An Analysis Approach to MLSE (and RxFFE) Implementation Penalty

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Introduction

- In the January 2024 Interim meeting equation U1.c was adopted to calculate and represent MLSE effect in COM reference receivers
- MLSE implementation penalty (IP) in this equation is TBD
- This contribution highlights a few common implementation challenges and describes an approach to formulate their effects
- Quantization (or equivalent) noise between CTLE and RxFFE influences optimization of equalization (balance between CTLE and RxFFE) that consequently changes noise and its coloring and should be analyzed in the presence of RxFFE (not just MLSE)
- A set of 112 channels was used for generating test data (see backup slides for channel info)
- COM version: com_ieee8023_93a_430_hs1p0 (see backup slides for COM config)
  - _hs1p0 customizes COM to add quantization noise
- A separate function to execute U1.c, including implementation penalties specific to MLSE
  - Not integrated to speed up massive sweeps

Equation U1.c

$$\Delta COM \approx 20\log_{10}\left(\frac{1}{A_s}CDF_{noise}^{-1}\left(1-\frac{2}{3}DER_{MLSE}\right)\right)-IP$$

$$DER_{MLSE} \approx 2\sum_{j=1}^{\infty}\left(\frac{3}{4}\right)^{j}\left(1-CDF_{noise,jEE}\left(A_s\frac{\left(\mathrm{trace}\left(\rho_{noise,jEE}\right)\right)^{\frac{3}{2}}}{\sqrt{\sum_{vertical}\sum_{horizontal}\left(\rho_{noise,jEE}\right)}}\right)\right)$$

$$PDF_{noise,jEE}(x)^{\dagger} = PDF_{noise}(x) * \mathrm{conv}_{i=2}^{j}\frac{1}{1-\alpha}PDF_{noise}\left(\frac{x}{1-\alpha}\right) * \frac{1}{\alpha}PDF_{noise}\left(\frac{x}{\alpha}\right)$$

$$\rho_{noise,jEE} = \begin{bmatrix} 1 & -(1-\alpha)\rho_1 & +(1-\alpha)\rho_2 & \cdots & (-1)^{j+1}\alpha\rho_j \\ -(1-\alpha)\rho_{-1} & (1-\alpha)^2 & -(1-\alpha)^2\rho_1 & \cdots & (-1)^{j}\alpha(1-\alpha)\rho_{j-1} \\ +(1-\alpha)\rho_{-2} & -(1-\alpha)^2\rho_{-1} & (1-\alpha)^2 & \cdots & (-1)^{j-1}\alpha(1-\alpha)\rho_{j-2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ (-1)^{j+1}\alpha\rho_{-j} & (-1)^{j}\alpha(1-\alpha)\rho_{-(j-1)} & (-1)^{j-1}\alpha(1-\alpha)\rho_{-(j-2)} & \cdots & \alpha^2 \end{bmatrix}$$

← α is the DFE tap and ρ_i's are R_{NN} values symmetrically around $\rho_0 = 1$

$$R_{NN}(\tau) = \mathcal{F}^{-1}\{PSD_{noise}\}$$

$$PSD_{Noise} = PSD_{Rx\ Noise} + PSD_{Tx\ Noise} + PSD_{Xtalk\ Noise} + PSD_{Jitter\ Noise} + PSD_{ISI\ Noise}$$

← At the Rx FFE Output

† Note that this is the same equation as in previous presentations, but with PDF normalization explicitly shown

Pre-MLSE Screening

- There was a concern with cases where although MLSE output may meet COM target, its input may not be adequate for clock recovery
- These case are not likely since MLSE improvement is not huge (maximum a couple of dBs)
- Regardless, a pre-screening can be put in place to ignore MLSE for these cases
- The easiest screening is to ignore cases with poor pre-MLSE COM
  - Screening based on pre-MLSE COM < 0 was implemented in U0 in COM v4.0 beta
  - Since COM is relative and based on the target error rate, it is not a direct proxy of the quality of signal
- A better approach is to monitor a more direct proxy such as error rate (or SNR) at the DFE output
  - Easy to implement as COM already generates this information
  - Need to agree on the CDR error rate or SNR threshold

Sequence Truncation

- One of the practical simplifications to MLSE is to limit length of the sequence
  - To reduce cost and latency
- There are several ways this can be implemented, but they all share a similar concept
- The case considered here for analysis is the extreme case
  - Reduces the sequence processing and trace-back to the truncated length
- Error events longer than the truncated sequence length (sl) will not converge (sub-optimum, hence penalty)
- See backup slides for more details

Equation U1.c Including Sequence Truncation Penalty

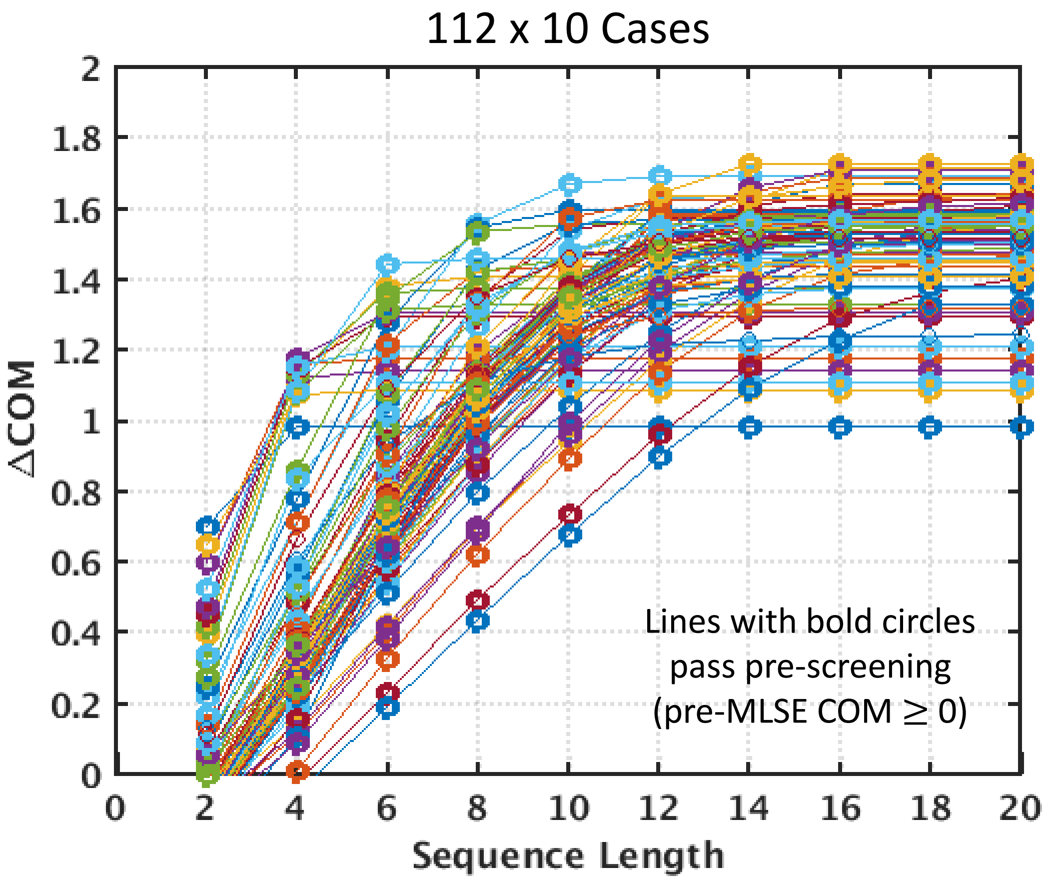
$$PDF_{noise,jEE}(x) = \begin{cases} PDF_{noise}(x) * \mathrm{conv}_{i=2}^{j} \frac{1}{1-\alpha} PDF_{noise}\left(\frac{x}{1-\alpha}\right) * \frac{1}{\alpha} PDF_{noise}\left(\frac{x}{\alpha}\right) & , j < sl \\ PDF_{noise}(x) * \mathrm{conv}_{i=2}^{sl} \frac{1}{1-\alpha} PDF_{noise}\left(\frac{x}{1-\alpha}\right) & j = sl \end{cases}$$

$$\rho_{noise,jEE} = \begin{cases} \rho_{noise,jEE}\big((j+1) \times (j+1)\big) & , j < sl \\ \rho_{noise,jEE}\big((1{:}\,sl) \times (1{:}\,sl)\big) & j = sl \end{cases}$$

$$DER_{MLSE} \approx 2 \sum_{j=1}^{sl} \left(\frac{3}{4}\right)^{j} \left(1 - CDF_{noise,jEE}\left(A_s \frac{\left(\mathrm{trace}\left(\rho_{noise,jEE}\right)\right)^{\frac{3}{2}}}{\sqrt{\sum_{vertical} \sum_{horizental}\left(\rho_{noise,jEE}\right)}}\right)\right)$$

$$\Delta COM \approx 20 \log_{10}\left(\frac{1}{A_s} CDF_{noise}^{-1}\left(1 - \frac{2}{3} DER_{MLSE}\right)\right) - IP(other\ than\ Truncation)$$

