Effects of Non-Ideal Equalizer Coefficients on COM

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July 2019

Outline

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- RX CTLE Coefficient Sensitivity
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Motivation

- The reference equalizer architecture is composed of a TX FFE, and RX CTLE and an RX DFE, each with various coefficients which need to be adapted for optimal performance
- Currently adaptation in COM is done as follows:
  - brute force search for the TX FFE and the RX CTLE coefficients
  - DFE tap coefficients directly measured from the singe bit response
- Some parameters are quantized (e.g. TX FFE, RX CTLE) and some are not (RX DFE)
- In [1], Adam reviewed the 3dB COM "bucket"
  - impairments included: voltage noise, sampling jitter, RX distortion (linearity), RX package crosstalk, quantization noise
- In [2], Mau-Lin reviewed the impact of receiver noise on COM
  - results showed a mean COM degradation of ~1dB going from current noise value (η_0 = 0.82e-8 V^2/GHz) to a realistic thermal noise value (η_0 = 1.64e-8 V^2/GHz)
- This presentation will look at the effects of quantization, as well as the impact of non-ideal coefficient values

Implementation allowance "bucket" (don't let it overflow!)

- Difference between reference receiver and implementation
- Difference between reference receiver package (loss) and implementation
- Receiver package crosstalk
- Receiver analog front-end distortion
- Receiver analog front-end noise
- Sampling clock jitter
- Analog-to-digital converter (ADC) quantization noise — OR — Slicer noise and offset
- Equalizer coefficient quantization effects
- Approximation errors (e.g., no EOJ model, simplified phase-to-amplitude noise conversion, nominal termination resistors)

Receiver Noise – Impact to COM_{min}

Conf.	Sys. Noise	RX Noise	COM loss in dB (to Conf. 1, which is w.o. RX noise)			
			Mean	Min	Max	Std
0	Off	Off	-0.21	-0.36	-0.06	0.07
1	On	Off	0	0	0	0
2	On	η_0 = 0.82e-8 V^2/GHz	1.52	0.18	3.61	0.83
3	On	η_0 = 1.23e-8 V^2/GHz	2.03	0.25	4.55	1.05
4	On	**η_0 = 1.64e-8 V^2/GHz**	**2.46**	0.32	**5.29**	**1.21**

Simulated Channels

Updated P802.3ck Critical Channels

Contribution	Channel	#	Name	IL (dB)
heck_3ck_01_1118	~~28dB Cabled Backplane/Cable_BKP_28dB_0p575m_more_isi~~	~~14~~	~~Heck1~~	~~28.8~~
heck_3ck_01_1118	16dB Cabled Backplane/Cable_BKP_16dB_0p575m_more_isi	2	Heck2	15.2
mellitz_3ck_adhoc_02_081518	24,28,30dB including BGA Via/CaBP_BGAVia_Opt2_28dB	53	Mellitz1	26.3
tracy_3ck_01_0119	Traditional Backplane Channels/Std_BP_12inch_Meg7	21	Tracy1	15.7
tracy_3ck_01_0119	Orthogonal Backplane Channels/DPO_IL_12dB	17	Tracy2	12.2
kareti_3ck_01a_1118	Measured Orthogonal Backplane Channels/OAch4	96	Kareti1	27.7
kareti_3ck_01a_1118	~~Measured Orthogonal Backplane Channels/Och4~~	~~103~~	~~Kareti2~~	~~28.1~~
kareti_3ck_01a_1118	Measured Cabled Backplane Channels/CAch3_b2	89	Kareti3	28.5
kareti_3ck_01a_1118	~~Measured Traditional Backplane Channels/Bch2_a7p5_7~~	~~63~~	~~Kareti4~~	~~28.4~~
(Modified to fix non-physical response)	Measured_Traditional_Backplane_Channels/Bch2_b7p5_7	70	Kareti5	28.9
(Replacement for Heck1)	28dB_Cabled_Backplane/Cable_BKP_28dB_0p575	13	Heck3	29.0

