Significance of Including Quantization Noise in COM Evaluation

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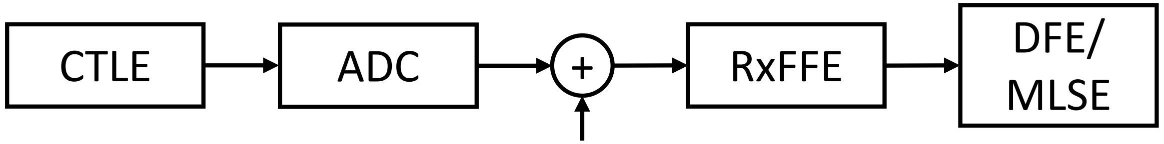
Introduction

- Majority of the recent receivers for high-loss channels use ADC
- Receiver DSP performs heavy equalization (e.g. FFE and DFE/MLSE)
- Quantization noise is currently not a part of the overall noise during COM evaluation
- Quantization noise affects link performance and COM results:
  1) Reduces SNR
  2) Influences optimization of equalization (equalization balance among TxFFE, CTLE, RxFFE, and DFE/MLSE)
  3) Affects noise coloring (becoming increasingly important in the new MMSE RxFFE method and MLSE)
- Tweaking existing noise components (such as eta_0) is not a good approach
- Even without an ADC, it is a good practice to include additional noise before FFE+DFE/MLSE
- A set of 112 channels is used for generating test data
- COM version: com_ieee8023_93a_450beta3_hs2p0 (see backup slide for COM config)
  - _hs2p0 customizes COM to add quantization noise

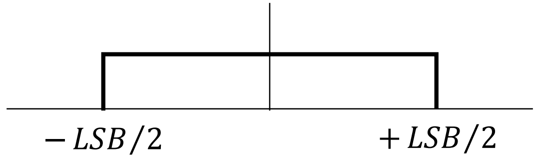
Importance of Quantization Noise



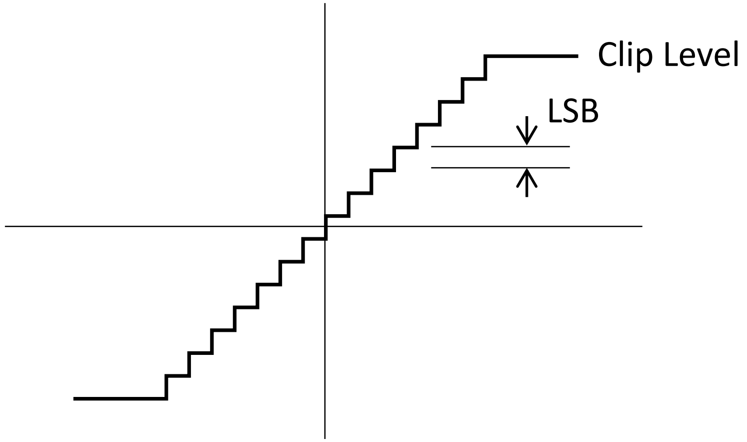
- Since the reference CTLE is a low-order filter (only one high-frequency pole-zero), in the absence of quantization noise, the optimizer tends to favor RxFFE over CTLE
- CTLE equalization will be marginalized to mostly only low-frequencies, for which FFE does not have enough taps
- As a result of CTLE under-utilization, its output could be severely under-equalized
- This forces a large input dynamic range, hence increased number of required ADC bits
- In the absence of ADC (or if it is after RxFFE), considering an ‘equivalent’ noise between CTLE and FFE is still reasonable and helpful