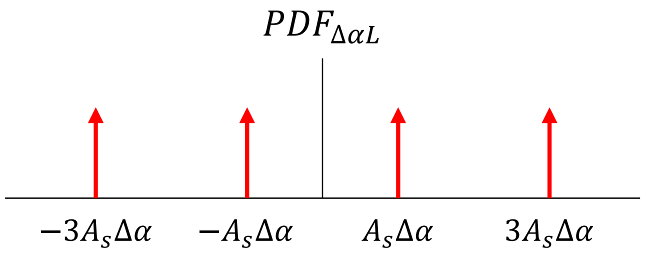
Test Results – Sequence Truncation



- Truncating to shorter than 16-20 samples causes noticeable drop of ΔCOM for several cases

α Mismatch

- What if the MLSE parameter is not exactly matched to the post-curser of the equalized pulse response?
  - Post-curser $= \alpha$
  - MLSE parameter $= \alpha' = \alpha + \Delta\alpha$
- MLSE error analysis (shakiba_3dj_elec_01a_230504.pdf) shows that this mismatch can be modeled with a new noise component with this PDF:



- Add this noise to the noise and proceed with U1.c
- See backup slides for more details

Equation U1.c Including α Mismatch Penalty

$$PDF_{noise+mismatch} = PDF_{noise} * PDF_{\Delta\alpha L}$$

$$PDF_{noise+mismatch,jEE}(x) = \begin{cases} PDF_{noise+mismatch}(x) * \mathrm{conv}_{i=2}^{j} \frac{1}{1-\alpha'} PDF_{noise+mismatch}\left(\frac{x}{1-\alpha'}\right) * \frac{1}{\alpha'} PDF_{noise+mismatch}\left(\frac{x}{\alpha'}\right) & ,j < sl \\ PDF_{noise+mismatch}(x) * \mathrm{conv}_{i=2}^{sl} \frac{1}{1-\alpha'} PDF_{noise+mismatch}\left(\frac{x}{1-\alpha'}\right) & j = sl \end{cases}$$

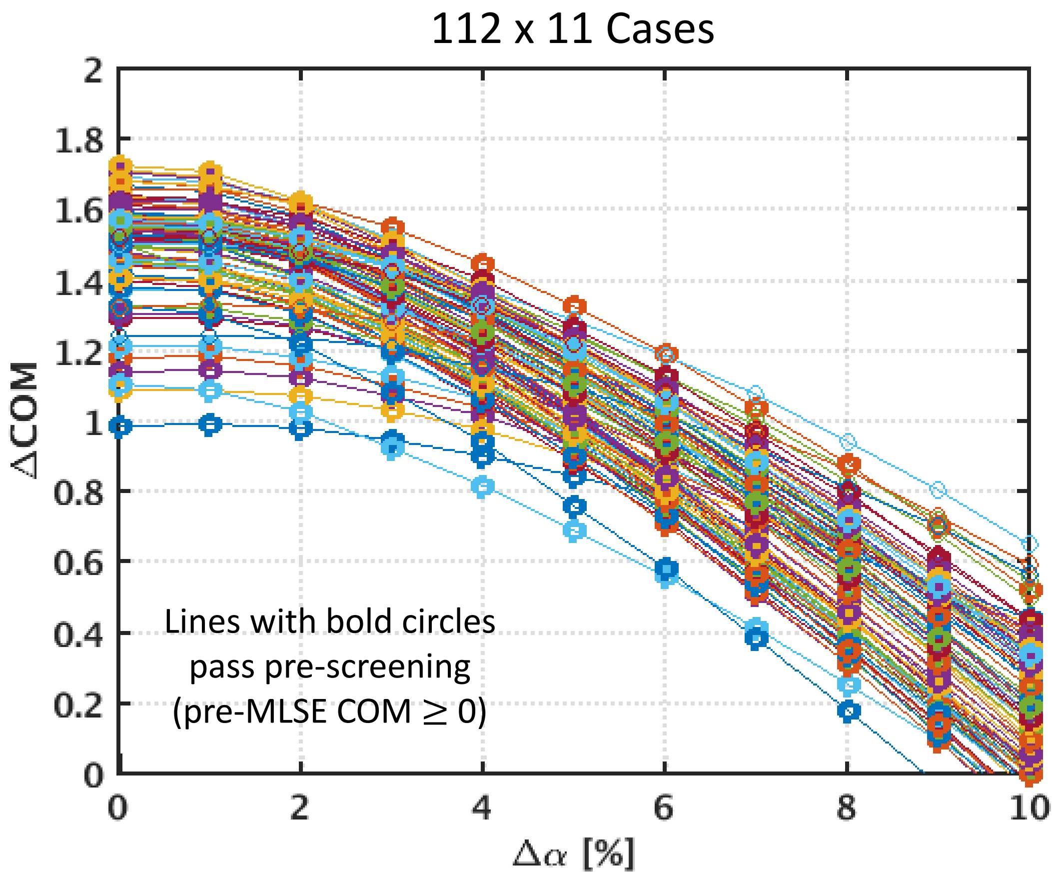
$$\rho_{noise,jEE} = \begin{cases} \rho_{noise,jEE}\big((j+1)\times(j+1)\big) & ,j < sl \\ \rho_{noise,jEE}\big((1:sl)\times(1:sl)\big) & j = sl \end{cases}$$

$$DER_{MLSE} \approx 2\sum_{j=1}^{sl}\left(\frac{3}{4}\right)^{j}\left(1 - CDF_{noise+mismatch,jEE}\left(A_s \frac{\left(\mathrm{trace}(\rho_{noise,jEE})\right)^{\frac{3}{2}}}{\sqrt{\sum_{vertical}\sum_{horizental}(\rho_{noise,jEE})}}\right)\right)$$

$$\Delta COM \approx 20\log_{10}\left(\frac{1}{A_s} CDF_{noise+mismatch}^{-1}\left(1 - \frac{2}{3} DER_{MLSE}\right)\right) - IP(other\ than\ Truncation\ and\ Mismatch)$$

- Equations also include the effect of sequence truncation

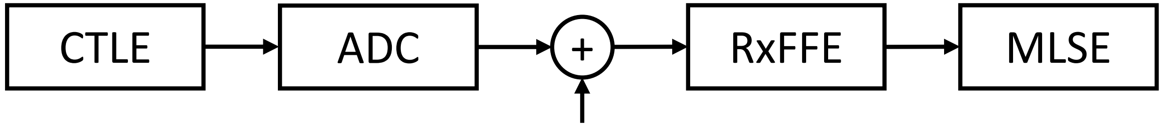
Test Results – α Mismatch



- α mismatch of more than 2% causes noticeable drop of ΔCOM for majority of cases

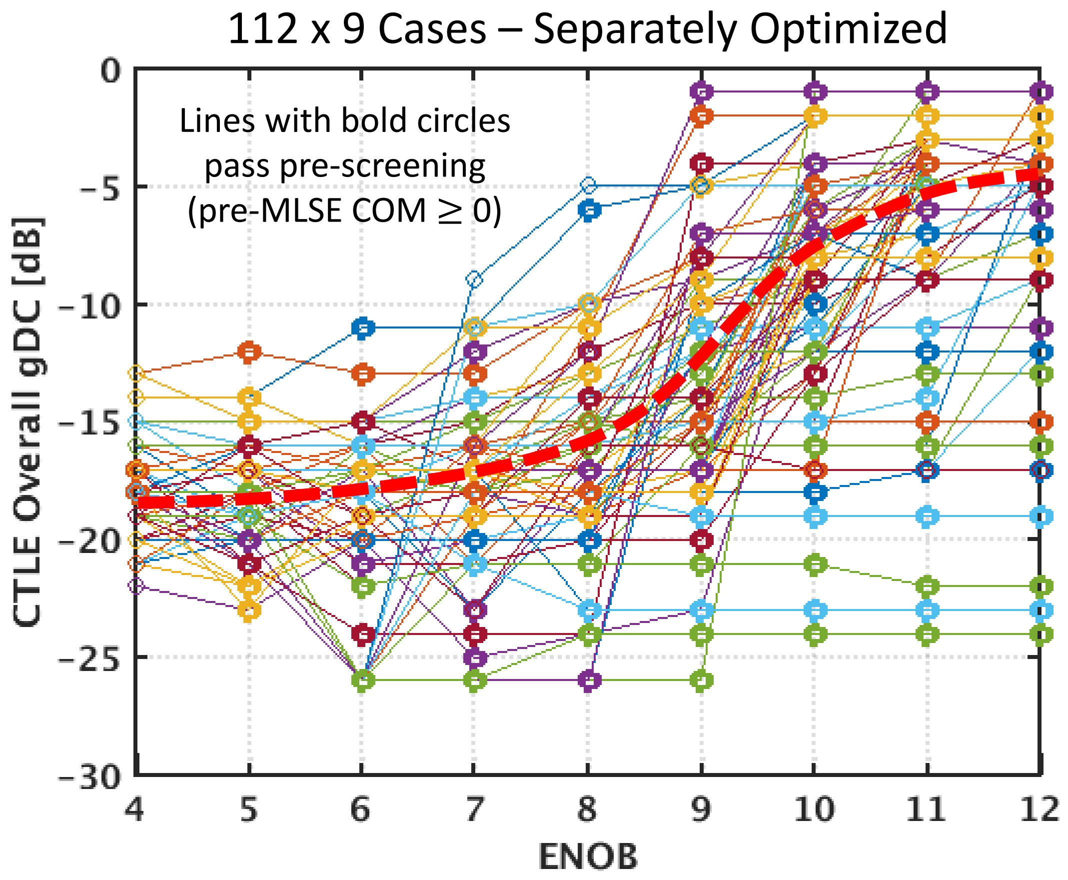
Quantization Noise

- Since ADC almost always precedes RxFFE, its quantization noise affects both RxFFE and MLSE