- Simulations run using updated channel list from **heck_3ck_adhoc_01a_071019** [4] based on channels from **kochuparambil_3ck_01c_0119** [3]

COM Worksheet: COM 2.6

Table 93A-1 parameters			
Parameter	**Setting**	**Units**	**Information**
f_b	53.125	GBd	
f_min	0.05	GHz	
Delta_f	0.01	GHz	
C_d	[1.1e-4 1.1e-4]	nF	[TX RX]
z_p select	[1 2]		[test cases to run]
z_p (TX)	[12 30; 1.8 1.8]	mm	[test cases]
z_p (NEXT)	[12 30; 1.8 1.8]	mm	[test cases]
z_p (FEXT)	[12 30; 1.8 1.8]	mm	[test cases]
z_p (RX)	[12 30; 1.8 1.8]	mm	[test cases]
C_p	[0.87e-4 0.87e-4]	nF	[TX RX]
R_0	50	Ohm	
R_d	[50 50]	Ohm	[TX RX]
A_v	0.413	V	vp/vf=.694
A_fe	0.413	V	vp/vf=.694
A_ne	0.608	V	
L	4		
M	32		
filter and Eq			
f_r	0.75	*fb	
c(0)	0.54		min
c(-1)	[-0.34:0.02:0]		[min:step:max]
c(-2)	[0:0.02:0.12]		[min:step:max]
c(-3)	[-0.06:0.02:0]		[min:step:max]
c(1)	[-0.1:0.05:0]		[min:step:max]
N_b	16	UI	
b_max(1)	0.85		
b_max(2..N_b)	0.2		
g_DC	[-20:1:0]	dB	[min:step:max]
f_z	21.25	GHz	
f_p1	21.25	GHz	
f_p2	53.125	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	0.6640625	GHz	
ffe_pre_tap_len	**0**	UI	
ffe_post_tap_len	0	UI	
ffe_tap_step_size	0		
ffe_main_cursor_min	0.7		
ffe_pre_tap1_max	0.3		
ffe_post_tap1_max	0.3		
ffe_tapn_max	0.125		
ffe_backoff	0		

I/O control		
DIAGNOSTICS	1	logical
DISPLAY_WINDOW	1	logical
CSV_REPORT	1	logical
RESULT_DIR	.\results\100GEL_WG_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 3 2 4]	
RUNTAG	CR_eval_	
COM_CONTRIBUTION	0	logical
Operational		
COM Pass threshold	3	dB
ERL Pass threshold	10.5	dB
DER_0	1.00E-04	
T_r	6.16E-03	ns
FORCE_TR	1	logical
Include PCB	0	logical
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	logical
TR_TDR	0.01	ns
N	1000	
TDR_Butterworth	1	logical
beta_x	1.70E+09	
rho_x	**0.25**	
fixture delay time	0	enter sec
Receiver testing		
RX_CALIBRATION	0	logical
Sigma BBN step	5.00E-03	V
Noise, jitter		
sigma_RJ	0.01	UI
A_DD	0.02	UI
eta_0	8.20E-09	V^2/GHz
SNR_TX	33	dB
R_LM	0.95	

