Investigation of COM for DFE- and FFE-based reference receivers

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More information are provided based on Spokane discussion…

- Explore differences between mix-signal (DFE-based) and DSP (FFE-based) receivers.
  - Behavior, COM and time response
  - Can we cover FFE-based receiver by DFE-based receiver model?
  - Can we use DFE-based receiver model and a new COM margin to cover FFE-based receiver?

- Explore impacts of RX FFE noise amplification and ADC quantization.
  - Can we ignore the FFE noise amplification?
  - Can we ignore the ADC quantization noise?
- Explore impact of FFE & DFE weight quantization.
  - Can we ignore the FFE & DFE weight quantization?

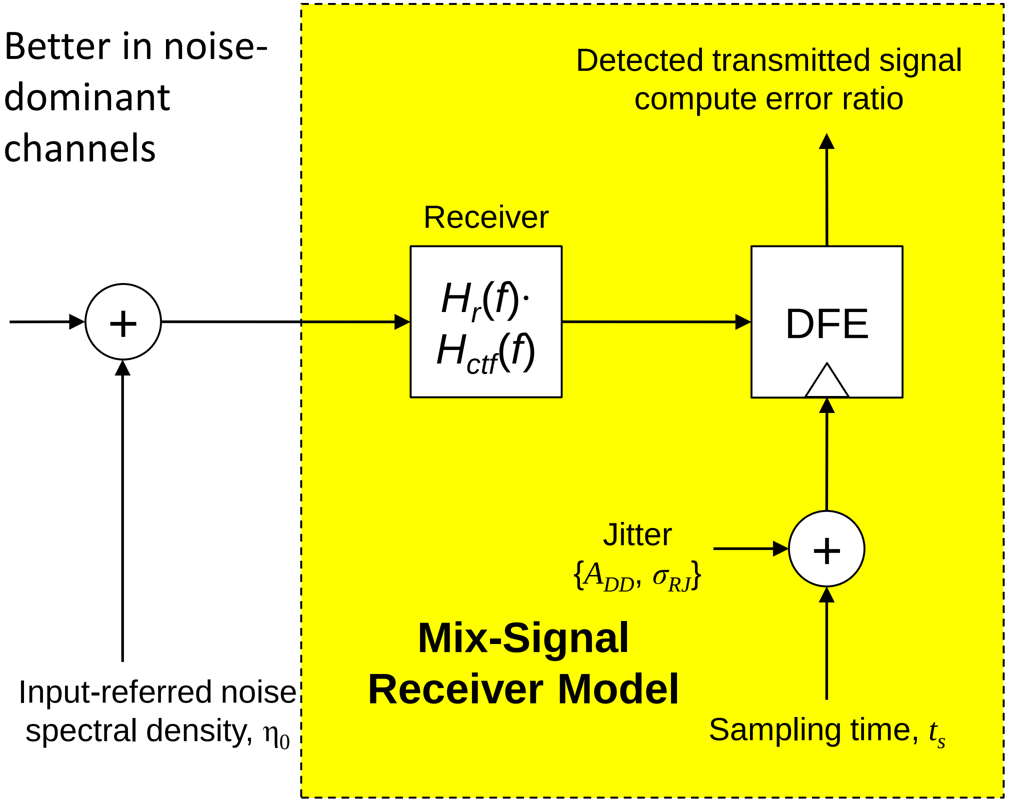
- **Explore performance differences in satisfying the IEEE 802.3ck objectives.**
  - IEEE 802.3ck objective: insertion loss ≤28dB at 26.56GHz.
  - Can DFE-based receiver meet the 28dB insertion loss objective?

Table of Contents

- Reference receivers under investigation
  - Mix-signal receiver (a.k.a. DFE-based receiver, Annex 93A, without RX FFE)
  - ADC-DSP receiver (a.k.a. FFE-based receiver, lu_3ck_adhoc_01_082918)
- Comparison of COM for DFE- and FFE-based receivers
  - Behavior, COM and time response
  - Performance concern of DFE-based receiver, parallel simulations in hidaka_3ck_adhoc_01_102418 (Credo) and li_3ck_02_1118.pdf (Intel)
- More consideration on FFE-based receiver quantization
  - Impact of FFE noise amplification and ADC quantization
  - Impact of FFE & DFE weight quantization
- Preliminary sensitivity study of b_max on COM of FFE-based receiver
- Summary, Suggestion and Future Work

Mix-signal receiver (DFE-based) and ADC-DSP (FFE-based) receiver

Long DFE taps, FFE-free.



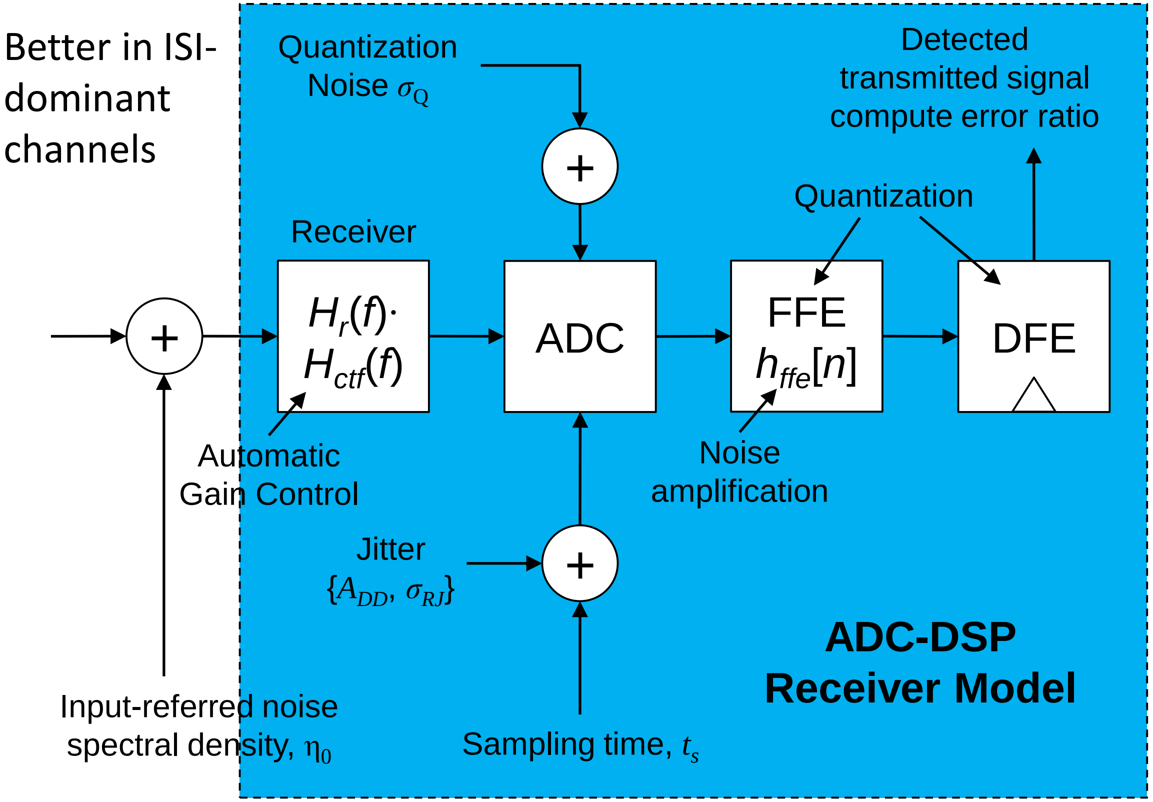
Reference: IEEE Std 802.3-2015, Annex 93A

TX FFE taps deal with pre-cursors, DFE taps deal with the post cursors without noise amplification.

