Further on Possibilities of the MLSE Proposal

Hossein Shakiba
Huawei Technologies Canada
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Outline

● Introduction

● Summary of the Proposal

● Previous Contribution

● Equation Options

● Test Channels

● Com Configuration and Version

● Test Channel Results

● White or Colored Noise?

● Actual or Gaussian Noise?

● Summary and Conclusions

● Backup Slides (Noise Shaping and Correlation)

Introduction

- Defining MLSE for COM reference receivers was highlighted as one of the priorities in phase 1 (lusted_3dj_elec_01_231207.pdf)
- 1st priority is to agree if MLSE representation is needed to be a part of the reference receiver
- January 11th 2024 dj ad hoc Straw Polls 6-9 were favorable particularly for CR/KR:

Straw Poll #6

- I would support including the MLSE effect in COM for 200G/lane CR:
  - Results (all): Y: 33 N: 6 A: 10

Straw Poll #7

- I would support including the MLSE effect in COM for 200G/lane KR:
  - Results (all): Y: 33, N: 6, A: 10

Straw Poll #8

- I would support including the MLSE effect in the reference RX for 200G/lane AUI C2M:
  - Results (all): Y: 20, N: 16, A: 13

Straw Poll #9

- I would support including the MLSE effect in COM for 200G/lane AUI C2C:
  - Results (all): Y: 18, N:16, A: 14

Introduction

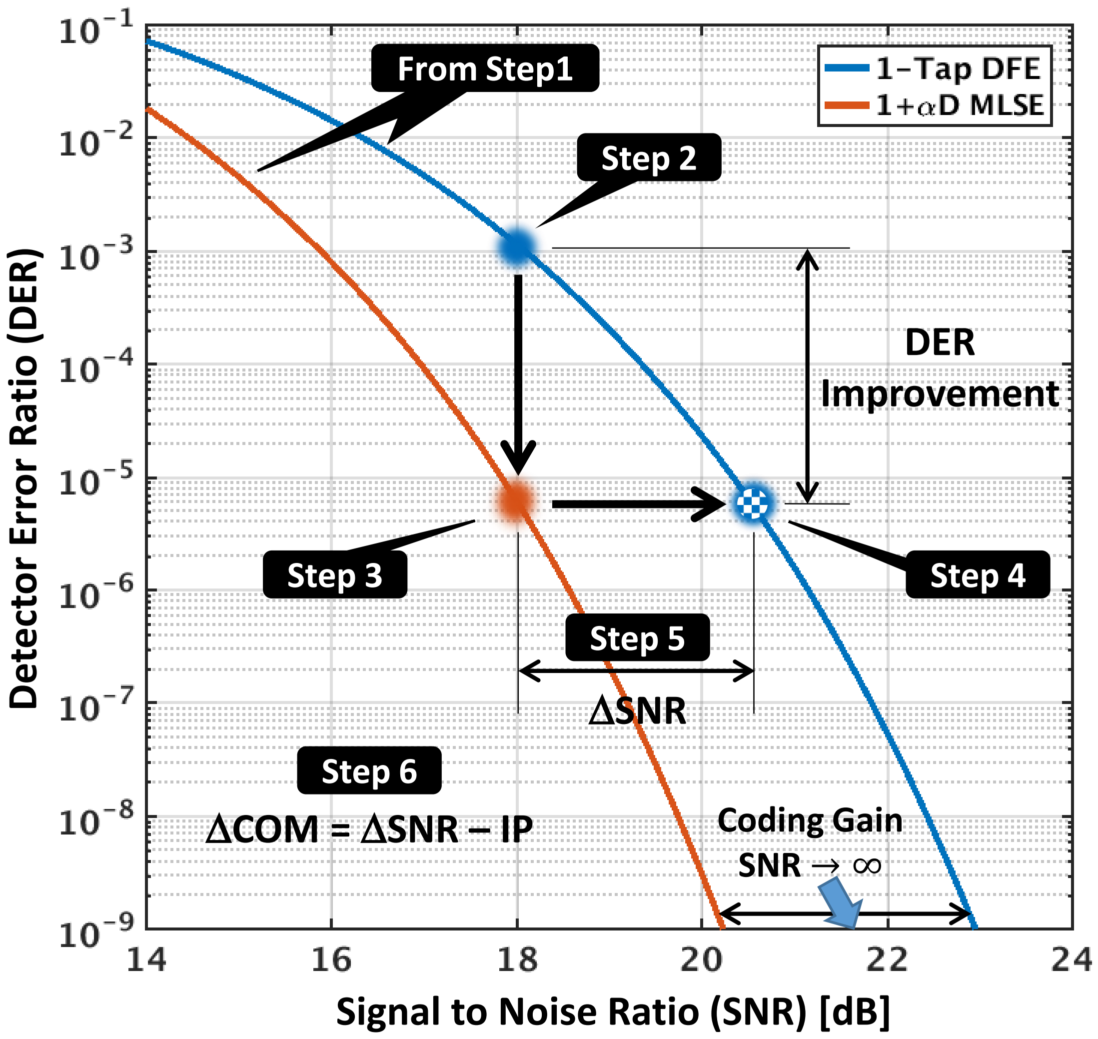
- 2nd priority is to find the best practical approach to achieve the 1st goal
- Considered options:
  A. Use MLSE ΔCOM calculations based on the existing proposal
  B. Use MLSE coding gain as a rough estimate
  C. Relax COM margin by a constant amount
- January 11th 2024 dj ad hoc Straw Poll 10 favored Option A:

> For the 200G/lane electrical interfaces having MLSE capability, the MLSE solution approach that I prefer is:
>
> A. Include MLSE COM calculations based on shakiba_3dj_elec_01_240111, slide 5 with MLSE implementation penalty TBD)
>
> B. Use MLSE coding gain as a rough estimate (i.e. shakiba_3dj_elec_01_240111, slide 6 middle graph and equation with MLSE implementation penalty TBD)
>
> C. Relax COM margin by a fixed amount (exact amount is TBD)
>
> (choose one)
>
> Results (all): A: 32 , B: 2 , C: 7

- Next step is to further explore possibilities offered by Option A

Summary of the Proposal (Option A)