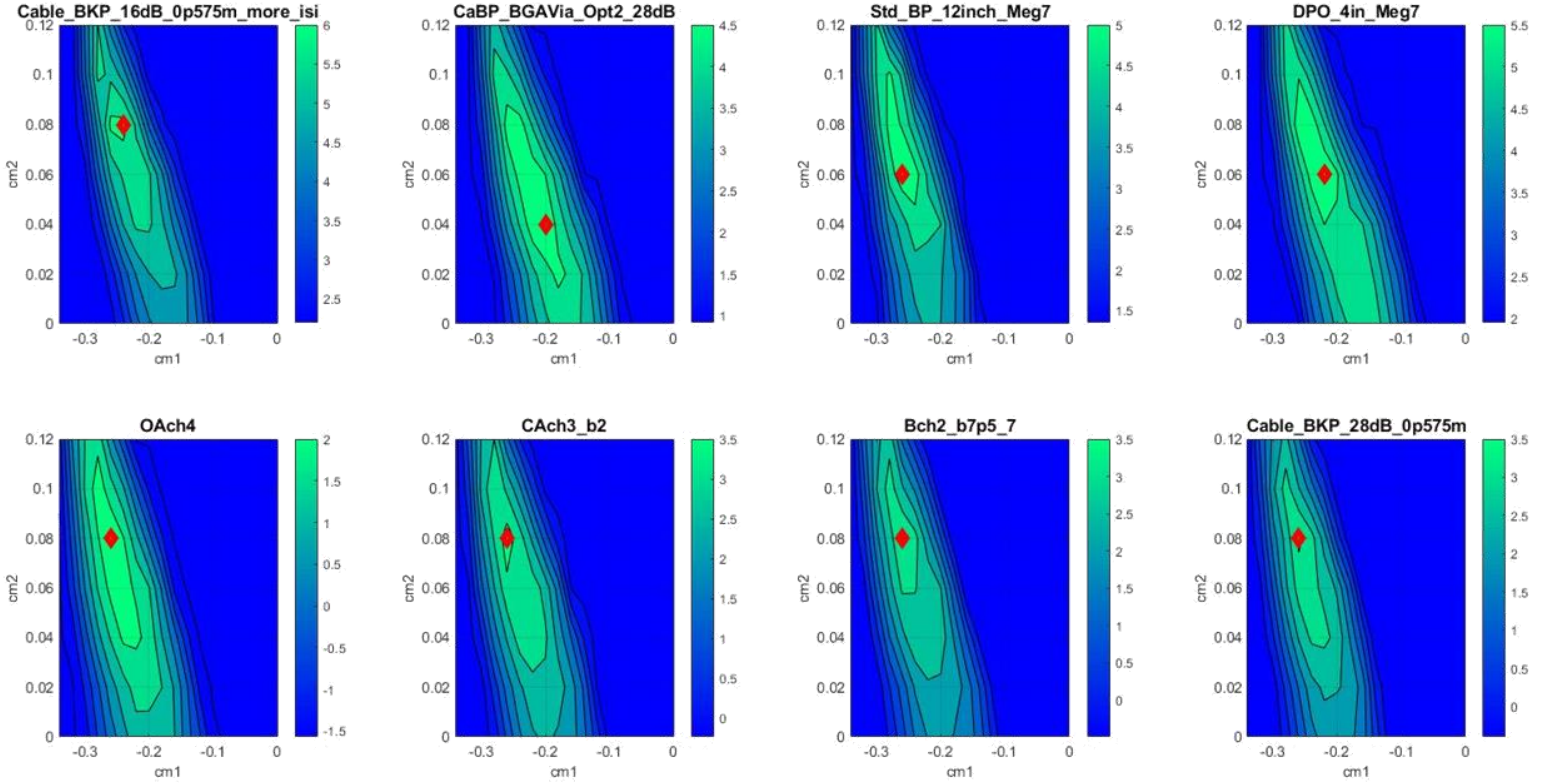
Table 93A–3 parameters		
Parameter	**Setting**	**Units**
package_tl_gamma0_a1_a2	[0 0.0009909 0.0002772]	
package_tl_tau	6.141E-03	ns/mm
package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm

Table 92–12 parameters		
Parameter	**Setting**	
board_tl_gamma0_a1_a2	*[0 3.8206e-04 9.5909e-05]*	
board_tl_tau	*5.790E-03*	ns/mm
board_Z_c	90	Ohm
z_bp (TX)	*119*	mm
z_bp (NEXT)	*119*	mm
z_bp (FEXT)	*119*	mm
z_bp (RX)	*119*	mm