Pros: High tolerance to noisy channels.

Cons: Low tolerance to high loss channels.

Long FFE taps, short DFE taps (usually 1 tap).



Reference: lu_3ck_adhoc_01_082918, lu_3ck_01_0918.

RX FFE taps can deal with both pre- and post cursors, but RX FFE will amplify the noise.

Pros: High tolerance to high loss channels.

Cons: Low tolerance to noisy channels.

COM simulations of DFE- and FFE-based receivers

Channel	ID	IL fitted(dB)	ICN (mV)	FOM_ILD (dB)	COM (dB) MS	COM (dB) Full DSP	COM (dB) DSP ADC QUAT.	COM (dB) DSP no QUAT.	COM Delta (MS vs. DSP)	COM Delta (ADC quant.)	COM Delta (FFE&DFE Quant.)
lim_3ck_01_0718	1	-10.24	2.41	0.13	3.79	4.36	4.51	4.81	-0.57	0.30	0.15
	2	-12.27	2.15	0.13	5.31	4.31	4.44	4.76	1.00	0.32	0.13
	3	-14.13	1.97	0.13	5.15	4.45	4.56	4.85	0.70	0.29	0.11
	4	-16.03	1.83	0.13	5.15	4.46	4.53	4.85	0.69	0.32	0.07
mellitz_100GEL_adhoc_02_010318	5	-15.88	2.63	1.24	2.34	1.48	1.48	1.67	0.86	0.19	0.00
lim_100GEL_02_0318	6	-10.24	2.41	0.13	3.79	4.36	4.51	4.81	-0.57	0.30	0.15
	7	-12.27	2.15	0.13	5.31	4.31	4.44	4.76	1.00	0.32	0.13
	8	-14.13	1.97	0.13	5.15	4.45	4.56	4.85	0.70	0.29	0.11
mellitz_3ck_01_0518_C2M	9	-9.03	1.70	0.10	5.98	4.91	5.06	5.34	1.07	0.28	0.15
	10	-9.30	3.38	0.48	2.95	2.36	2.41	2.58	0.59	0.17	0.05
	11	-11.12	1.44	0.09	6.25	5.35	5.46	5.77	0.90	0.31	0.11
	12	-11.17	2.97	0.46	3.38	2.89	2.98	3.19	0.49	0.21	0.09
	13	-13.21	1.25	0.09	6.32	5.46	5.56	5.87	0.86	0.31	0.10
	14	-12.96	2.38	0.47	3.66	3.21	3.30	3.51	0.45	0.21	0.09
tracy_100GEL_02_0118	15	-15.73	0.67	0.37	5.15	4.71	4.85	5.18	0.44	0.33	0.14
	16	-16.03	0.68	0.28	4.27	3.85	3.94	4.24	0.42	0.30	0.09
tracy_100GEL_06_0118	17	-14.31	0.62	0.21	5.07	4.34	4.40	4.69	0.73	0.29	0.06
	18	-14.29	0.70	0.23	5.46	4.93	5.01	5.34	0.53	0.33	0.08
mellitz_100GEL_adhoc_04_010318	19	-30.34	1.97	1.61	-1.64	-2.06	-2.39	-2.37	0.42	0.02	-0.33
mellitz_100GEL_adhoc_03_010318	20	-25.55	2.00	1.48	0.63	0.35	0.30	0.39	0.28	0.09	-0.05
mellitz_100GEL_adhoc_02_021218	21	-25.15	1.46	0.55	1.32	1.03	1.09	1.26	0.29	0.17	0.06
	22	-27.84	1.42	0.57	0.25	0.24	0.22	0.40	0.01	0.18	-0.02
heck_100GEL_85ohm_nom_01_011718	23	-29.74	1.52	2.29	-0.45	-0.09	-0.07	0.08	-0.36	0.15	0.02
heck_100GEL_85ohm_lhl_01_011718	24	-29.85	1.53	2.23	-0.41	0.21	0.08	0.23	-0.62	0.15	-0.13
heck_100GEL_85ohm_hlh_01_011718	25	-29.62	1.52	2.37	-0.53	-0.06	-0.09	0.07	-0.47	0.16	-0.03
mellitz_3ck_adhoc_02_081518 Opt1	26	-23.79	0.56	0.23	4.19	4.49	4.74	5.13	-0.30	0.39	0.25
	27	-27.59	0.42	0.26	2.53	3.49	3.66	4.06	-0.96	0.40	0.17
	28	-31.36	0.33	0.29	0.49	1.88	2.03	2.41	-1.39	0.38	0.15
mellitz_3ck_adhoc_02_081518 Opt2	29	-22.98	0.66	0.46	3.72	4.56	4.73	5.08	-0.84	0.35	0.17
	30	-26.72	0.49	0.51	2.93	3.62	3.86	4.23	-0.69	0.37	0.24
	31	-30.42	0.37	0.58	0.96	2.28	2.40	2.75	-1.32	0.35	0.12
tracy_100GEL_04_0118	32	-22.94	0.36	1.28	4.73	4.67	4.87	5.22	0.06	0.35	0.20
tracy_100GEL_05_0118	33	-23.90	0.54	1.50	3.46	3.72	4.01	4.35	-0.26	0.34	0.29
zambell_100GEL_02_0318	34	-27.40	0.29	0.27	2.92	3.83	3.93	4.29	-0.91	0.36	0.10

FFE- fail, DFE- pass. (IDs 10, 12)

FFE- pass, DFE- fail. (IDs 27, 30, 34)

Use parameters modified from COM2.50.
Cd=130fF, Cp = 110fF.
N_b = 24 (DFE-based, 24 taps DFE),
N_b = 1, N_post_ffe = 24
(FFE-based, 24 post taps, 3-pre taps).
Noise amplification of FFE is considered.

(1) Low loss, high crosstalk.

(2) Low loss, low crosstalk.

