Reference Receiver FFE with Floating Taps in COM Methodology

Mike Li, Hsinho Wu, Masashi Shimanouchi, Itamar Levin, Ariel Cohen, Ilia Radashkevich

Intel

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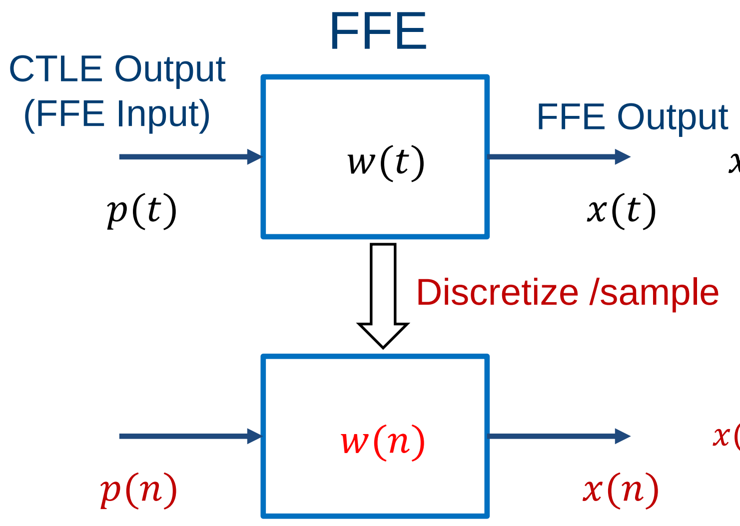
Supporters

- **Richard Mellitz, Samtec**

Background and Goals

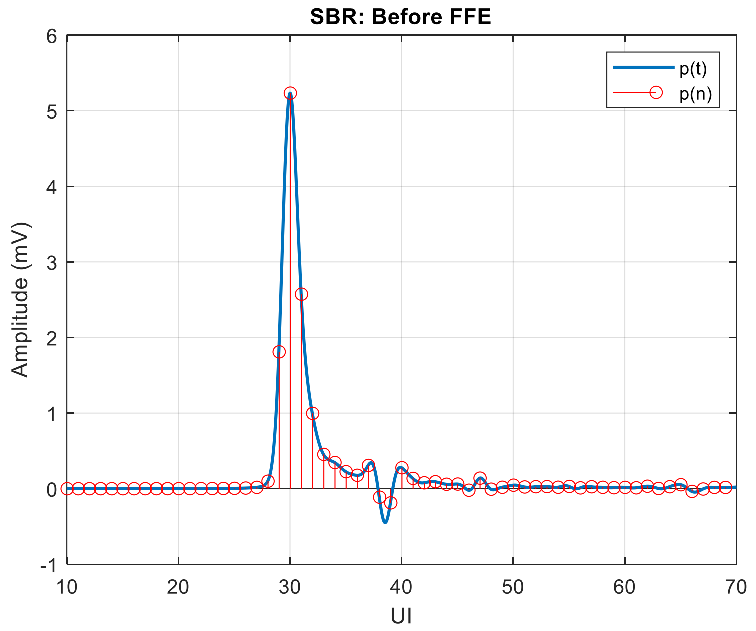
- **802.3dj COM RX trending**
  - RX EQ will be equipped with CTLE, +long FFE, +short (1-tap) MLSD or DFE
- **802.3dj July plenary straw poll showed**
  - Desired to support FFE in COM reference RX
- **Issues**
  - Observed ill-converged FFE coefficients with v4.0 code with some 802.3dj KR/CR channels
- **Goals**
  - Propose RX FFE coefficient determination methodology and descriptions for Annex 93A
  - Improve FFE performance and stability (over v4.0 implementation)
  - Propose FFE floating tap coefficient/location determination methodology