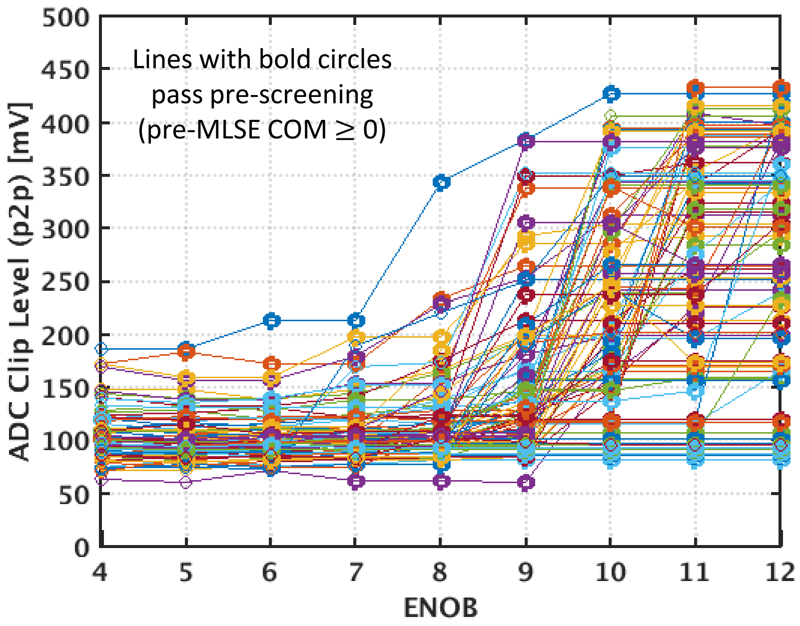
- This makes study of the quantization noise dependent on RxFFE and its optimization
- In the absence of quantization noise, the optimizer tends to favor RxFFE over CTLE
- As a result of CTLE under-utilization, its output could be severely under-equalized
- This forces a large input dynamic range, hence increased number of required bits, on the ADC
- The bottom line is that the quantization noise is impactful, changes the optimization results, and must be considered for the combination of RxFFE and MLSE
- In the absence of ADC or when it is after RxFFE, considering an 'equivalent' noise between CTLE and FFE is still reasonable and helpful
- As for the MLSE IP, once quantization noise is added to COM, U1.c takes it into consideration

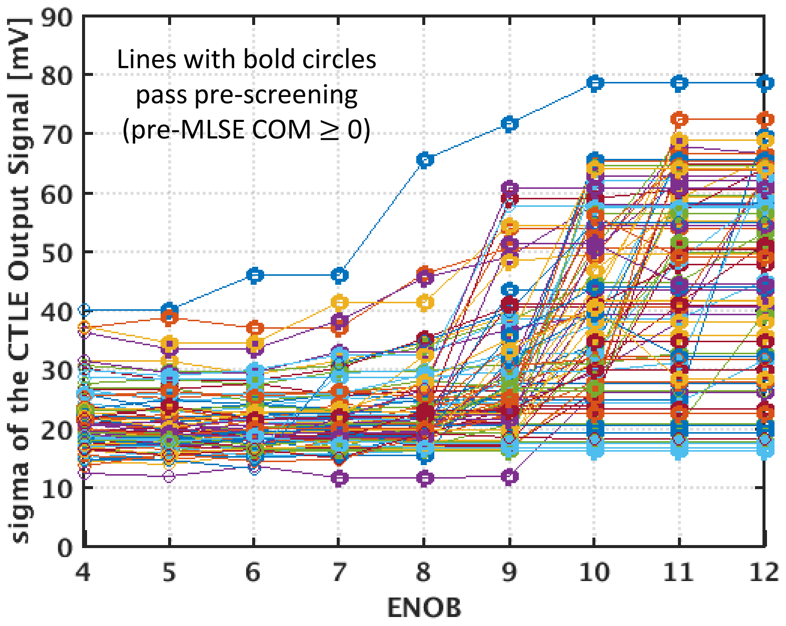
Test Results – Effect of Quantization Noise (Not Including MLSE)

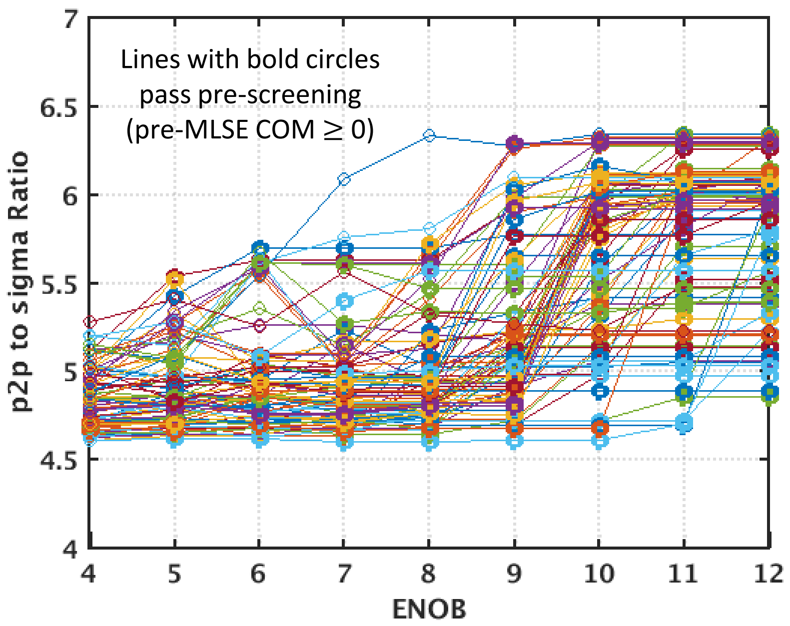


- Finer quantization (larger ENOB) pushes more equalization to RxFFE and less to CTLE
- CTLE utilization on average reduces from ~18dB to ~5dB as ENOB increases from 4 to 12 bits

Test Results – Effect of Quantization Noise (Not Including MLSE)