DFE-based receiver gives better COM

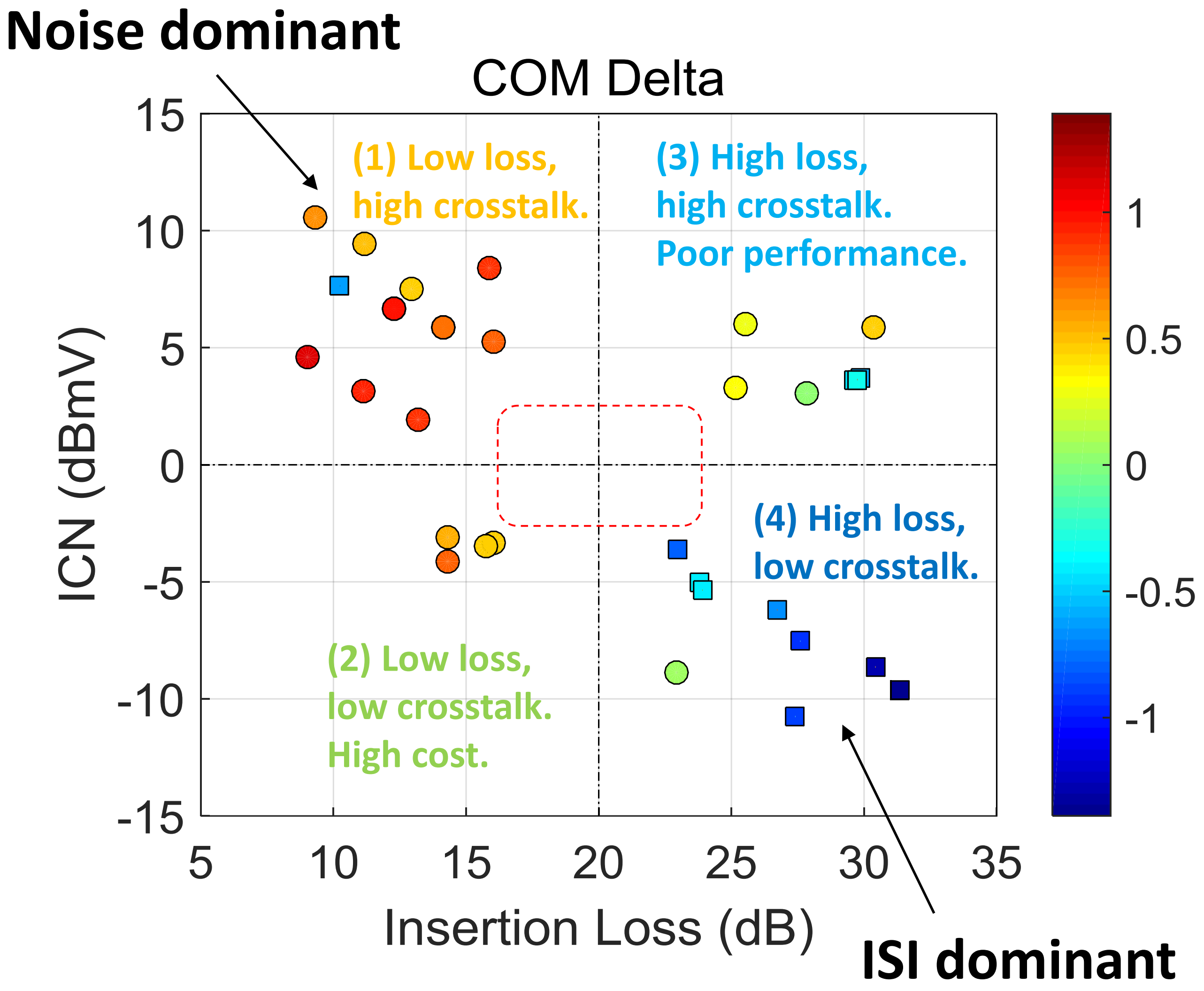
(3) High loss, high crosstalk.

(4) High loss, low crosstalk.

FFE-based receiver gives better COM

1/32 UI phase shift towards pre-cursor is applied which gives better results for FFE-based receiver compared with lu_3ck_adhoc_01_102418.

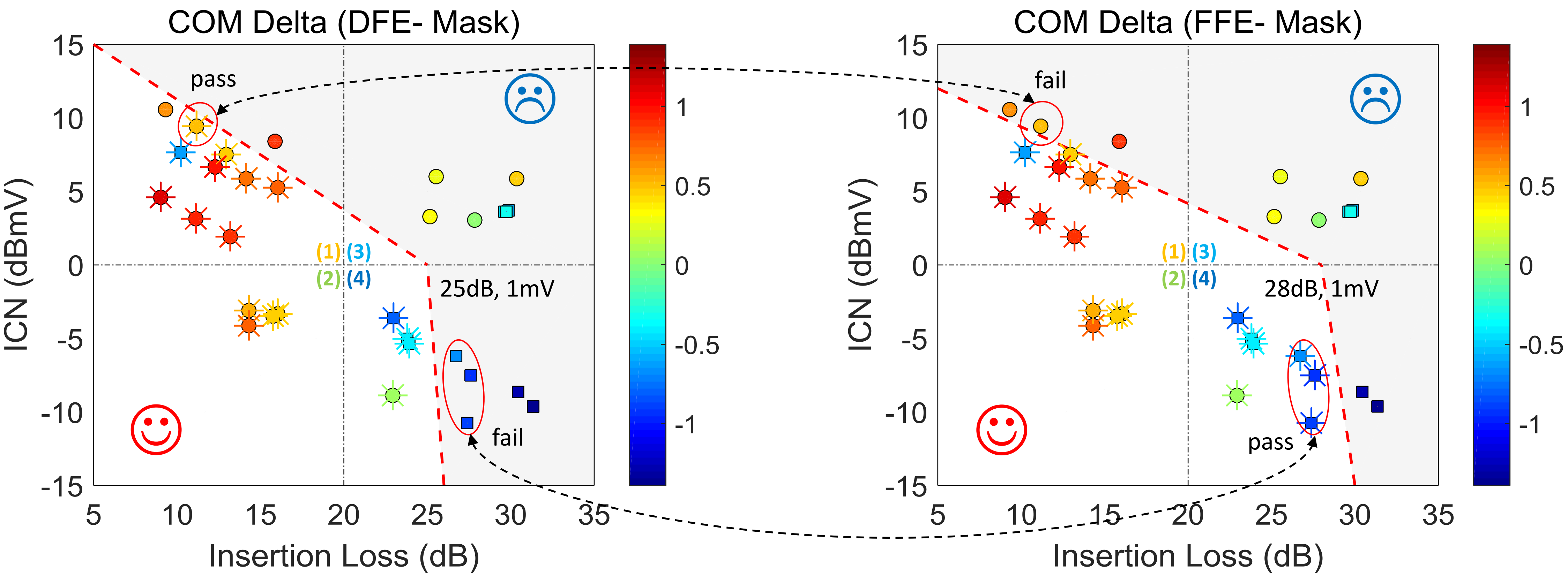
Behaviors of DFE- and FFE-based receivers in different “IL and ICN” regions



- ‘Circle’: DFE-based receiver model gives better COM.
- ‘Square’: FFE-based receiver model gives better COM.
- DFE- and FFE-based receivers show different behaviors in different “IL and ICN” regions.
- The COM delta deviation is approaching 3dB margin.
  - Cannot cover FFE-based receiver by DFE-based model.
  - Cannot attribute receiver difference to COM margin.

Note: COM Delta is the difference in COM between FFE- and DFE-based receivers.

DFE- and FFE-based receivers may yield 'pass' or 'fail' for the same channel



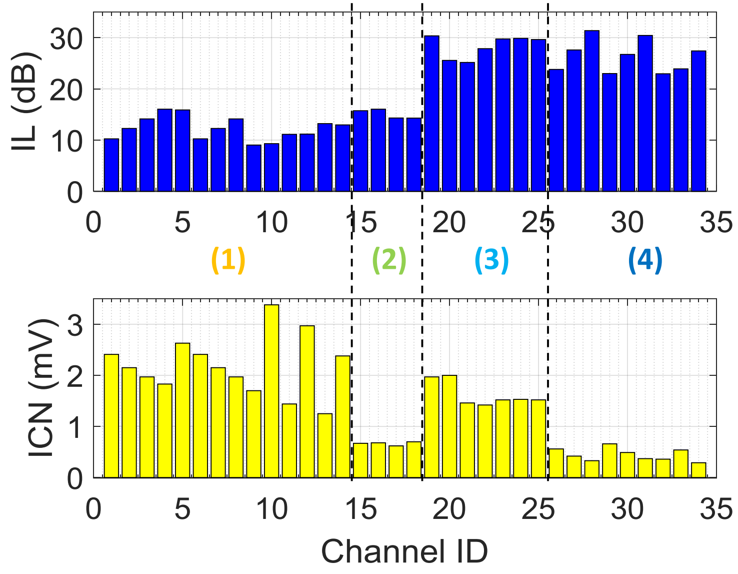
- The "ICN vs. IL" masks for FFE- and DFE-based receivers are different.
  - DFE-based receiver model gives better COM in low loss and high crosstalk channels.
  - FFE-based receiver model gives better COM in high loss and low crosstalk channels.
- For the same channel, DFE- and FFE-based receiver model may yield a 'pass' or a 'fail'.