- In its nutshell, the proposed method calculates SNR advantage if the 1-tap DFE is replaced with a 1+αD MLSE (α is the DFE tap)
- The proposal uses analysis to derive equations needed to calculate this ΔSNR
- ΔSNR is calculated depending on the channel and noise characteristics
- The proposal offers equation options based on the thoroughness vs. complexity trade-off
- An MLSE implementation penalty (IP) (method and value TBD) de-rates ΔSNR to yield ΔCOM



Previous Contributions

- For details of the analysis and derivation of equations refer to:

Date	Content	Reference Contribution
November 2022	Original Proposal	shakiba_3df_01a_2211.pdf
January 2023	Further Details	shakiba_3dj_01_230116.pdf
February 2023	Recap	shakiba_3dj_elec_01_230223.pdf
February 2023	First COM Matlab Code	mellitz_3dj_elec_01a_230223.pdf
April 2023	First Update (U1.a, U1.b, U1.c)	shakiba_3dj_elec_01_230420.pdf
April 2023	MLSE Error Propagation	shakiba_3dj_elec_02_230420.pdf
January 2024	Recap and Test Data	shakiba_3dj_elec_01a_240104.pdf
January 2024	Executive Summary	shakiba_3dj_elec_01a_240111.pdf

- In particular:
  - shakiba_3df_01a_2211.pdf suggested considering an implementation penalty at a later stage
  - shakiba_3dj_elec_01_230420.pdf explains three methods for calculating ΔCOM (IP not included)
  - shakiba_3dj_elec_01a_240111.pdf adds the implementation penalty as the last step in calculating ΔCOM

Current MLSE in Matlab COM Function v4.0 Beta1L (U0)

- The original equations of the proposal is coded in COM function v4.0
- The code methodically executed the steps by which the MLSE COM analysis was conducted and presented (steps 1-5)
- Step 6 (implementation penalty) was not included at the time
- This first version used SER rather than DER and must be updated as per next slides
- Skipping the interim steps, purposely included for clarity of the analysis description, the calculations boil down to:

$$DER_{MLSE} \approx 2\sum_{j=1}^{\infty} j\left(\frac{3}{4}\right)^{j}\left(1 - CDF_{noise}\left(A_s\sqrt{1+(j-1)(1-\alpha)^2+\alpha^2}\right)\right)$$

← Intermediate parameter directly calculated form the COM-generated data

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

Equation Options

- Based on the feedback, the following updated equations were provided (shakiba_3dj_elec_01_230420.pdf):

U1.a) ΔCOM equation was updated based on target DER (as opposed to SER)

U1.b) A more comprehensive MLSE noise PDF was employed in the ΔCOM equation

U1.c) Effect of noise coloring was analyzed and added to the ΔCOM equation

- Equation U0 is no-longer an option and should be updated (including COM Matlab function)

- The intend of this contribution is to provide background information and gauge support on one of the above equation options

- If during this process a more compelling option emerges, it can be considered

Equation Option U1.a (Baseline from Hereon)

- Changes the target from SER (U0) to DER

- This is the minimum update to implement

$$DER_{MLSE} \approx 2\sum_{j=1}^{\infty}\left(\frac{3}{4}\right)^{j}\left(1 - CDF_{noise}\left(A_s\sqrt{1+(j-1)(1-\alpha)^2+\alpha^2}\right)\right)$$

← Intermediate parameter directly calculated form the COM-generated data

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

- This is even simpler than U0 and executes at no noticeable time:

```
Calculating MLSE Advantage ...
Elapsed time is 0.023777 seconds.
```

- The analysis is based on assuming the same input noise PDF/CDF profile for MLSE noise for all error events (j) but scaling SNR individually for each event by a ratio of $1+(j-1)(1-\alpha)^2+\alpha^2$

- This is a simplifying compromise to reduce the computation complexity

Equation Option U1.b

- Built on U1.a (maintains DER target)

- Uses an improved method to calculate the MLSE noise PDF/CDF profile individually for every error event ($PDF_{noise,jEE}$ / $CDF_{noise,jEE}$)

$$DER_{MLSE} \approx 2\sum_{j=1}^{\infty}\left(\frac{3}{4}\right)^{j}\left(1 - CDF_{noise,jEE}\left(A_s(1+(j-1)(1-\alpha)^2+\alpha^2)\right)\right)$$

where $CDF_{noise,jEE}$ is calculated from $PDF_{noise,jEE}$:

Intermediate parameter directly calculated form the COM-generated data

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

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

- Less compromised than U1.a at the expense of more computation

- Still runs very fast:

```
Calculating MLSE Advantage ...
Elapsed time is 0.079546 seconds.
```

Equation Option U1.c

- Built on U1.b (maintains DER target and improved MLSE noise calculation)
- Adds noise coloring effect by calculating the noise PSD and correlation matrix

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

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

- Uses the same MLSE noise PDF/CDF profile of U1.b, but calculates SNR with noise coloring
- Some simplification as the MLSE noise PDF/CDF with coloring is not analytically computable
- Nevertheless, less compromised than U1.b at the expense of a little more computation
- For more information on noise coloring and correlation see shakiba_3dj_elec_01_230420.pdf and also the backup slides
- Still runs reasonably fast*:

```
Calculating MLSE Advantage ...
Elapsed time is 1.969777 seconds.
```

* Run time is dominated by reading s4p files for calculating noise filters. Expected run time after full integration with COM code is ~0.2s.