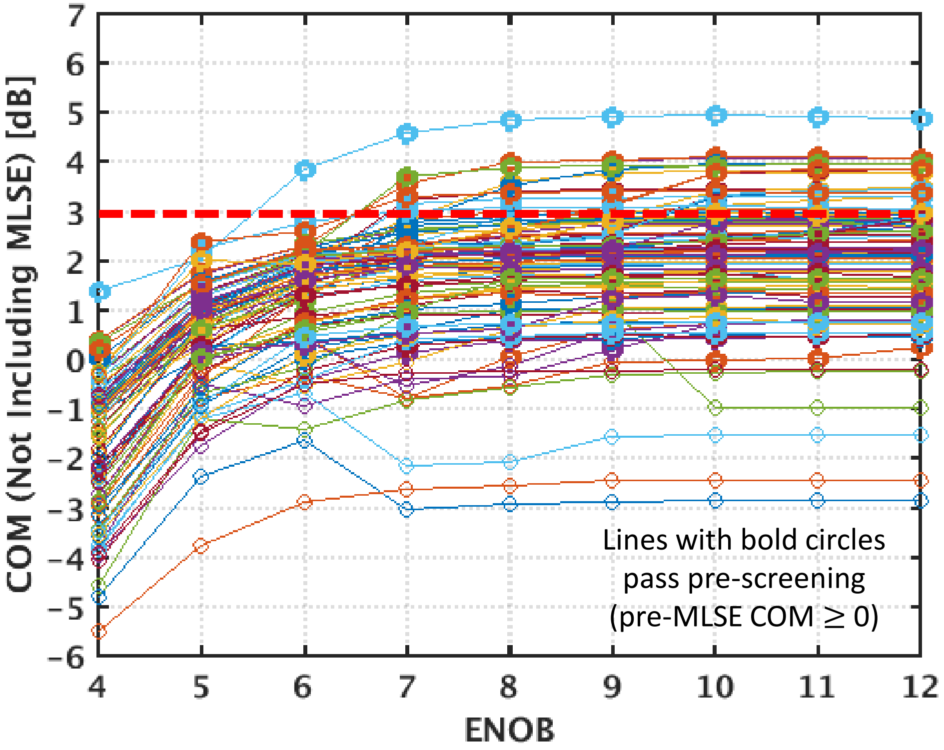


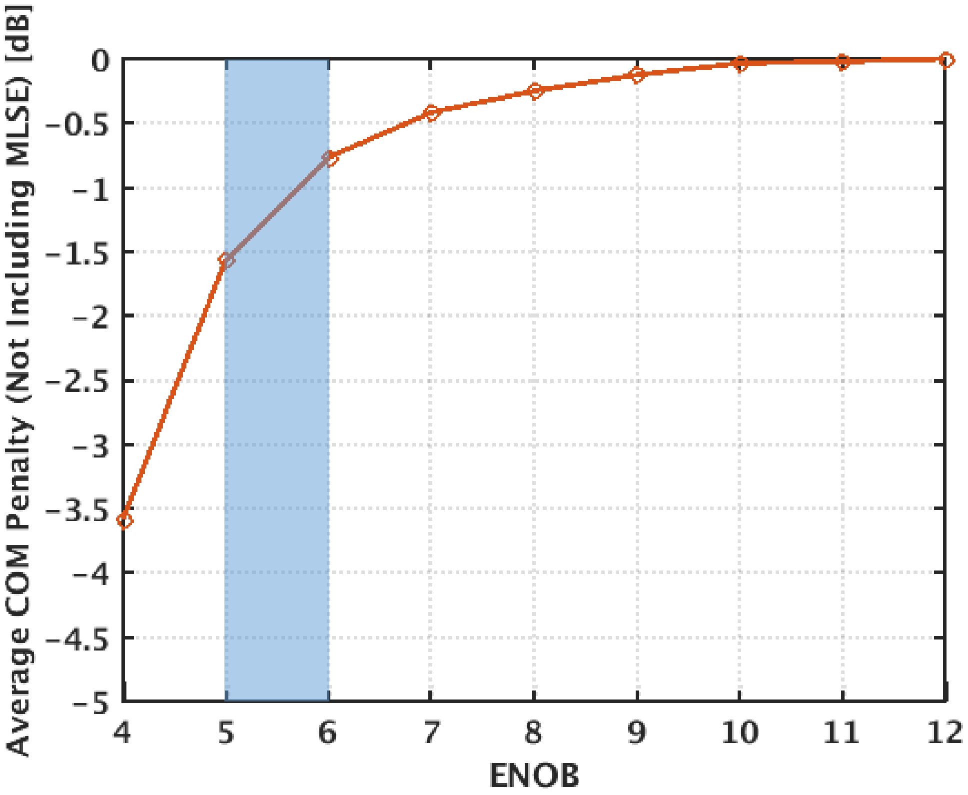




- CTLE marginalization increases p2p and sigma of the (under-equalized) signal at its output (ADC input)
- To mimic this in practice, ADCs with large dynamic range and ENOB are required (beyond what is readily available in today’s technologies
- Clip level is calculated from the signal PDF for a clipping frequency equal to error rate

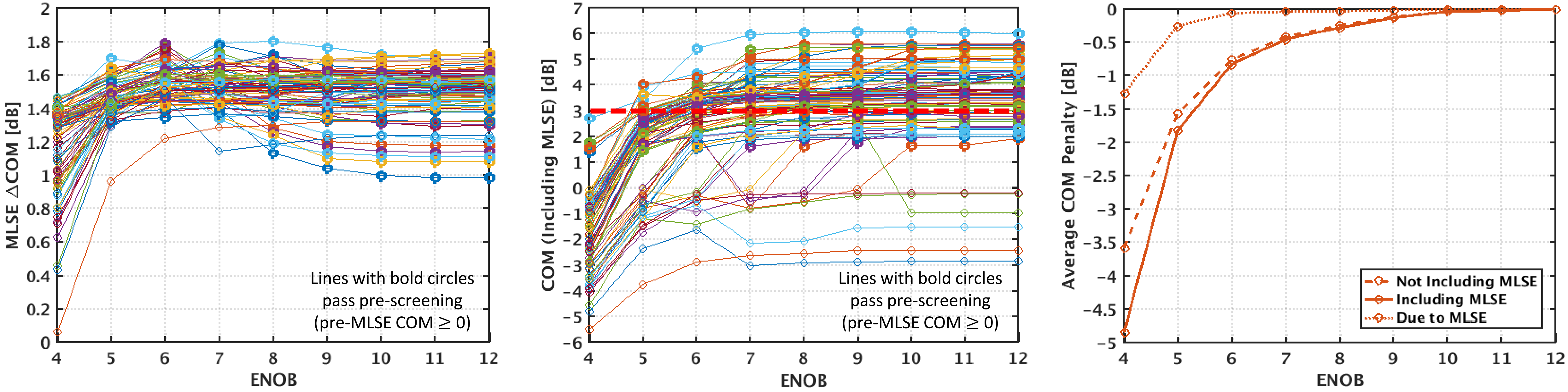
Test Results – Effect of Quantization Noise (Not Including MLSE)





- A considerable drop in COM is expected unless much better ADCs become available
- For example, for ENOB of 5 to 6 average COM drops by 1.57dB to 0.77dB
- Even if ENOB improves by 1-2 bits, there is still a COM penalty that cannot be ignored

Test Results – Effect of Quantization Noise (Including MLSE)



- If COM (not including MLSE) is negative, MLSE ΔCOM is ignored and set to zero for calculating COM (including MLSE)
- For ENOBs of 6 and larger, average COM penalty is almost entirely due to the overall effect of quantization noise and not because of MLSE
- For ENOBs less than 6, although MLSE penalty increases, but the overall penalty is still mostly due to the overall effect of quantization noise
- For the reason of reduced MLSE ΔCOM at larger ENOB for some channels see backup slides

Summary

- MLSE implementation penalty (IP) in equation U1.c is TBD
- An analysis approach was presented to estimate common implementation penalties of MLSE
  - CDR concern
  - Sequence length truncation
  - α mismatch
  - Quantization (or equivalent) noise
- These penalties are considered common denominator of different implementation techniques
- Effect of quantization (or equivalent) noise goes beyond MLSE and extends to FFE and optimization results
- Naturally, the implementation penalties are case dependent and could vary considerably
- A set of 112 channels used for generating test data
- Data shows how the analysis can estimate the penalties on a case basis

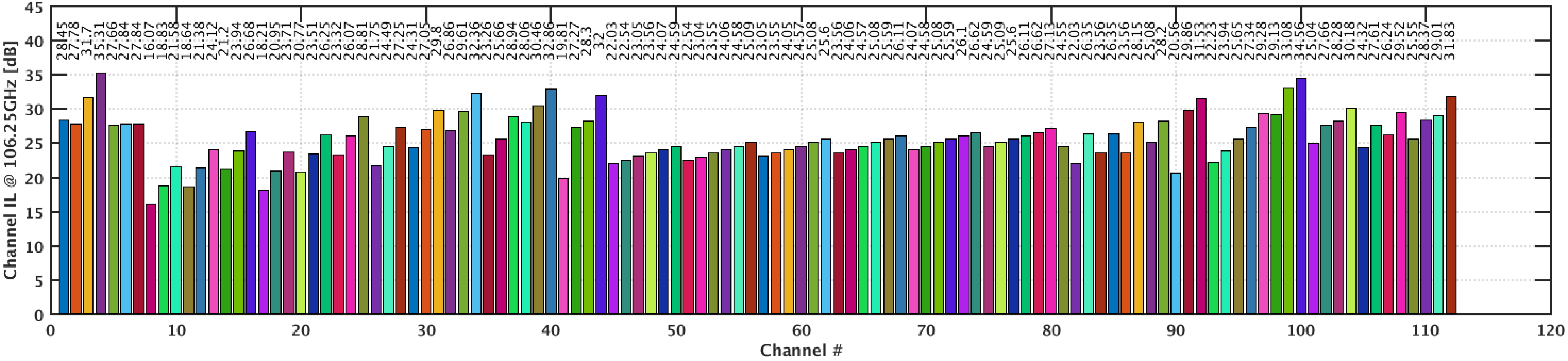
Backup Slides

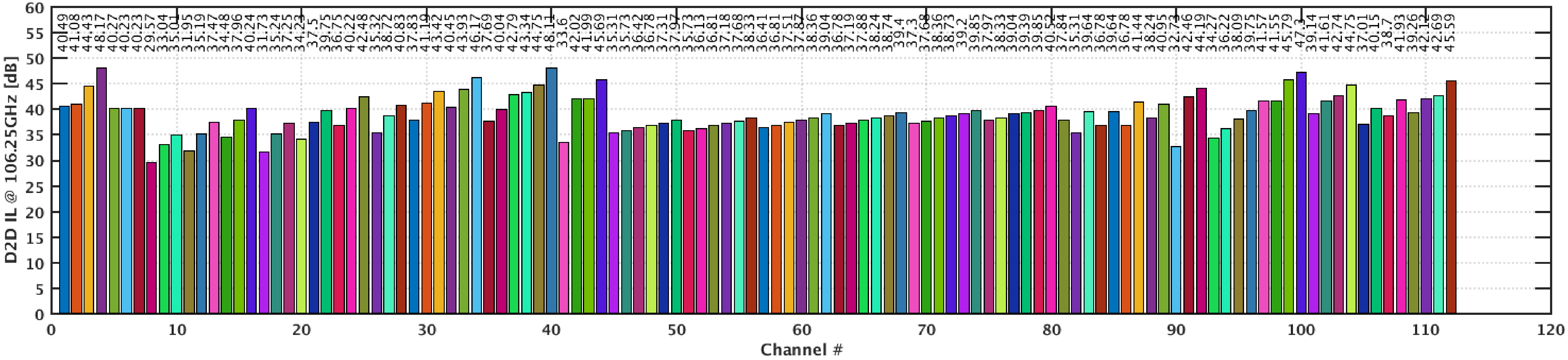
Test Channels

- The same set of 112 channels used in shakiba_3dj_01b_2401.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