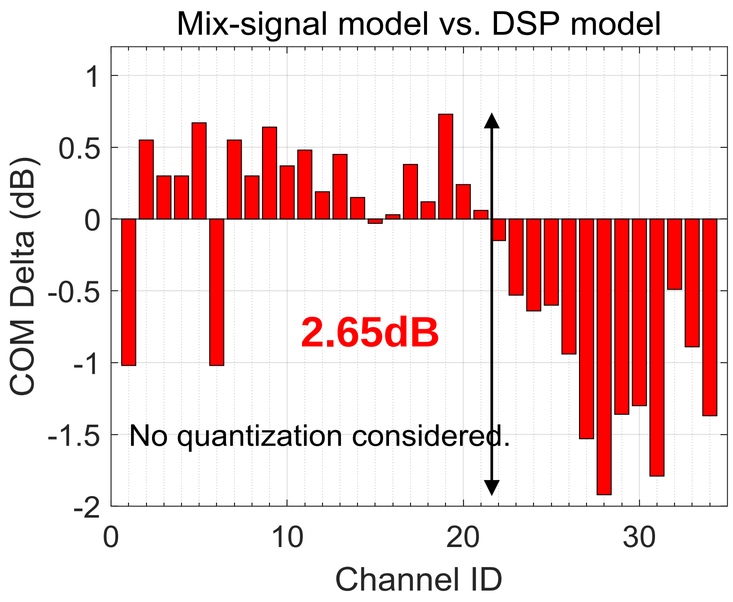
COM difference is approaching 3dB and varies case by case

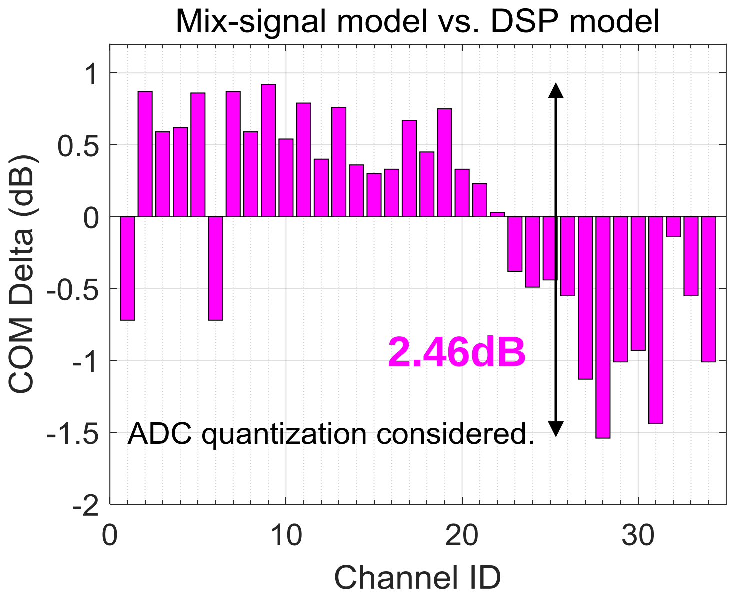
The COM Delta varies case by case.

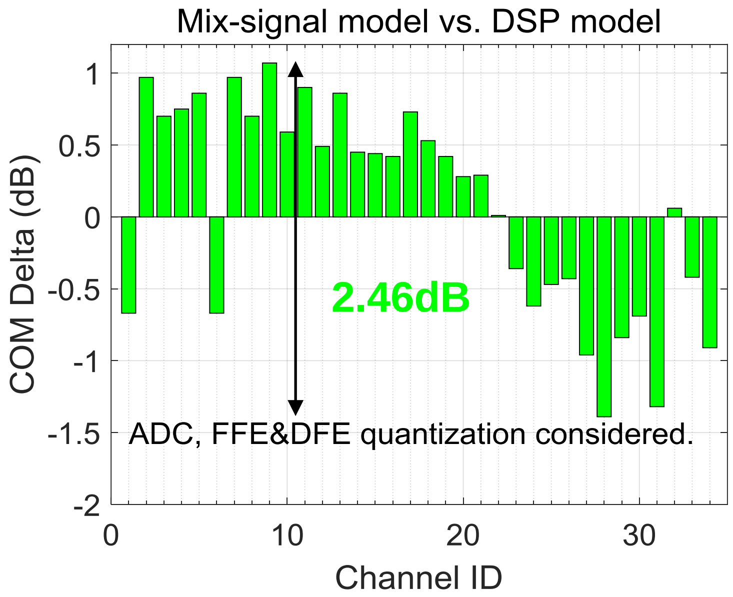
COM Delta deviation is approaching 3dB.

If the noise amplification of RX FFE is ignored, the COM Delta will be larger.