Quantization Noise Model

- Uniformly distributed over –LSB/2 to +LSB/2



$$\sigma_{qn} = \frac{LSB}{\sqrt{12}}$$



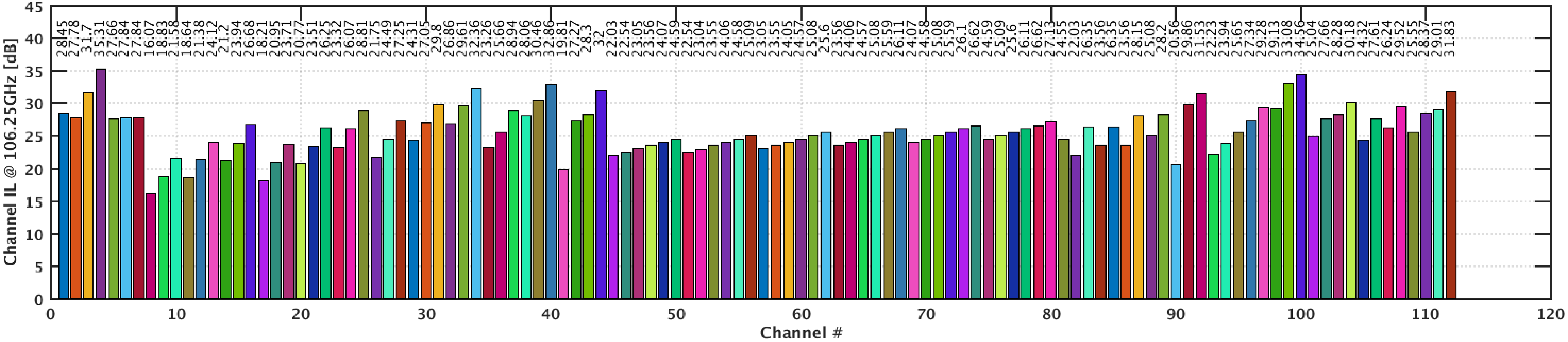
- To optimally utilize the ADC input dynamic range, its clip level is set so that clipping does not happen too frequently
- “too frequently” is defined relative to the target error rate
- ADC clip level is chosen so that clipping frequency is equal to the target error rate
- At this early stage, the analysis assumes ADC delivers $\overline{\text{ENOB}}$ bits on “average”
- In future, actual ENOB may be used that results in quantization noise being colored

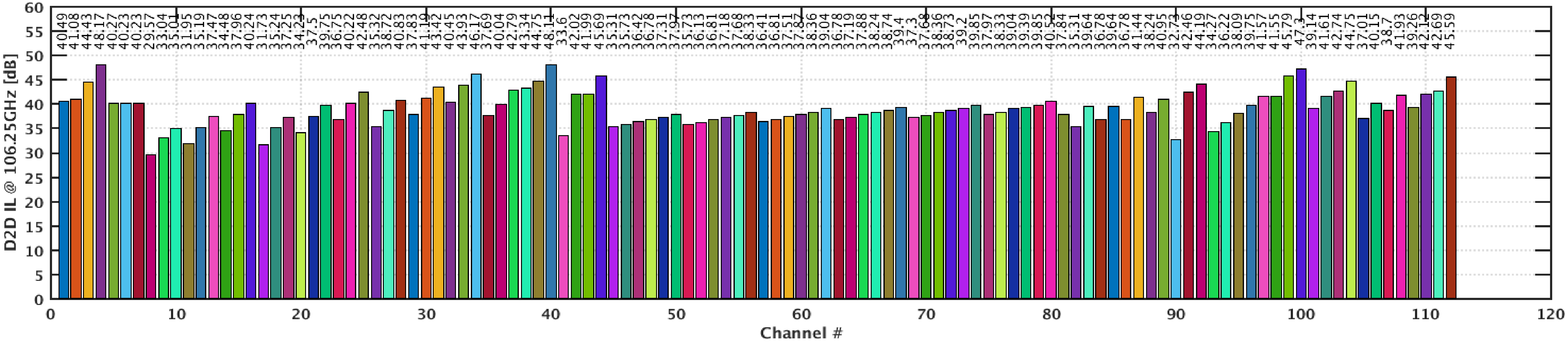
Test Channels

- Same set as in shakiba_3dj_01a_2403.pdf

Channel #	Channel Source
1	https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_03_230629.zip
2	https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_04_230629.zip
3 – 7	https://www.ieee802.org/3/dj/public/tools/CR/kocsis_3dj_02_2305.zip
8 – 34	https://www.ieee802.org/3/dj/public/tools/KR/mellitz_3dj_02_elec_230504.zip
35 – 40	https://www.ieee802.org/3/dj/public/tools/CR/shanbhag_3dj_01_2305.zip
40 – 44	https://www.ieee802.org/3/dj/public/tools/KR/shanbhag_3dj_02_2305.zip
45 – 80	https://www.ieee802.org/3/dj/public/tools/KR/weaver_3dj_02_2305.zip
80 – 88	https://www.ieee802.org/3/dj/public/tools/KR/weaver_3dj_elec_01_230622.zip
89	https://www.ieee802.org/3/dj/public/tools/CR/lim_3dj_07_2309.zip
90 – 96	https://www.ieee802.org/3/dj/public/tools/KR/akinwale_3dj_01_2310.zip
97 – 100	https://www.ieee802.org/3/dj/public/tools/CR/akinwale_3dj_02_2311.zip
101 – 112	https://www.ieee802.org/3/dj/public/tools/CR/weaver_3dj_02_2311.zip

