TX/RX, Channel, and Signaling Investigations at 448 Gbps

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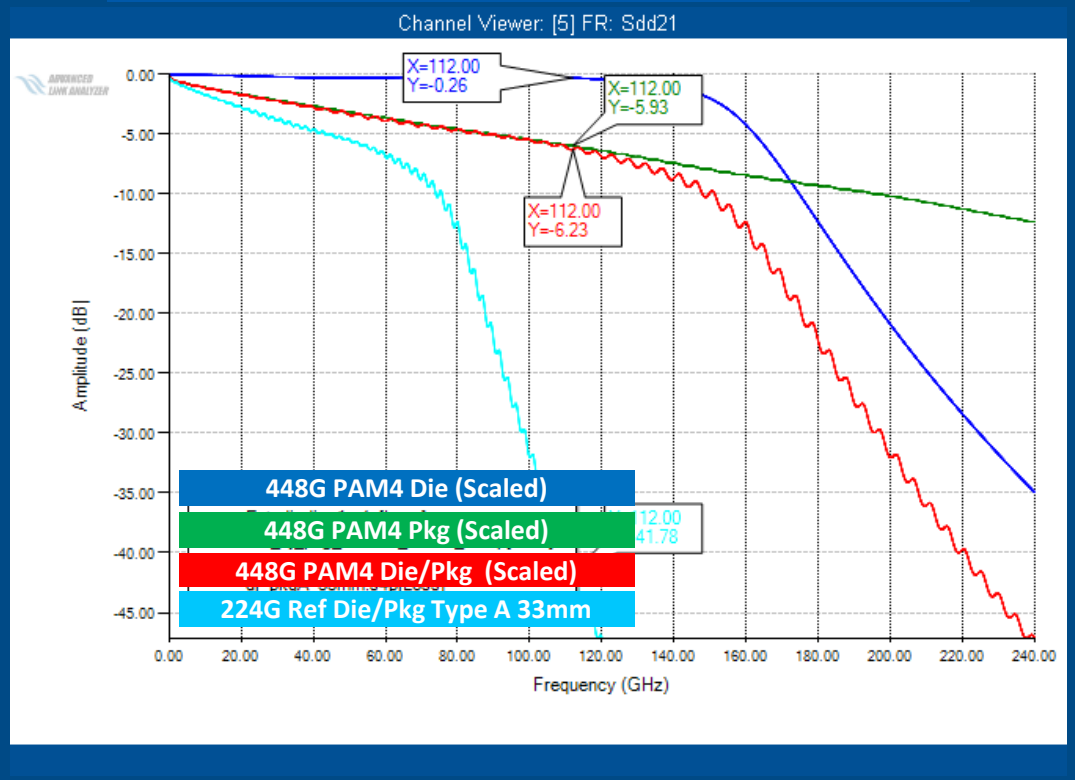
448 Gbps COM Performance Evaluations

PAM4 versus PAM6 Modulation

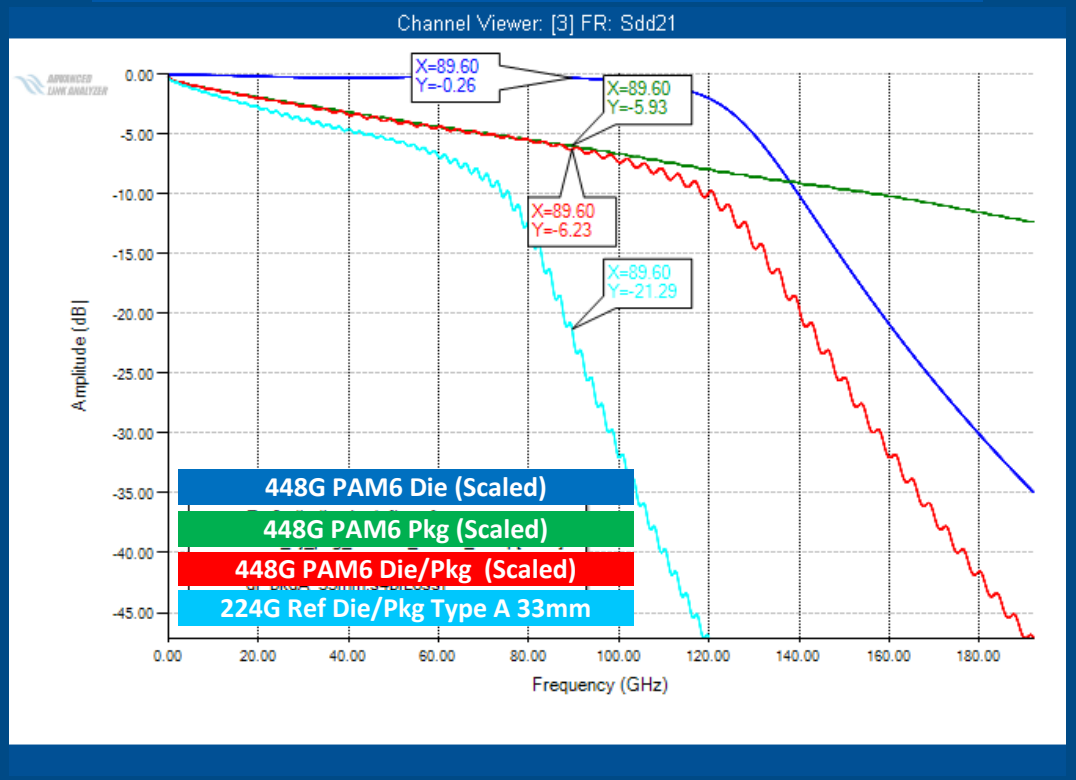
Case 1: Packages/channels have adequate bandwidth to accommodate the PAM4/PAM6 modulation schemes

448Gbps PAM4 and PAM6 Die/Package Characteristics

448Gbps PAM4 Die/Pkg vs 224Gbps Die/Pkg Type A 33mm

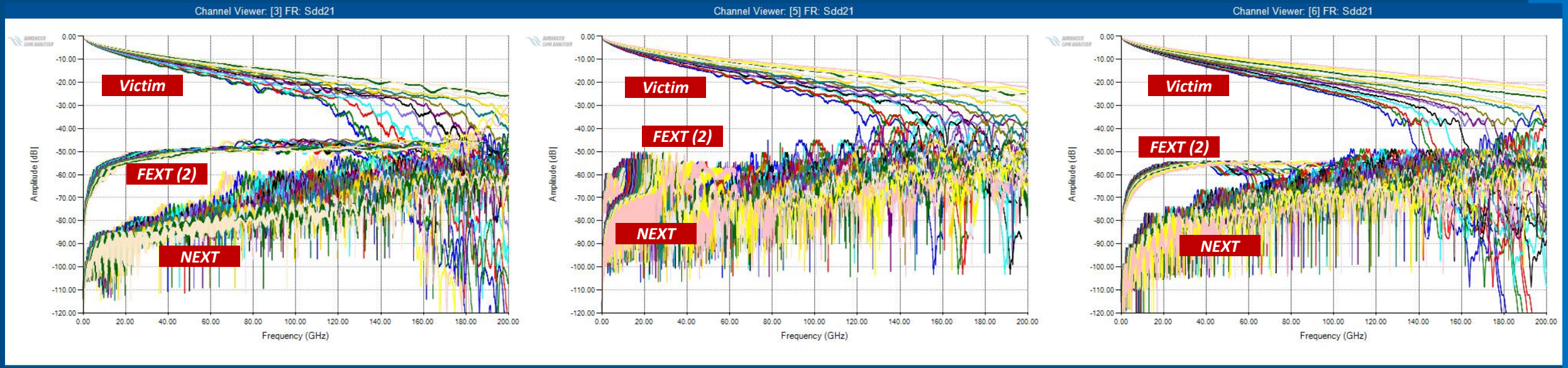


448Gbps PAM6 Die/Pkg vs 224Gbps Die/Pkg Type A 33mm



- Die and package models were frequency scaled from 224 Gbps-PAM4 to support 448Gbps-PAM4/PAM6