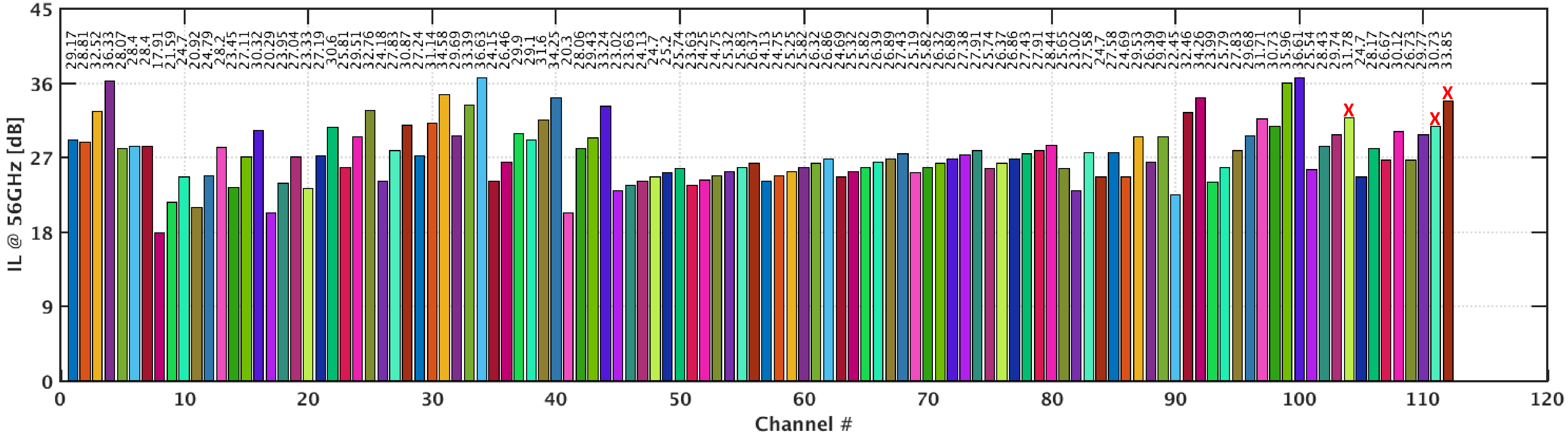
Summary of Equation Options

Equation Option	Rating	Execution Runtime Estimate	Reference Slide	Description
U1.a	Good	~ 20ms	9	Baseline
U1.b	Better	~ 80ms	10	U1.a + Improved MLSE noise calculation
U1.c	Best	~ 200ms	11	U1.b + Noise coloring

Test Channels

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



- IL (channel only) ranges from 17.9dB to 36.6dB (average 27.5dB)
- For channels 104, 111, and 112 COM function did not converge
  - Failed to find the floating tap locations:

```
Undefined function or variable 'best_floating_tap_locations'.

Error in com_ieee8023_93a_420beta3L>optimize_fom (line 7212)
    result.floating_tap_locations=best_floating_tap_locations;

Error in com_ieee8023_93a_420beta3L (line 422)
        fom_result = optimize_fom(OP,param, chdata, sigma_bn,do_C2M);
```

COM Configuration and Version

Table 93A-1 parameters			
Parameter	Setting	Units	Information
f_b	112	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]
z_p select	[2]		[test cases to run]
z_p (TX)	[12 33; 1.8 1.8]	mm	[test cases]
z_p (NEXT)	[12 31; 1.8 1.8]	mm	[test cases]
z_p (FEXT)	[12 33; 1.8 1.8]	mm	[test cases]
z_p (RX)	[12 31; 1.8 1.8]	mm	[test cases]
C_p	[0.4e-4 0.4e-4]	nF	[TX RX]
R_0	50	Ohm	
R_d	[46.25 46.25]	Ohm	[TX RX]
A_v	0.413	V	
A_fe	0.413	V	
A_ne	0.608	V	
AC_CM_RMS	0		[test cases]
L	4		
M	32		
filter and Eq			
f_r	0.5	*fb	
c(0)	0.54		min
c(-1)	[-0.4:0.02:0]		[min:step:max]
c(-2)	[0:0.02:0.16]		[min:step:max]
c(-3)	[-0.1:0.02:0]		[min:step:max]
C(-4)	[0:0.02:0.1]		[min:step:max]
C(-5)	0		[min:step:max]
C(-6)	0		[min:step:max]
c(1)	[-0.2:0.02:0]		[min:step:max]
N_b	1	UI	
b_max(1)	0.85		As/dffe1
b_max(2..N_b)	[0.3 0.2*ones(1,22)]		As/dfe2..N_b
b_min(1)	0.3		As/dffe1
b_min(2..N_b)	[-0.3 -0.2*ones(1,22)]		As/dfe2..N_b
g_DC	[-20:1:0]	dB	[min:step:max]
f_z	44.8	GHz	
f_p1	44.8	GHz	
f_p2	112	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	1.4	GHz	
MLSE	1		
ffe_pre_tap_len	6		
ffe_post_tap_len	24		
ffe_tap_step_size	0		
ffe_main_cursor_min	0.7		
ffe_pre_tap1_max	0.7		
ffe_post_tap1_max	0.7		
ffe_tapn_max	0.7		
ffe_backoff	0		
ffe_float	0		1:FFE float
ffe_bg	4		float FFE groups
ffe_bf	5		taps per group
ffe_Nf	60		float taps range
LF_PreTap_Ext	10		LF FFE pre-tap ext
LF_PostTap_Ext	10		LF FFE post-tap ext

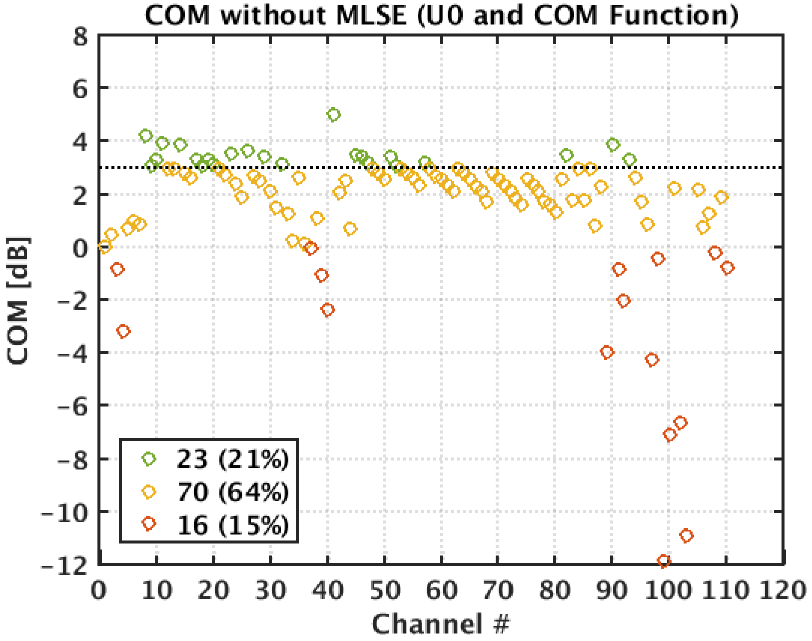
I/O control		
DIAGNOSTICS	0	logical
DISPLAY_WINDOW	0	logical
CSV_REPORT	0	logical
RESULT_DIR	.\results\100GEL_KR_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 3 2 4]	
RUNTAG	KR_eval_	
COM_CONTRIBUTION	0	logical
Operational		
COM Pass Threshold	3	dB
ERL Pass Threshold	8	dB
DER_0	1.00E-04	
T_r	4.00E-03	ns
FORCE_TR	1	logical
Local Search	2	
BREAD_CRUMBS	1	logical
SAVE_CONFIG2MAT	1	logical
PLOT_CM	0	
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	logical
TR_TDR	0.01	ns
N	3500	
beta_x	0	
rho_x	0.618	
fixture delay time	[0 0]	[port1 port2]
TDR_W_TXPKG	0	
N_bx	21	UI
Tukey_Window	1	logical
Noise, Jitter		
sigma_RJ	0.01	UI
A_DD	0.02	UI
eta_0	5.00E-09	V^2/GHz
SNR_TX	33	dB
R_LM	0.95	