COM Spreadsheet

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/dffe1
b_max(2..N_b)	0.3		As/dfe2..N_b
b_min(1)	0		As/dffe1
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	4.00E-09	dB
SNR_TX	33	
R_LM	0.95	
BREAD_CRUMBS	1	logical
[illegible]	[illegible]	[illegible]

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 11; 11 1 1 ; 0	mm	[test cases to run]
z_p (NEXT)	1 11; 11 1 1 ; 0	mm	[test cases]
z_p (FEXT)	1 11; 11 1 1 ; 0	mm	[test cases]
z_p (RX)	1 11; 11 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	0	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

COM Spreadsheet

.START	PKG_LowR_CLASSA	[2.44 5.7] db	
Table 93A-3 parameters			
Parameter	Setting	Units	Information
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	
R_d	[50 50]	Ohm	[TX RX]
z_p (TX)	[12 33 33 33 ; 1.8 1.8 1.8 1.8 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[12 33 33 33 ; 1.8 1.8 1.8 1.8 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[12 33 33 33 ; 1.8 1.8 1.8 1.8 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (RX)	[12 33 33 33 ; 1.8 1.8 1.8 1.8 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
C_p	[0.4e-4 0.4e-4]	nF	[TX RX]
A_v	[0.4057 0.4143 0.4143 0.4143]	V	Vf=0.400
A_fe	[0.4057 0.4143 0.4143 0.4143]	V	Vf=0.399
A_ne	[0.600 0.600 0.600 0.600]	V	Vf=0.400
.END			

.START	PKG_HiR_CLASSB	[2.8 5.6 6.7 9.4] db	
Table 93A-3 parameters			
Parameter	Setting	Units	Information
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	
R_d	[50 50]	Ohm	[TX RX]
z_p (TX)	[8 24 30 45 ; 2 2 2 2; 1.3 1.3 1.3 1.3 ; 1.5 1.5 1.5 1.5]	mm	[test cases]
z_p (NEXT)	[8 24 30 45 ; 2 2 2 2; 1.3 1.3 1.3 1.3 ; 1.5 1.5 1.5 1.5]	mm	[test cases]
z_p (FEXT)	[8 24 30 45 ; 2 2 2 2; 1.3 1.3 1.3 1.3 ; 1.5 1.5 1.5 1.5]	mm	[test cases]
z_p (RX)	[8 24 30 45 ; 2 2 2 2; 1.3 1.3 1.3 1.3 ; 1.5 1.5 1.5 1.5]	mm	[test cases]
C_p	[0.4e-4 0.4e-4]	nF	[TX RX]
A_v	[0.4049 0.4114 0.4132 0.4173]	V	Vf=0.400
A_fe	[0.4049 0.4114 0.4132 0.4173]	V	Vf=0.399
A_ne	[0.600 0.600 0.600 0.600]	V	Vf=0.400
.END			

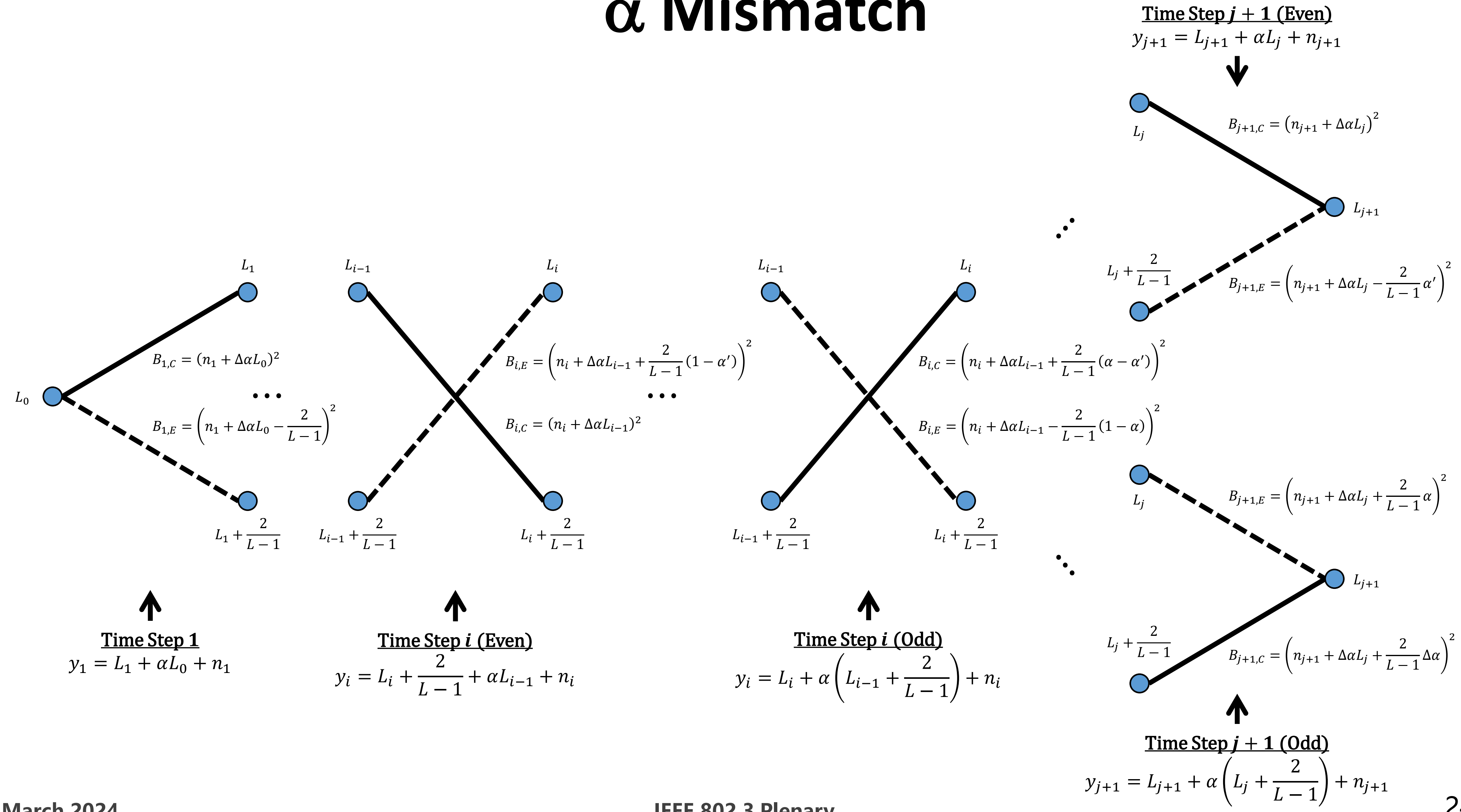
.START	PKG_Module		
Table 93A-3 parameters			
Parameter	Setting	Units	Information
package_tl_gamma0_a1_a2	[0.0005 0.00089 0.0002]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[87.5 87.5 ; 95 95 ; 100 100; 100 100]	Ohm	
R_d	[50 50]	Ohm	[TX RX]
z_p (TX)	[8 8 8 8 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[8 8 8 8 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[8 8 8 8 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (RX)	[8 8 8 8 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
C_p	[0.4e-4 0.4e-4]	nF	[TX RX]
A_v	[0.4057 0.4057 0.4057 0.4057]	V	Vf=0.400
A_fe	[0.4057 0.4057 0.4057 0.4057]	V	Vf=0.399
A_ne	[0.600 0.600 0.600 0.600]	V	Vf=0.400
.END			

.START	PKG_Null		
Table 93A-3 parameters			
Parameter	Setting	Units	Information
package_tl_gamma0_a1_a2	[5e-4 0.001 0.03]		
package_tl_tau	0.006141	ns/mm	
package_Z_c	[92 92 ; 70 70; 80 80; 100 100]	Ohm	
R_d	[50 50]	Ohm	[TX RX]
z_p (TX)	[0 0 0 0 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (NEXT)	[0 0 0 0 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[0 0 0 0 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (RX)	[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	0.5	V	Vf=0.400
A_fe	0.5	V	Vf=0.400
A_ne	0.61	V	
.END			