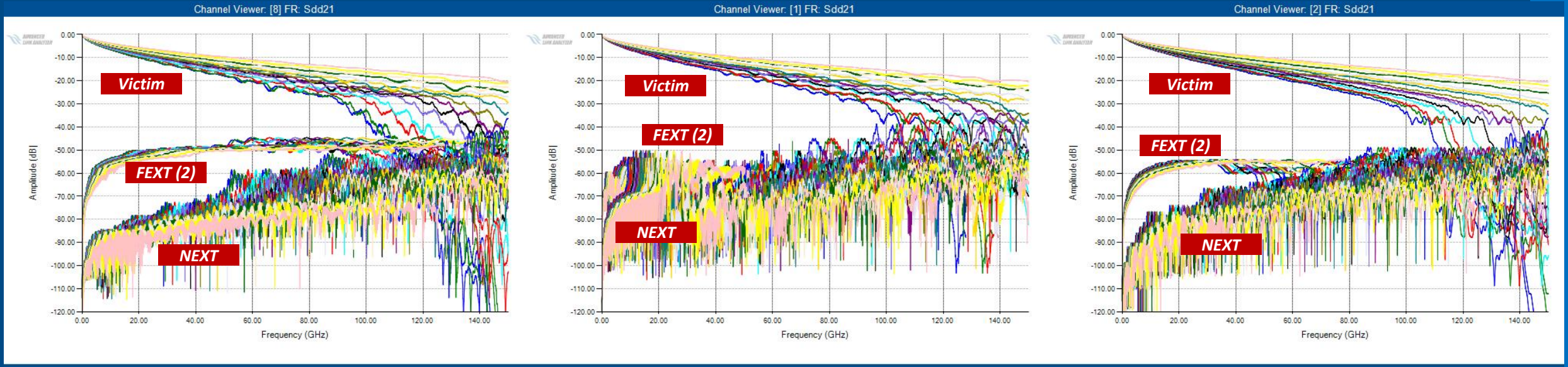
448Gbps PAM4 Test Channel Characteristics



- Frequency scaled from the 224 Gbps-PAM4 end-to-end channels [1][2][3], which include 1m cable assembly.
  - 448G-PAM4 Nyquist freq., 112GHz, IL ~= 16 to 28dB (39 test channels)
  - Including 2 FEXT and 1 NEXT

Note:
[1] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_04_230629.zip
[2] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_03_230629.zip
[3] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_07_2309.zip

448Gbps PAM6 Test Channel Characteristics



- Frequency scaled from 224 Gbps-PAM4 end-to-end channels [1][2][3], which include 1m cable assembly.
  - 448G-PAM6 Nyquist freq., 89.6 GHz, IL ~= 16 to 28 dB (39 test channels)
  - Including 2 FEXT and 1 NEXT

Note:
[1] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_04_230629.zip
[2] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_03_230629.zip
[3] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_07_2309.zip

448Gbps PAM4 COM Configuration #1/ #2 Highlights

- Scaling from 224G-PAM4 based on the latest CEI-224G-LR (oif2023.235.08) spec
  - Baud rate (f_b): 224 Gbd
  - Die/Package:
    - Based on Reference Package Type A with trace length 33mm (TX) and 31mm (RX)
    - Frequency scaled to maintain same IL as with 224G PAM4
  - AFE/Noise BW (f_r): Scale by baud rate
  - Jitter (A_DD, sigmaRJ): #1: Scale by baud rate; #2: PAM6 Jitter
  - Noise (eta_0): #1: eta_0 is inversely scaled down per baud rate; #2: PAM6 eta_0
  - Rise/Fall Time (T_r): #1: Scale by baud rate; #2: PAM6 Rise/Fall Time
  - Equalizer:
    - TX FFE not used to save computation time. Spec. configuration TBD.
    - RX CTLE: Scale by baud rate, i.e. same HF Pole/Zero divider ratio, LF Pole/Zero divider ratio = 160
    - RX FFE fixed taps: 8 pre-taps + 16 post-taps
    - RX FFE floating taps: 4 group of 4 consecutive taps up to 160 UI
    - MLSE: 1 tap

448Gbps PAM6 COM Configuration #1/#2

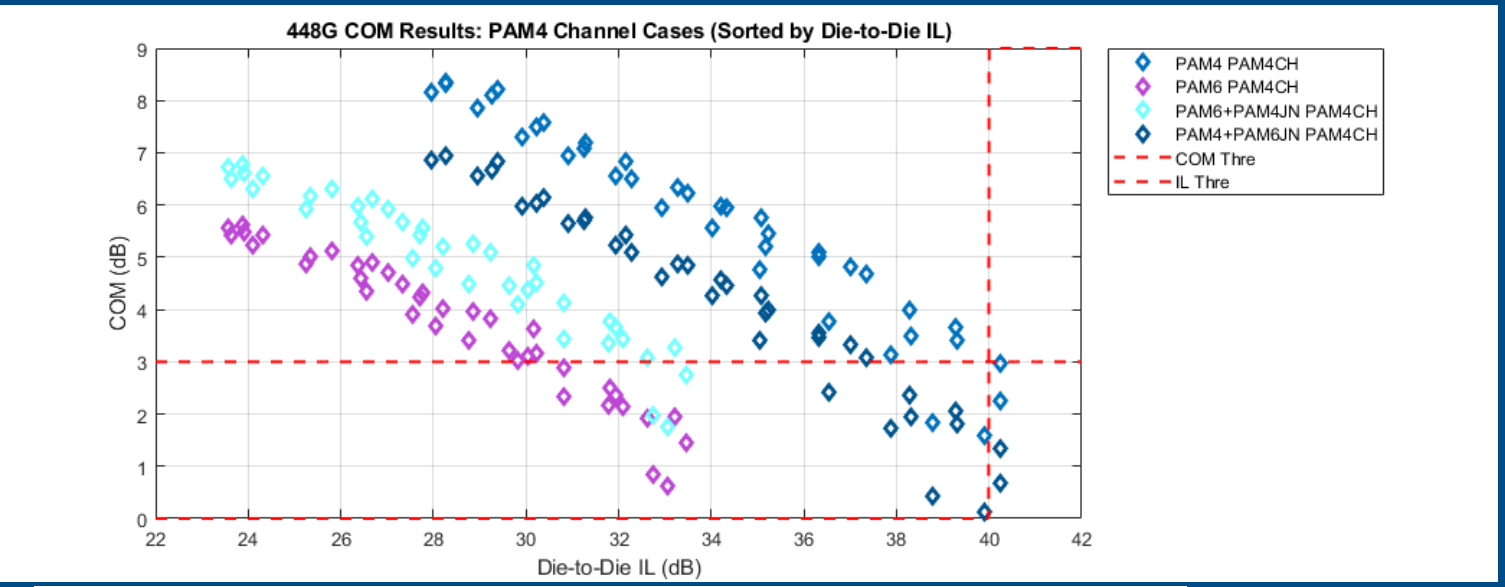
- Scaling from 224G-PAM4 based on latest CEI-224G-LR (oif2023.235.08) spec
  - Baud rate (f_b): 179.2 Gbd
  - Die/Package:
    - Based on Reference Package Type A with trace length 33mm (TX) and 31mm (RX)
    - Frequency scaled to maintain same IL as with 224G PAM4
  - AFE/Noise BW (f_r): Scale by baud rate
  - Jitter (A_DD, sigma_RJ): #1: Scale by baud rate; #2: PAM4 Jitter
  - Noise (eta_0): #1: eta_0 is inversely scaled down per baud rate; #2: PAM4 eta_0
  - Rise/Fall Time (T_r): #1: Scale by baud rate; #2: PAM4 Rise/Fall Time
  - Equalizer:
    - TX FFE not used to save computation time. Spec. configuration TBD.
    - RX CTLE: Scale by baud rate, i.e. same HF Pole/Zero divider ratio, LF Pole/Zero divider ratio = 128
    - RX FFE fixed taps: 8 pre-taps + 16 post-taps
    - RX FFE floating taps: 4 group of 4 consecutive taps up to 160 UI
    - MLSE: 1 tap