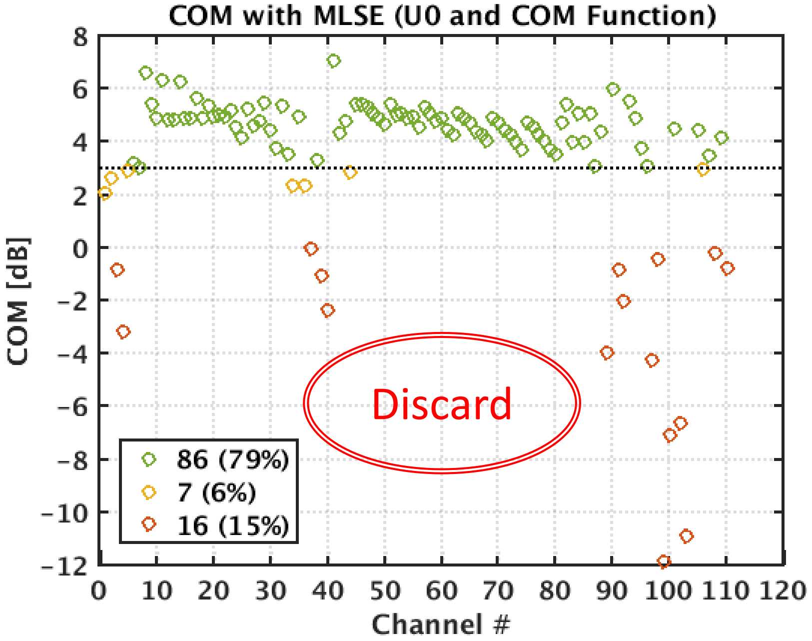
Table 93A-3 parameters		
Parameter	Setting	Units
package_tl_gamma0_a1_a2	[0.5E-3 0.89E-3 0.2E-3]	
package_tl_tau	6.141E-03	ns/mm
package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm
Table 92-12 parameters		
Parameter	Setting	
board_tl_gamma0_a1_a2	[0 3.8206e-04 9.5909e-05]	
board_tl_tau	5.79E-03	ns/mm
board_Z_c	100	Ohm
z_bp (TX)	110.3	mm
z_bp (NEXT)	110.3	mm
z_bp (FEXT)	110.3	mm
z_bp (RX)	110.3	mm
C_0	[0.29E-4]	nF
C_1	[0.19E-4]	nF
Include PCB	0	logical
Floating Tap Control		
N_bg	4	0 1 2 or 3 groups
N_bf	5	taps per group
N_f	60	UI span for floating taps
bmaxg	0.05	max DFE value for floating taps
B_float_RSS_MAX	0.02	rss tail tap limit
N_tail_start	25	(UI) start of tail taps limit
ICN parameters (v2.73+)		
f_v	0.528	*Fb
f_f	0.528	*Fb
f_n	0.528	*Fb
f_2	80	GHz
A_ft	0.6	V
A_nt	0.6	V
Receiver testing		
RX_CALIBRATION	0.000	logical
Sigma BBN step	5.00E-03	V

- COM Version: com_ieee8023_93a_420beta3L
  - ❖ Calculates MLSE ΔCOM based on SER (U0)
- COM Version: com_ieee8023_93a_420beta3L_hs1p0
  - ❖ Calculates MLSE ΔCOM based on SER (U0), DER (U1.a), with the improved MLSE noise for white (U1.b) and colored (U1.c)
  - ❖ Will be made available if there is interest
- Both versions also calculate for Gaussian noise scenarios
- Implementation penalty still not included

Test Channel Results – U0

- U0 should be discarded, this slide is FYI if you have already used COM function MLSE