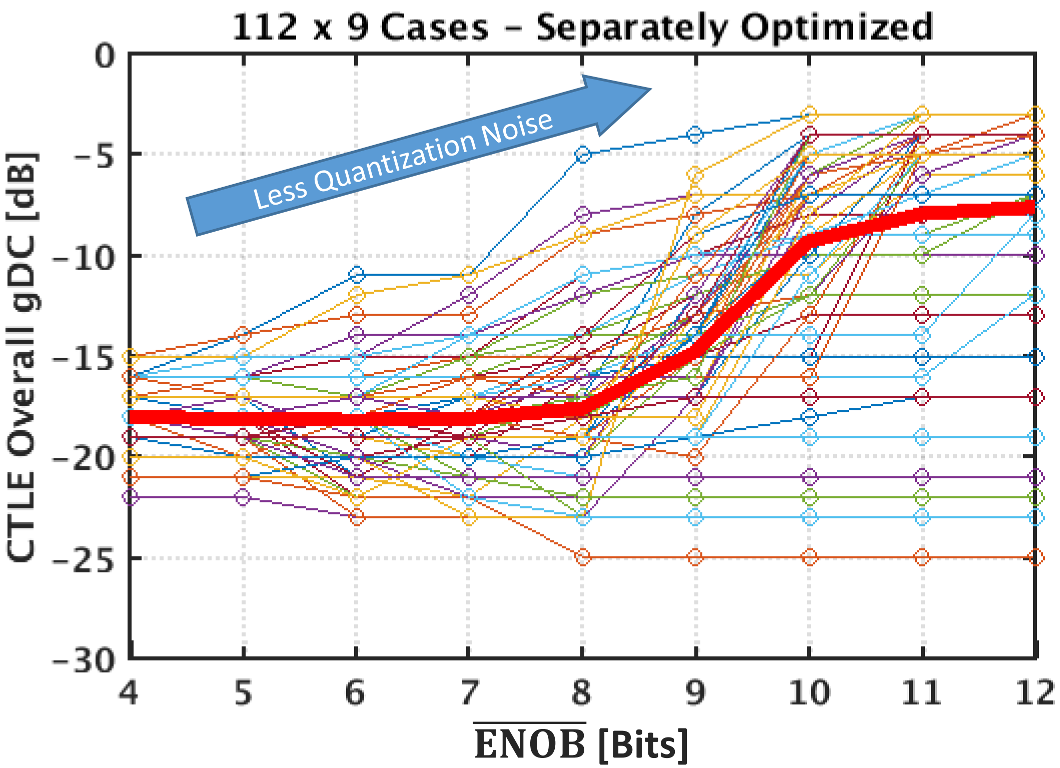
Test Channels





Test Results – CTLE Utilization

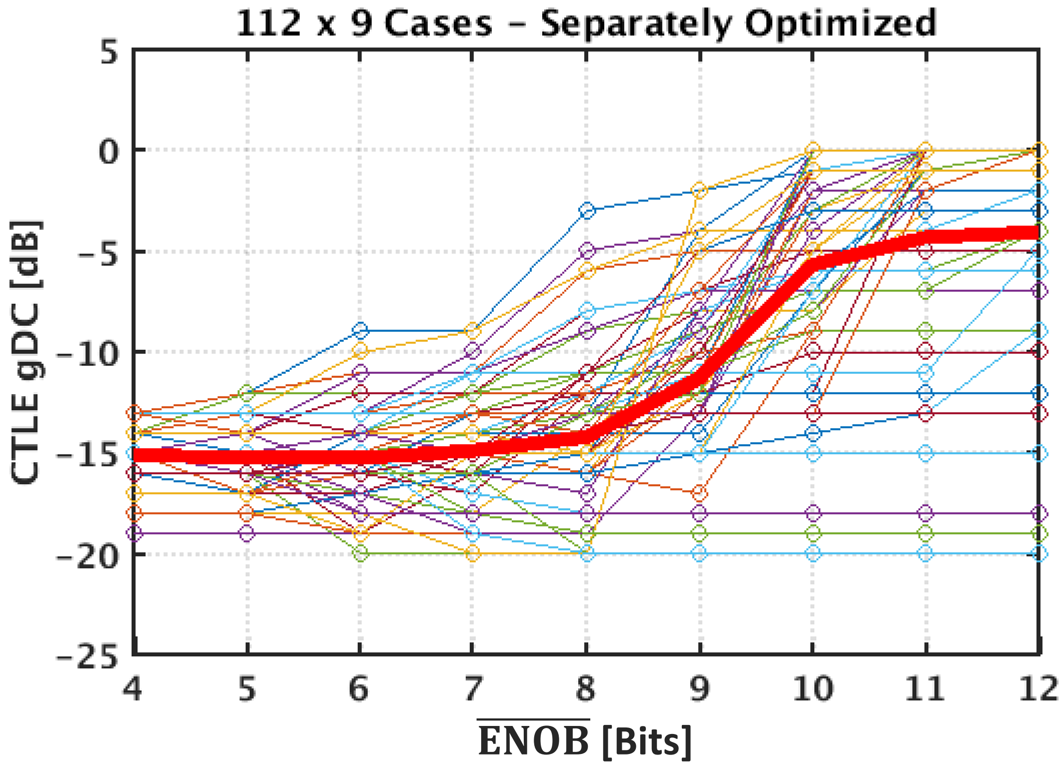
- COM was run on 112 test channel cases, and for each case 9 times for $\overline{\mathrm{ENOB}}$ range of 4:1:12 bits