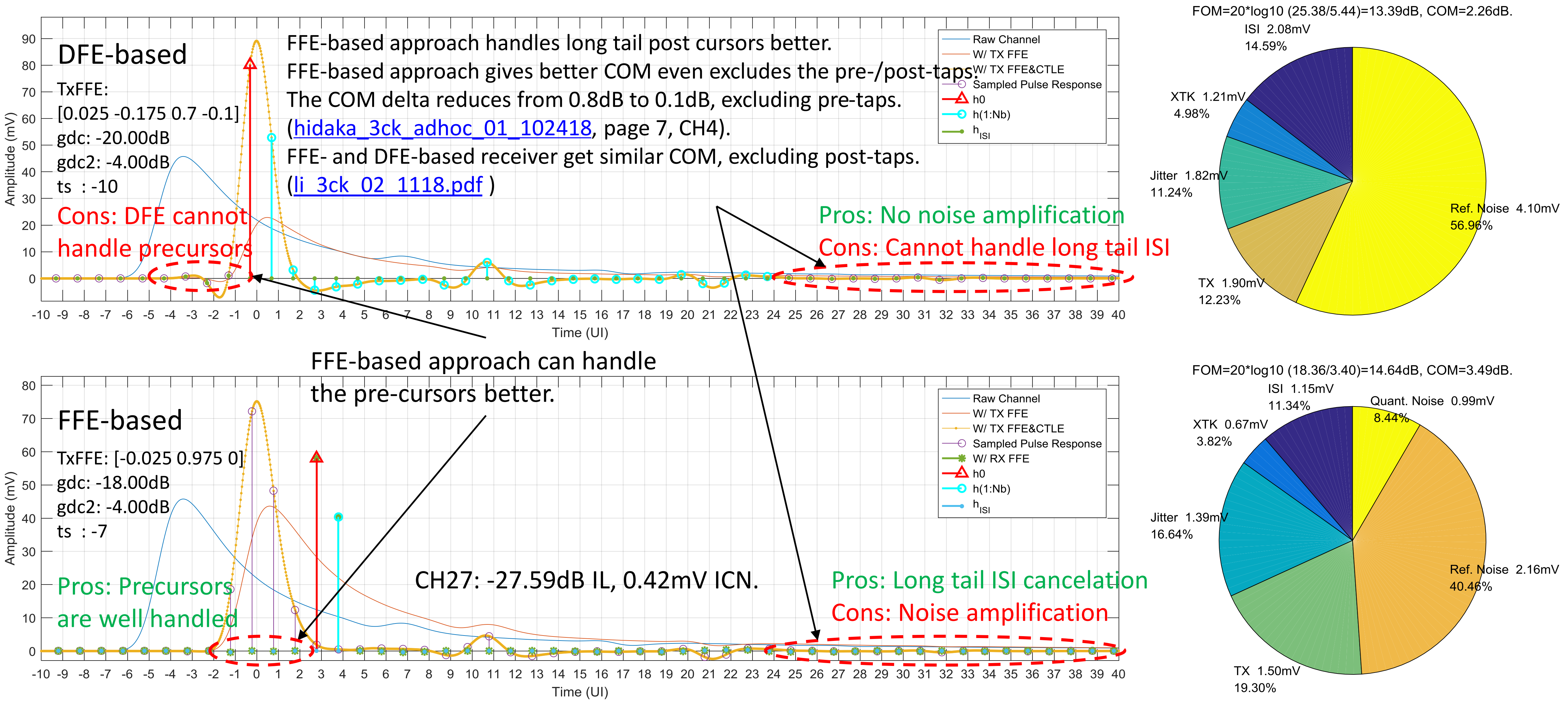




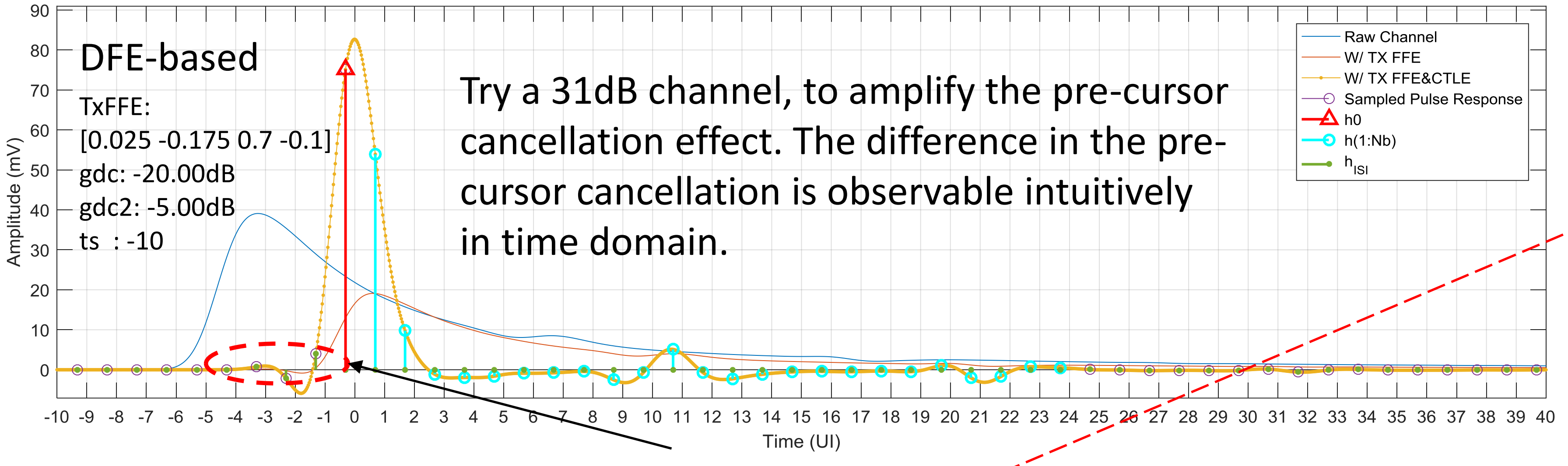


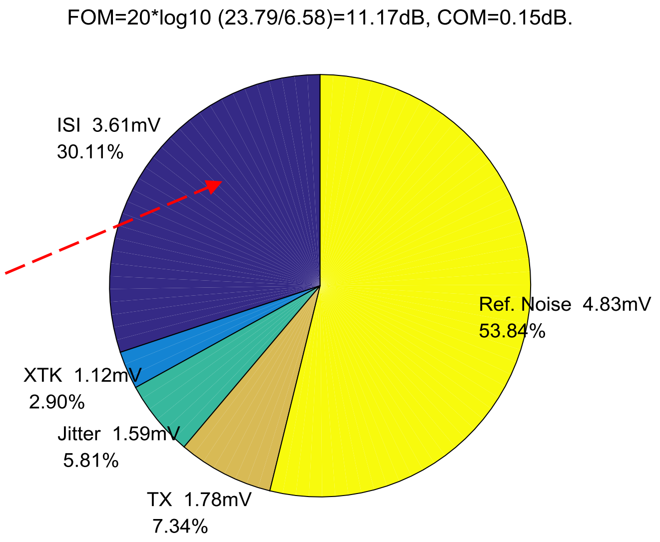


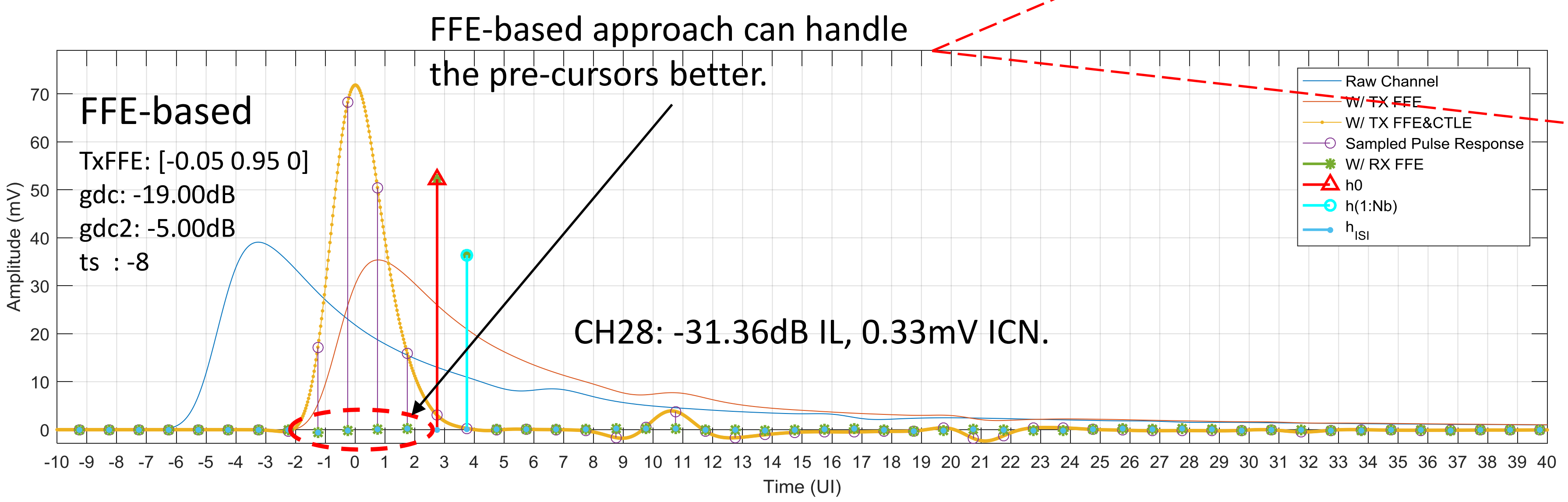
Precursor cancellation leads to the performance gap in ISI dominant region