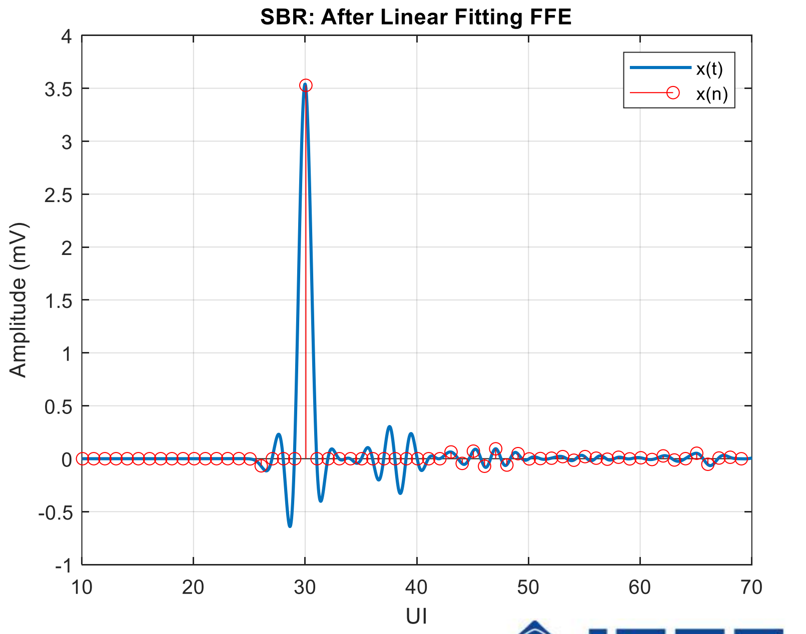
FFE Fundamentals



$x(t) = p(t) \otimes w(t)$ (Continuous Convolution)

$x(n) = \sum_i p(i-n)w(i)$ (Discrete Convolution)



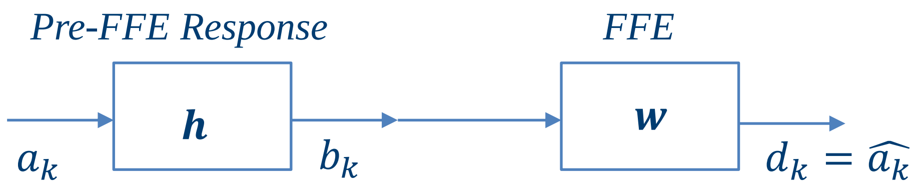


*Note: *:The FFE is with 3 pre-taps and 12 post-taps in this illustration*

Two Types of FFE Output Targets

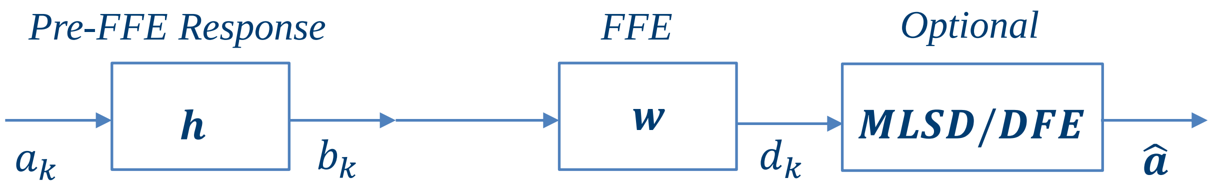
(1) No ISI Target

Signal is detected/decided at FFE output

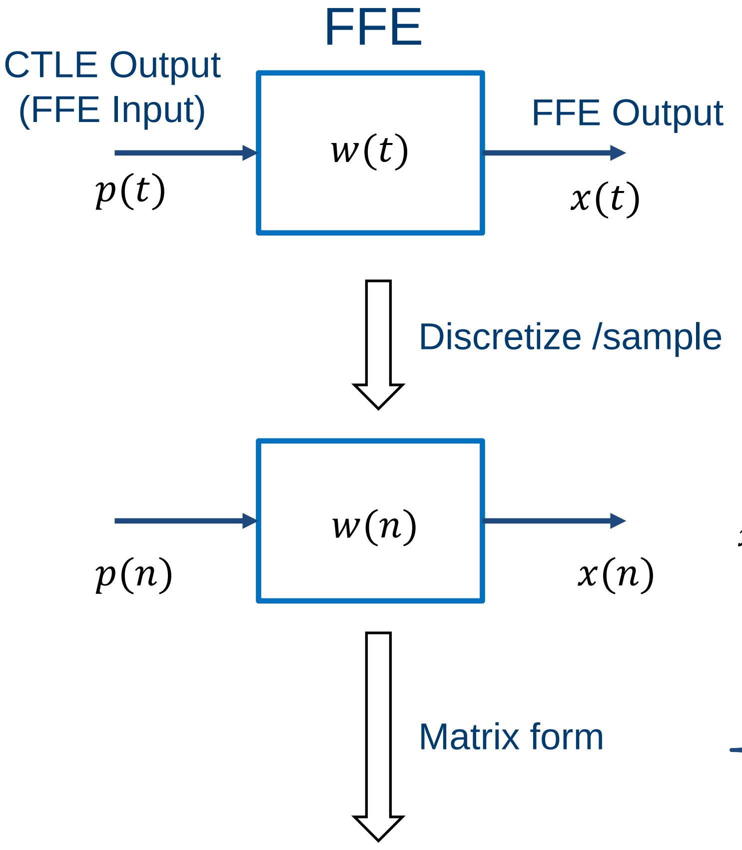


(2) Partial Response Target

FFE output is further processed by MLSD/DFE for signal detection/decision



Determine FFE Coefficients with Linear-Fitting (LF) Method



$x(t) = p(t) \otimes w(t)$ (Continuous Convolution)