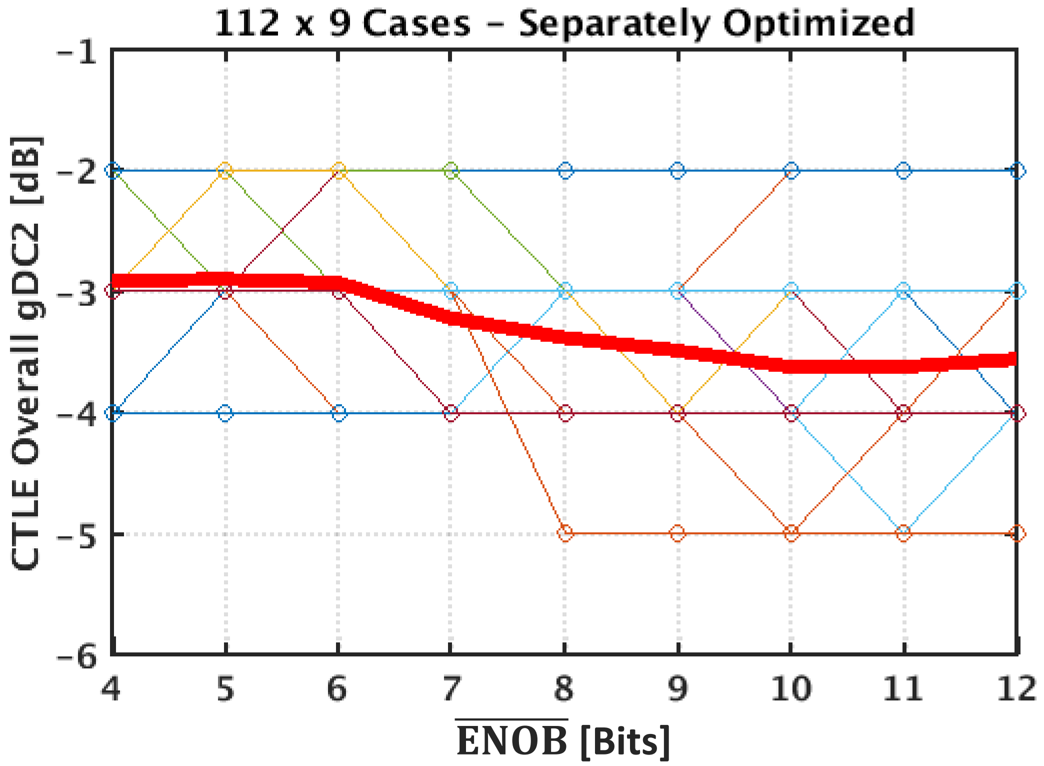


- Finer quantization (larger $\overline{\mathrm{ENOB}}$) pushes more equalization to RxFFE and less to CTLE

- CTLE utilization on average reduces from ~18dB to ~7.6dB as $\overline{\mathrm{ENOB}}$ increases from 4 to 12
  - This is what happens if quantization noise is ignored