TX FFE Coefficient Sensitivity: Simulation Overview

- For each channel the solution space for the TX FFE cm1 and cm2 coefficients was swept
  - cm1 = [-0.34 : 0.02 : 0.0]
  - cm2 = [0.0 : 0.02 : 0.12]
  - for every combination of cm1 and cm2 the normal COM adaptation was run for all other coefficients
  - cm1 and cm2 were chose as these have the largest amount of equalization impact for the FFE
- The heat map for the COM results is shown on the next slide
  - in each heatmap the lower COM limit was set to max(COM) – 4dB
  - this was done in order to maintain resolution for the higher values of COM
- A red diamond shows the location where the full COM adaptation selects
  - this shows the COM adaptation is selecting the best TX FFE coefficients

TX FFE Coefficient Sensitivity: COM Heatmap



TX FFE Coefficient Sensitivity

- The results show a significant COM sensitivity to the TX FFE coefficients
  - the degradation is largely due to the precursor ISI, given that the reference receiver is defined as a CTLE + DFE, with no specific precursor correction
  - in this reference receiver all precursor correction needs to be done in the TX FFE
- In some ways the sensitivity of the COM performance to the TX FFE setting is problematic
  - it is difficult to arrive at the best case TX FFE setting via a directional search
  - a brute force search (similar to what is done in COM) gives the best result, however with a 5-tap FFE the time required for this search is likely prohibitively
- In actuality the sensitivity of the COM performance to the TX FFE setting is not problematic
  - an actual implementation would likely have an FFE in the receiver with several precursor taps
  - this would reduce the sensitivity of the receiver to the TX FFE coefficients

RX CTLE Coefficient Sensitivity: Quantization

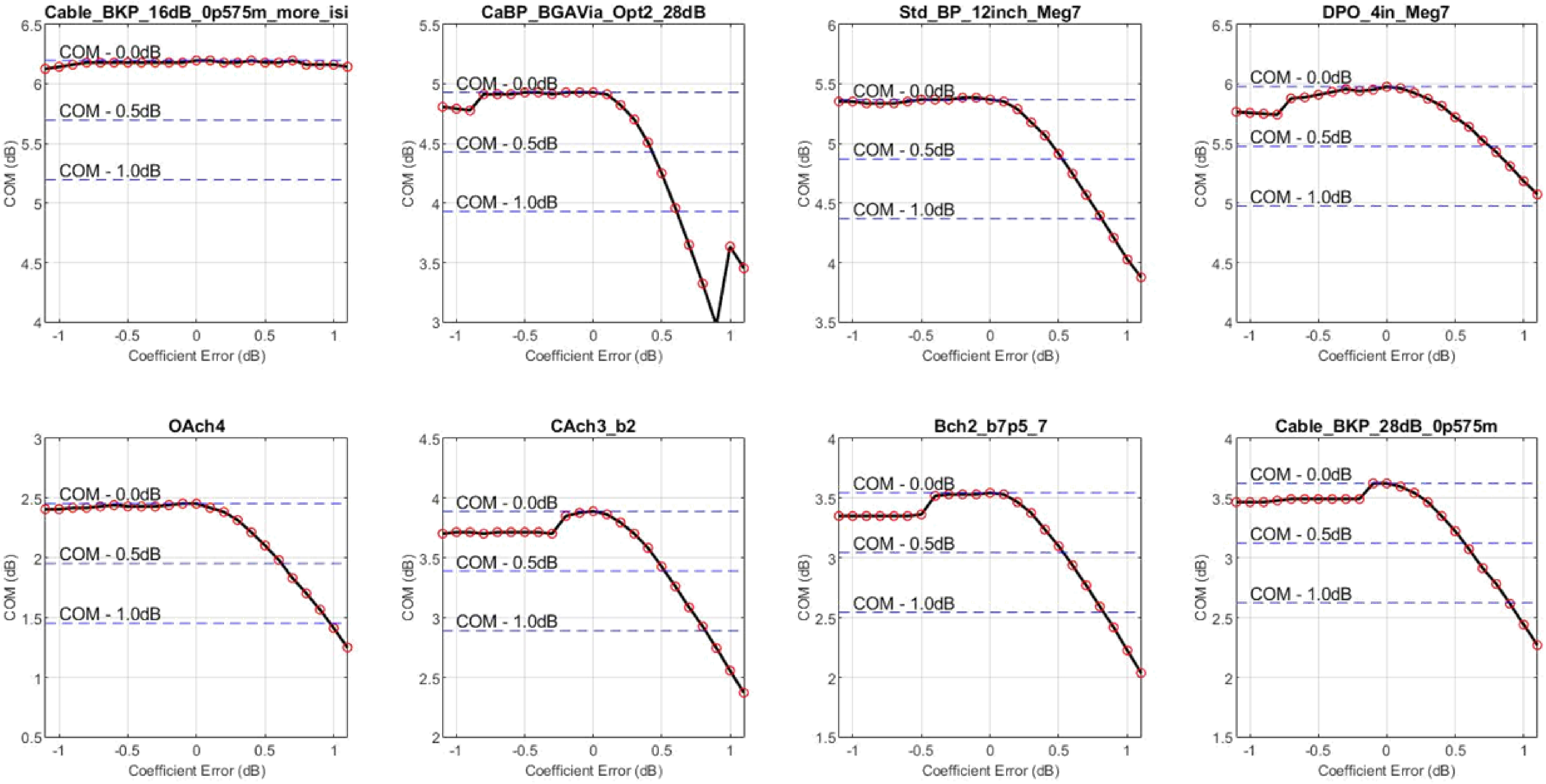
- The CTLE in the reference receiver is searched in the COM script for the optimal setting, the nominal settings are:
  - high-frequency BOOST: -20:1:0
  - low-frequency BOOST: -6:1:0
- This quantization in the search space creates a channel dependent non-ideality in the CTLE coefficients
  - some channels will have close to the optimal coefficients
  - some channels will have an error of as much as 0.5dB per coefficient
- COM results below show that the quantization of the CTLE settings does not have a significant impact on the COM result
  - even with a BOOST delta of ~0.4dB the COM delta is only 0.12dB