$x(n) = \sum_i p(i-n)w(i)$ (Discrete Convolution)

$$\begin{cases} p(n) \Rightarrow P \ (Np\ x\ Np\ matrix) \\ w(n) \Rightarrow w \ (Nw\ x\ 1\ vector) \\ x(n) \Rightarrow \mathrm{x} \ (Nw\ x\ 1\ vector) \end{cases}$$

$$Pw = x$$

With the linear fitting (LF) method as in IEEE 802.3 Clause 85.8.3.3.5 and 85.8.3.3.6, we can determine FFE coefficients, i.e. *w(n), with the following steps:*

- Create *P (Np x Np matrix)* from CTLE Output
- Create *x* vector *(Nw x1 vector)* with:
  - Main tap = 1
  - All other taps = 0
- Compute *w (Nw x 1):*

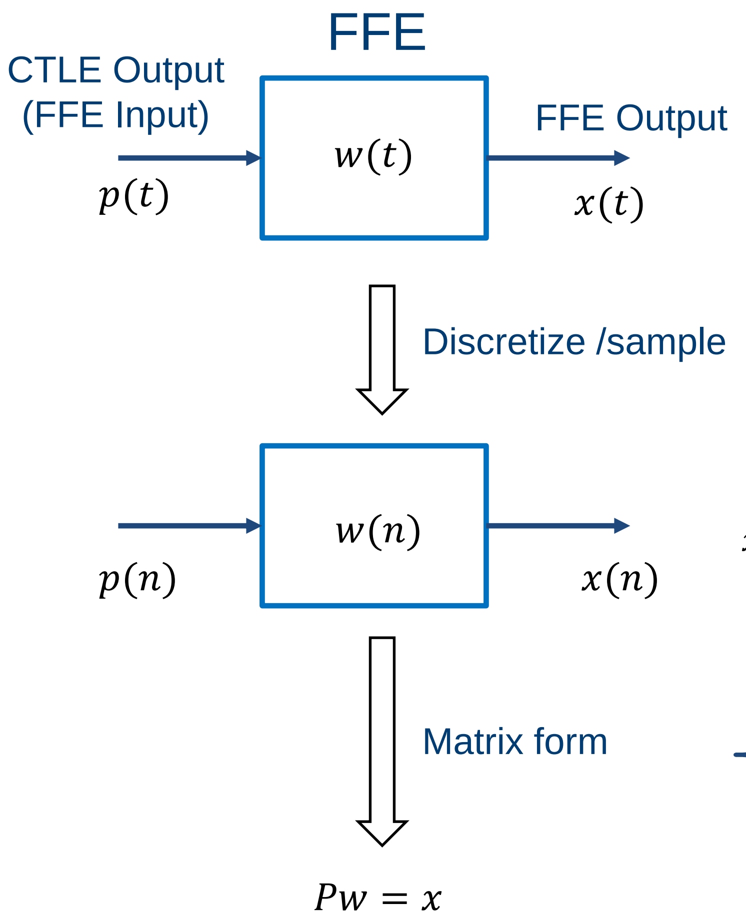
No ISI after LF FFE

$$\therefore \hat{w} = (P^T P)^{-1} P^T x$$

Same as *eq. 85-12* in CL-85.8.3.3.6

Determine FFE Coefficients with MLSD/DFE Provisioning using Linear-Fitting with Partial-Response (LF/PR FFE) Method

To accommodate MLSD/DFE with FFE, partial response (PR) is used as the target in the linear fitting process where certain post-cursor(s) are set or preserved.



$x(t) = p(t) \otimes w(t)$ (Continuous Convolution)

$x(n) = \sum_i p(i-n)w(i)$ (Discrete Convolution)

$$\begin{cases} p(n) \Rightarrow P\ (Np\ x\ Np\ matrix) \\ w(n) \Rightarrow w\ (Nw\ x\ 1\ vector) \\ x(n) \Rightarrow \mathrm{x}\ (Nw\ x\ 1\ vector) \end{cases}$$

With the linear fitting (LF) method as in IEEE 802.3 Clause 85.8.3.3.5 and 85.8.3.3.6, we can determine FFE coefficients, i.e. *h(n), with the following steps:*

- Create *P (Np x Np matrix)* from CTLE Output
- Create *x* vector *(Nw x1 vector)* with:
  - Main tap = 1
  - Post tap 1 (or more) = MLSD/DFE provisioning taps
  - All other taps = 0