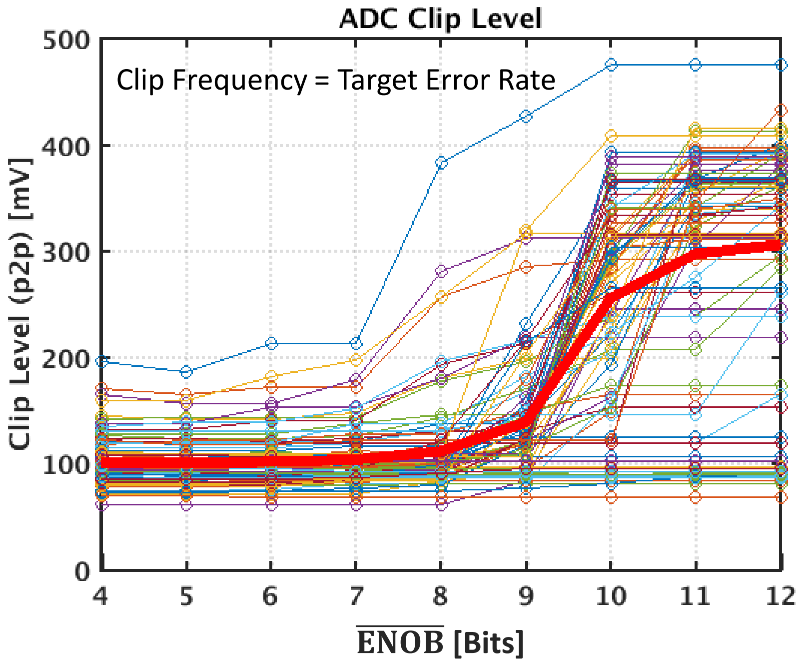
Test Results – CTLE Utilization

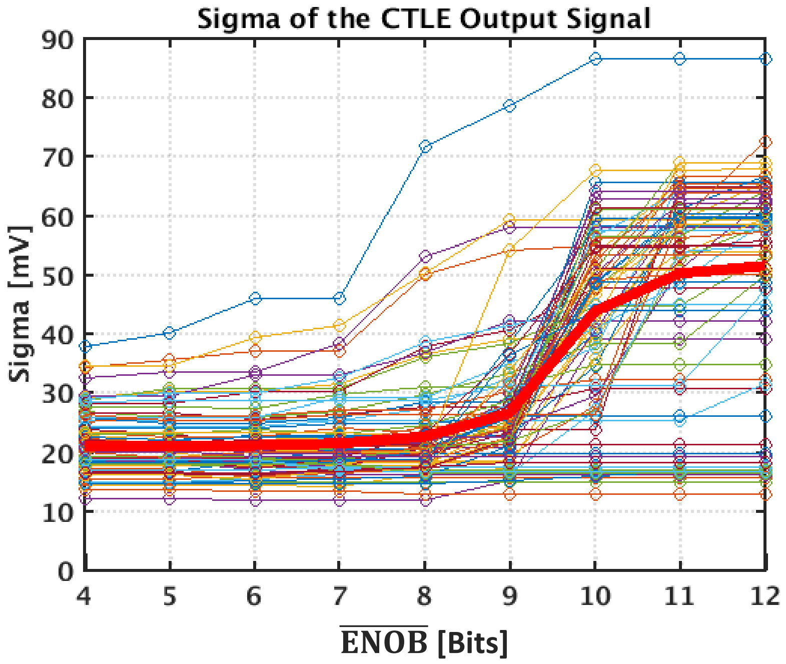


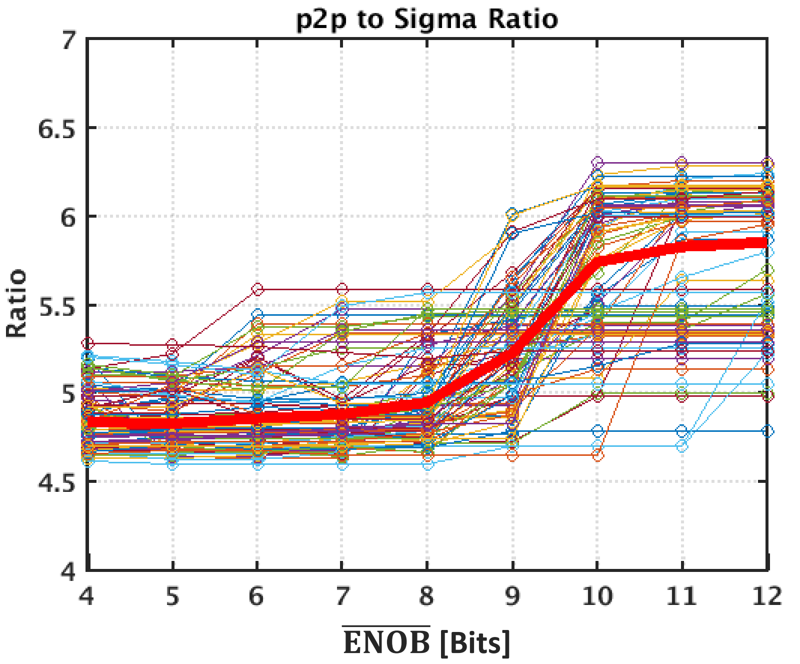


- As expected, CTLE under-utilization is entirely at high frequencies (from 15.1dB to 4.1dB)
- CTLE continues to equalize low frequencies