	COM			CTLE_DC_gain_dB		g_DC_HP	
	1dB steps	**0.1dB steps**	**delta**	**1dB steps**	**0.1dB steps**	**1dB steps**	**0.1dB steps**
Cable_BKP_28dB_0p575m_more_isi	3.31	3.43	0.12	-16	-15.58	-3	-3.36
CaBP_BGAVia_Opt2_28dB	4.91	4.93	0.02	-15	-14.36	-4	-3.97
Std_BP_12inch_Meg7	5.35	5.37	0.02	-7	-7.09	-2	-2.11
DPO_4in_Meg7	5.95	5.98	0.03	-4	-3.73	-2	-2.08
OAch4	2.43	2.45	0.02	-15	-14.38	-4	-3.89
Och4	1.31	1.32	0.01	-11	-11.09	-4	-3.73
CAch3_b2	3.77	3.89	0.12	-13	-12.8	-3	-3.81
Bch2_a7p5_7	2.24	2.28	0.05	-10	-9.44	-3	-3.08

RX CTLE Coefficient Sensitivity: Coefficient Error

- The final CTLE coefficients may deviate from the ideal CTLE coefficients for various reasons, including:
  - CTLE BOOST resolution
  - CTLE BOOST DNL
  - sub-optimal adaptation
  - adaptation dither
- The effect of non-ideal CTLE coefficients is studied
  - an error term is added with respect to the ideal coefficients found previously (0.1dB resolution)
  - error term is swept: [-1.0 : 0.1 : 1.0] dB
- The COM results show some sensitivity to the CTLE coefficients
  - the degradation for under-equalization is less than the degradation for over-equalization
  - for a BOOST error of 0.5dB the COM degradation averages ~0.5dB for over-equalization
- For non-ideal CTLE coefficients the DFE is able to compensate