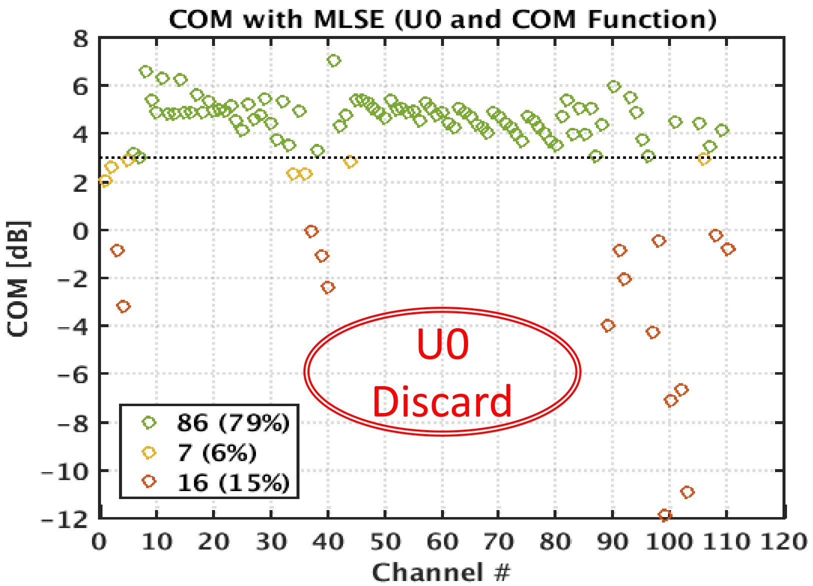




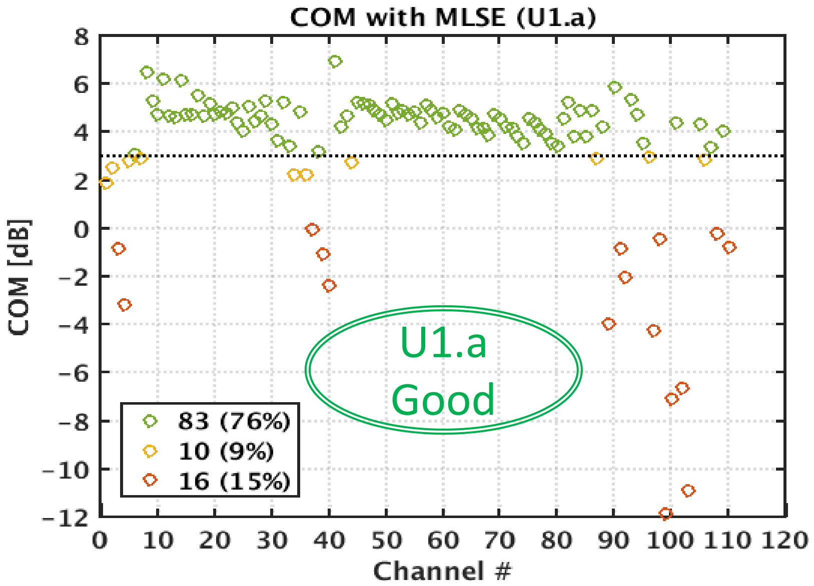
- Currently COM function ignores MLSE and reports ΔCOM = 0 if the original COM is negative
- As a result 16 cases were not considered for MLSE calculations (also removed in next slides)
  - Channels: 3, 4, 37, 39, 40, 89, 91, 92, 97, 98, 99, 100, 102, 103, 108, 110
- If needed, this screening can be relaxed to allow more channels to be considered
- Implementation penalty not applied