Test Results – CTLE Output Signal Statistics

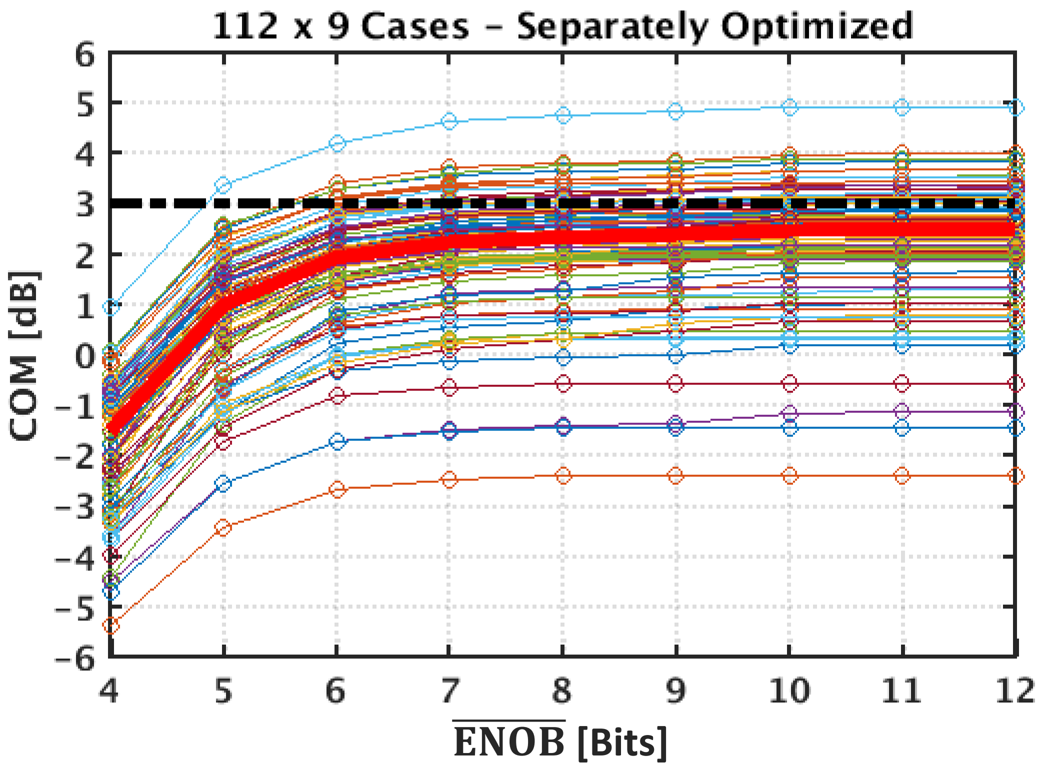


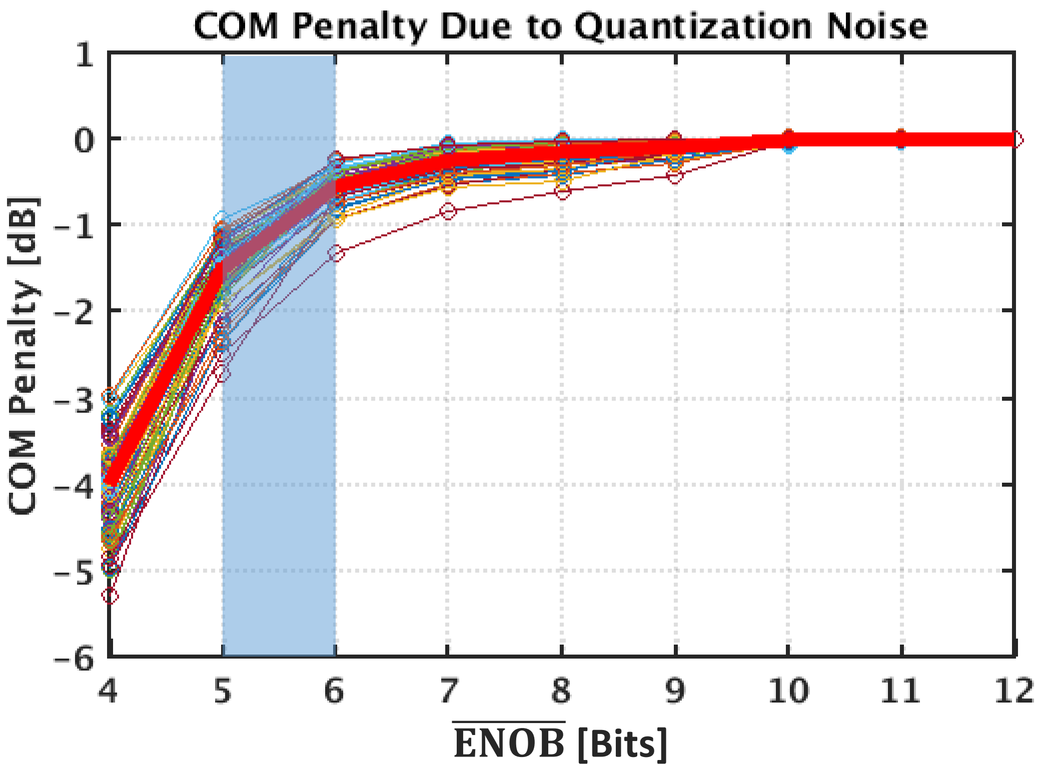




- CTLE marginalization increases p2p and sigma of the (under-equalized) signal as well as their ratio at the CTLE output (ADC input)
- To mimic this in practice, ADCs with large dynamic range and $\overline{\text{ENOB}}$ are required (beyond what is readily available in today's technologies)

Test Results – COM