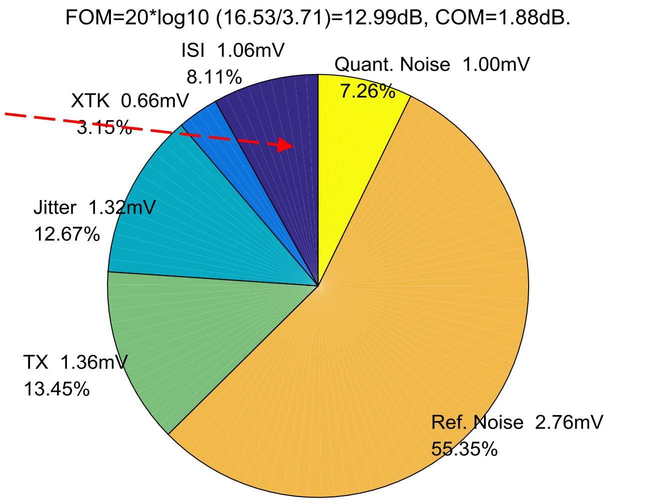


Precursor cancellation leads to the performance gap in ISI dominant region



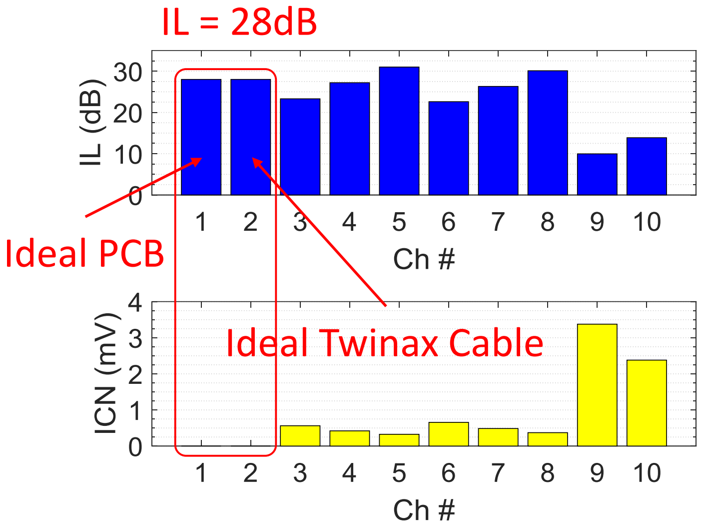


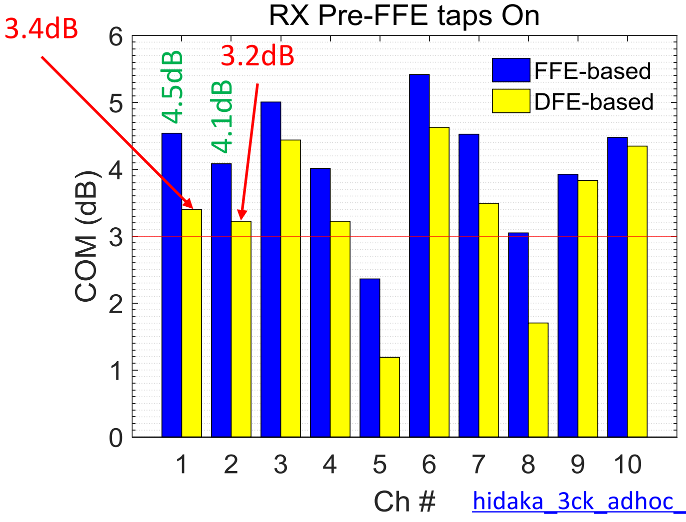


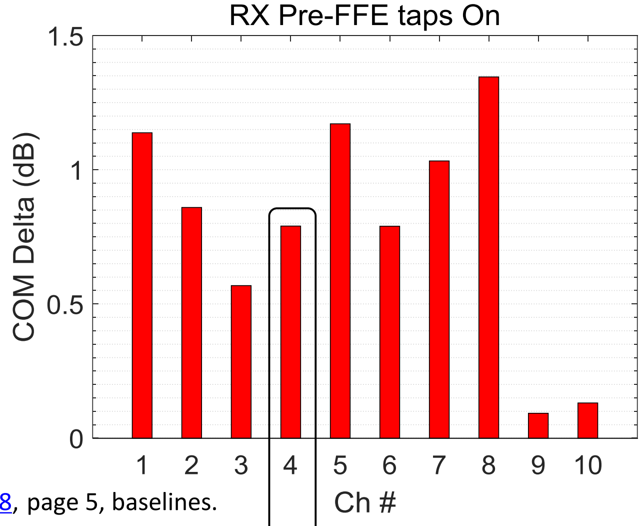


Performance concern of DFE-based receiver based on parallel simulations

Thanks Yasuo and Phil for their simulations and data in hidaka_3ck_adhoc_01_102418.







hidaka_3ck_adhoc_01_102418, page 5, baselines.

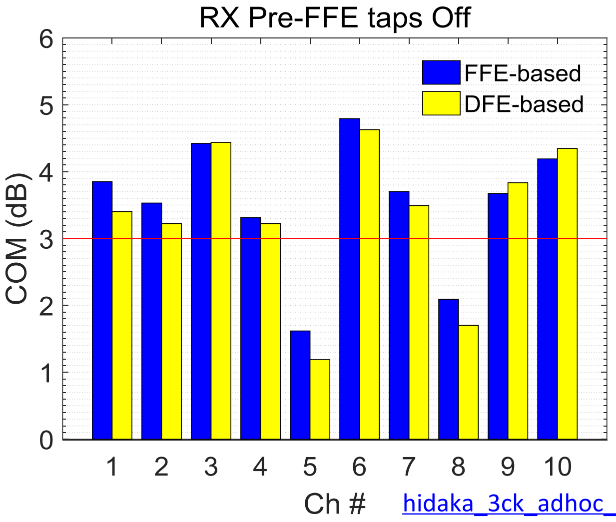
ILD and ICN are not considered yet.

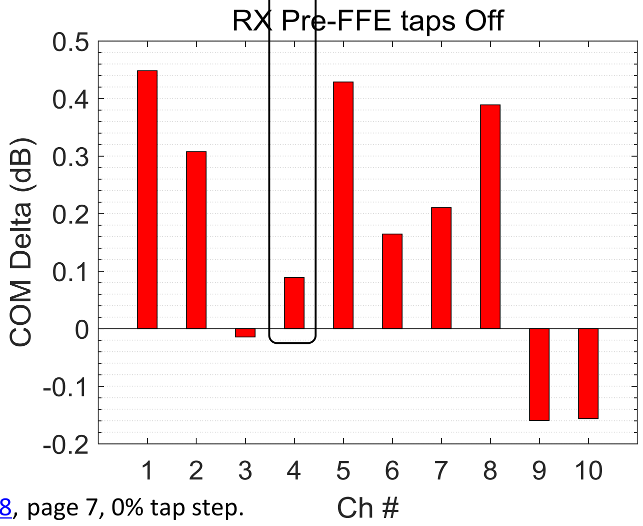
Reference	Cd, Cp Values
IEEE 802.3bj	Cd=250fF, Cp=180fF
IEEE 802.3cd	Cd=180fF, Cp=110fF
li_3ck_02_0918	Cd=130fF, Cp=110fF
hidaka_3ck_adhoc_01_102418	Cd=110fF, Cp=70fF

	FFE	DFE
CH1	**3.40**	**2.11**
CH2	**3.02**	**2.01**
CH1	**4.08**	3.07
CH2	**3.71**	2.88
CH1	**4.5**	3.4
CH2	**4.1**	3.2

Better package is used.

28dB@26.56GHz ideal channel: mellitz_3ck_adhoc_02_072518





hidaka_3ck_adhoc_01_102418, page 7, 0% tap step.

The FFE-based receiver gives better COM margin, same as li_3ck_02_1118.pdf and our simulations.

