COM MLSE and DFE Simulation and the Hunt for 0.5 dB

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Contributor's and Supporters

Contributors

- Bill Kirkland, Semtech

Supporters

Summary

- Two minor inaccuracies within the COM tool were found (4.0 and earlier).
  - In practical use (ISI, XC, Jitter) these error impact COM by < 0.5 dB
  - Causes small discrepancies when verifying simulations results....
- These inaccuracies have been corrected in this work

- Simulation results are presented for:
  - MLSE with and without error propagation
    - Only MLSE with error propagation was simulated.
    - Predicted MLSE results (COM MLSE code) are noticeably optimistic
      - Results were converted to “single error events” by counting run lengths > 1 as 1 symbol error
  - DFE with and without error propagation.
    - Predicted DFE results (COM MLSE code) are just slightly optimistic
      - DFE results with error propagation were converted to “single error events” as well for comparison

- The relative deltas between Predicted MLSE and Predicted DFE versus simulated MLSE and simulated DFE are shown to be similar after the inaccuracies are corrected
  - Absolute values don’t quite line up for MLSE with error propagation and DFE with error propagation (very small offset)

Nomenclature

- Within the context of “COM”, DER means PAM symbol error ratio, with the additional concept of excluding error propagation
  - DER: Detector Error Ratio (PAM Symbol Detector)
  - SER: PAM Symbol Error Ratio
    - hence DER = SER
    - With MLSE results, we must clarify, with or without error propagation
  - The MLSE results are with Error Propagation
  - Hence, we must be careful which COM results we look at

  - BER, FLR, Coding Symbol are not used in the context of COM

- Noise Color: Indicates the noise correlation
  - Has nothing to due with the PDF except affect the noise “power”
  - COM tool colors the noise according to Rx Filter, CTLE and FFE
  - COM tool calculates the appropriate PDFs and uses the final PDF to calculate DER

Motivation

- To investigate and understand the MLSE addition to COM tool (4.0 Beta)
  - 4.0 Beta is consistent with the released COM 4.0 wrt MLSE.
- To compare COM tool results against simulation results
- Then investigate the small discrepancy between COM Rx FFE/DFE results and the simulation results
  (Single Error Event i.e. no error propagation)

Simulation Details

- Using COM 4.0Beta, which is consistent with COM 4.0 (for this work)
- Using Akinwale 85 ohm channels and base configuration
  - R_LM set to 1: (too many variations to simulate with)
  - Jitter set to 0: time to amplitude characteristic is troublesome
- COM tool was modified to return required information
  - chdata, XC sampling points, PDF's,
- Simulation used actual chdata, com ctle impulse, Rx FFE and DFE – i.e. as close to COM as can be.
- Simulations were verified against COM. (next slide)
- For MLSE/DFE results: (up to 100e6 Symbols)
  - Initial com results were determined based on the channel and the COM configuration sheet.
  - An A_ni "gain" was applied against the extracted "A_ni" signal to vary the PAM4_SER operating point

COM Config Details for MLSE/DFE Simulation
24 Tap Rx FFE, 1 DFE Tap

RX FFE		
ffe_pre_tap_len	0	UI
ffe_post_tap_len	24	UI
ffe_tap_step_size	0	
fe_main_cursor_mi	0.7	default
ffe_pre_tap1_max	0.7	default
ffe_post_tap1_max	0.7	default
ffe_tapn_max	0.7	default
ffe_backoff	0	

Noise, jitter		
sigma_RJ	0	UI
A_DD	0	UI
eta_0	2.05E-08	V^2/GHz
SNR_TX	32	dB
R_LM	1	

f_r	0.75	*fb	
c(0)	0.54		min
c(-1)	[-0.34:0.02:0]		[min:step:max]
c(-2)	[-0.1:0.02:0.12]		[min:step:max]
c(-3)	[-0.04:0.02: 0]		[min:step:max]
c(1)	[-0.1:0.02:0.2]		[min:step:max]
N_b	1	UI	
b_max(1)	**0.85**		**As/dffe1**
b_max(2..N_b)	**[0.3 0.3 0.2*ones(1,5)]**		**As/dfe2..N_b**
b_min(1)	**0**		**As/dffe1**
b_min(2..N_b)	**[-0.05 -0.05 -0.03*ones(1,5)]**		**As/dfe2..N_b**
g_DC	[-13:1:-2]	dB	[min:step:max]
f_z	42.5	GHz	
f_p1	42.5	GHz	
f_p2	106.25	GHz	
g_DC_HP	[-3:0.5:-0]		[min:step:max]
f_HP_PZ	2.65625	GHz	
G_Qual	[-2 -13 ;-3 -12; -4 -11;5 -10]	dB	ranges
G2_Qual	[0 -1 -2 -3]	dB	ranges
GDC_Min	0	dB	0 disables check.

- **24 tap post cursor Rx FFE**
- **1 Rx DFE tap at h1**
- Tx FFE

- Jitter set to 0
- R_LM set to 1

Verification Details

- COM tool was modified to return:
  - [results, chdata, param, COM_SNR_Struct, Noise_Struct, fom_result]

- The pdf for each A_NI contributor was verified against simulation results based on chdata, CTLE, Rx FFE, DFE

- Eta_0 was found to be 0.5 dB optimistic at the 1e-4 cdf point.
  - In practice, this causes very little error to COM because of the dominance of other A_NI contributors (ISI, XC, Jitter, Tx SNR)
  - The error is in the “normal_dist” function
  - Fixed with: nsigma=2*nsigma; with this function

- After the fix, there remained an ever so small discrepancy:
  With A_NI set for 1e-4 DER, the simulation always yielded 1.5e-4

Thank You Jonathan King

- see page 4 in Jonathan King's presentation: https://www.ieee802.org/3/bs/public/adhoc/smf/15_12_01/king_01_1215_smf.pdf

- We have neglected to account for the change in probabilities due to 3 thresholds versus 1 threshold for PAM 2!

- Relative prob. of errors per symbol = 2.(M-1)/M = 3/2, M=4
  - Rel_Prob_Errors_per_Symbol = 2*(M-1) / M;
  - Qt_PAM2 = qfuncinv(DER);
  - Qt_PAM = qfuncinv(DER / Rel_Prob_Errors_per_Symbol);
  - Qt_Correct = Qt_PAM2 / Qt_PAM;

  - Results in a 0.9735 (-0.23 dB) correction for PAM4_SER (or DER) = 1e-4
  - see attached verification script, 'Gaussian_COM.m'

Simulation

- Run COM tool (with changes) per spread sheet and return:

  results, chdata, OP, param, output_args, COM_SNR_Struct, Noise_Struct, fom_result
  - plus a couple of extra modifications, e.g. Xtalk sampling points

- Generate Tx Data and run it through the channels (chdata) along with Tx Noise, Xtalk, and Rx Noise

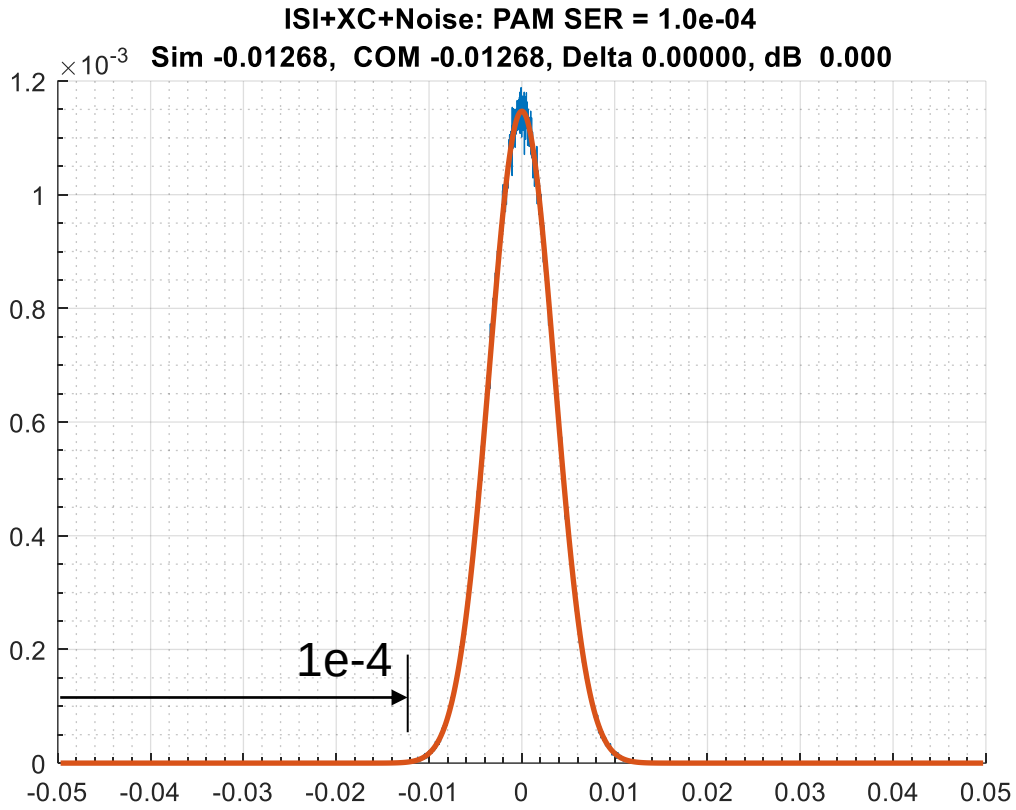
- Form an error signal as:

  $N_I = S_{Rx}$ - $S_{Ideal\ Eq}$, i.e. $S_{Ideal\ Eq}$ has no residual ISI, XT, Noise

- Form the PDF and CDF of Ni
  - By applying a gain to “Ni” and making using of the CDF, one can vary the PAM SER for the simulation.

$$S_{Rx} = S_{Ideal\ Eq} + GN_I$$

COM PDF versus Sim PDF for COM Configuration Spread Sheet: 10 dB 85 ohm Akinwale Channel

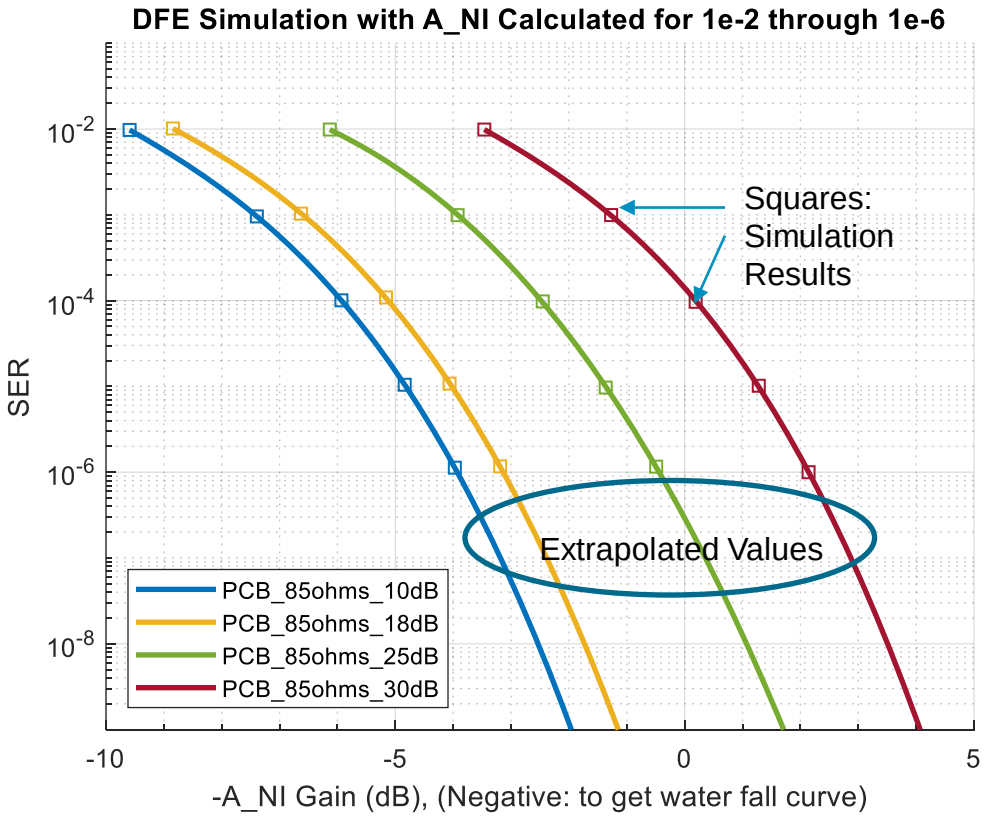


PDF's from COM and Simulation with CDF points for 1e-4
From COM: -0.01268
From Sim: -0.01268

With Correctly Scaled Ni, Simulation Results are Correct

- Based on the Ni PDF/CDF, Ni Gains are calculated for PAM SERs of 1e-2, 1e-3, 1e-4, 1e-5 and 1e-6.
- PAM SER >= 1e-5, SER results are within +/-10%
- No error propagation

- Squares: values from simulation.
- Solid line is curve fit through the squares



COM MLSE Information

Borrowed the COM *MLSE* function

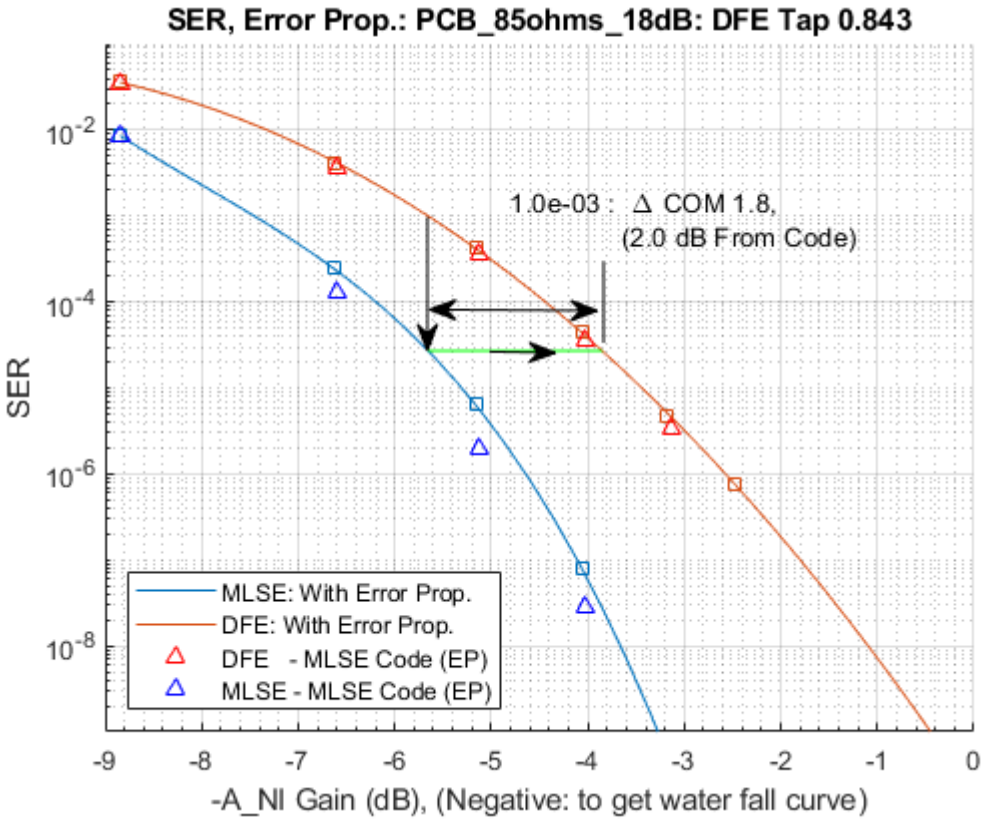
MLSE_results = COM_tool_MLSE(param, fom_result.DFE_taps(1), Fixed_A_s, Adjusted_A_ni(jj), PDF, CDF);

COM_orig(jj) = 20*log10(Fixed_A_s/Adjusted_A_ni(jj));
COM_MLSE(jj) = MLSE_results.COM_CDF;
MLSE_A_ni(jj) = Fixed_A_s/10.^(COM_MLSE(jj)/20);
DFE_ep(jj) = MLSE_results.DER_DFE_CDF;
MLSE_ep(jj) = MLSE_results.DER_MLSE_CDF;