448Gbps COM Investigation Configurations Summary

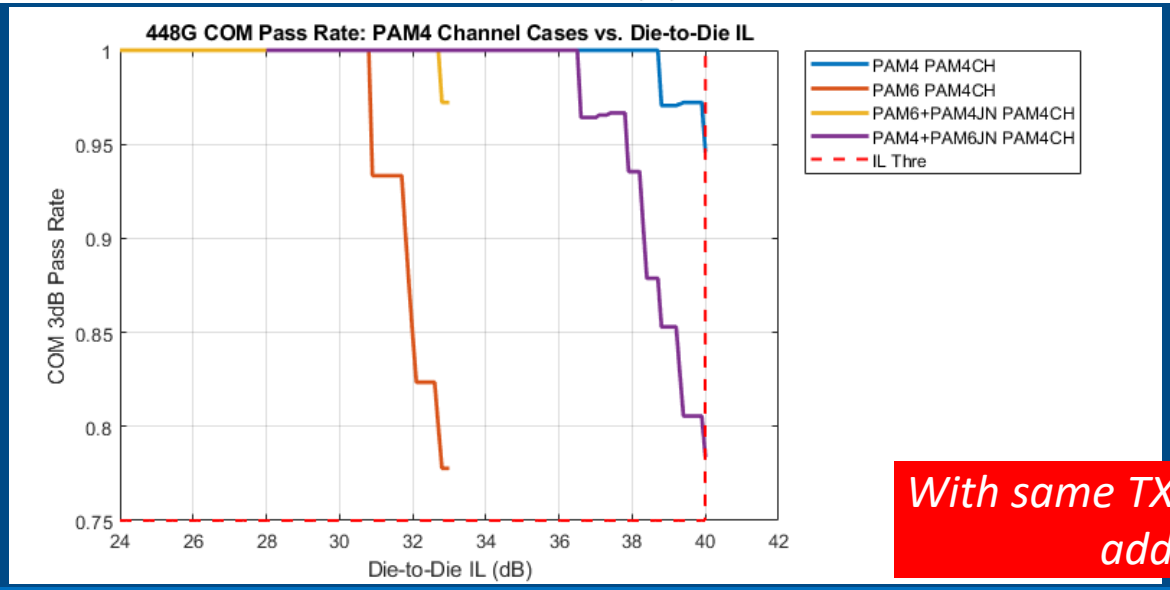
Parameter	448G-PAM4 Config #1	448G-PAM4 Config #2*	448G-PAM6 Config #1	448G-PAM6 Config #2*
f_b (Gbd)	224		179.2	
Die/Package	Scaled from OIF-CEI-224G per PAM4 baud rate		Scaled from OIF-CEI-224G per PAM6 baud rate	
L	4		6	
CTLE Pole/Zero	f_b / [2.5, 1, 2.5, 160]		f_b/ [2.5, 1, 2.5, 128]	
T_r (ps)	1.9	2.37	2.37	1.9
sigma_RJ (UI)	0.01	0.0125	0.01	0.008
A_DD (UI)	0.02	0.025	0.02	0.016
eta_0 (V^2/GHz)	5e-9	6.25e-9	6.25e-9	5e-9

*Note: *: Config #2 is an alternative of Config #1 with device characteristics from the other modulation scheme.*

448G COM Analysis Results w/ PAM4 Channels



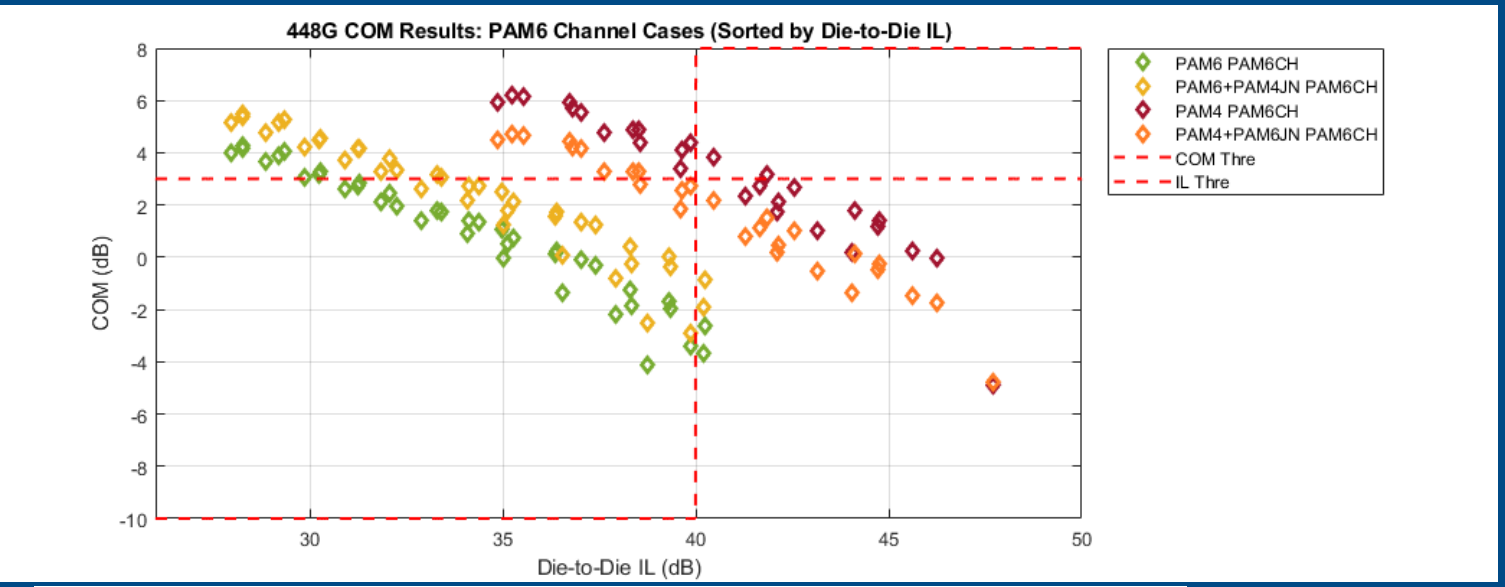
- COM scales inverse-linearly with die-to-die IL
- COM performance per die-to-die IL:
  - PAM4 Config #1 > PAM4 Config #2 > PAM6 Config #2 > PAM6 Config #1