Sequence Truncation

- Reduces both sequence processing and trace-back to the truncated length
- Equation U1.c executes to the truncated sequence length (sl) terms
- All the error events of smaller than sl will be processed fully and:
  - U1.c directly applies
- The last error event of length sl will be processed partially and:
  - The MLSE sequence noise now has sl terms (instead of $sl + 1$)
  - The PDF convolution expression iterates $sl - 1$ times (lacks the last term due to truncation)
  - Particularly, lack of the last convolution term ($* (1/\alpha)PDF_{noise}(x/\alpha)$) reflects lack of convergence of the error event due to truncation
  - For the last term in U1.c, the correlation matrix $\rho_{noise,jEE}((sl+1) \times (sl+1))$ is truncated to the $\rho_{noise,jEE}(sl \times sl)$ sub-matrix

α Mismatch


Time Step $j+1$ (Even)
$y_{j+1} = L_{j+1} + \alpha L_j + n_{j+1}$
L_j
$B_{j+1,C} = (n_{j+1} + \Delta\alpha L_j)^2$
L_{j+1}
$L_j + \frac{2}{L-1}$
$B_{j+1,E} = \left(n_{j+1} + \Delta\alpha L_j - \frac{2}{L-1}\alpha'\right)^2$
L_1
L_{i-1}
L_i
L_{i-1}
L_i
$B_{1,C} = (n_1 + \Delta\alpha L_0)^2$
L_0
$B_{1,E} = \left(n_1 + \Delta\alpha L_0 - \frac{2}{L-1}\right)^2$
$B_{i,E} = \left(n_i + \Delta\alpha L_{i-1} + \frac{2}{L-1}(1-\alpha')\right)^2$
$B_{i,C} = (n_i + \Delta\alpha L_{i-1})^2$
$B_{i,C} = \left(n_i + \Delta\alpha L_{i-1} + \frac{2}{L-1}(\alpha-\alpha')\right)^2$
$B_{i,E} = \left(n_i + \Delta\alpha L_{i-1} - \frac{2}{L-1}(1-\alpha)\right)^2$
L_j
$B_{j+1,E} = \left(n_{j+1} + \Delta\alpha L_j + \frac{2}{L-1}\alpha\right)^2$
$L_1 + \frac{2}{L-1}$
$L_{i-1} + \frac{2}{L-1}$
$L_i + \frac{2}{L-1}$
$L_{i-1} + \frac{2}{L-1}$
$L_i + \frac{2}{L-1}$
L_{j+1}
$L_j + \frac{2}{L-1}$
$B_{j+1,C} = \left(n_{j+1} + \Delta\alpha L_j + \frac{2}{L-1}\Delta\alpha\right)^2$
Time Step 1
$y_1 = L_1 + \alpha L_0 + n_1$
Time Step i (Even)
$y_i = L_i + \frac{2}{L-1} + \alpha L_{i-1} + n_i$
Time Step i (Odd)
$y_i = L_i + \alpha\left(L_{i-1} + \frac{2}{L-1}\right) + n_i$
Time Step $j+1$ (Odd)
$y_{j+1} = L_{j+1} + \alpha\left(L_j + \frac{2}{L-1}\right) + n_{j+1}$

α Mismatch

- An error event occurs if:

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

$$\left(n_1 + (1-\alpha')\sum_{i=2}^{j} n_i + \alpha' n_{j+1}\right) + \Delta\alpha\left(L_0 + (1-\alpha')\sum_{i=2}^{j} L_{i-1} + \alpha' L_j\right) > \frac{1}{L-1}\left(1 + (j-1)(1-\alpha')^2 + {\alpha'}^2\right) - \frac{2\Delta\alpha}{L-1}\left(\left\lfloor\frac{j-1}{2}\right\rfloor(1-\alpha') - \alpha' \mathrm{mod}(j+1\,,2)\right)$$

- Two new terms in red are due to α mismatch (zero if there is no mismatch)
- The LHS red term is random (depends on PAM levels throughout the error event)
- The RHS red term is constant for each error event and negligible
- After rewriting, a new mismatch noise term ($\Delta\alpha L_i\ , i = 0\ to\ j$) is added to each previous noise sample ($n_i\ , i = 1\ to\ j+1$)

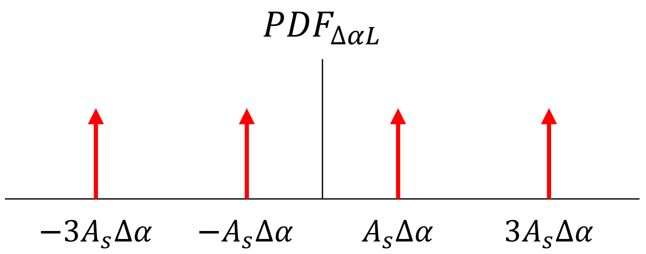
$$(n_1 + \Delta\alpha L_0) + (1-\alpha')\sum_{i=2}^{j}(n_i + \Delta\alpha L_{i-1}) + \alpha'\left(n_{j+1} + \Delta\alpha L_j\right) > \frac{1}{L-1}\left(1 + (j-1)(1-\alpha')^2 + {\alpha'}^2\right)$$

α Mismatch

- New combined PDF for the total noise:

$$PDF_{noise+mismatch} = PDF_{noise} * PDF_{\Delta\alpha L}$$

- PDF_{noise} is the PDF of the previous noise (calculated by COM)
- PDF of the new mismatch noise ($PDF_{\Delta\alpha L}$) depends on PAM levels (A_s) and mismatch ($\Delta\alpha$)

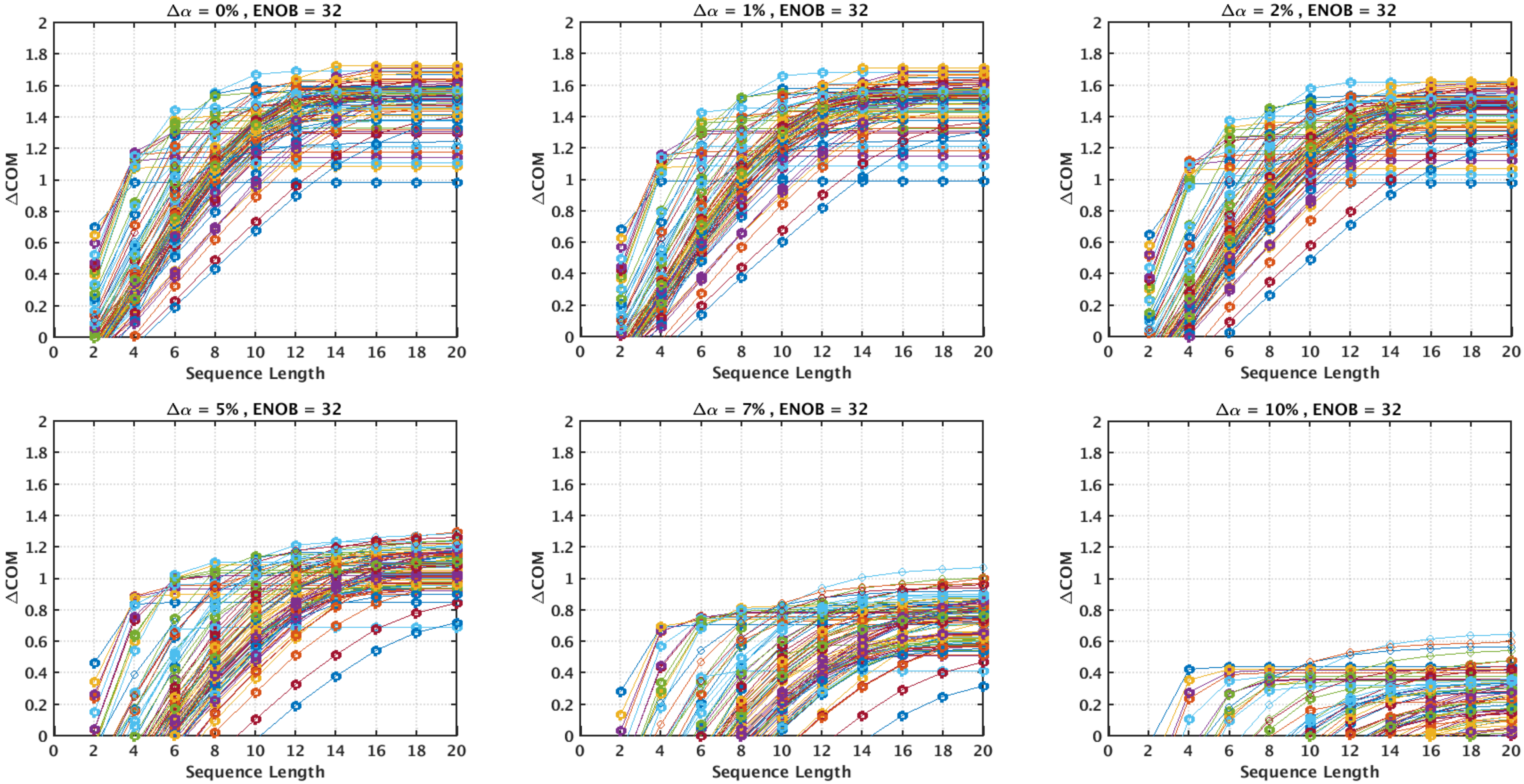


- Mismatch can be modeled as a new noise term
- In executing U1.c the following changes should be applied:
  1) Replace α with α'
  2) Replace PDF_{noise} with $PDF_{noise+mismatch}$
  3) Replace $CDF_{noise,jEE}$ with $CDF_{noise+mismatch,jEE}$ (which would result from 1)

