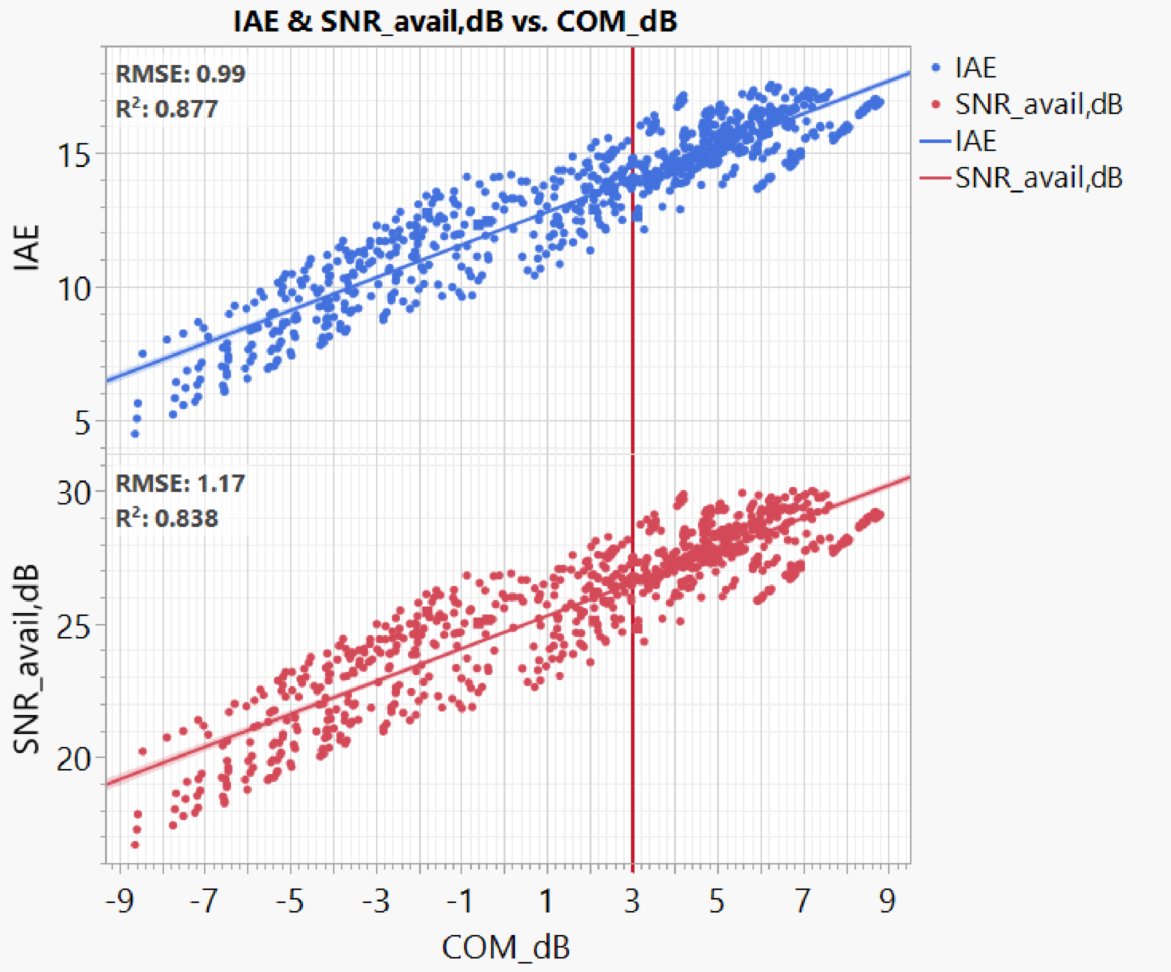


- ❑ R^2 degrades a just little

  But

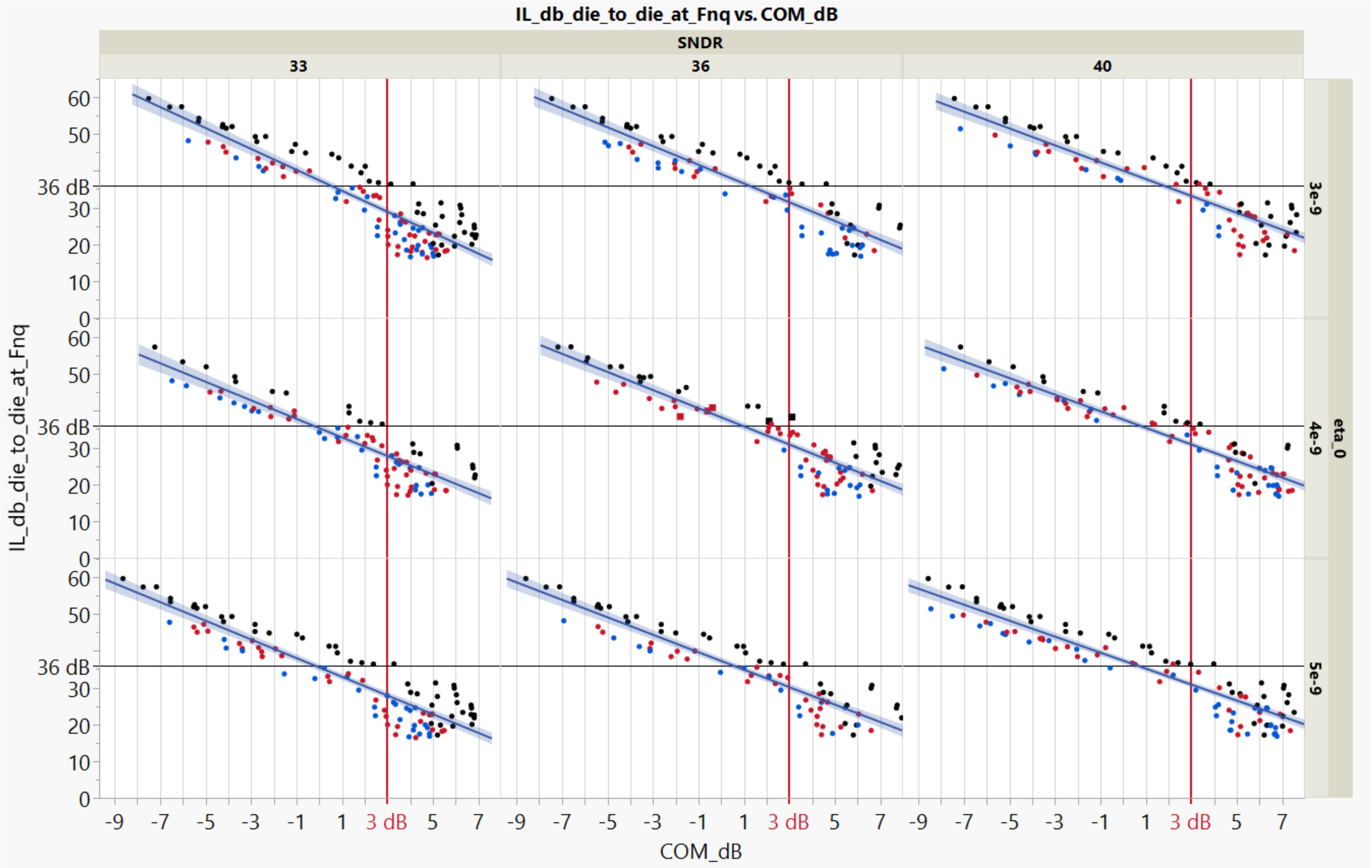
- ❑ RMSE (Root mean squared error) increases for IAE$_{PEN}$
  - 0.6 dB – 0.95 dB → 0.91 dB – 1.2 dB
- ❑ Future refinement to reduce RMSE and improve correlation is possible.