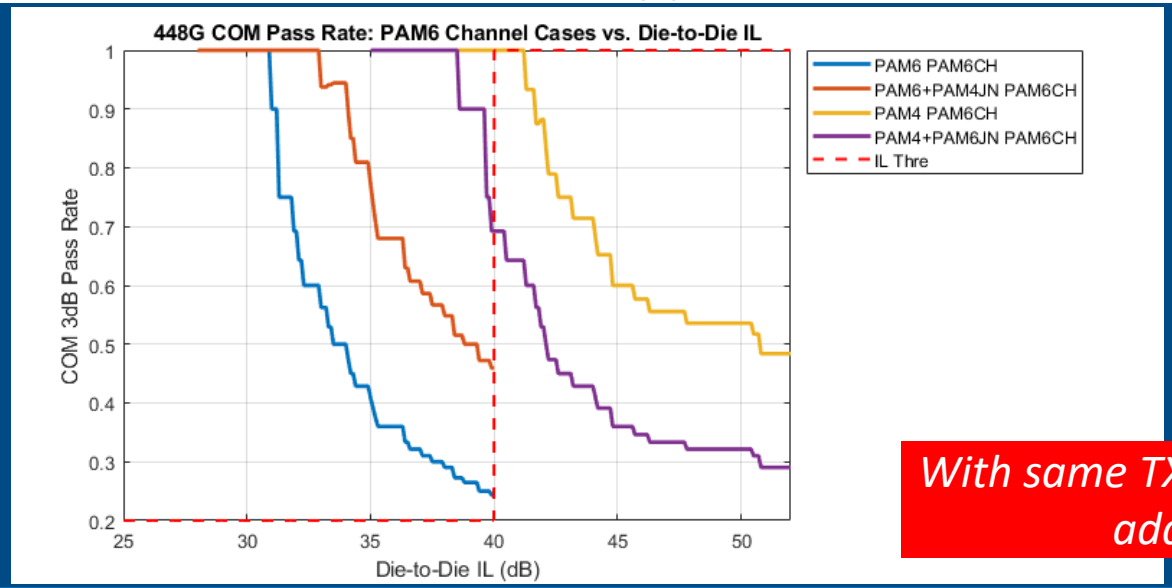
- IL limit target based on 3dB COM pass rate
  - PAM4 Config #1: ~39 dB
  - PAM4 Config #2: ~37 dB
  - PAM6 Config #1: ~31 dB
  - PAM6 Config #2: ~33 dB

With same TX/RX Jitter/Noise/Rise-Fall-Time, PAM4 outperforms PAM6 by additional ~6 dB die-to-die IL with PAM4 test channels

448G COM Analysis Results w/ PAM6 Channels



- COM scales inverse-linearly with die-to-die IL
- COM performance per die-to-die IL:
  - PAM4 Config #1 > PAM4 Config #2 > PAM6 Config #2 > PAM6 Config #1



- IL limit target based on 3dB COM pass rate
  - PAM4 Config #1: ~41 dB
  - PAM4 Config #2: ~39 dB
  - PAM6 Config #1: ~31 dB
  - PAM6 Config #2: ~33 dB

With same TX/RX Jitter/Noise/Rise-Fall-Time, PAM4 outperforms PAM6 by additional ~8 dB die-to-die IL with PAM6 test channels

Case 1: Summary and Conclusions

- When channel bandwidth is sufficient to support PAM4/PAM6 modulation schemes, the maximum die-to-die IL:

Modulation Scheme	Max. Die-to-Die IL (dB)	*Notes*
PAM4 Config #1	39	*Channel BW >> 112 GHz, Scaled TX/RX Performance*
PAM4 Config #2	37	*Channel BW >> 112 GHz, Scaled TX/RX w/ PAM6 Jitter/T_r*
PAM6 Config #1	31	*Channel BW >> 89.6 GHz, Scaled TX/RX Performance*
PAM6 Config #2	33	*Channel BW >> 89.6 GHz, Scaled TX/RX w/ PAM4 Jitter/T_r*

448 Gbps COM Performance Evaluations

PAM4 versus PAM6 Modulation

Case 2: Packages/channels bandwidth is restricted to ≥PAM4 or ≥ PAM6 Nyquist frequency

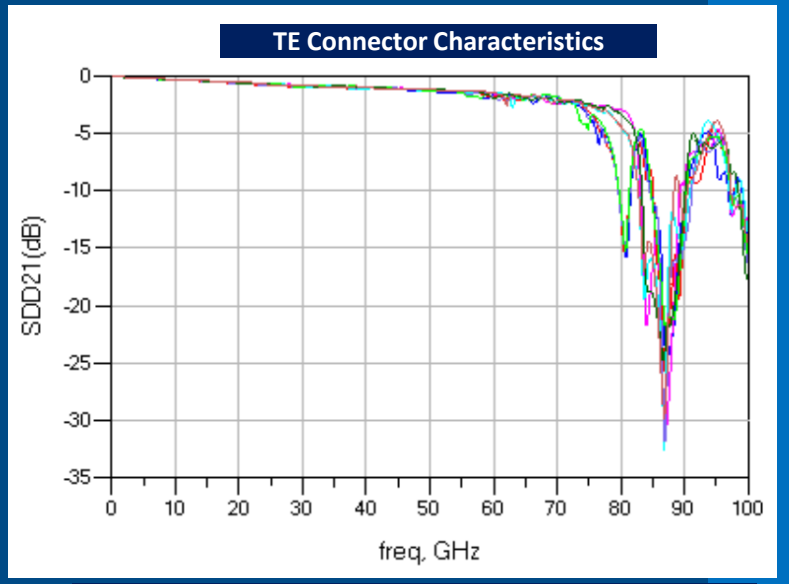
448G Channel Modifications to Emulate Bandwidth Limitations

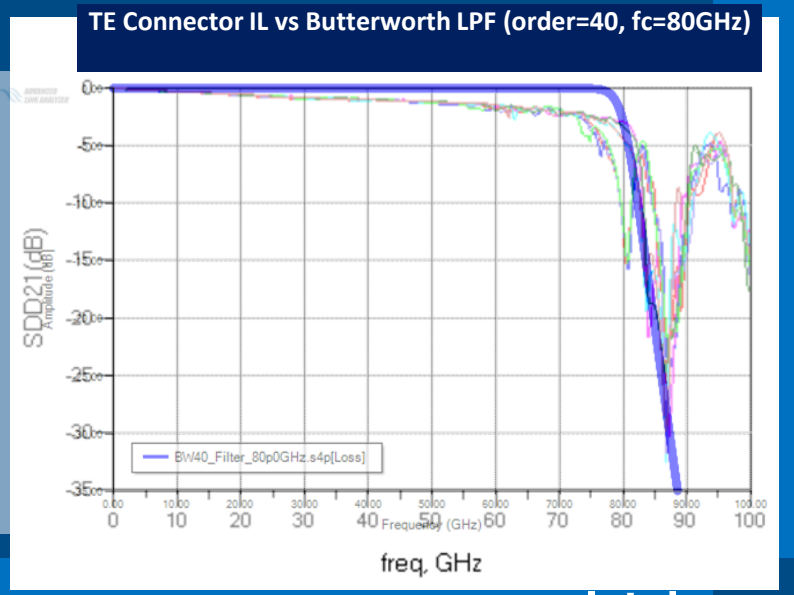
- TE [4] showed today's interconnects have 3 dB BW ~= 80 GHz and ~30 dB IL degradation within <10 GHz
  - Note that 80 GHz BW won't be able to support 448 Gbps PAM6