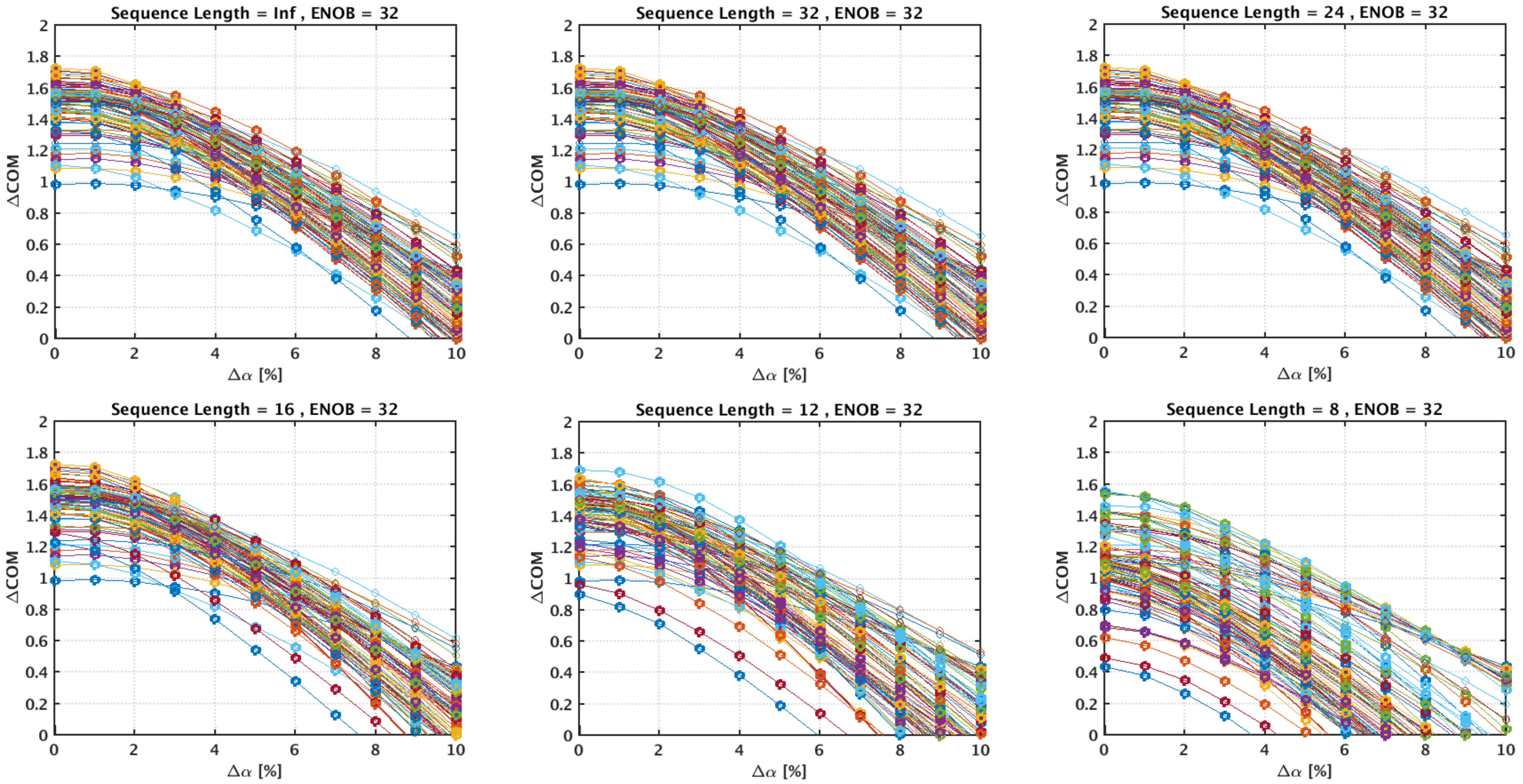
Combination of Penalties

- Pre-screening will bypass MLSE for the cases with a pre-MLSE signal quality concern for proper CDR operation
- Equation U1.c on slide 10 reflects the combined effects of sequence truncation and α mismatch
- By adding quantization (or equivalent) noise to the COM flow, COM will include it in the optimization process and generates the overall noise, including the quantization (or equivalent) noise, and consequently the proper input to the MLSE calculator to execute U1.c
- Following slides show example test results with multiple sweeps for when more than one penalty is considered at a time

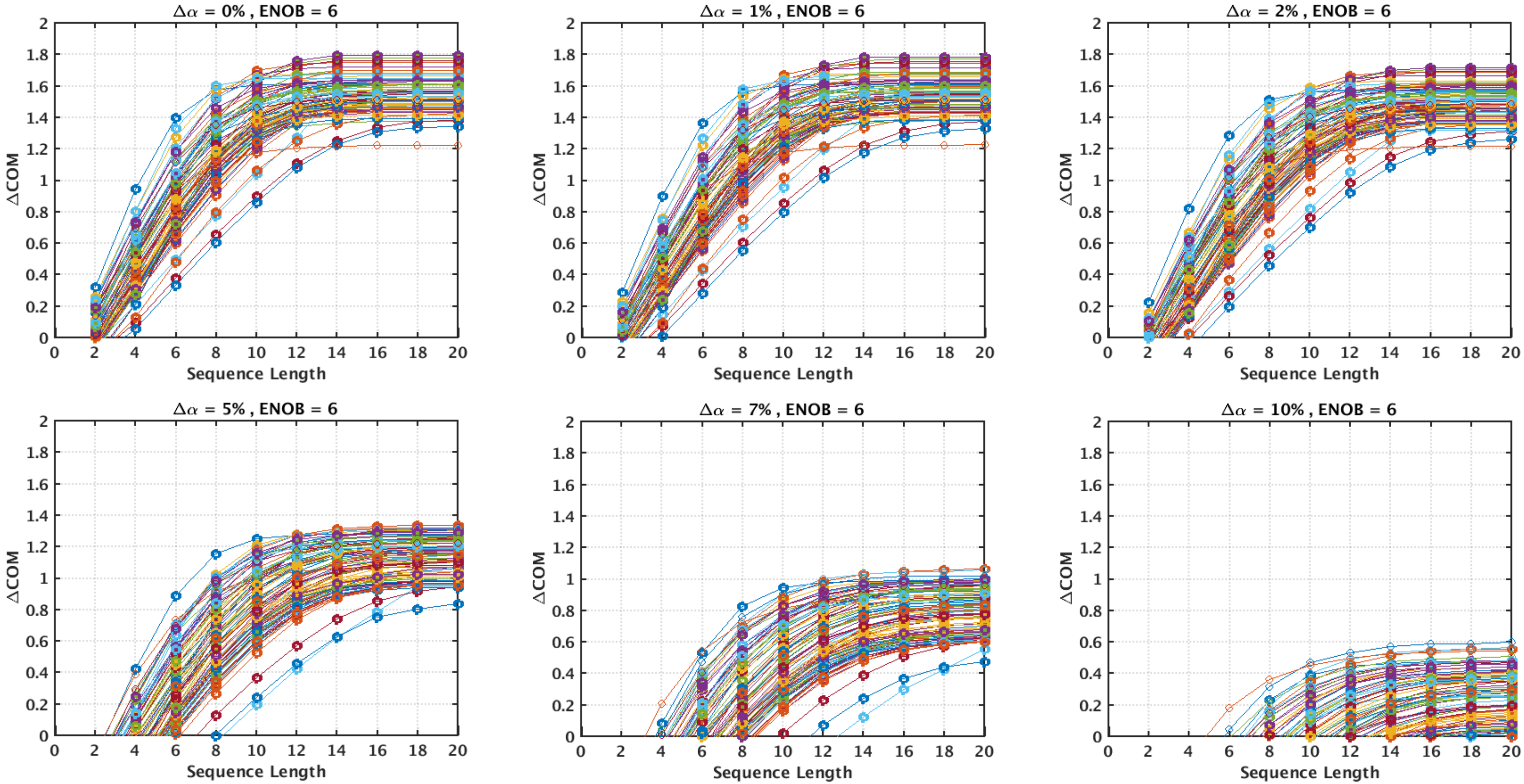
Test Results – Sequence Truncation and α Mismatch at ENOB = 32