Test Channel Results – Updating to U1.a, U1.b, U1.c

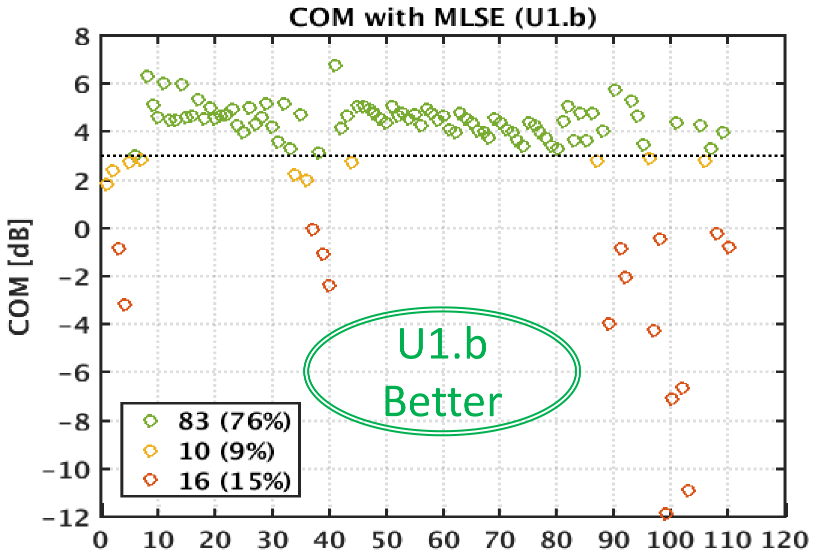
IP not applied



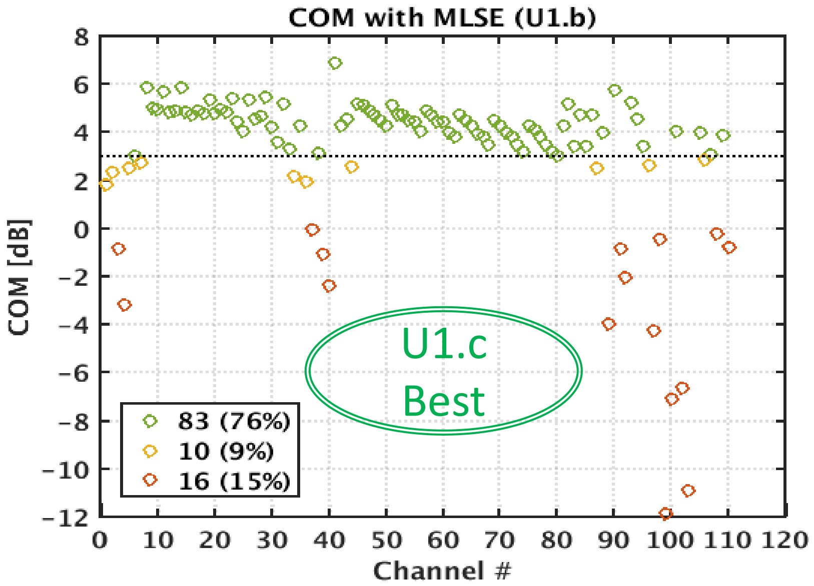
U1.a



U1.b

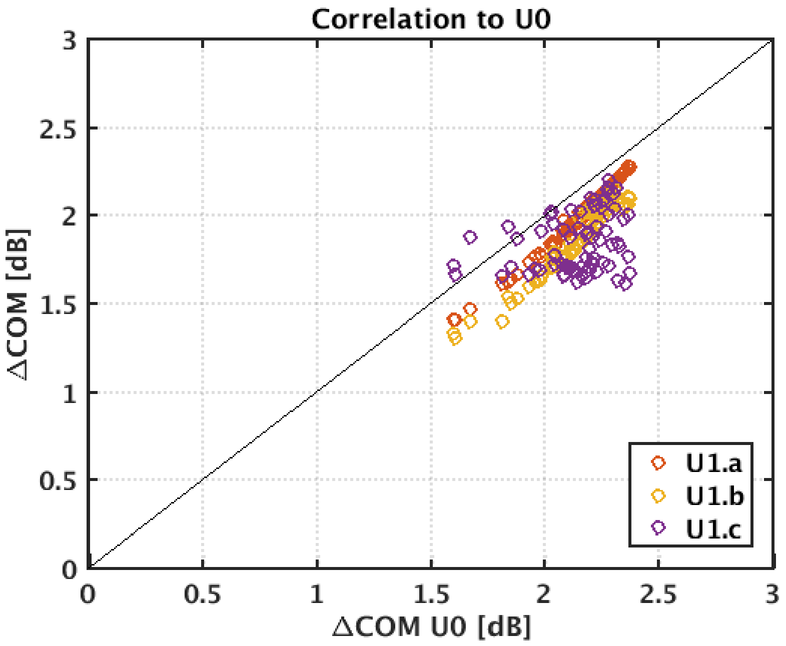


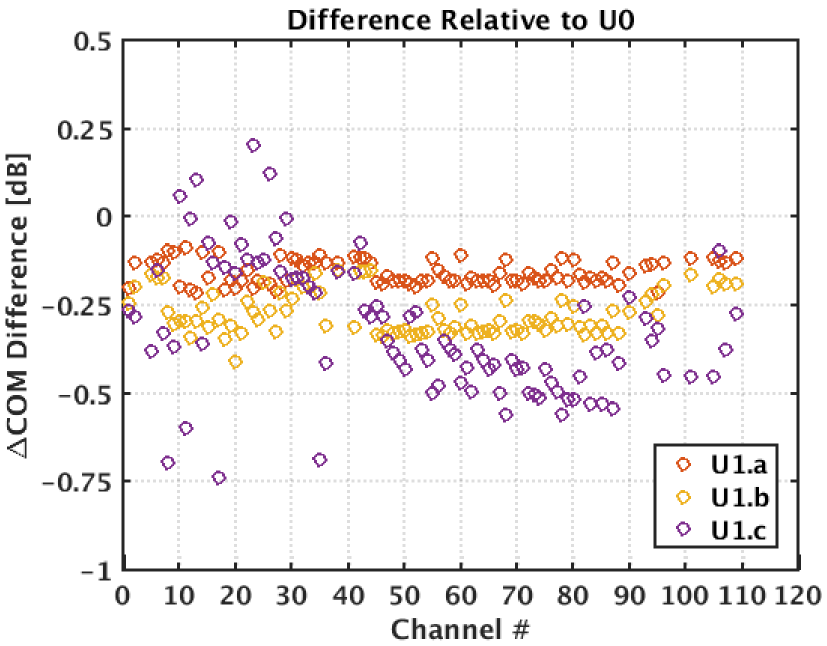
U1.c



Test Channel Results – U1.a, U1.b, U1.c vs. U0

- U0 should be discarded, this slide is FYI if you have already used COM function MLSE
- Updated equations on average predict less ΔCOM
- Gap widens as updates kick in
- MLSE becomes more channel dependent as updates kick in
- Noise coloring makes the most effect and in some cases gives better results
- Suggests favoring U1.b and U1.c over U1.a
- IP not applied

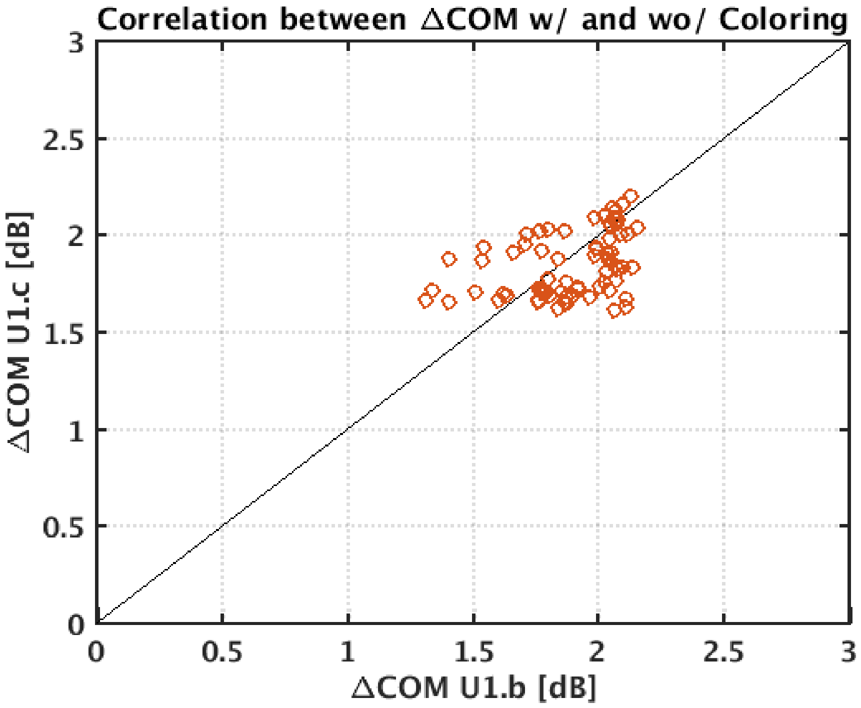




[dB]	U0 (Currently Reported by the COM Function)	U1.a (Excludes Error Propagation)	U1.b (U1.a + Improved MLSE Noise PDF)	U1.c (U1.b + Noise Coloring)
ΔCOM (Average)	2.14	1.98	1.87	1.82
Difference (Average)	0	-0.16	-0.27	-0.32

White (U1.b) or Colored (U1.c)?