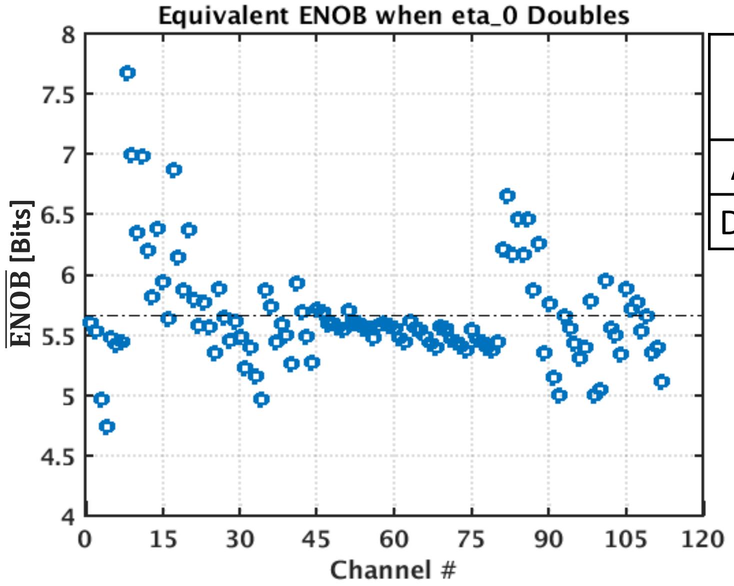




- Expect a considerable (unattended) drop in COM unless much better ADCs become available
- For example, for $\overline{\text{ENOB}}$ of 5 to 6 bits, average COM drops by 1.5dB to 0.6dB
- Even if $\overline{\text{ENOB}}$ improves by 1-2 bits, there is still a COM penalty that cannot be easily ignored

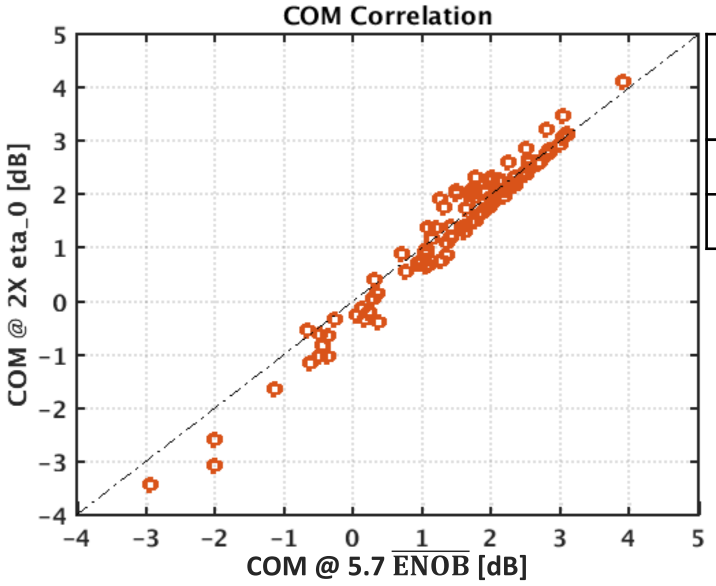
Can I Tweak eta_0 to Mimic Quantization Noise Effect?