RX CTLE Coefficient Sensitivity: Coefficient Error



RX DFE Coefficient Non-Ideality

- In this analysis the number of DFE taps is swept while two effects non-idealities are considered:
  - DFE tap quantization
  - non-ideal DFE tap coefficients
- Quantization of the DFE taps is present in the COM script via the ***dfe_delta*** parameter [5]
  - the spreadsheet parameter is N_b_step, however this parameter is not utilized in current COM spreadsheets
  - in this analysis ***dfe_delta*** parameter set to 0.01
- In addition to quantization the effect of non-ideal DFE tap coefficients is studied by way of an optional error term added to each tap
  - both the worst case and a set of 50 runs with random +1/0/-1 LSB errors added to each tap are considered
  - non-ideal DFE tap coefficients can happen due to: tap resolution, tap DNL, sub-optimal adaptation or adaptation dither
- The effect of DFE tap quantization on the COM performance is minimal
  - above 20 DFE taps a COM degradation of ~0.2dB is seen for a quantization of ***dfe_delta = 0.01***
  - with only the effect of DFE tap quantization included there is no penalty for increasing the number of DFE taps
- The effect of non-ideal DFE tap coefficients is substantial
  - the degradation increases as the number of taps increases
  - the worst case dither results in 1.5dB to 2dB of COM degradation for every channel at 24 DFE taps

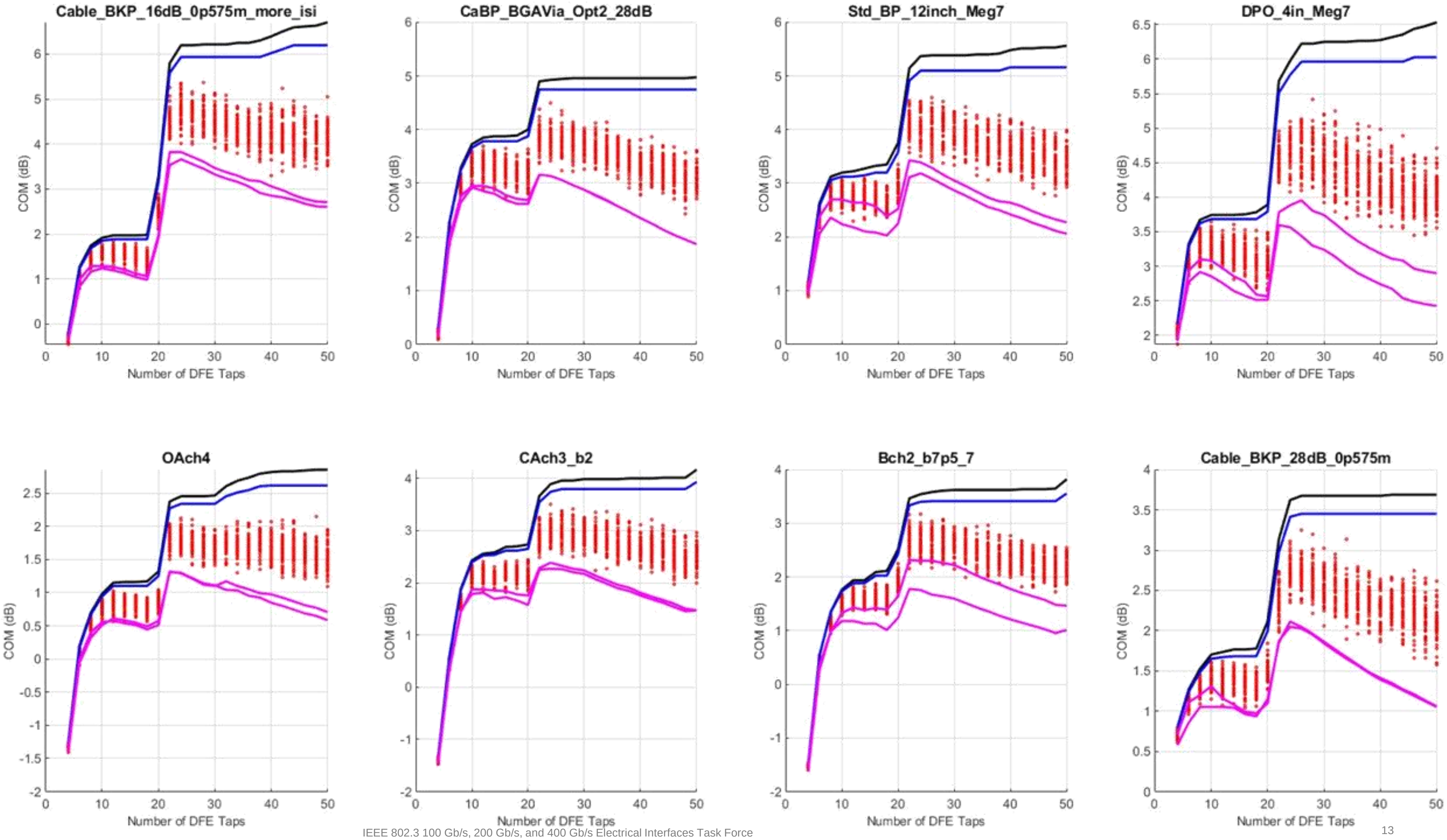
COM Simulation Results: DFE Quantization and Dither