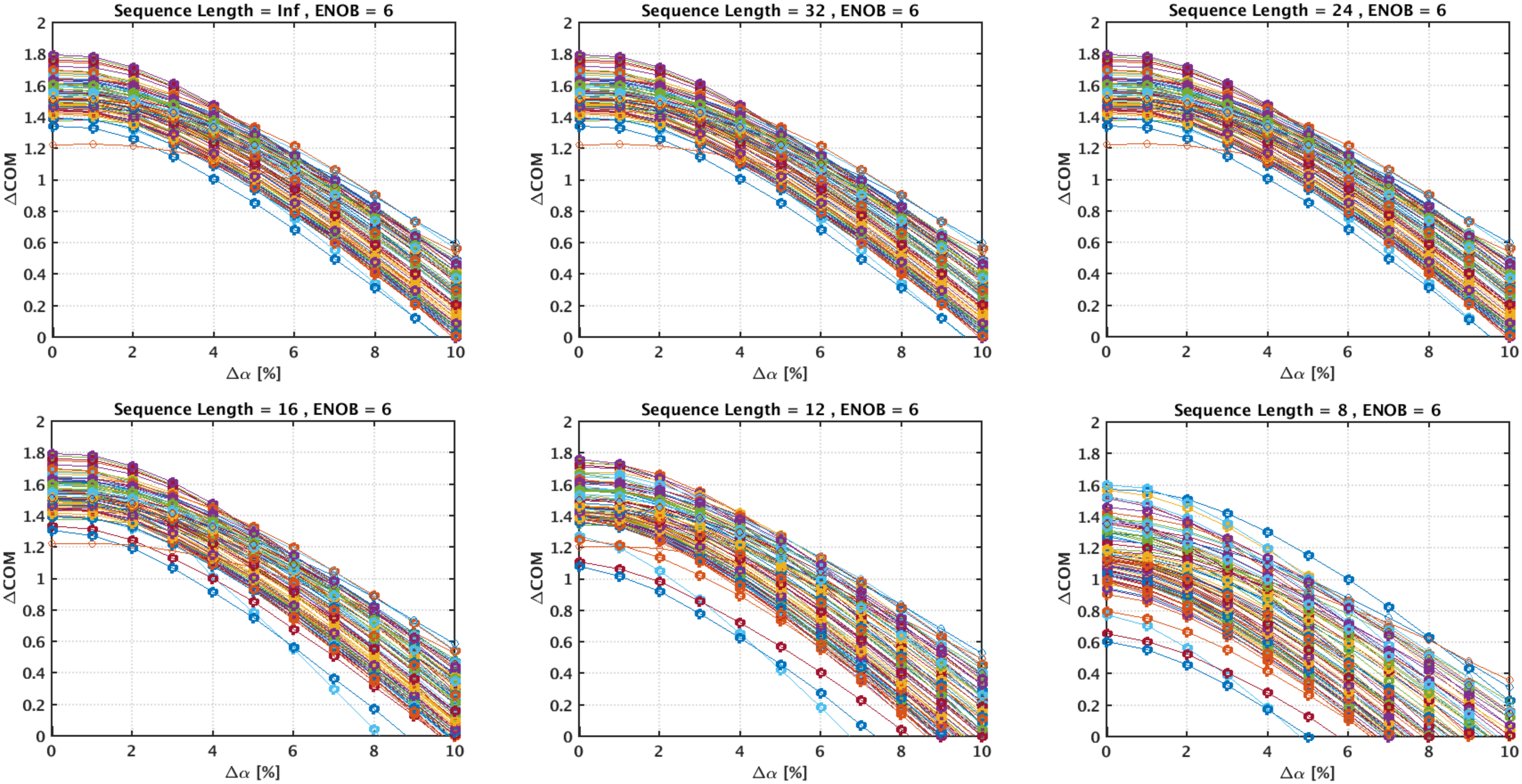
Test Results – α Mismatch and Sequence Truncation at ENOB = 32



Test Results – Sequence Truncation and α Mismatch at ENOB = 6

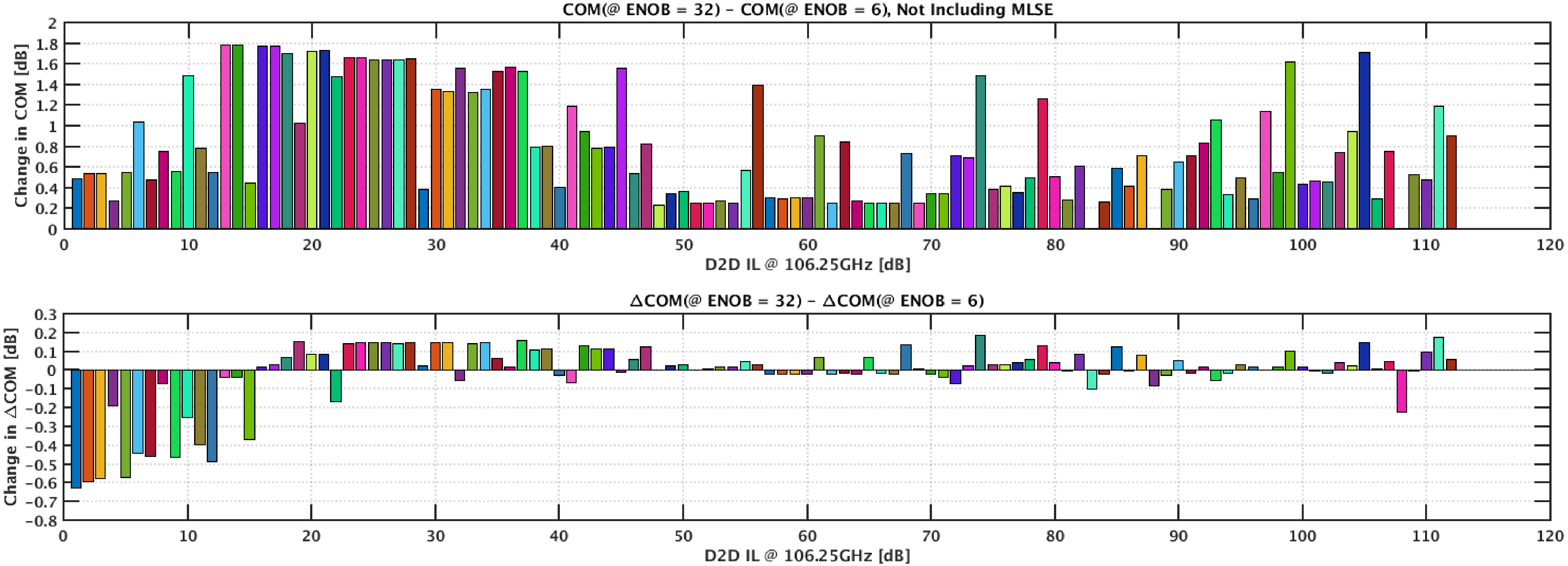


Test Results – α Mismatch and Sequence Truncation at ENOB = 6



Reduction of ΔCOM at Larger ENOB for some Channels

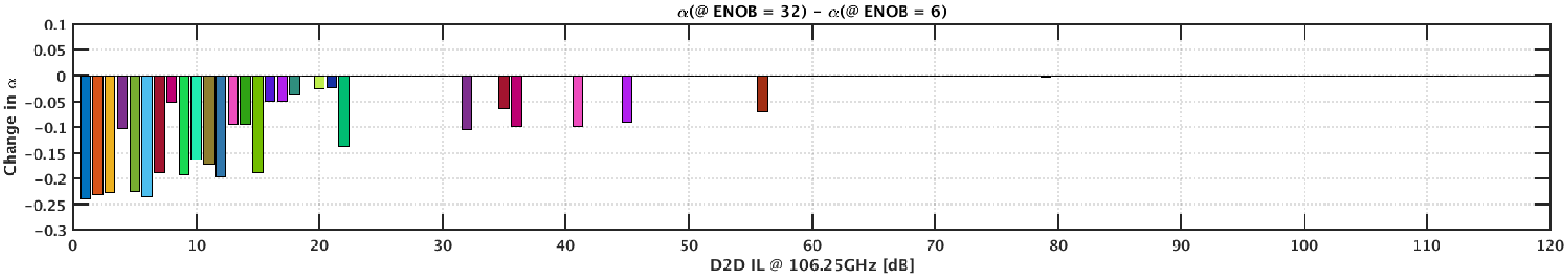
- Test data show that for some channels ΔCOM degrades even though quantization noise reduces and pre-MLSE COM improves



- More pronounced for lower loss channels

Reduction of ΔCOM at Larger ENOB for some Channels

- Every time ENOB changes optimizer re-optimizes
- Optimizer ignores MLSE and assumes DFE
- As a result, α can reduce even if quantization noise reduces



- α saturates for most of the high loss channels
- MLSE performance also depends on other case parameters as well
- A proper optimizer when MLSE exists would consider maximizing α