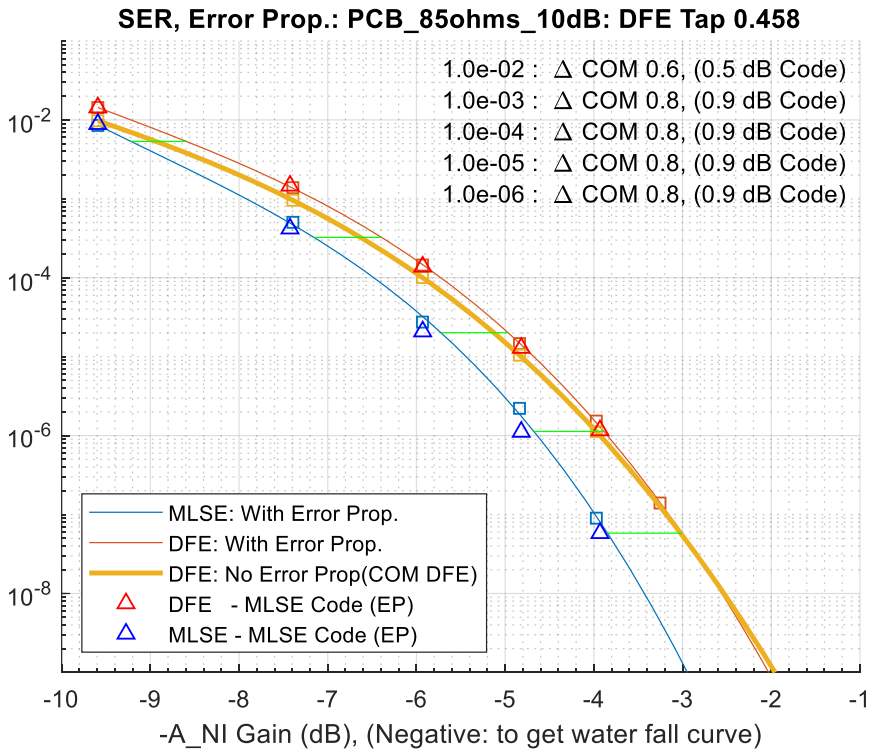
Results are for COM_orig = 0 dB,

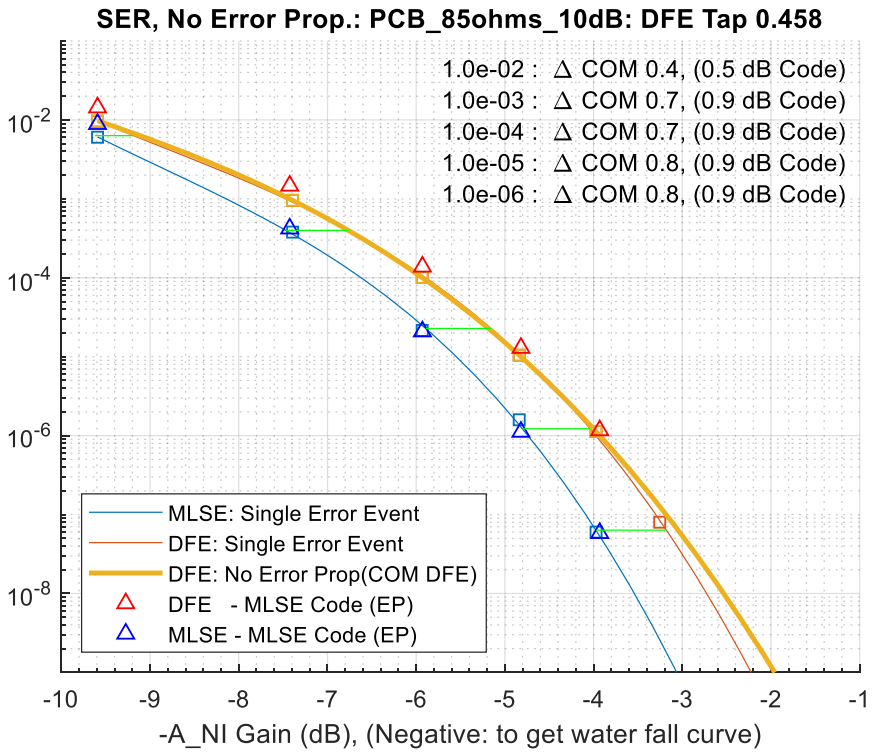
Delta COM

- The MLSE code in the COM tool is for MLSE with error propagation.
- Hence it needs to be compared against a DFE with error propagation.
  - The base COM code is for a DFE with No error propagation.



10 dB 85 ohm Akinwale Channel

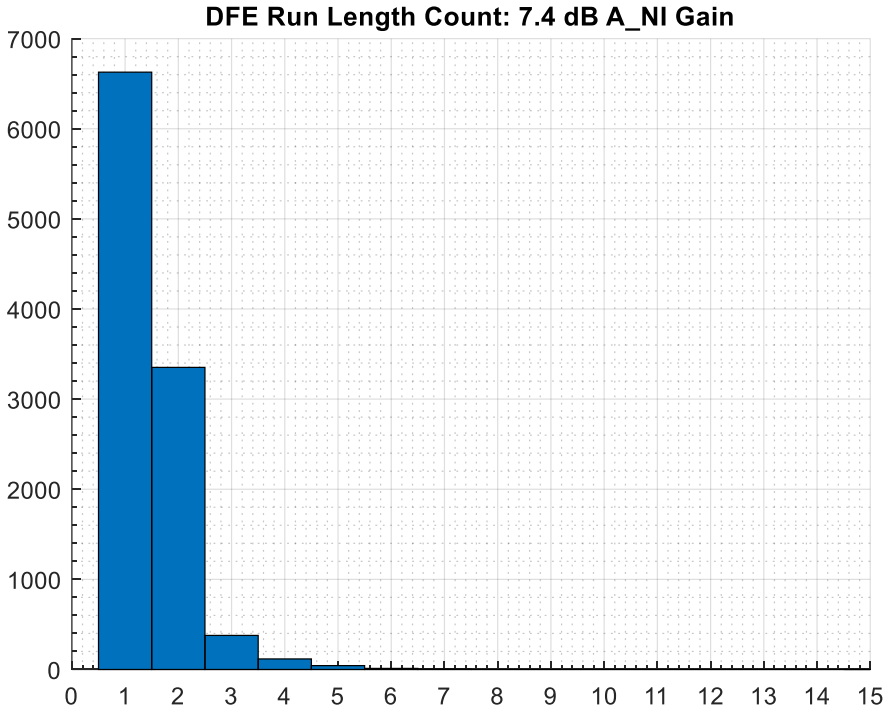


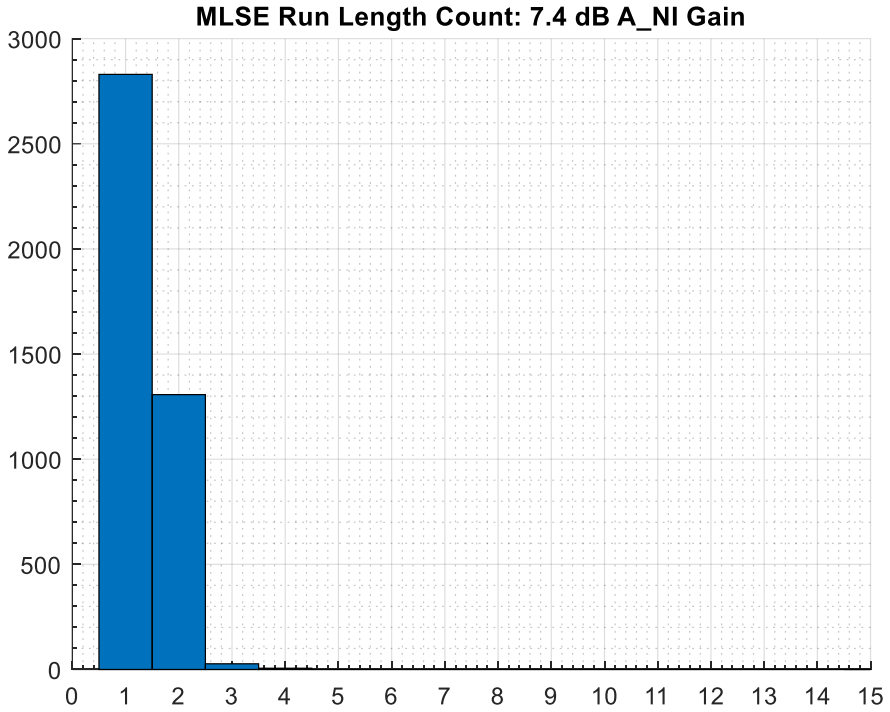


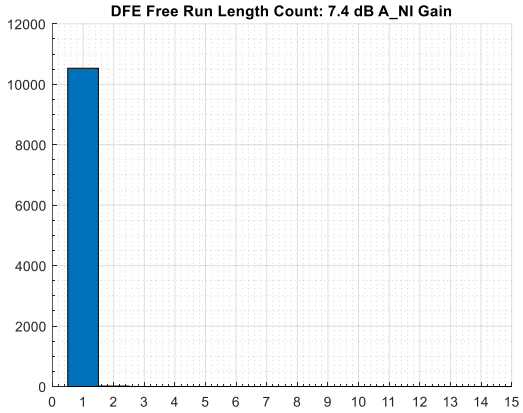
- Squares: values from simulation. Solid line is curve fit through the squares
- Solid Amber line represents DFE with no error propagation, i.e. Perfect symbol knowledge