- PAM6 BW-limited Channel Experiments
  - For 448Gbps PAM6, BW_{3dB} needs to above 89.6GHz (Nyq. freq. of 448Gbps PAM6)
    - Experimented with BW_{3dB}: 89.6~97.6GHz
  - Also need a LPF with steep roll-off to emulate IL notch(s):
    - Butterworth LPF was chosen due to its characteristics
    - Experiments showed that we need ≥40^{th} order Butterworth LPF to emulate the TE connector characteristics

- Similar experiments was set up for PAM4 BW-limited channels
  - BW_{3dB}: 112~120 GHz

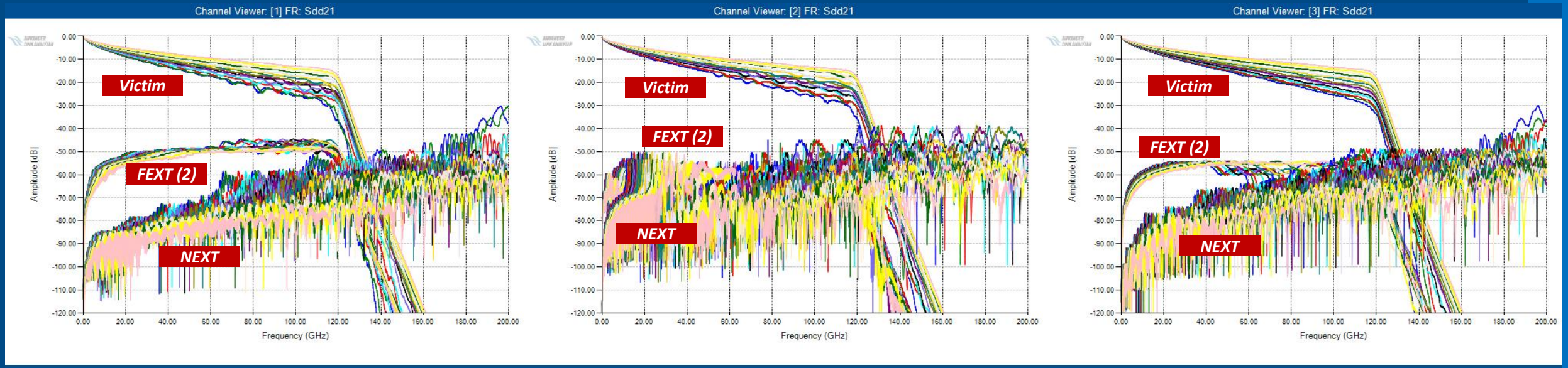
[4] Introductory Contribution on Some 448 Gbps Tradeoffs





448Gbps PAM4 Test Channels with Bandwidth Limits Characteristics

(Butterworth LPF 40th-order BW_{3dB} = 120 GHz shown)

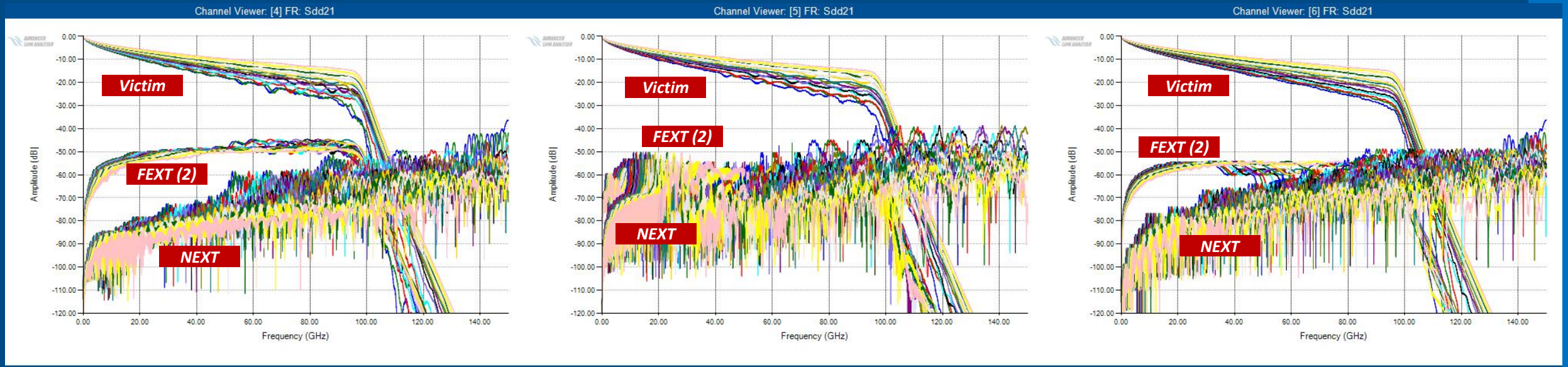


- Frequency scaled 224 Gbps end-to-end channels [1][2][3], which include 1m cable assembly.
  - 448G-PAM4 Nyquist freq., 112 GHz, IL ~= 14 to 28 dB (45 test channels)
  - Including 2 FEXT and 1 NEXT
  - Butterworth LPF 40th-order BW = 120 GHz was applied on victim and FEXT

Note:
[1] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_04_230629.zip
[2] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_03_230629.zip
[3] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_07_2309.zip

448Gbps PAM6 Test Channels with Bandwidth Limits Characteristi

(Butterworth LPF 40th-order BW_{3dB} = 97.6 GHz shown)



- Frequency scaled 224 Gbps end-to-end channels [1][2][3], which include 1m cable assembly.
  - 448G-PAM6 Nyquist freq., 89.6 GHz, IL ~= 14 to 28 dB (45 test channels)
  - Including 2 FEXT and 1 NEXT
  - Butterworth LPF 40th-order BW = 97.6 GHz was applied on victim and FEXT