BLACK:
no quantization,
no dither

BLUE:
0.01 quantization,
no dither

MAGENTA:
0.01 quantization,
WC dither

RED circles:
0.01 quantization,
rand +1/0/-1 dither



Summary

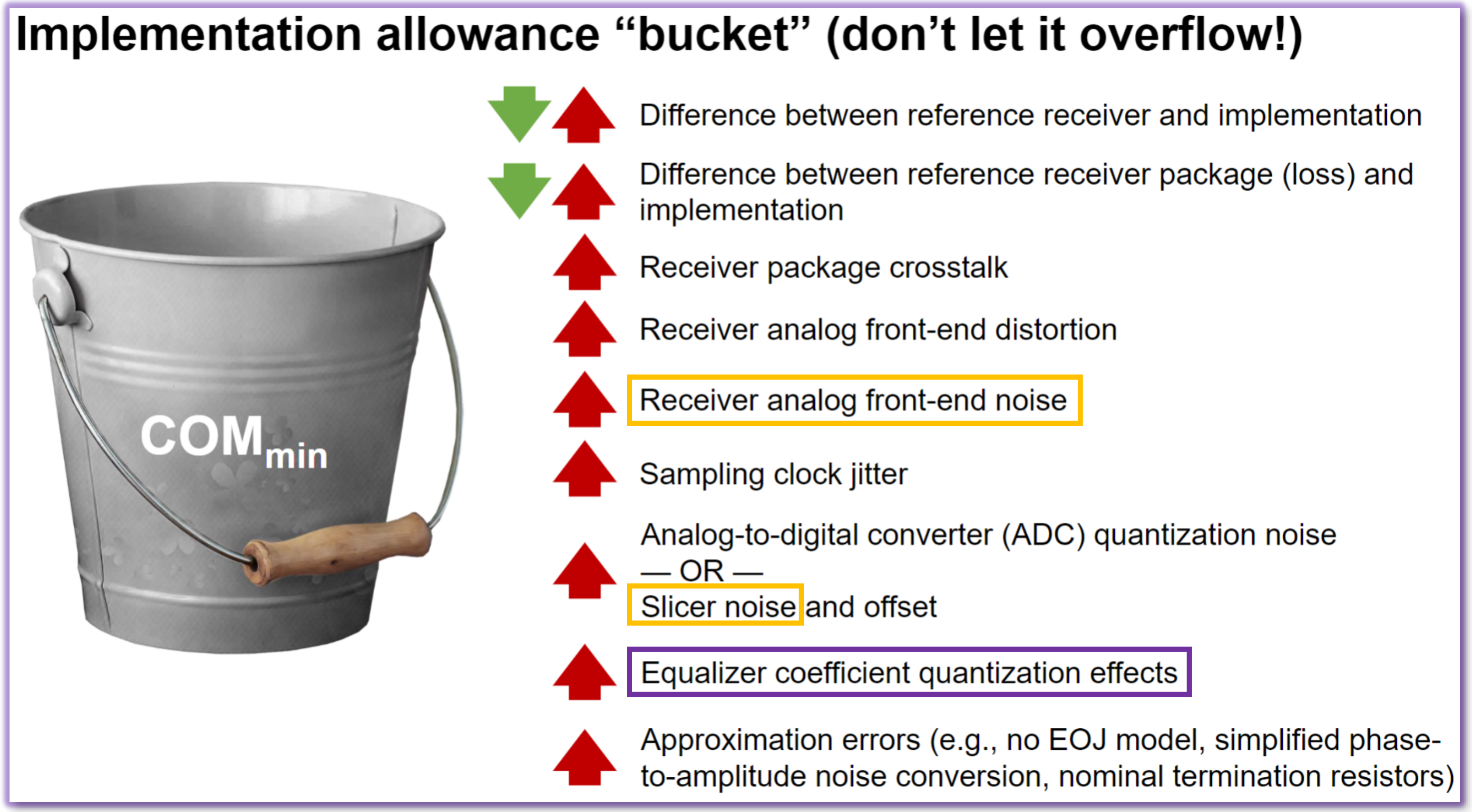
- Based on the current settings, the effects of quantization on the coefficients of the various equalizers is not substantial
- The effects of non-ideal coefficient settings on the COM performance is substantial
  – For the CTLE a 0.5dB step results in ~0.5dB COM degradation
  – For the DFE +/-1 LSB tap dither results in 1.5dB - 2dB COM degradation
- In the current setup there is no COM penalty for additional DFE taps (fixed or floating), the performance always improves
  – in reality non-optimal DFE tap coefficients result in a performance degradation
  – non-optimal DFE tap coefficients can occur due to quantization, but more so due to non-ideal DFE tap adaptation or DFE tap adaptation dither
  – in an actual system adding more taps can cause performance to decrease, unless they are actually cancelling ISI

Implementation Bucket Budget