- DFE weight has not been clipped
- Plotted Negative A_NI gain to get water fall curves.,
- i.e. an x-axis value of -8 corresponds to 8 dB A_NI gain

Error Propagation Characteristics

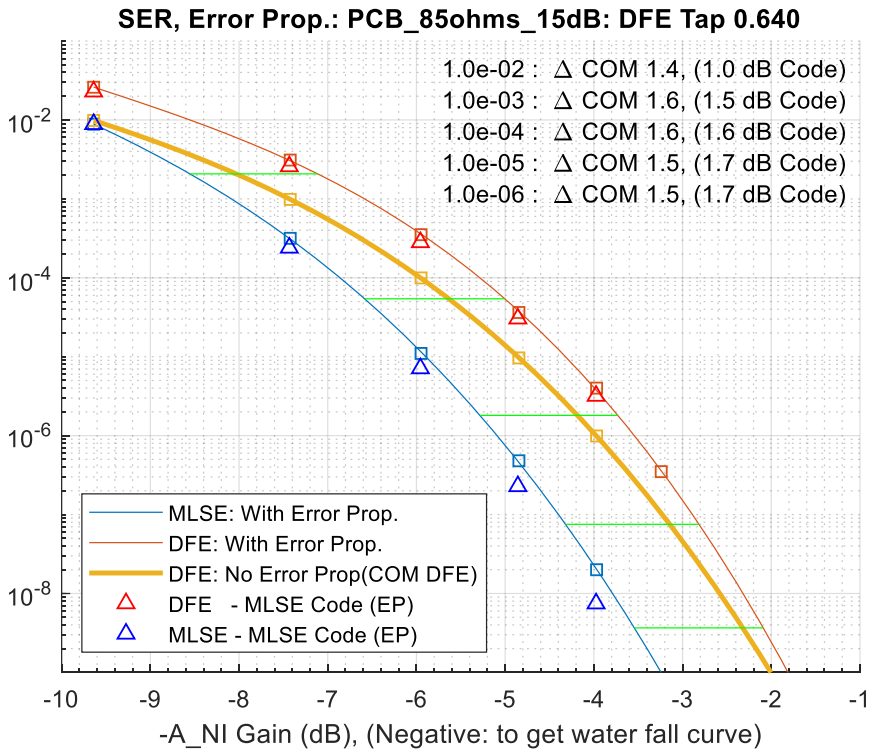


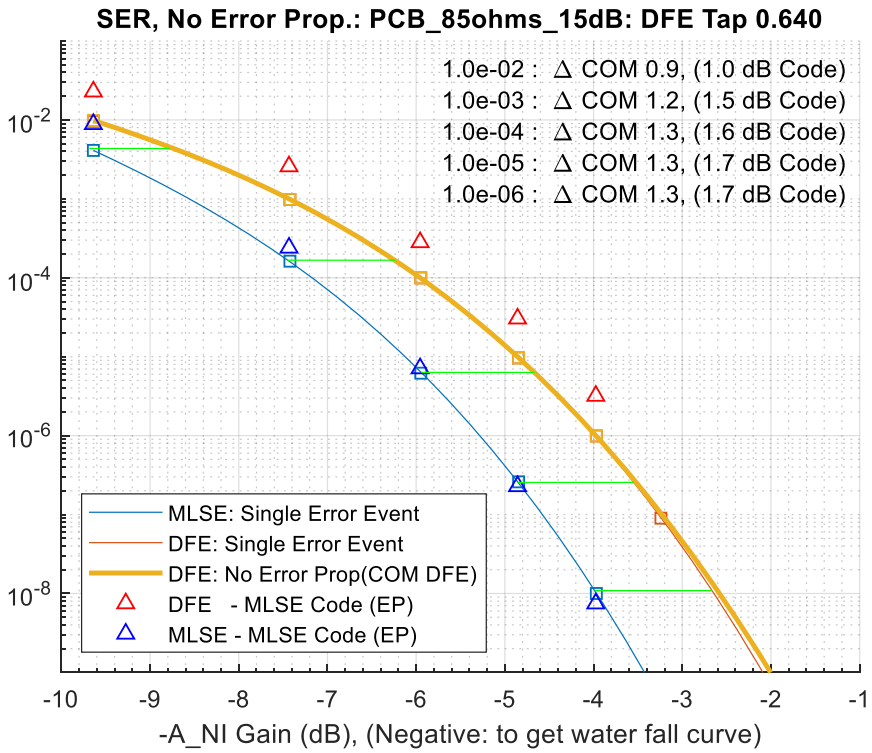




No error propagation

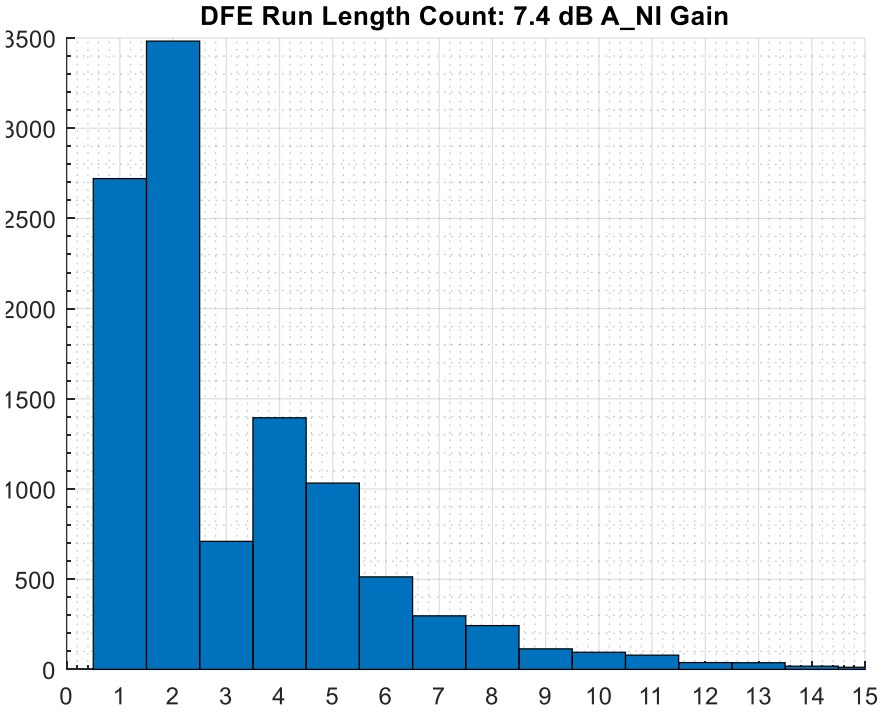
15 dB 85 ohm Akinwale Channel

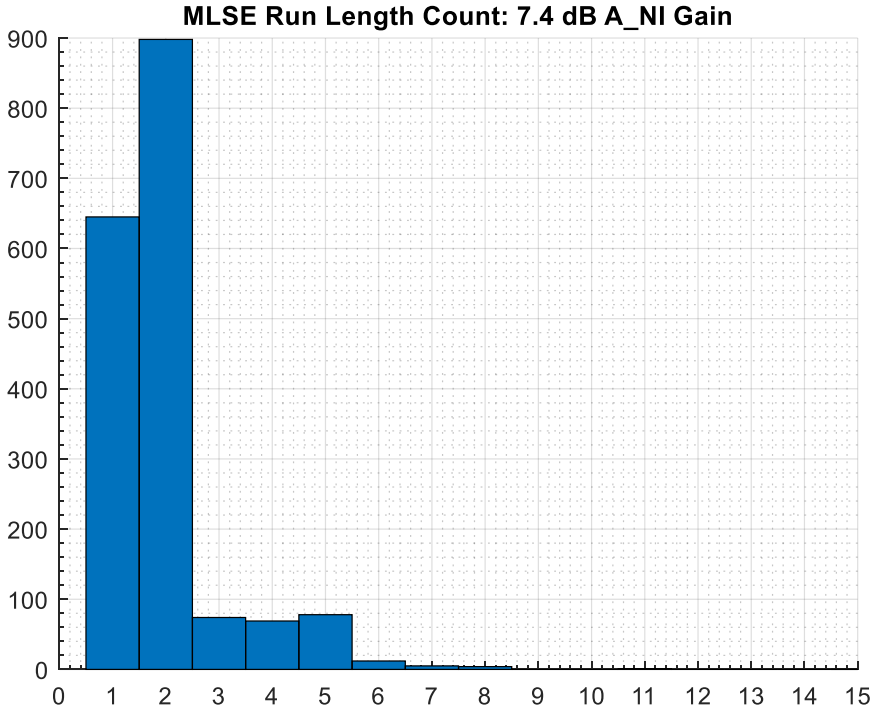


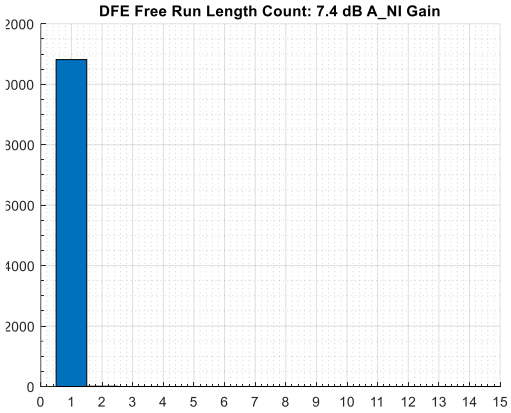


- DFE weight has not been clipped

Error Propagation Characteristics

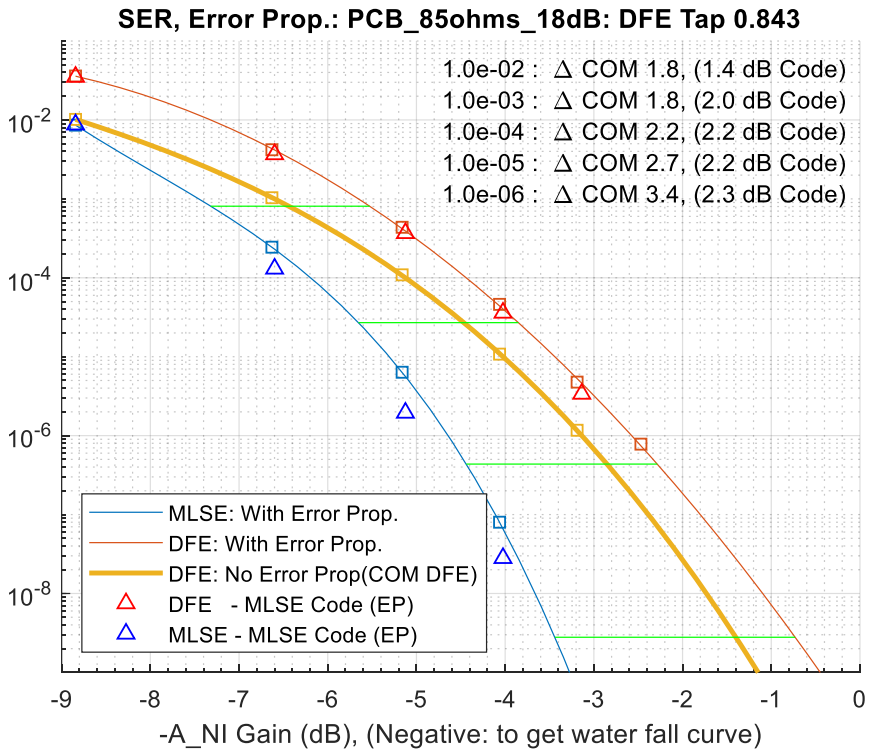


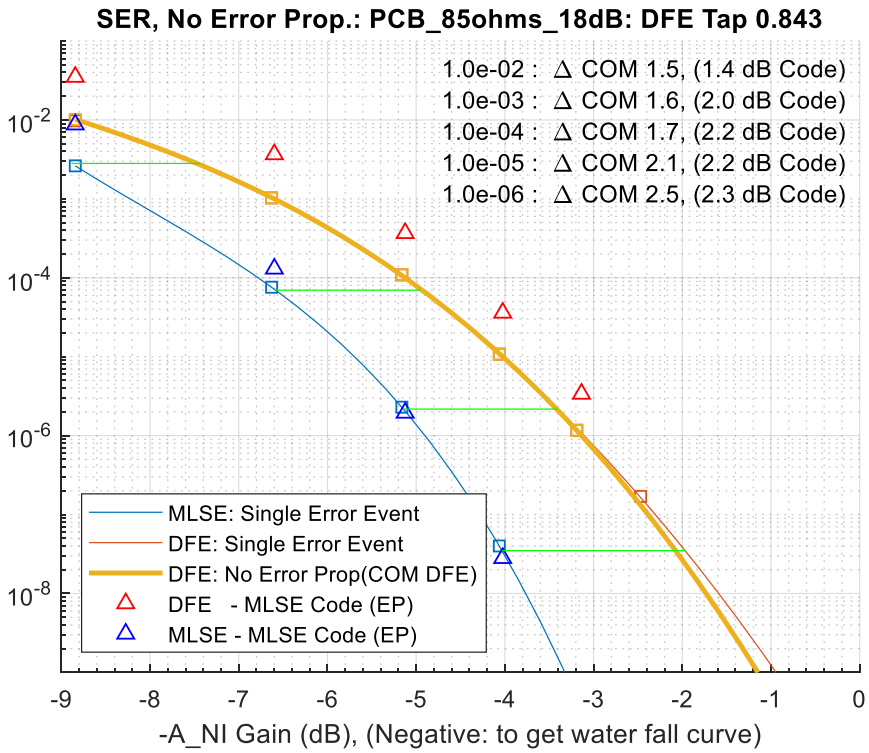




No error propagation

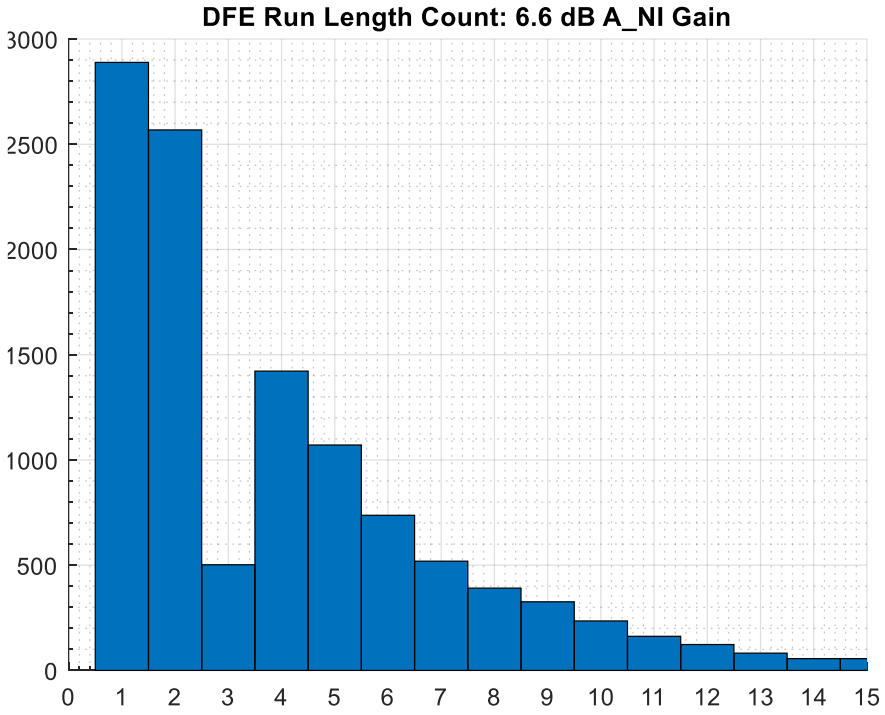
18 dB 85 ohm Akinwale Channel

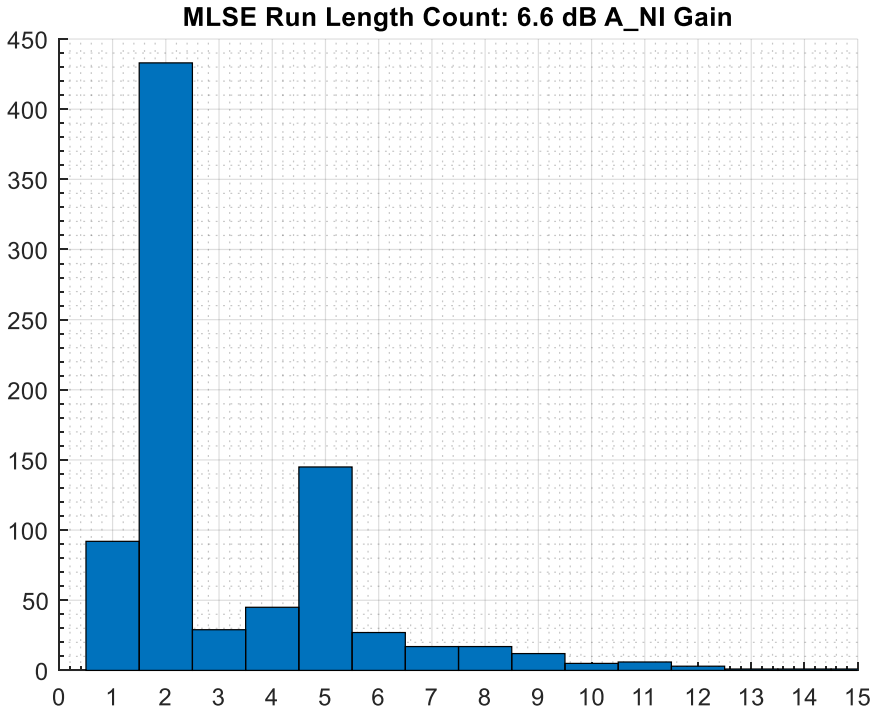


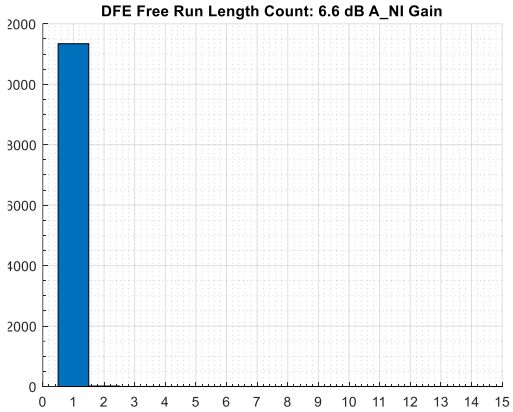