Note:
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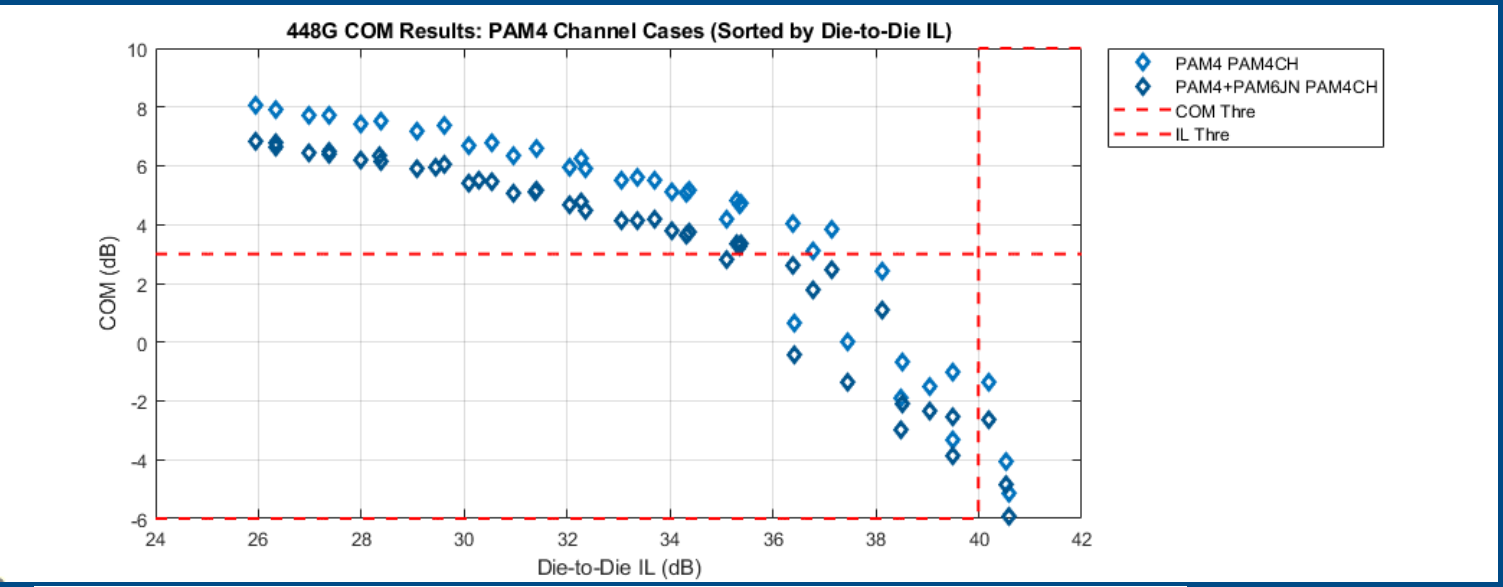
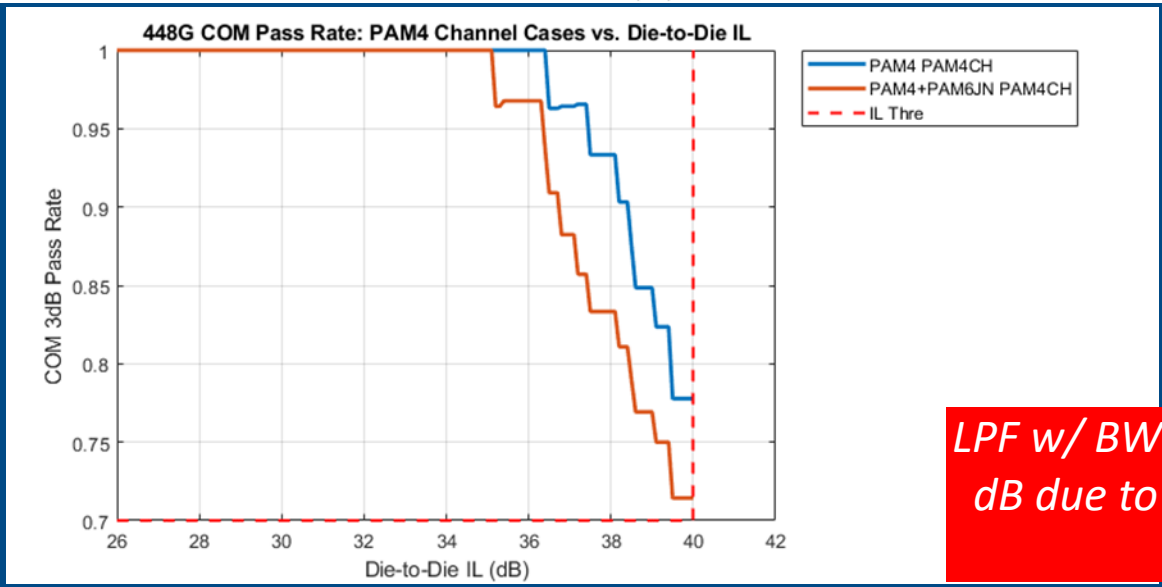
[3] https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_07_2309.zip

448G PAM4 COM Analysis Results w/ Bandwidth-limited PAM4 Channels

Butterworth LPF 40th-order BW_{3dB} = 112 GHz shown)



- COM scales inverse-linearly with die-to-die IL
- COM performance per die-to-die IL:
  - PAM4 Config #1 > PAM4 Config #2

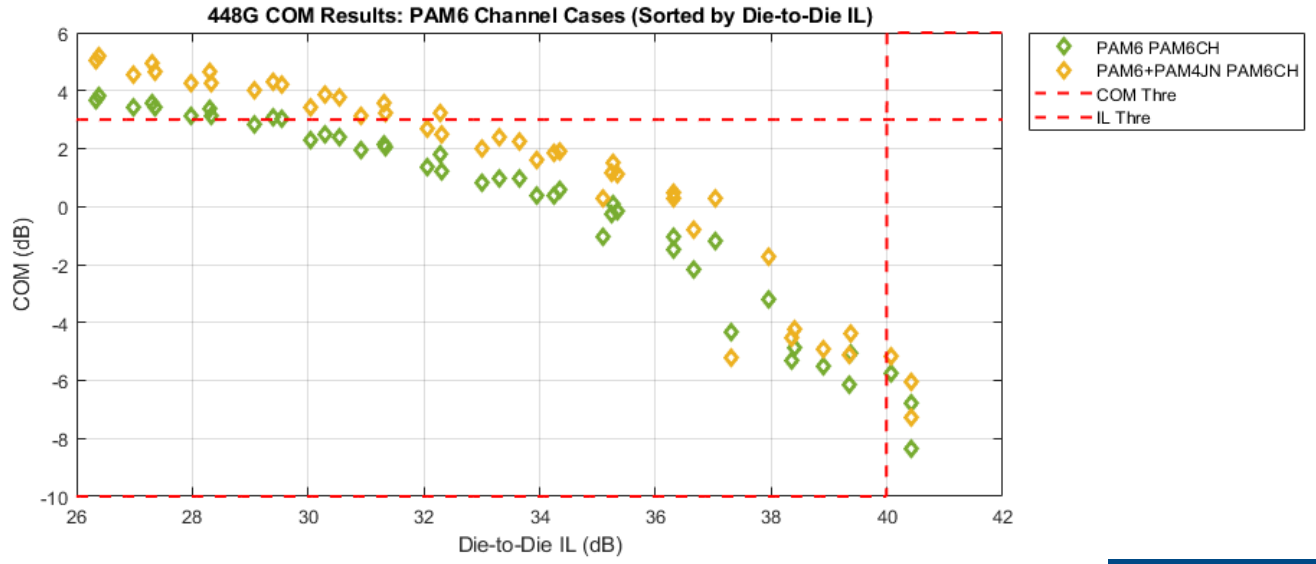


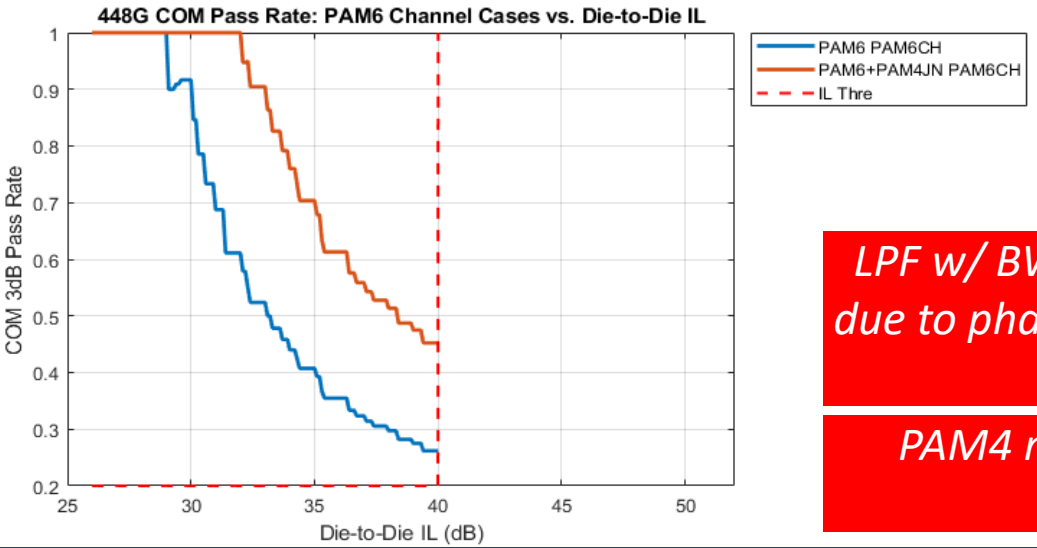
- IL limit target based on 3dB COM pass rate
  - PAM4 Config #1: ~38 dB
  - PAM4 Config #2: ~36.5 dB