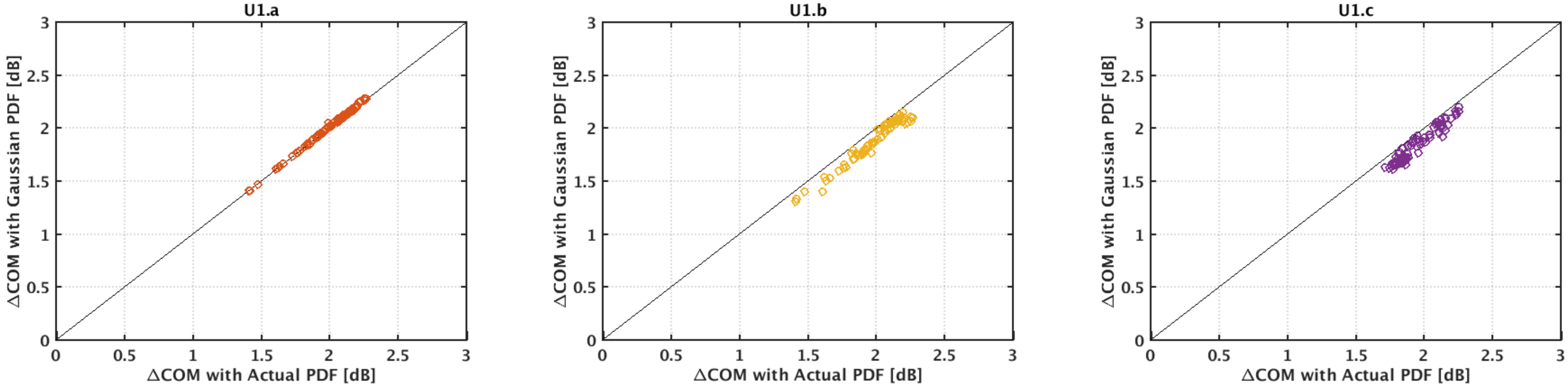
- From the test channel results:



- Correlation between ΔCOM calculated with (U1.c) and without (U1.b) noise coloring is weak
- It is a good idea to include the effect of noise coloring (U1.c)
- Implementation penalty not applied

Actual or Gaussian Noise?

- Is using Gaussian noise PDF instead of the actual PDF something to consider?



- Using the actual noise PDF (as calculated by the COM function) makes more sense as the accuracy of the MLSE calculator improves
- These test channel results do not guarantee results for other channels
- COM calculates and is fundamentally based on the actual noise PDF, there is no compelling reason to use Gaussian (may still help to use as a reference to crosscheck and debug)
- Implementation penalty not applied

Summary and Conclusions

- Representing MLSE in COM reference receiver for CR/KR was supported by a straw poll
- Using the MLSE proposal was supported by a straw poll
- The proposal provides possibility to choose from three equation options based on the thoroughness vs. complexity trade-off
- These three equation options were presented and compared using data from a set of test channels (93 yielded out of 112 channels)
- Three equation options include an MLSE implementation penalty (TBD)
- A customized version of the COM function that supports three equation options and runs reasonably fast is available (if there is interest)
    - ❖ Code quickly put together, not optimized, and currently requires Matlab toolboxes for non-essential functions
- Need consensus to refine which equation option to use

Backup Slides

Noise Filters and Correlation Matrix

- Correlation matrix $\rho_{noise,jEE}$ is calculated from the correlation coefficients of the noise:

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

Correlation coefficients in RED are due to noise coloring.

- Correlation coefficients are obtained from inverse Fourier transform of the overall noise PSD:

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

- Noise PSD is obtained as power sum of the individual noise PSDs, each calculated based on their corresponding shaping filters (next slides)

$$PSD_{noise}=PSD_{N}+PSD_{TX}+PSD_{XT}+PSD_{ISI}+PSD_{J}$$

- There is calculation overlap with the method recently considered or RX FFE optimization (healey_3dj_elec_01a_240111.pdf) that cane be leveraged

Noise Shaping Filters – eta0

- Appendix 93A:

$$\sigma_N^2 = \eta_0 \int_0^{\infty} |H_r(f) H_{ctf}(f)|^2 df \qquad (93A\text{–}35)$$

$$H_r(f) = \frac{1}{1 - 3.414214(f/f_r)^2 + (f/f_r)^4 + j2.613126(f/f_r - (f/f_r)^3)} \qquad (93A\text{–}20)$$

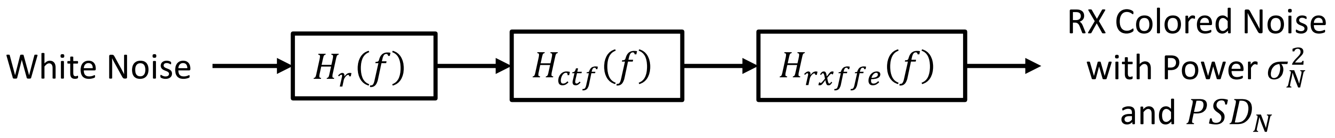
$$H_{ctf}(f) = \frac{\left(10^{\frac{g_{DC}}{20}} + j\frac{f}{f_z}\right)\left(10^{\frac{g_{DC2}}{20}} + j\frac{f}{f_{LF}}\right)}{\left(1 + j\frac{f}{f_{p1}}\right)\left(1 + j\frac{f}{f_{p2}}\right)\left(1 + j\frac{f}{f_{LF}}\right)} \qquad (93A\text{–}22)$$

- Now RX FFE should be added, similar to (93A-21) for TX:

$$H_{ffe}(f) = \sum_{i=-1}^{1} c(i) \exp(-j2\pi(i+1)(f/f_b)) \qquad (93A\text{–}21)$$

Need a similar expression for RX FFE

- eta0 noise coloring filter:



Noise Shaping Filters – TX SNR

- Appendix 93A:

$$\sigma_{TX}^2 = [h^{(0)}(t_s)]^2 10^{-SNR_{TX}/10} \qquad (93A\text{–}30)$$

$$h^{(k)}(t) = \int_{-\infty}^{\infty} X(f)H^{(k)}(f)\exp(j2\pi ft)df \qquad (93A\text{–}24)$$

$$X(f) = A_t T_b \operatorname{sinc}(fT_b) \qquad (93A\text{–}23)$$

$$H^{(k)}(f) = H_{ffe}(f)H_t(f)H_{21}^{(k)}(f)H_r(f)H_{ctf}(f) \qquad (93A\text{–}19)$$

$$H_{ffe}(f) = \sum_{i=-1}^{1} c(i)\exp(-j2\pi(i+1)(f/f_b)) \qquad (93A\text{–}21)$$

$$H_t(f) = \exp(-2(\pi f T_r/1.6832)^2) \qquad (93A\text{–}46)$$

$$H_r(f) = \frac{1}{1-3.414214(f/f_r)^2+(f/f_r)^4+j2.613126(f/f_r-(f/f_r)^3)} \qquad (93A\text{–}20)$$