- DFE Weight is just below clipping threshold of 0.85

Error Propagation Characteristics

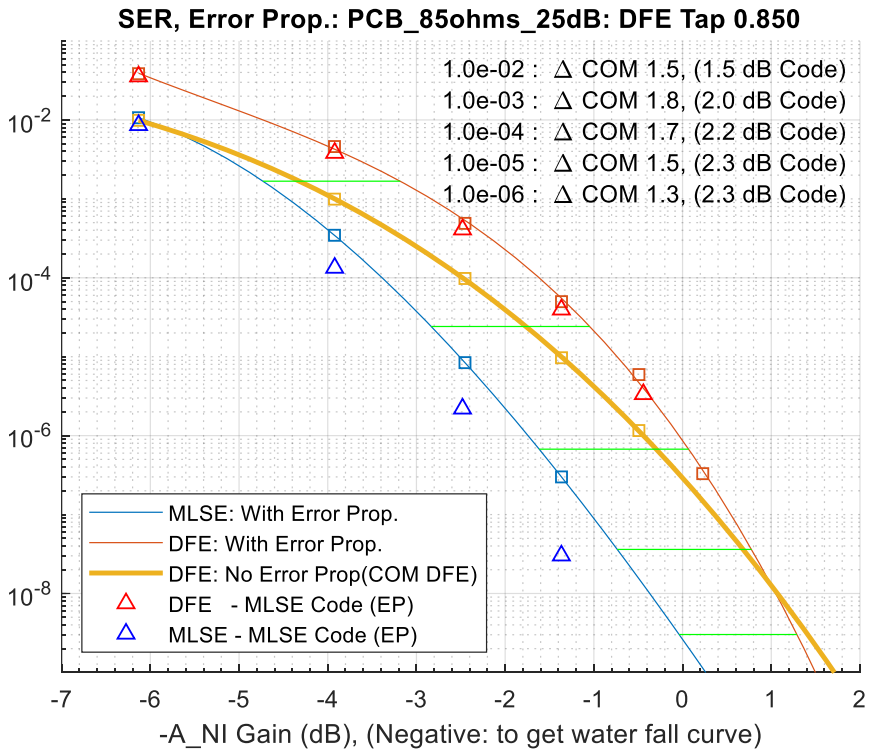


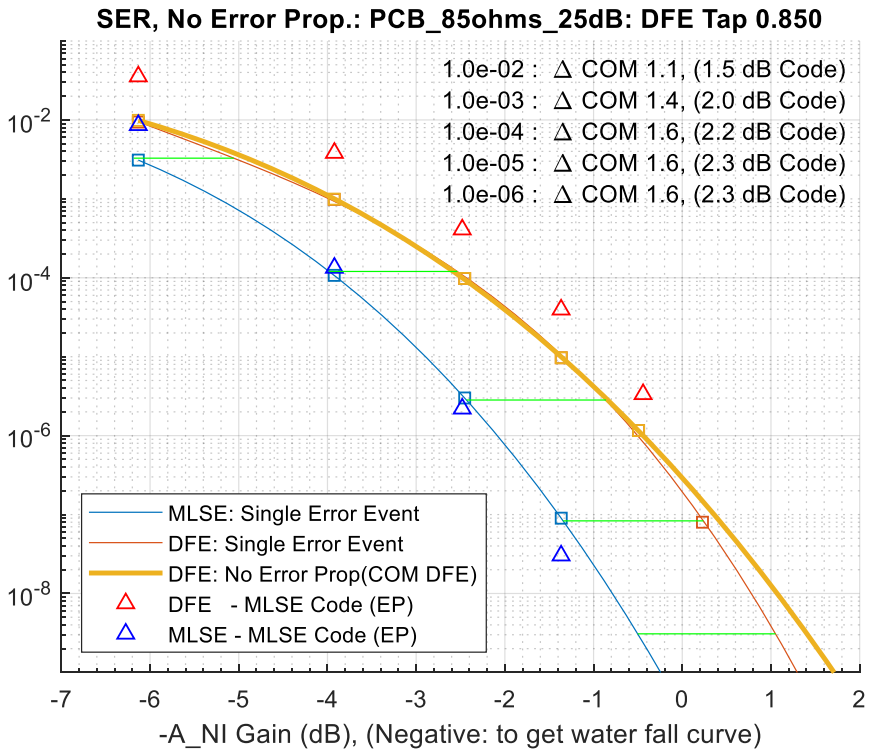




No error propagation

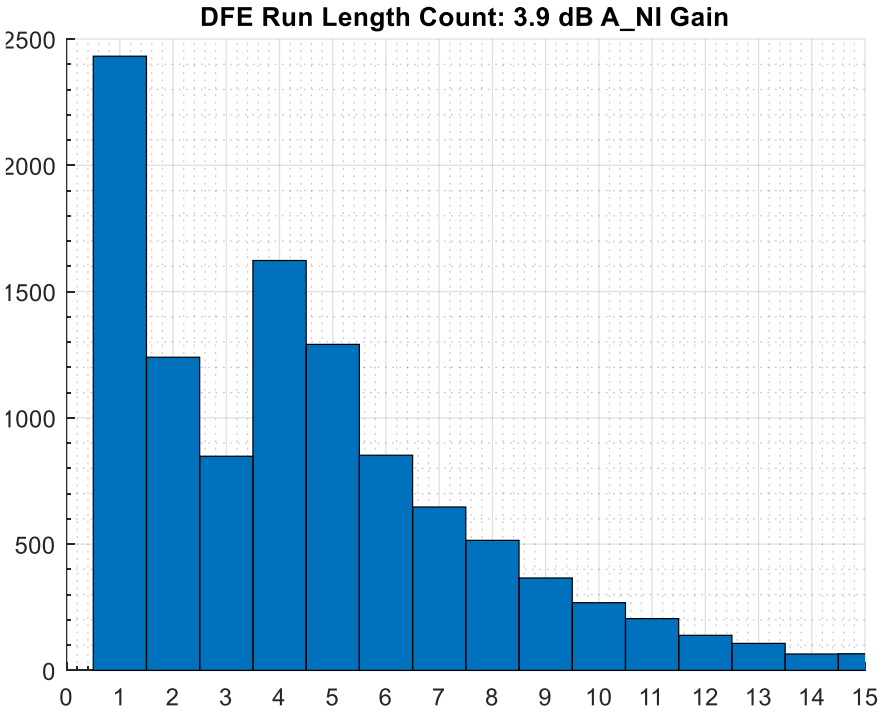
25 dB 85 ohm Akinwale Channel

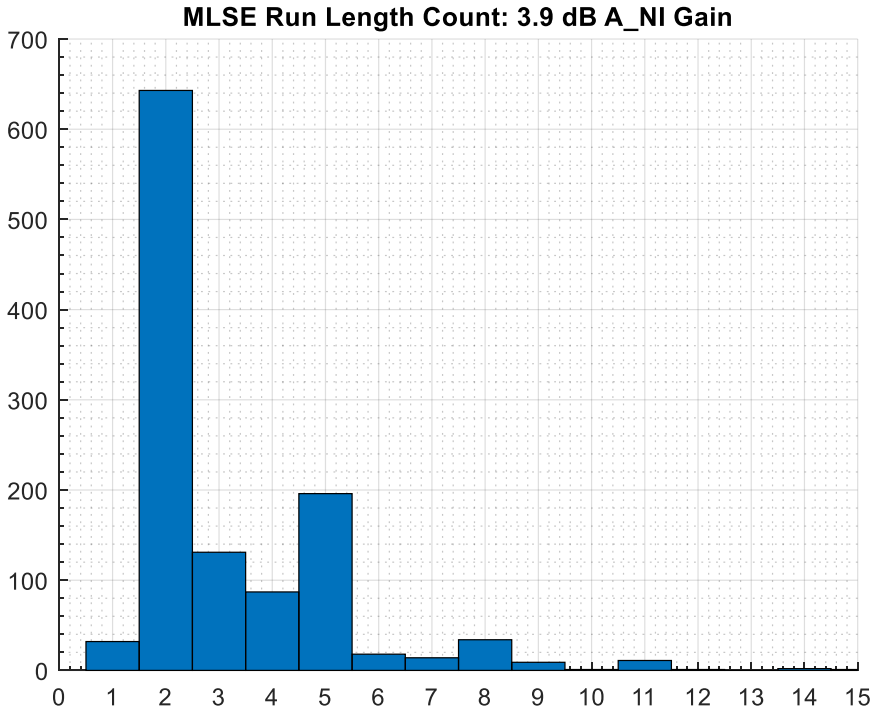


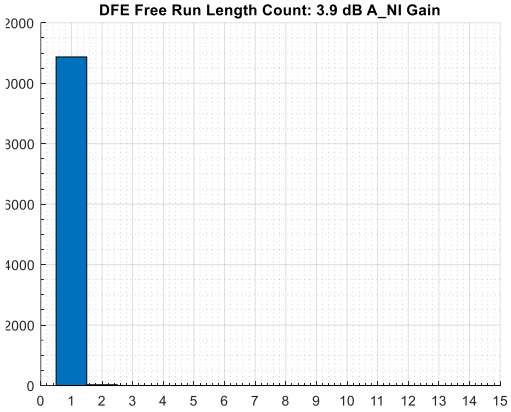


- DFE weight has been clipped.