LPF w/ BW=120 GHz slightly reduced PAM4 supportable Die-to-Die IL by 1~1.5 dB due to phase distortion and Gibbs phenomenon caused by the sharp roll-off LPF

448G PAM6 COM Analysis Results w/ Bandwidth-limited PAM6 Channels

(Butterworth LPF 40th-order BW_{3dB} = 97.6 GHz shown)





- COM scales inverse-linearly with die-to-die IL
- COM performance per die-to-die IL:
  - PAM6 Config #2 > PAM6 Config #1
- IL limit target based on 3dB COM pass rate
  - PAM6 Config #1: ~30 dB
  - PAM6 Config #2: ~33 dB

LPF w/ BW=97.6 GHz slightly PAM6 reduced supportable Die-to-Die IL by 1 dB due to phase distortion and Gibbs phenomenon caused by the sharp roll-off LPF

PAM4 modulation does not have solution space due to >70dB IL at PAM4 Nyquist freq. of 112 GHz

Case 2: Summary and Conclusions

- When channels are bandwidth-limited w.r.t. PAM4 modulation scheme, max. $IL_{Die\text{-}to\text{-}Die}$:

Modulation Scheme	Channel Bandwidth (GHz)	Max. Die-to-Die IL (dB)	*Notes*
PAM4 Config #1	112	38	*Scaled TX/RX Performance*
	120	38	
PAM4 Config #2	112	36.5	*Scaled TX/RX w/ PAM6 Jitter/T_r*
	120	36.5	

  - PAM6 is expected to support $IL_{Die\text{-}to\text{-}Die}$ up to 30~32 dB per studies in Case 1.

- When channels are bandwidth-limited w.r.t. PAM6 modulation scheme, max. $IL_{Die\text{-}to\text{-}Die}$:

Modulation Scheme	Channel Bandwidth (GHz)	Max. Die-to-Die IL (dB)	*Notes*
PAM6 Config #1	89.6	<29	*Scaled TX/RX Performance*
	97.6	30	
PAM6 Config #2	89.6	29	*Scaled TX/RX w/ PAM4 Jitter/T_r*
	97.6	33	

  - PAM4 does not have solution space due to IL roll-off

Summary and Conclusions

- When channel bandwidth (BW) is way beyond PAM4 Nyquist freq., PAM4 always outperforms PAM6
  - PAM4 can support additional 6 dB $IL_{Die\text{-}to\text{-}Die}$ than PAM6
- When channel is bandwidth-limited with significant roll-off, the modulation scheme works if:
  - PAM4: Channel BW ≥ 112 GHz and $IL_{Die\text{-}to\text{-}Die}$ ≤ ~38 dB
  - PAM6: Channel BW ≥ 90 GHz and $IL_{Die\text{-}to\text{-}Die}$ ≤ ~30 dB
- Note
  - The above conclusions are under the assumptions that SerDes TX/RX and package are scaled per Slides 6-8 and Appendix B.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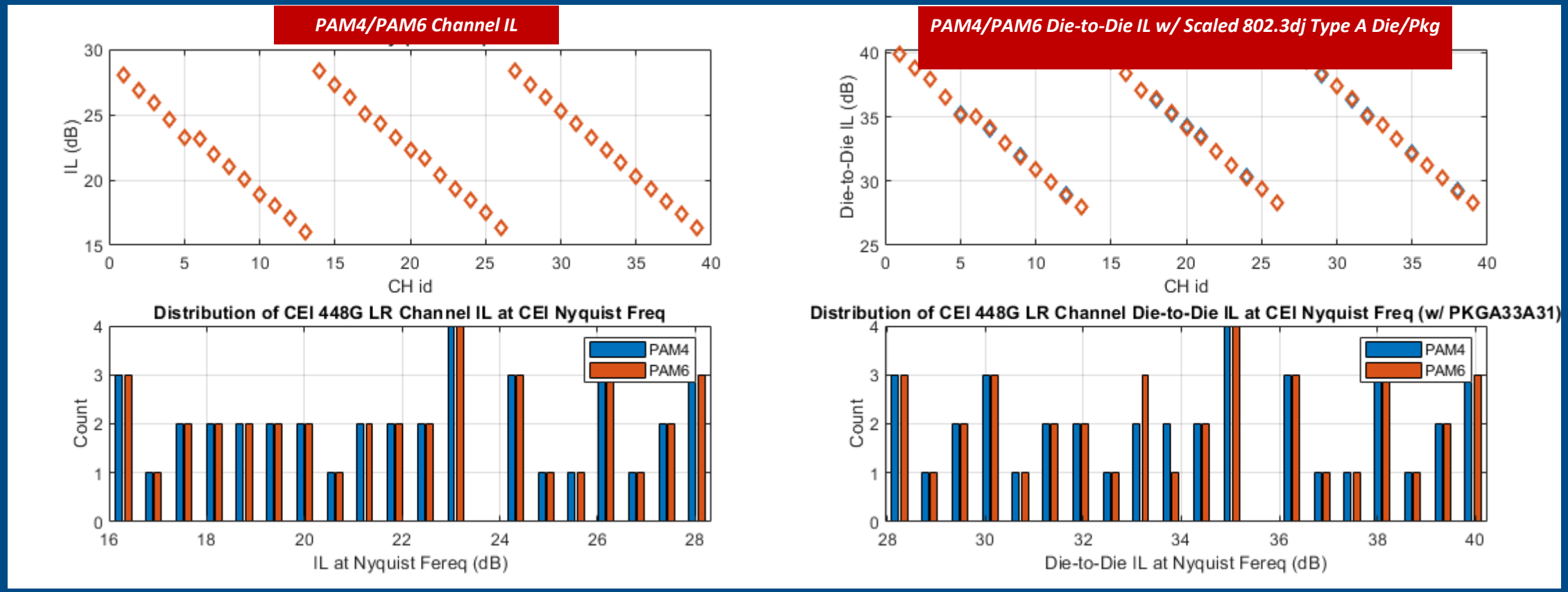
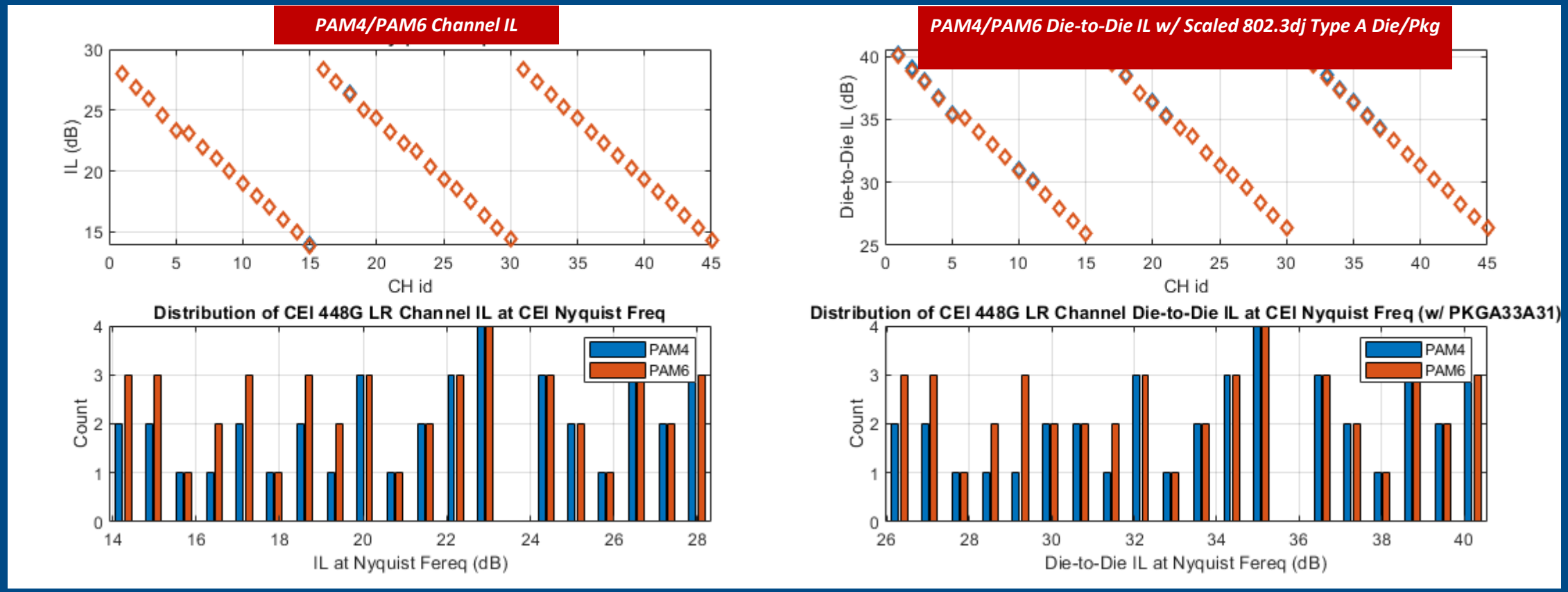
Appendix A.