- Current budget:
  - receiver noise (from Mau-Lin [2]) : ~1.0dB
  - non-ideal CTLE coefficient setting: ~0.5dB
  - non-ideal DFE tap coefficient setting: ~1.5dB

  current total: ~3.0dB

- Unaccounted for items:
  - RX AFE linearity
  - Residual offsets of AFE and slicers
  - Sampling jitter (CDR self-noise)
  - RX package crosstalk



References

[1] Adam Healey, “Considerations for the minimum COM limit”, IEEE 802.3ck 2019 March Plenary Meeting [healey_3ck_01_0319.pdf]

[2] Mau-Lin Wu, et al., “Baseline proposal for Receiver noise model in COM for KR/CR”, IEEE 802.3ck 2019 May Interm Meeting [wu_3ck_01a_0519.pdf]

[3] Beth Kochuparambil, “Summary of System Discussion of Backplane Channels”, IEEE 802.3ck 2019 January interim Meeting [kochuparambil_3ck_01c_0119.pdf]

[4] Howard Heck, “Backplane Reference Receiver Baseline”, IEEE 802.3ck July 10, 2019 Ad-Hoc Meeting [heck_3ck_adhoc_01a_071019.pdf]

[5] Richard Mellitz, et al., “Reference Architecture Proposals and Channel Data”, IEEE 802.3ck 2018 July Plenary Meeting [mellitz_3ck_01_0718.pdf]

Thank You