Error Propagation Characteristics

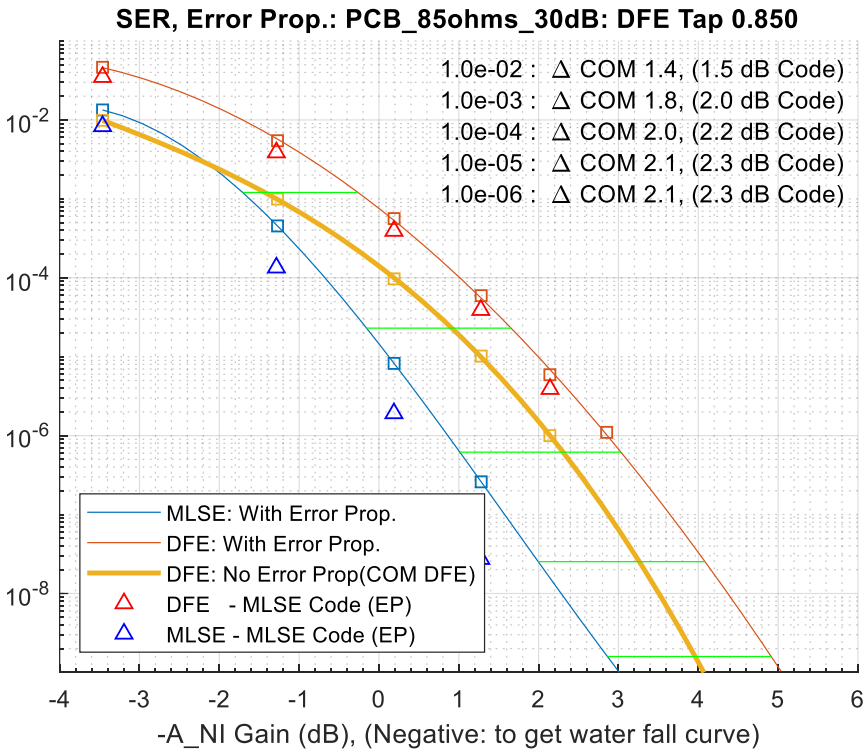


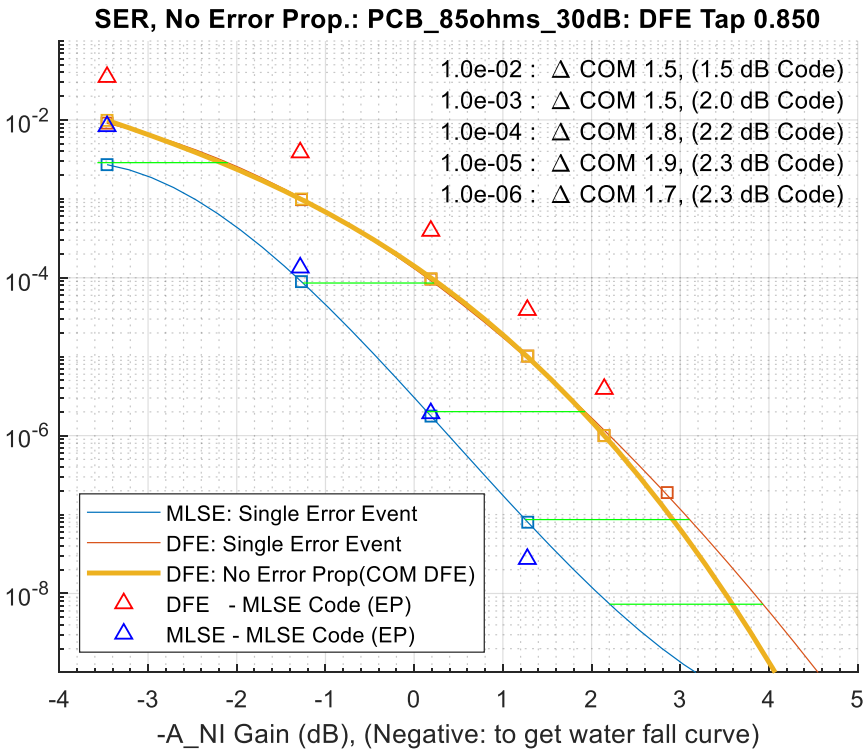




No error propagation

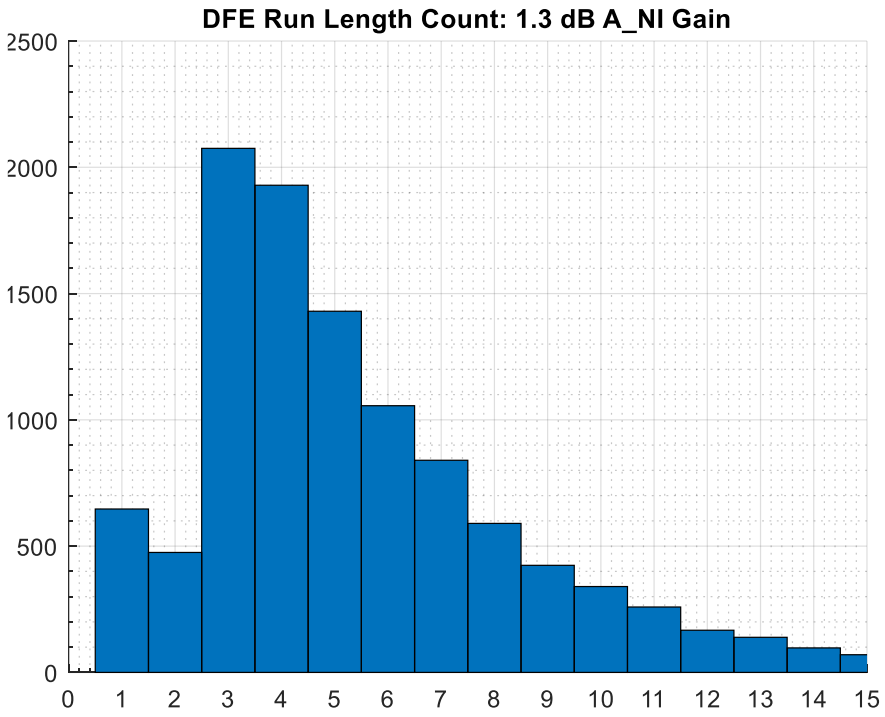
30 dB 85 ohm Akinwale Channel

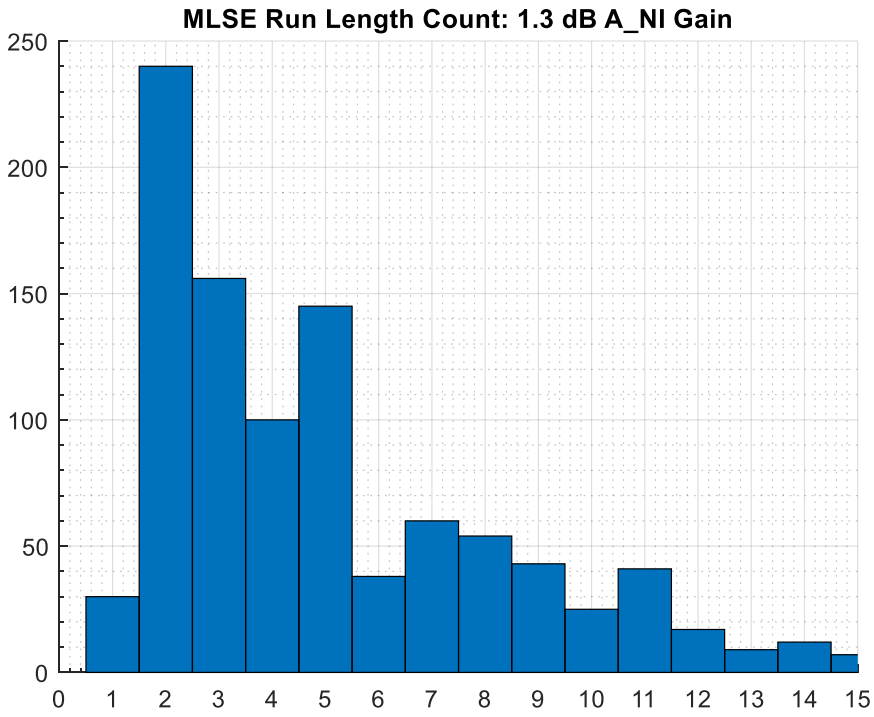


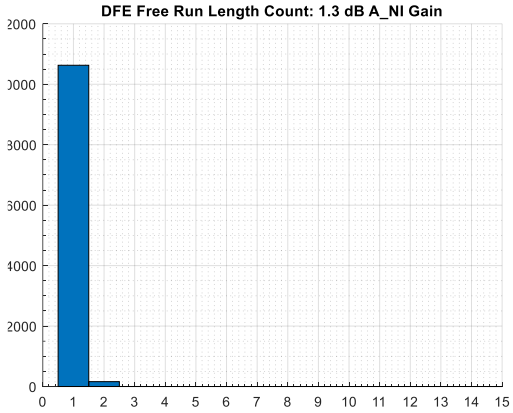


- DFE weight has been clipped

Error Propagation Characteristics







No error propagation

Summary

- For the no error propagation case, the corrected COM code results line up with simulation results for DFE.
  - Two minor inaccuracies within the COM tool were found and are being addressed by Rich and company
- With error propagation (ep), simulation results are quite close to results from the corrected COM MLSE code for MLSE and DFE.
- COM MLSE ep is slightly add number() more optimistic than COM DFE ep wrt simulation results.
- When the DFE is forced to limit the DFE weight to b1_max, COM MLSE results are even more optimistic()
- Suspect MLSE code fails to account for the error caused by limiting h1. h1_calculated – h1_limited

Next Steps

- COM
  - With or Without Error Propagation ?
  - Understand the implications for high layers in terms of FEC
- Hossein investigating the equations to:
  - Remove Error Propagation from MLSE
  - Improve accuracy of equations
  - Further analysis of MLSE/DFE with and without error propagation
  - Future:
    - Include effect Noise Coloring (from Rx Eq solution)
    - Noise Coloring on error propagation
    - Future: Colored system noise
- MLSE Implementation Penalty agreement ?

- How to adjust A_NI and hence COM for PAM 4.
  - Qt_Correct = qfuncinv(DER) / qfuncinv(DER / (3/2)), for PAM 4

Thank you

A shout out to those who's work inspired me to search for the tenths of dB