448 Gbps Test Channel Distributions

448G PAM4 and PAM6 Test Channel IL Distributions



448G PAM4 and PAM6 Test Channels (w/ LPF) IL Distributions



Appendix B.

448 Gbps COM Configuration

448Gbps COM Configuration (PAM4 Config #1 shown)

Table 93A-1 parameters			
Parameter	**Setting**	**Units**	**Information**
f_b	224	GBd	
f_min	0.05	GHz	
Delta_f	0.01	GHz	
C_d	[0.4e-4 0.9e-4 1.1e-4 ;0.4e-4 0.9e-4 1.1e-4]	nF	[TX RX]
L_s	[0.13 0.15 0.14; 0.13 0.15 0.14]	nH	[TX RX]
C_b	[0.15e-4 0.15e-4]	nF	[TX RX]
R_0	50	Ohm	
R_d	[46.25 46.25]	Ohm	[TX RX]
PKG_NAME	PKG_LowR_CLASSA PKG_LowR_CLASSA		TX RX
A_v	0.385	V	
A_fe	0.385	V	
A_ne	0.48125	V	
z_p select	[5]		
L	4		
M	32		
filter and Eq			
f_r	0.55	*fb	
c(0)	0.54		min
c(-1)	0		[min:step:max]
c(-2)	0		[min:step:max]
c(-3)	0		[min:step:max]
c(-4)	0		[min:step:max]
c(1)	0		[min:step:max]
N_b	1	UI	
b_max(1)	0.85		As/dffe1
b_max(2..N_b)	0.3		As/dfe2..N_b
b_min(1)	0		As/dffe1
b_min(2..N_b)	-0.3	S	As/dfe2..N_b
g_DC	[-20:1:0]	dB	[min:step:max]
f_z	89.60	GHz	
f_p1	89.60	GHz	
f_p2	224.00	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	1.4	GHz	
Butterworth	1	logical	include in fr

I/O control		
DIAGNOSTICS	1	logical
DISPLAY_WINDOW	1	logical
CSV_REPORT	1	logical
RESULT_DIR	.\results\CACR_set1_{date}\	
SAVE_FIGURES	0	logical
Port Order	**[1 3 2 4]**	
RUNTAG	KR_eval_	
COM_CONTRIBUTION	1	logical
TDR and ERL options		
TDR	0	logical
ERL	0	logical
ERL_ONLY	0	ns
TR_TDR	0.005	
N	7000	logical
TDR_Butterworth	1	
beta_x	0	
rho_x	0.618	
TDR_W_TXPKG	0	UI
N_bx	16	
fixture delay time	[0 0]	
Tukey_Window	1	
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	

Table 93A–3 parameters			
Parameter	**Setting**	**Units**	Information
package_tl_gamma0_a1_a2	[5e-4 0.00065 0.0003]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[92 92 ; 70 70; 80 80; 100 100]	Ohm	
z_p (TX)	[8 24 30 45 ; 1 1 1 1; 1 1 1 1 ; 0.5 0.5 0.5 0.5]	mm	[test cases to run]
z_p (NEXT)	[8 24 30 45 ; 1 1 1 1; 1 1 1 1 ; 0.5 0.5 0.5 0.5]	mm	[test cases]
z_p (FEXT)	[8 24 30 45 ; 1 1 1 1; 1 1 1 1 ; 0.5 0.5 0.5 0.5]	mm	[test cases]
z_p (RX)	[8 24 30 45 ; 1 1 1 1; 1 1 1 1 ; 0.5 0.5 0.5 0.5]	mm	[test cases]
C_p	[0.4e-4 0.4e-4]	nF	[test cases]
Operational			
ERL Pass threshold	10	dB	
COM Pass threshold	3	db	
DER_0	1.00E-04		
T_r	0.00190	ns	
FORCE_TR	1	logical	
PMD_type	C2C		
EW	1		
MLSE	1	logical	
ts_anchor	1		
sample_adjustment	[-16, 16]		
Local Search	0		
Filter: Rx FFE			
ffe_pre_tap_len	8	UI	
ffe_post_tap_len	16	UI	
ffe_pre_tap1_max	0.7		
ffe_post_tap1_max	0.7		
ffe_tapn_max	0.7		
FFE_OPT_METHOD	MMSE		FV-LMS or MMSE
num_ui_RXFF_noise	2048		
Floating Tap Control			
N_bg	4	0 1 2 or 3 groups	
N_bf	4	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	
N_tail_start	17	(UI) start of tail taps limit	

SAVE_CONFIG2MAT	0	
Receiver testing		
RX_CALIBRATION	0	logical
Sigma BBN step	5.00E-03	V
ICN parameters		
f_v	0.268	Fb
f_f	0.268	Fb
f_n	0.268	Fb
f_2	60.000	GHz
A_ft	0.450	V
A_nt	0.600	V

Parameter	**Setting**	
board_tl_gamma0_a1_a2	*[0 6.44084e-4 3.6036e-05]*	1.4 db/in @ 53.125G
board_tl_tau	*5.790E-03*	ns/mm
board_Z_c	100	Ohm
z_bp (TX)	*32*	mm
z_bp (NEXT)	*32*	mm
z_bp (FEXT)	*32*	mm
z_bp (RX)	*32*	mm
C_0	[0.2e-4 0]	nF
C_1	[0.2e-4 0]	nF
Include PCB	**0**	**logical**
Seletions (rectangle, gaussian,dual_rayleigh,triangle		
Histogram_Window_Weight	gaussian	selection
Qr	*0.02*	UI

Notes:

- ***COM v4.80 was used in this study***