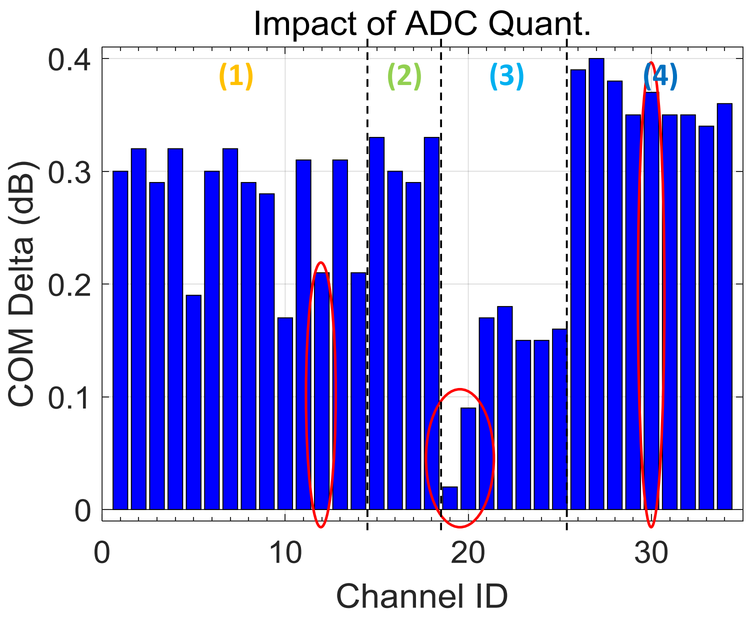
Performance concern of DFE-based receiver: Cd & Cp boundaries

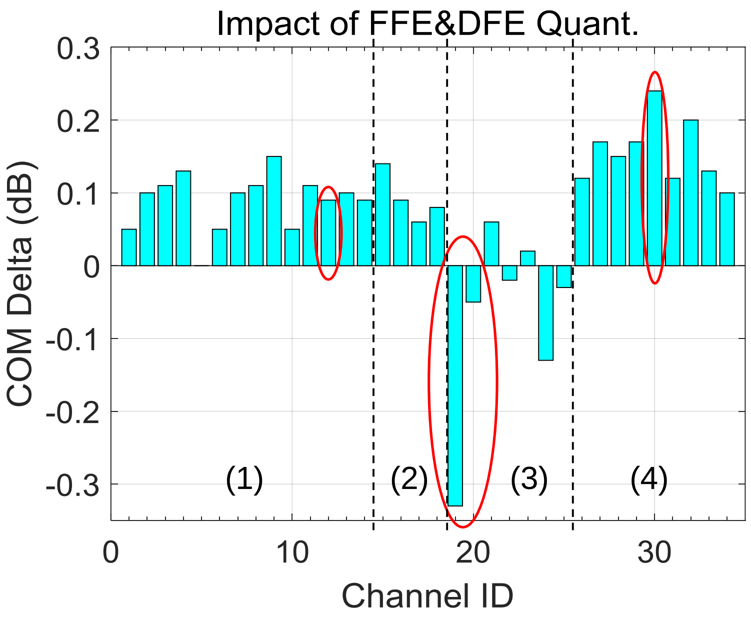
Channel	IL (dB)	ICN (mV)	FFE-based receiver			DFE-based receiver		
			COM 2.50 Cd=130fF/ 180fF, Cp=110fF	COM 2.50 Cd=110fF, Cp=70fF	hidaka_3ck_adhoc_01_102418 Cd=110fF, Cp=70fF	COM 2.50 Cd=130fF/ 180fF, Cp=110fF	COM 2.50 Cd=110fF, Cp=70fF	hidaka_3ck_adhoc_01_102418 Cd=110fF, Cp=70fF
main_mellitz_3ck_adhoc_02_072518	28	0	**4.08**/3.40	**4.68**	**4.83**	3.07/**2.11**	**3.85**	**4.06**
	28	0	**3.71**/3.02	**4.19**	**4.49**	2.88/**2.01**	**3.69**	3.88
main_mellitz_3ck_adhoc_02_081518_opt1	27.59	0.42	**3.49**/2.95	**4.07**	**4.33**	**2.53/1.70**	3.28	3.45
main_mellitz_3ck_adhoc_02_081518_opt2	26.72	0.49	**3.62**/3.09	**4.20**	**4.51**	2.93/**2.14**	**3.56**	3.78
zambell_100GEL_02_0318	27.40	0.29	**3.83**/3.31	**4.15**	**4.36**	2.92/**2.34**	2.63	2.77

- To meet the objective of 28dB at 26.56GHz.
  - FFE-based receiver pass COM test with large margin, >1dB with good packages (Cd=110fF, Cp=70fF) .
  - DFE-based receiver only pass COM test with good packages ("Cd=110fF, Cp=70fF") with small margin.
  - DFE-based receiver fail almost all COM test with package of "Cd=130fF, Cp=110fF".
  - **FFE-based receiver gives ~1dB larger margin than DFE-based receiver.**
- The Cd & Cp boundary for DFE-based receiver is "**Cd=110fF, Cp= 70fF**".
- The Cd & Cp boundary for FFE-based receiver is "**Cd=180fF, Cp=110fF**".

Cd=130fF, Cp=110fF?

Impact of ADC quantization and FFE&DFE quantization





- **The FFE noise amplification should be considered. Input noise impacts EQ settings.**
- ADC quantization noise has obvious impact, and the impact varies case by case, determined by the noise proportion.
- FFE&DFE quantization has smaller impact and also varies case by case.
- MMSE only consider ISI noise which is sub-optimal, there are exceptions that considering FFE&DFE quantization gives better COM.

Channel 19, 30.34dB, 1.97mV	No Quant. : TxFFE: [0 0 1 0], gdc: -18dB, gdc2: -4dB, ts:-2 w/ ADC Quant. : TxFFE: [0 -0.05 0.95 0], gdc: -19dB, gdc2: -4dB, ts:-2 Full DSP : TxFFE: [0 -0.15 0.85 0], gdc: -17dB, gdc2: -4dB, ts:-4	MS COM=-1.80dB DSP COM=-2.06dB
Channel 20, 25.55dB, 2.00mV	No Quant. : TxFFE: [0 -0.075 0.925 0], gdc: -14dB, gdc2: -3dB, ts:-4 w/ ADC Quant. : TxFFE: [0 -0.100 0.900 0], gdc: -17dB, gdc2: -3dB, ts:-3 Full DSP : TxFFE: [0 -0.175 0.825 0], gdc: -14dB, gdc2: -3dB, ts:-5	MS COM=0.47dB DSP COM=0.35dB
Channel 30, 26.72dB, 0.49mV	No Quant. : TxFFE: [0 -0.050 0.950 0], gdc: -15dB, gdc2: -4dB, ts:-7 w/ ADC Quant. : TxFFE: [0 -0.075 0.925 0], gdc: -18dB, gdc2: -4dB, ts:-5 Full DSP : TxFFE: [0 -0.2 0.800 0], gdc: -16dB, gdc2: -4dB, ts:-9	MS COM=2.54dB DSP COM=3.62dB
Channel 12, 11.17dB, 2.97mV	No Quant. : TxFFE: [0.0500 -0.200 0.75 0], gdc: -3dB, gdc2: -3dB, ts:-7 w/ ADC Quant. : TxFFE: [0.0250 -0.175 0.80 0], gdc: -7dB, gdc2: -3dB, ts:-5 Full DSP : TxFFE: [0 -0.200 0.80 0], gdc: -6dB, gdc2: -2dB, ts:-5	MS COM=3.31dB DSP COM=2.89dB