Rich Mellitz,

Hossein Shakiba

Adee Ran,

Piers Dawe,

Mike Dudek,

Adam Healey,

Ed Frlan,

Mark Kimber

and so many others

A special thank you to the work of the late Jonathan King

Back Up Material

Side Bar: Impact of MMSE Equalizer Solutions

- The use of the Minimum Mean Squared Error for equalizer optimization causes a slight bias to the solution.
  - The threshold detectors and symbol levels need to be corrected slightly

- Consider PAM 4 with 18 dB SNR and No ISI. Just AWGN
- The optimum gain for MMSE is 0.985, i.e. -0.134 dB.

  (See attached script: MSE_bias.m)

- For the 85ohms_10dB channel the corrections for A_NI are
  - SER: 1.0e-02, PAM 4 Correction: -0.54 dB
  - SER: 1.0e-03, PAM 4 Correction: -0.33 dB
  - SER: 1.0e-04, PAM 4 Correction: -0.23 dB
  - SER: 1.0e-05, PAM 4 Correction: -0.18 dB
  - SER: 1.0e-06, PAM 4 Correction: -0.15 dB
  - SER: 1.0e-07, PAM 4 Correction: -0.12 dB

COM Tool

COM Tool 4.0

- https://www.ieee802.org/3/dj/public/tools/COM/
- mellitz_3dj_elec_02_230223.zip

Modifications to COM Code for Simulations

```
[results,chdata, OP, param, output_args, COM_SNR_Struct, Noise_Struct, fom_result]
=com_ieee8023_93a(varargin)

%% Bill Kirkland: adding field mxV
chdata(1).('mxV') = 0;
chdata(1).('phase') = 0;

for i=1:param.number_of_s4p_files
if ~OP.DISPLAY_WINDOW, fprintf('%d ', i); end
[pdf, chdata(i)] = get_pdf(chdata(i), param.delta_y, fom_result.t_s, param, OP) ;

CDF=combined_interference_and_noise_cdf;
Noise_Struct.combined_interference_and_noise_pdf = combined_interference_and_noise_pdf;

[UNUSED_OUTPUT pxi] = max(mxV); %#ok<ASGLU>
%% Bill Kirkland
chdata.mxV   = UNUSED_OUTPUT; % worst case standard deviation of PDF
chdata.phase = pxi;           % Sampling point for worst case Xtalk
```