- Remove quantization noise and scale up eta_0 (e.g. X2)
- For each test case, calculate COM and interpolate the previous plot (COM vs. $\overline{\text{ENOB}}$) to obtain equivalent $\overline{\text{ENOB}}$ that would have resulted in the same COM (left plot)
- Set $\overline{\text{ENOB}}$ to the average equivalent $\overline{\text{ENOB}}$ and calculate COM for each test case (right plot)
- For the test channels, if X2 eta_0 is used to represent an $\overline{\text{ENOB}}$ of 5.7 bits, there will be ~1dB COM inaccuracy (Likely not acceptable)



Equivalent $\overline{\text{ENOB}}$ [Bits]	
Average	5.7
Deviation	+2 / -0.9

Can doubling eta_0 represent 5.7 bit $\overline{\text{ENOB}}$?



Y-x Deviation [dB]	
Min	-1
Max	+0.7

Summary and Conclusion

- Quantization noise is currently not represented in COM
- Quantization noise decreases SNR, influences noise coloring, and could have a major effect on equalization optimization and distribution
- RxFFE tap optimization MMSE method and MLSE ΔCOM are affected by noise coloring
- A set of 112 KR/CR channels were used to generate data
  - An $\overline{\text{ENOB}}$ of 5/6 bits drops COM by as much as 2.7dB/1.3dB and on average by 1.5dB/0.6dB
  - This is currently ignored during COM compliance evaluations
  - If eta_0 scaling were to be used to represent quantization noise, scaling by 2X corresponds to 5.7bit $\overline{\text{ENOB}}$, but results in as much as 1dB of COM inaccuracy
- Considering adding quantization noise as another noise component in the COM flow is suggested

Backup – COM Config

Table 93A-1 parameters			
Parameter	Setting	Units	Information
f_b	106.25	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	[0.3e-4 0.3e-4]	nF	[TX RX]
R_0	5.00E+01	Ohm	
R_d	[50 50]	Ohm	[TX RX]
PKG_NAME	PKG_HiR_CLASSB PKG_HiR_CLASSB		TX RX
A_v	0.413	V	
A_fe	0.413	V	
A_ne	0.608	V	
z_p select	[3]		
L	4		
M	32		
filter and Eq			
f_r	0.58	*fb	
c(0)	0.55		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)	0.75		As/dfe1
b_max(2..N_b)	0.3		As/dfe2..N_b
b_min(1)	0		As/dfe1
b_min(2..N_b)	-0.15	5	As/dfe2..N_b
g_DC	[-20:1:0]	dB	[min:step:max]
f_z	25.16	GHz	
f_p1	40.00	GHz	
f_p2	56.00	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	1.328125	GHz	
Butterworth	1	logical	include in fr

I/O control		
DIAGNOSTICS	0	logical
DISPLAY_WINDOW	0	logical
CSV_REPORT	0	logical
RESULT_DIR	.\results\CACR_set1_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 3 2 4]	
RUNTAG	KR_set1_eval_	
COM_CONTRIBUTION	1	logical
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	ns
TR_TDR	0.01	
N	4000	logical
TDR_Butterworth	1	
beta_x	0	
rho_x	0.618	
TDR_W_TXPKG	0	UI
N_bx	20	
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	8.00E-09	dB
SNR_TX	33	
R_LM	0.95	
BREAD_CRUMBS	1	logical
[illegible]	[illegible]	_hs1p0
[illegible]	[illegible]	_hs1p0

Table 93A-3 parameters			
Parameter	Setting	Units	Information
package_tl_gamma0_a1_a2	e-4 0.00065 0.0003]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	; 70 70; 80 80; 10	Ohm	
z_p (TX)	1 1 1; 1 1 1 1 ; 0	mm	[test cases to run]
z_p (NEXT)	1 1 1; 1 1 1 1 ; 0	mm	[test cases]
z_p (FEXT)	1 1 1; 1 1 1 1 ; 0	mm	[test cases]
z_p (RX)	1 1 1; 1 1 1 1 ; 0	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	0.00400	ns	
FORCE_TR	1	logical	
PMD_type	C2C		
EW	1		
MLSE	3	logical	
ts_anchor	1		
sample_adjustment	[-8 8]		
Local Search	2		
Filter: Rx FFE			
ffe_pre_tap_len	6	UI	
ffe_post_tap_len	24	UI	
ffe_pre_tap1_max	1		
ffe_post_tap1_max	1		
ffe_tapn_max	1		
FFE_OPT_METHOD	MMSE		FV-LMS or MMSE
num_ui_RXFF_noise	512		
Floating Tap Control			
N_bg	0	0 1 2 or 3 groups	
N_bf	4	taps per group	
N_f	80	UI span for floating taps	
bmaxg	0.2	max DFE value for floating taps	
B_float_RSS_MAX	0.1	rss tail tap limit	
N_tail_start	25	(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	0.278	Fb
f_f	0.278	Fb
f_n	0.278	Fb
f_2	61.625	GHz
A_ft	0.450	V
A_nt	0.450	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