Partial Response

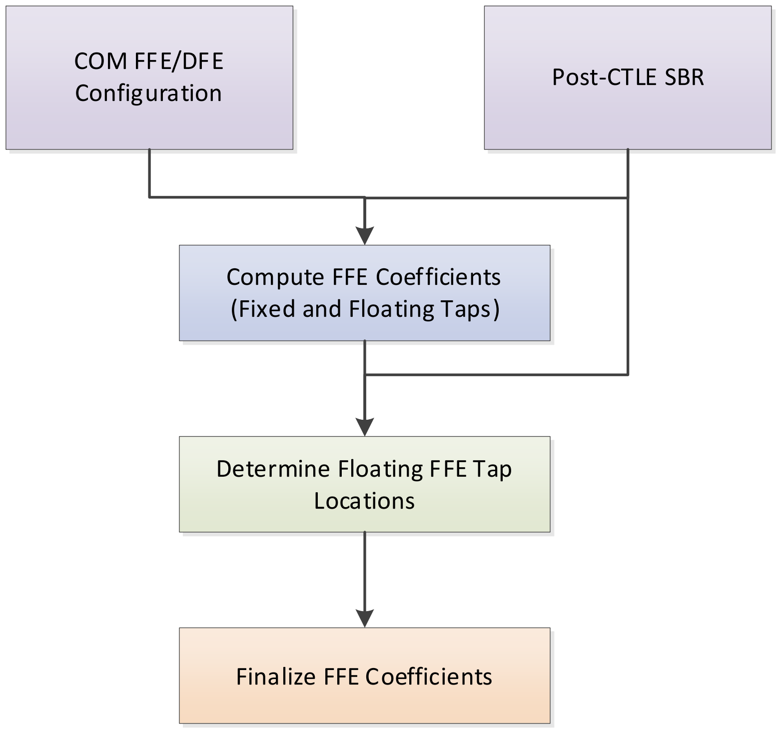
- Compute *w (Nw x 1):*

$$\therefore \hat{w} = (P^T P)^{-1} P^T x$$

Same as *eq. 85-12* in CL-85.8.3.3.6

Linear Fitting with Partial Response (LF/PR) FFE and Floating Taps

- For 802.3dj, we need a method to determine both fixed and floating FFE taps. Three step procedures:
  - Step 1: Compute FFE coefficients for both fixed taps and floating taps
  - Step 2: Determine floating FFE tap locations
  - Step 3: Finalize FFE coefficients



Linear Fitting with Partial Response (LF/PR) FFE and Floating Taps *(cont.)*

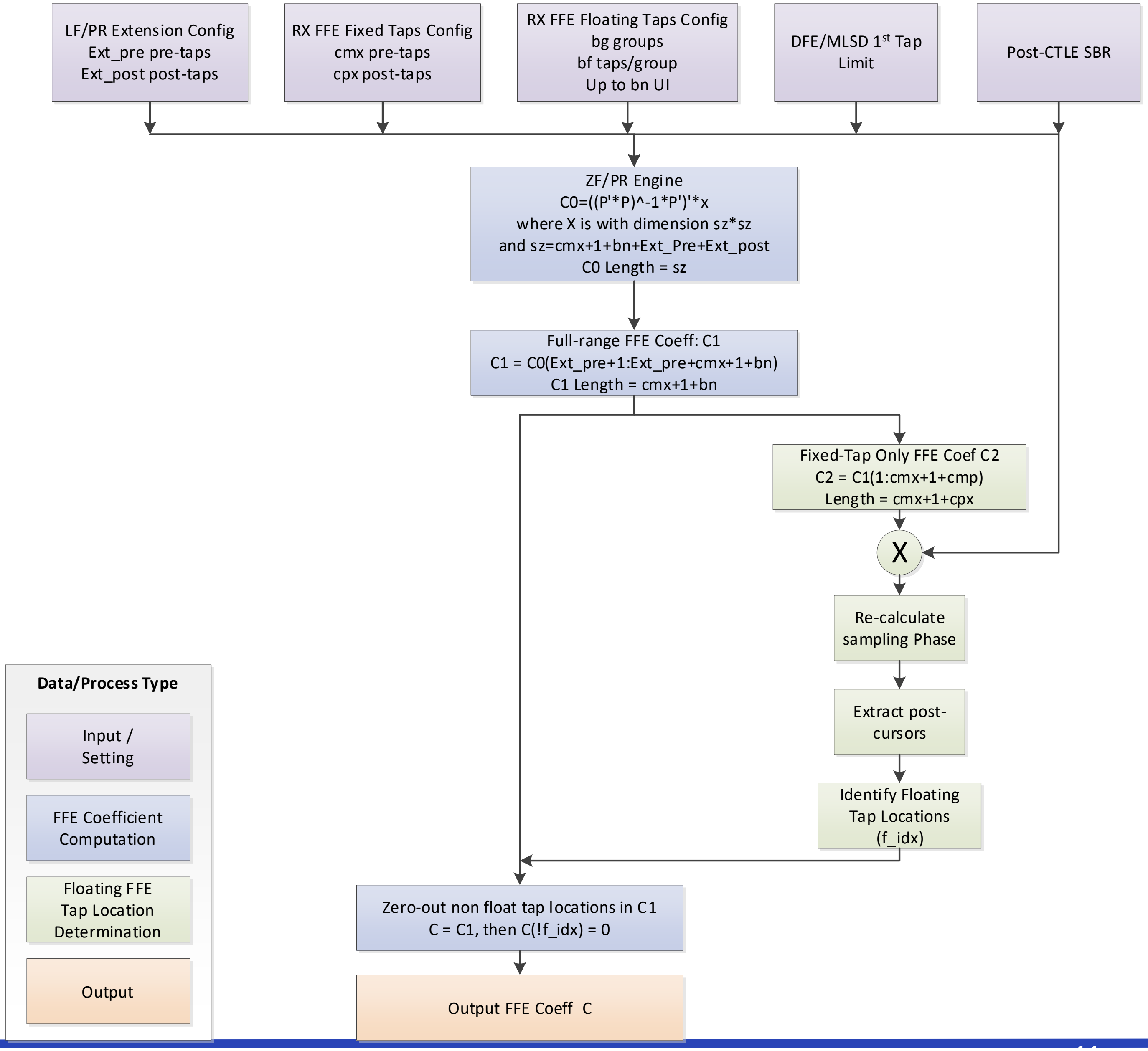
- **Step 1: Compute FFE Coefficients for all taps**
  - Compute FFE coefficients for pre-taps and all post taps within floating tap range using LF/PR FFE method shown in slide 6
  - COM v4.0 uses LF/PR FFE method which covers the range [FFE pre-taps, main cursor, FFE post-taps]
    - Issue: Observed ill-converged FFE coefficients for some 802.3dj KC/CR channels
  - Improved LF/PR FFE method
    - LF/PR FFE with pre-/post-tap extension (LF/PR FFE Ext)
      - FFE coef. are calculated w/ extended range but only the target taps/coefficients are kept
        - » See Slide 10 for details
      - Shown to improve LF/PR FFE stability and performance. Reasoning:
        - » The extended tap range guards the target range ISI performance
        - » Align with physics where signal energy is usually more concentrated toward the main cursor
      - Propose to extend LF/PR FFE by 10 pre-taps and 10 post-taps (LF/PR FFE Ext (10/10))
        - » Experiments showed Ext 10/10 is sufficient for the 802.3dj KR/CR test channels

Linear Fitting with Partial Response (LF/PR) FFE and Floating Taps *(cont.)*

- **Step 2: Determine FFE Floating Tap Locations**
  - Goal: Choose FFE tap locations that result in the least residual ISI
  - Proposed float tap location determination method
    - Reuse v4.0's floating DFE tap location method (called COM-DFE in this document)
      - Apply the COM-DFE location method on the SBR after the fixed-tap FFE
        - » See Slide 10 for details
      - Advantages
        - » Quick
        - » Tested (since 802.3ck)
        - » Documented (already included in Annex 93A)

- **Step 3: Finalize FFE Coefficients**
  - With FFE coefficients found in Step 1 and floating tap locations found in Step 2
    - All not-selected floating taps are set to 0

Flow Chart: LF/PR FFE Ext w/ COM-DFE Tap-Location Method



COM Analysis with 802.3dj KR/CR Channels using LF/PR FFE Ext and Floating Taps Method

Test Channels

Ch #	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
41~44	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
81~88	https://www.ieee802.org/3/dj/public/tools/KR/weaver_3dj_elec_01_230622.zip

KR/CR/LR End-to-End COM Configuration using LF/PR FFE Ext and Floating Taps

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	[.13 .15 .14; .13 .15 .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	V	[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		
b_max(2..N_b)	[0.3 0.2*ones(1,22)]		
b_min(1)	0.3		
b_min(2..N_b)	[-0.3 -0.2*ones(1,22)]		
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	0.7	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	1		1: FFE float
ffe_bg	4		float FFE groups
ffe_bf	5	UI	taps per group
ffe_Nf	60	UI	float taps range
LF_PreTap_Ext	10	UI	LF FFE pre-tap ext
LF_PostTap_Ext	10	UI	LF FFE post-tap ext

DIAGNOSTICS	0	logical
DISPLAY_WINDOW	0	logical
CSV_REPORT	1	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	0.0001	
T_r	0.004	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	

Parameter	Setting	Units
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 ; 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	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	0	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	50	(UI) start of tail taps limit
ICN & FOM_ILD parameters		
f_v	0.528	*Fb
f_f	0.528	*Fb
f_n	0.528	*Fb
f_2	80.000	GHz
A_ft	0.600	V
A_nt	**0.600**	V

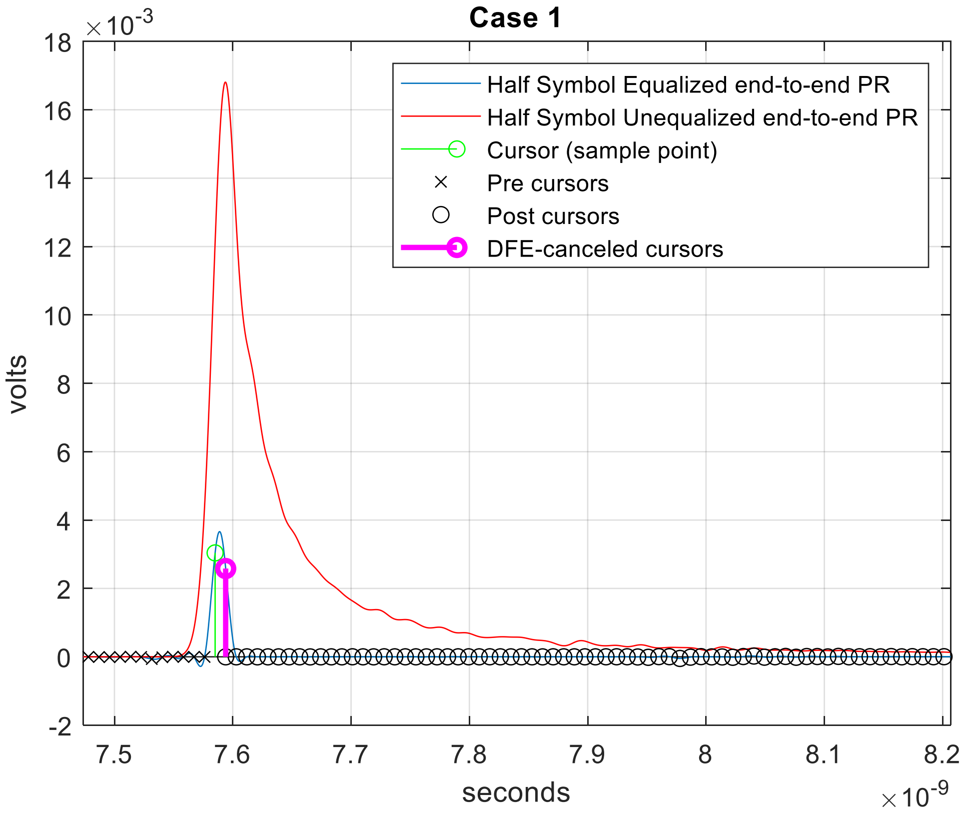
Receiver testing		
RX_CALIBRATION	0	logical
Sigma BBN step	5.00E-03	V

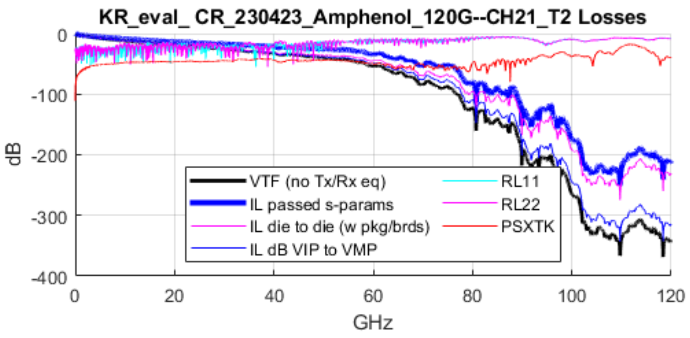
Notes:

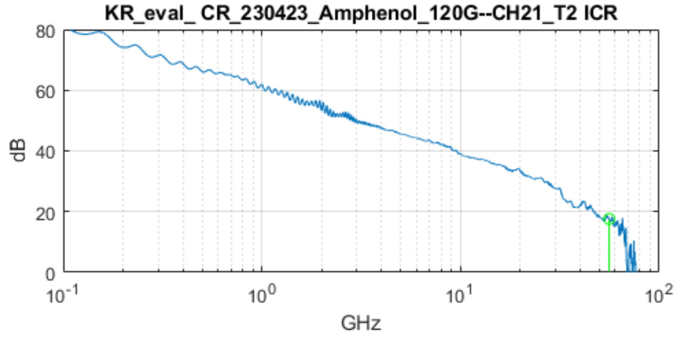
- ***Changes are marked in yellow***
- ***Modified COM v4.0 was used in this study***

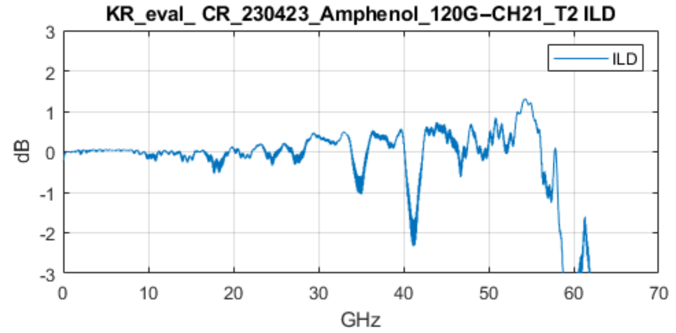
Preliminary CR/LR End-to-End COM Analysis

CH1 with LF/PR FFE Ext (10/10) and COM-DFE Float Location Method

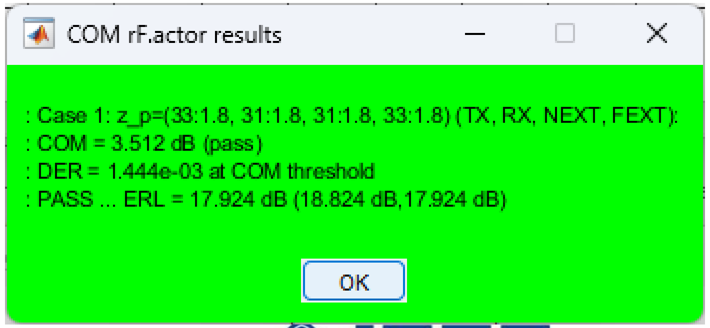






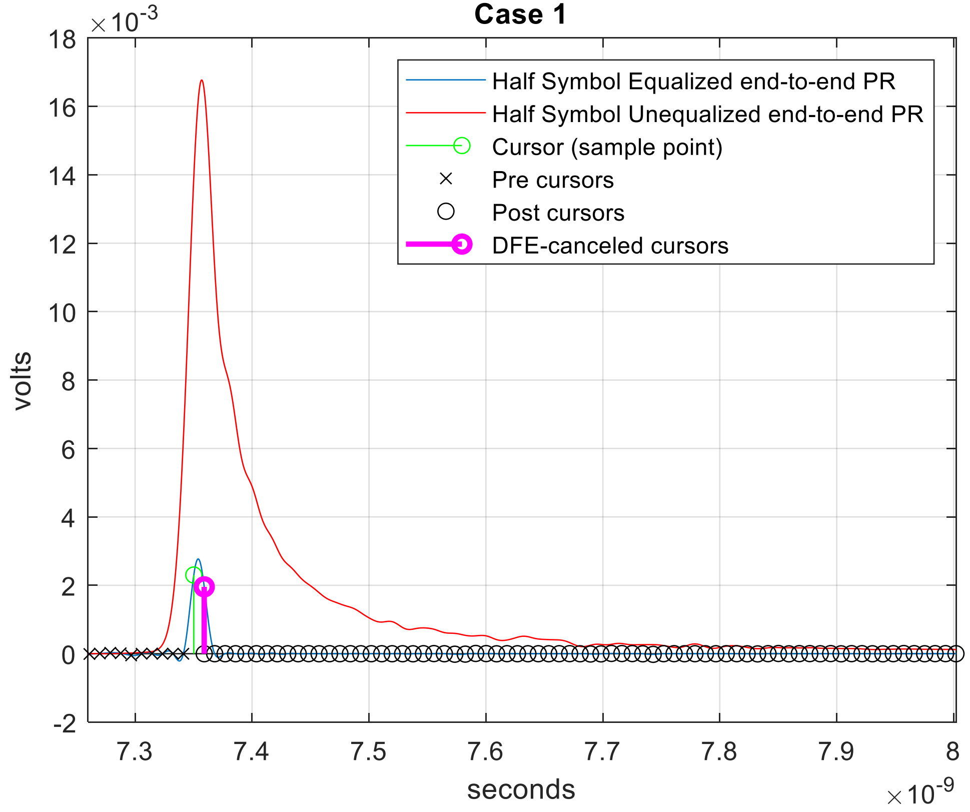


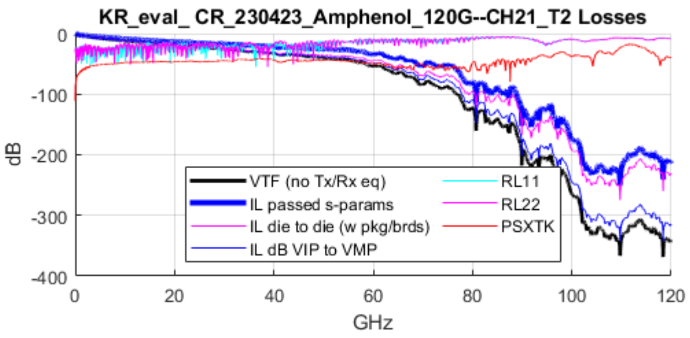
- 2x FEXT + 1 x NEXT
- FFE Taps = (6+M+24) + 4x5
- COM = 3.51 dB (vs 3.31 dB)
- DER = 1e-4
- DFE tap 1 = 0.8495
- COM DFE = 1.1797 dB
- TX FIR = [0.0400 0 0 -0.2800 0.6800 0]
- CTLE = -18/-1 dB
- RX FFE float tap loc = [25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 44 45 46 47 48]
  - DFE float tap loc: [30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49]

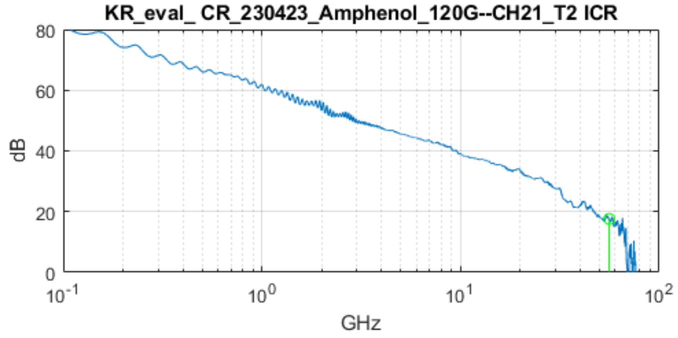


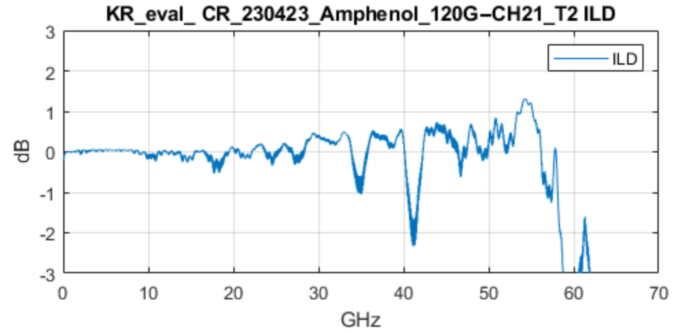
Preliminary CR/LR End-to-End COM Analysis

CH2 with LF/PR FFE Ext (10/10) and COM-DFE Location Method









- 2x FEXT + 1 x NEXT
- FFE Taps = (6+M+24) + 4x5
- COM = 4.01 dB (vs 3.34 dB)
- DER = 1e-4
- DFE tap 1 = 0.85
- COM DFE = 1.6499 dB
- TX FIR = [0.0400 0 0 -0.3400 0.6200 0]
- CTLE = -20/-2 dB
- RX FFE float tap loc = [28 29 30 31 32 33 34 35 36 37 44 45 46 47 48 49 50 51 52 53]
  - DFE float tap loc: [26 27 28 29 30 33 34 35 36 37 42 43 44 45 46 47 48 49 50 51]

COM rF.actor results

: Case 1: z_p=(33:1.8, 31:1.8, 31:1.8, 33:1.8) (TX, RX, NEXT, FEXT):
: COM = 4.009 dB (pass)
: DER = 8.255e-04 at COM threshold
: PASS ... ERL = 18.438 dB (18.688 dB,18.438 dB)

OK

LF/PR FFE Ext and Floating Taps COM Analysis with 802.3dj KR/CR Channels Results*

Float EQ	FFE Coefficient Method	Pre-tap Extension	Post-tap Extension	Float Tap Location Method	802.3dj KR/CR Channels (88) ΔCOM (dB)
DFE	LF/PR FFE	0	0	COM-DFE	0.0
FFE	LF/PR FFE Ext	10	10	COM-DFE	+0.284

Baseline (FFE + Float DFE)

Proposed FFE & Float FFE Method

Observations and Conclusions

- Based on existing linear fitting (LF) method as in IEEE 802.3 CL-85.8.3.3, we can update Annex 93A to support FFE with fixed and floating taps
- To accommodate MLSD and DFE in 802.3dj, partial response (PR) will be used within the LF FFE method (LF/PR FFE)
- To improve the performance and stabilities of LF/PR FFE, additional pre-taps and post-taps are included in the LF/PR FFE calculations (LF/PR FFE Ext)
  - Experiments showed that additional 10 pre-taps and 10 post-taps are sufficient
- Existing floating location determination method in COM v4.0 can be reused in finding floating FFE tap locations.
- Experiments with latest 802.3dj KR/CR test channels, LF/PR FFE Ext with floating FFE taps shown to improve COM results (w/ MLSD) moderately by ~0.28dB (vs. LF/PR FFE + float DFE taps)