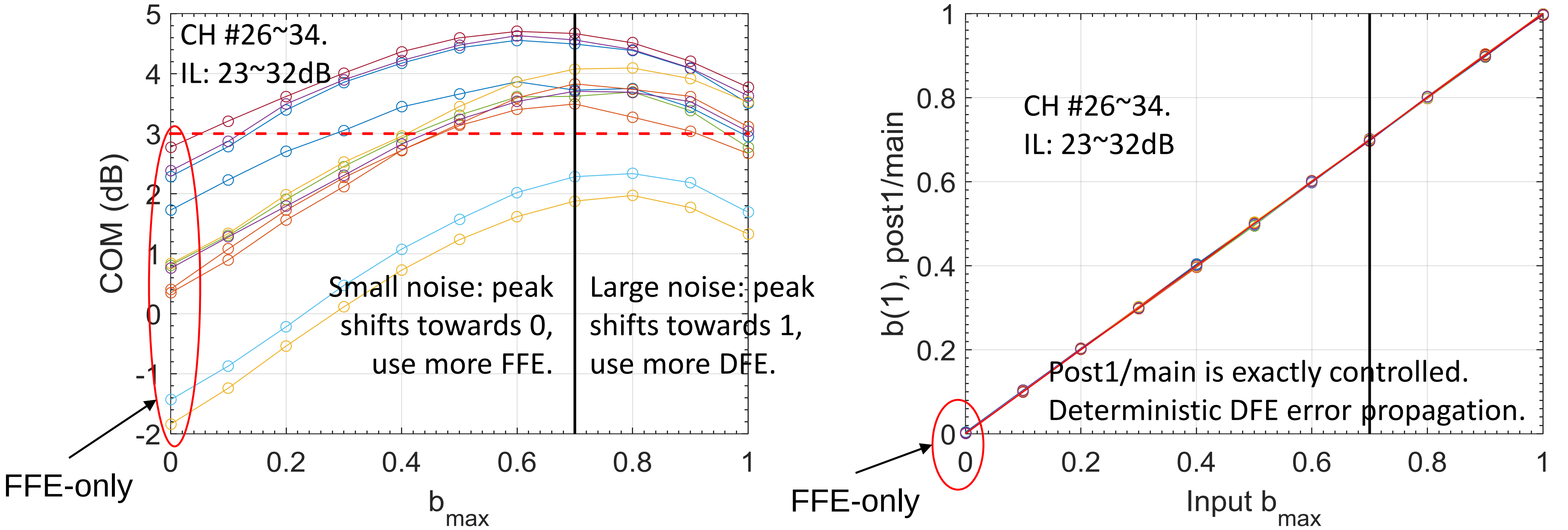
Equalizers with less impairment are preferred.

If FFE noise amplification is not dominant:

RX FFE > CTLE, TX FFE

- Plug in ADC quantization noise, the EQ work load transfer to CTLE and TX FFE.
- With FFE&DFE quantization further considered, the EQ workload further transfer to TX FFE.

Preliminary sensitivity study of b_max on COM of FFE-based receiver



- The interaction between FFE and DFE can be translated into sensitivity study of COM on b_max.
- For LR cannels (CH #26 to 34) the COM values are stable around b_max=0.7. The deviation of COM of b_max=0.6 and b_max=0.8 is smaller than 0.35dB.
- b_max=0.7 was a lucky choice for LR channels. Needs more exploration for C2M VSR channels.
- Post1/main ratio (i.e. b1) is exactly controlled by the b_max. Deterministic DFE error propagation.
- Support pure FFE receivers for C2M without model modification, just set b_max=0.

Summary: DFE- and FFE-based receivers are different!

- DFE- and FFE-based receivers behave differently in different “IL and ICN” regions.
  - DFE-based receiver gives better COM in noise-dominant region (low IL, high ICN).
  - FFE-based receiver gives better COM in ISI-dominant region (high IL, low ICN).

- DFE-based and FFE-based receiver model may yield a ‘pass’ or a ‘fail’ for the same channel.
  - The deviation of COM difference is approaching 3dB COM margin. Receiver difference is not implementation penalty.
  - The impairments covered by 3dB COM margin in DFE-based receiver also exist in FFE-based receiver.
    - Both have CTLE, no evidence shows ADC has more or less impairments than DFE.
    - The impairments covered by 3dB COM margin: Limited bandwidth, CTLE noise, nonlinearity, calibration etc.
    - ADC quantization are on top of the impairments covered by 3dB COM margin.

- The differences are due to the **pre-cursor cancellation** and **FFE noise amplification**
  - For ISI-dominant channels, the inadequate pre-cursor cancelation of DFE-based receiver is the key factor.
  - For noise-dominant channels, the noise amplification of FFE-based receiver is the key factor.

Summary: FFE- receiver outperforms under current COM settings

- To meet the objective of 28dB at 26.56GHz, **FFE-based receiver is ~1dB better.**
  - Three independent works with different package and different receiver configurations are provided.
  - li_3ck_02_1118.pdf (Intel), hidaka_3ck_adhoc_01_102418 (Credo), lu_3ck_adhoc_01_102418 (Huawei)

- FFE-based receiver requires less improvements on IEEE802.3cd package.
  - The Cd & Cp in IEEE 802.3cd is "Cd=180fF, Cp=110fF".
  - The Cd & Cp boundary for DFE-based receiver is "**Cd=110fF, Cp= 70fF**".
  - The Cd & Cp boundary for FFE-based receiver is "**Cd=180fF, Cp=110fF**".

  Cd=130fF, Cp=110fF?

  - "**Cd=130fF, Cp=110fF**" may be a reasonable value for package improvement for FFE-based receiver?
    - Proposed and investigated in ran_3ck_02_0518 (Intel). Modified from IEEE 802.3cd.
    - Investigated with COM of FFE-based receiver and with cross-talk noise margin considered.

Summary: Reference receiver models for COM

#	Arch.	Reference Receiver	Performance	Modeling Complexity	Further exploration?
A	DFE-based	DFE-Only	Low ✘	Zero	Performance improvement
B.1	FFE-based	FFE (3-pre & n-post) + 1-tap DFE	High ✓	Medium**	FFE&DFE, FFE&CDR interaction 1. Fix b_max=0.7 or scan b_max? 2. MM-phase (ts) or scan ts? 3. b_max and ts interaction.
* B.2		FFE (3-pre & 0-post) + DFE (n-taps) Exclude post FFE taps	High ✓		

* From li_3ck_02_1118.pdf.

** #B.1 need to address the FFE&DFE interaction problem (sensitivity study of b_max);
#B.2 need to address the FFE&CDR interaction problem (how to choose ‘ts’ to reserve ‘b_max=0.7’ criteria).

FFE noise amplification and **ADC quantization noise** are recommended to be considered in FFE-based model.

Suggestion and Future Work

- **Focus on the objective of 28dB at 26.56GHz**. Choose suitable equalizer and technologies to improve performance.
- **Seeking improvement is the top priority for DFE-based receiver**. Check if DFE-based receiver can meet 28dB objective, regardless of optimistic assumptions on PKG, ICN and ILD, apple-to-apple comparison.
  - Feasibility study was done with FFE-based receiver. Most of the studies are FFE receiver based.
  - FFE-based receiver shows better performance than DFE-based receivers, ~1dB better at the 28dB objective.
- **Use suitable equalizer and model**, recommend using FFE-based receiver model to cover FFE-based receivers.
  - The COM of FFE-based receiver is not a 'shift' of DFE-based receiver. No "trends" observed.
  - "Performance" → "Design compliance" → "modeling complexity".
- **FFE noise amplification** and **ADC quantization noise** are recommended to be considered for FFE-based receiver.
  - FFE amplification will impact the equalizer settings and the overall behavior of the transceiver.
  - The impairments covered by 3dB COM margin in DFE-based receiver also exist in FFE-based receiver.
  - The impact of ADC quantization noise on COM is large enough ~0.4dB, and varies case by case.
    - ADC quantization noise is on top of impairments that covered by 3dB COM margin.
  - The impact of FFE&DFE quantization is relatively smaller than ADC quantization and also varies case by case.
- **Future Work**
  - Other design spaces exploration for performance improvement, eg. Sampling phase (ts), Post1/Main (b_max).
  - Interaction of RX FFE and DFE (LMS?) and its impacts on error propagation and FEC performance.

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THANK YOU