IAE has a Tighter Spread than $SNR_{avail,dB}$



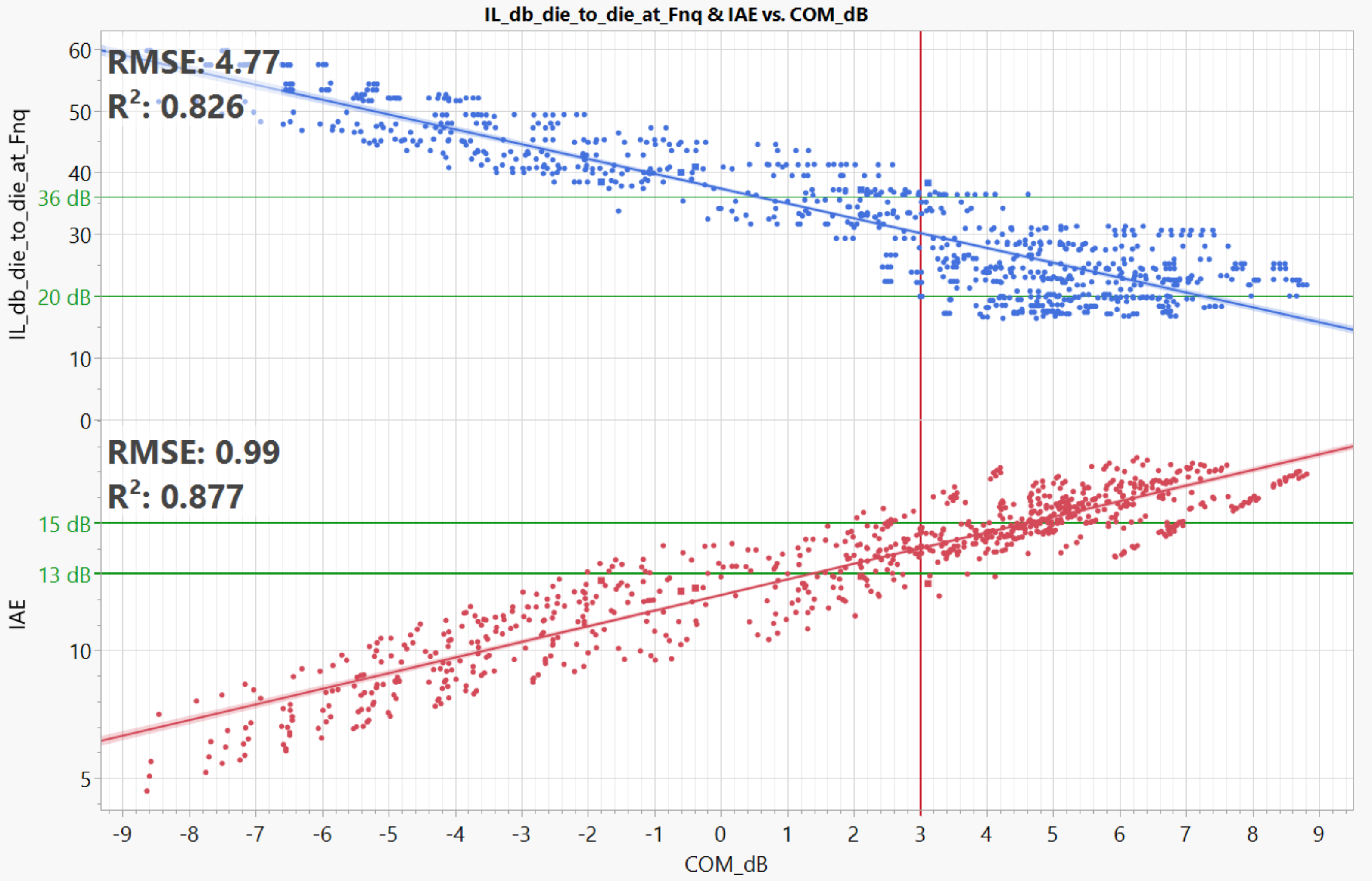
- This is for all the baud rates considered together
- For IAE, R^2 is 0.88 and RMSE is 0.99 dB
- For $SNR_{avail,dB}$, R^2 is 0.83 and RMSE is 1.2 dB
- Focus will be on IAE moving forward

Achieving High Loss has Challenges



- ❑ 36 dB $IL_{\text{die-to-die}}$ seems to be the limit for the COM reference receiver in this presentation
- ❑ Since IAE is positive perhaps there is an opportunity for an improved reference equalizer or better noise modeling

Limit Setting Thoughts



- Both IL and IAE correlate well to COM
- Proposal: Use to IAE as it appears to be a better predictor that IL
  - IL vs COM has a 4.8 dB RMSE
  - IAE vs COM has a 1 dB RSME

Summary

- ❑ Hitting a desired $IL_{die\text{-}to\text{-}die}$ objective of 40 dB is challenging
- ❑ IAE is positive meaning room remains for noise and a reference receiver improvement.
  - Analogous to a Salz limit, though not identical
- ❑ IAE avoids speculative receiver assumptions and predicts loss capability before the Rx equalizer scheme is settled
- ❑ Call to action: Explore the development of channels with an IAE > 15 dB and an $IL_{die\text{-}to\text{-}die}$ up to at least 40 dB
  - Explore a more capable reference receiver than in this presentation
  - An even more capable reference receiver could support IAE > 13 dB and $Il_{die\text{-}to\text{-}die}$ up to at least 45 dB
- ❑ Recommendation: Annotate that ACBW must be greater than half the baud rate (f_b/2) for loss objectives
  - Apply the same to the standard's baselines where loss at Nyquist is specified, as in RITOL or host, module, and cable loss budgets.

Thank You!