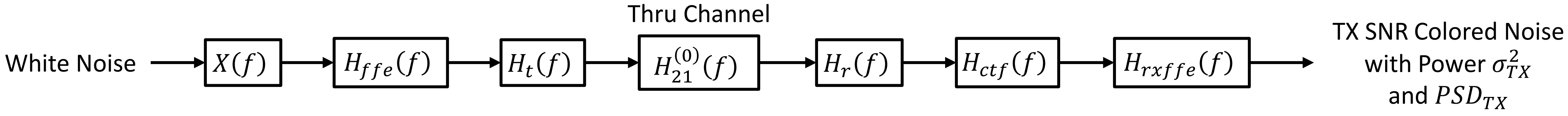
$$H_{ctf}(f) = \frac{\left(10^{\frac{g_{DC}}{20}}+j\frac{f}{f_z}\right)\left(10^{\frac{g_{DC2}}{20}}+j\frac{f}{f_{LF}}\right)}{\left(1+j\frac{f}{f_{p1}}\right)\left(1+j\frac{f}{f_{p2}}\right)\left(1+j\frac{f}{f_{LF}}\right)} \qquad (93A\text{–}22)$$

- Now RX FFE should be added, similar to (93A-21) for TX:

$$H_{ffe}(f) = \sum_{i=-1}^{1} c(i)\exp(-j2\pi(i+1)(f/f_b)) \qquad (93A\text{–}21)$$

Need a similar expression for RX FFE

- TX noise coloring filter:



Noise Shaping Filters – Xtalk

- Appendix 93A:

$$\sigma_{XT}^2 = \sum_{k=1}^{K-1} [\sigma_i^{(k)}]^2 \quad (93A–34)$$

$$[\sigma_m^{(k)}]^2 = \sigma_X^2 \sum_n [h^{(k)}((m/M+n)T_b)]^2 \quad (93A–33)$$

$$\sigma_X^2 = \frac{L^2-1}{3(L-1)^2} \quad (93A–29)$$

$$h^{(k)}(t) = \int_{-\infty}^{\infty} X(f)H^{(k)}(f)\exp(j2\pi ft)df \quad (93A–24)$$

$$X(f) = A_t T_b \operatorname{sinc}(fT_b) \quad (93A–23)$$

$$H^{(k)}(f) = H_{ffe}(f)H_t(f)H_{21}^{(k)}(f)H_r(f)H_{ctf}(f) \quad (93A–19)$$

$$H_{ffe}(f) = \sum_{i=-1}^{1} c(i)\exp(-j2\pi(i+1)(f/f_b)) \quad (93A–21)$$

$$H_t(f) = \exp(-2(\pi f T_r/1.6832)^2) \quad (93A–46)$$

$$H_r(f) = \frac{1}{1-3.414214(f/f_r)^2+(f/f_r)^4+j2.613126(f/f_r-(f/f_r)^3)} \quad (93A–20)$$

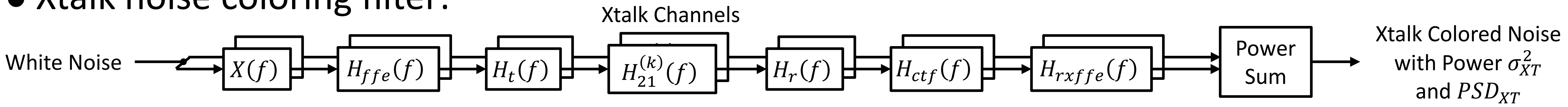
$$H_{ctf}(f) = \frac{\left(10^{\frac{g_{DC}}{20}}+j\frac{f}{f_z}\right)\left(10^{\frac{g_{DC2}}{20}}+j\frac{f}{f_{LF}}\right)}{\left(1+j\frac{f}{f_{p1}}\right)\left(1+j\frac{f}{f_{p2}}\right)\left(1+j\frac{f}{f_{LF}}\right)} \quad (93A–22)$$

- Now RX FFE should be added, similar to (93A-21) for TX:

$$H_{ffe}(f) = \sum_{i=-1}^{1} c(i)\exp(-j2\pi(i+1)(f/f_b)) \quad (93A–21)$$

Need a similar expression for RX FFE

- Xtalk noise coloring filter:



Noise Shaping Filters – ISI and Jitter

- Appendix 93A:

$$\sigma_{ISI}^2 = \sigma_X^2 \sum_n h_{ISI}^2(n) \qquad (93A\text{–}31)$$

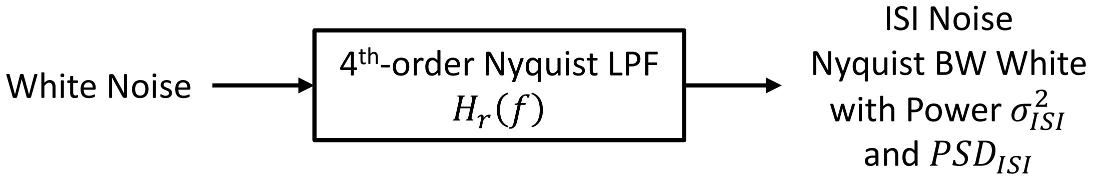
$$\sigma_J^2 = (A_{DD}^2 + \sigma_{RJ}^2)\sigma_X^2 \sum_n h_J^2(n) \qquad (93A\text{–}32)$$

- ISI and jitter noises are assumed to remain white, but within the Nyquist bandwidth

$$H_r(f) = \frac{1}{1 - 3.414214(f/f_r)^2 + (f/f_r)^4 + j2.613126(f/f_r - (f/f_r)^3)} \qquad (93A\text{–}20)$$

Arbitrary and reasonable choice

- ISI noise filter:



- Jitter noise filter: