Summary of IEEE 802.3ck Baseline Reference Receivers and Clarification of FFE-based Receiver Models

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Recap of COM reference receiver model exploration

- lu_3ck_adhoc_01_082918 (Huawei) proposed an ADC-DSP receiver model which matches the ADC-DSP receiver architecture.
- lu_3ck_01_0918 (Huawei) raised a concern that **Mixed-Signal and DSP based FFE receivers are different**, which led to the Straw Poll #9 minutes_3ck_0918_approved about the choice of DFE and FFE reference receiver architecture. (**DFE**: 28; **FFE**:13+4=17; **Need more information**: 14). FFE noise amplification effect was added in the COM2.52 test version and released by COM2.53 version mellitz_3ck_adhoc_01_121918. The revision is still based on Mixed-Signal FFE receiver, **which is still not a full ADC-DSP design and can be considered as a Mixed-signal FFE receiver**.
- wu_3ck_01_0918 (MediaTek) found the Rx FFE monotonic tap sensitivity issue. Alternative approach to calculate FFE/DFE coefficients is suggested. The refinement was done in COM2.51 version.
- hidaka_3ck_adhoc_01_102418 (Credo) showed that TX FFE pre taps will be dwarfed by RX FFE pre taps, FFE based RX model should not contain pre-taps. Mismatch between FFE and DFE receiver model was confirmed. The weakness of DFE receivers was also exposed; it is ~1dB worse than FFE receiver. **DFE receiver marginally passes the ideal 28dB PCB and twin axial cable channel without crosstalk and reflection, it may not achieve the 28dB@26.25GHz objective.**

Recap of COM reference receiver model exploration

- li_3ck_02a_1118 (Intel) proposed a FFE-lite receiver architecture (m pre-tap 0 post-tap FFE and n-tap DFE) and showed FFE-lite and FFE-heavy (m pre-tap n post-tap FFE and 1-tap DFE) give similar COM and FFE-based receiver is ~1dB better than DFE-based receiver. (Originally proposed in OIF). wu_3ck_01_1118 (MediaTek) confirmed the results. **We saw a hope to achieve a consensus.**
- lu_3ck_01_1118 (Huawei) raised the performance concern of DFE based receiver, confirmed the simulation results given in li_3ck_02a_1118 (Intel) and showed that **DFE based receiver can only marginally pass the 28dB channels with good packages (Cd=110fF, Cp=70fF)**. **Inconsistencies of FFE and DFE receivers were shown by examples. Two dominant effects were given** (**ADC-DSP based receiver model,** verified by independent simulations):
  - Pre-cursor cancellation for 'insertion loss' dominant channels (FFE-lite addresses this difference).
  - FFE noise amplification for 'noise dominant' channels (crosstalk, residue ISI, **not fully supported by COM2.5x**).
- kareti_3ck_01a_1118 (Cisco) showed that DFE has performance concerns and un-constrained DFE and floating tap DFE improves the performance. **It gave possible technical paths to improve the performance of DFE based receiver as well as FFE-based receiver.**
- heck_3ck_01_1118 (Intel) showed that at least a 20-tap DFE is required in RX EQ. However, even with 24 taps we don't meet 3dB for all channels, **confirmed the performance concern of DFE based receiver.**
- sakai_3ck_01a_1118 (Socionext) showed that using no Rx FFE pre-taps degrades COM by 0.55~0.96dB. **confirmed the performance concern of DFE based receiver.**

Recap of COM reference receiver model exploration

- sun_3ck_adhoc_01a_120518 (Credo) showed that with “2% or fine TX FIR resolution” and “relaxed b1max” the performance of DFE receiver may catch up with the **Mixed-Signal FFE receiver**. It also showed **FFE-lite may pass channels with large margins which can not be supported by FFE-heavy receivers**, by quoting data from li_3ck_02a_1118 (Intel) and sakai_3ck_01a_1118 (Socionext).
- lu_3ck_adhoc_01a_121218 (Huawei) the ‘b(1) control’ and ‘slightly outperformance’ FFE-lite receiver can be resolved by introducing a ‘modified-PD’ and using ‘b1max=0.6’. **The performance gap between FFE-lite and FFE-heavy is generally negligible and can be further reduced. The DFE receiver still has performance concerns and has less correlation with FFE-based receivers** even with unconstrained b(1) (2.5% TX FFE resolution was used in the simulation). **Exceptions were observed that long DFE receivers passed channels with large margins while FFE-heavy receiver failed**.
- lu_3ck_adhoc_01_121918 (Huawei) showed that the **FFE-lite receiver inherits advantages from FFE-heavy receiver and disadvantages from DFE receiver.** So FFE-lite generally has similar performance to FFE-heavy, and the same issue as DFE based receiver. **Long DFE receivers may pass channels with large margins which cannot be supported by long FFE receivers due to crosstalk and reflections.**
- hidaka_3ck_adhoc_01a_121918 (Credo) proposed a two-phase grid search algorithm for Fast COM calculation which will speed up the COM tool by 4.1x~5.9x. DFE based model is much faster than FFE based model (**Mixed-Signal FFE receiver based**).
- To be continued… ?

All the experimental results can be explained by the two insights

- **“Pre-cursor cancellation” is the main effect for loss dominant channels.**
  - DFE based receiver generally has lower performance than FFE based receiver.
  - “Introducing pre-taps in RX FFE” or “Unconstrained DFE” will mitigate this effect and improve the long DFE receiver performance.
  - “Using finer resolution TX FFE” will shift this effect to TX and it does not address the issue of receivers.
  - The ADC-DSP FFE receiver and Mixed-signal FFE generally generates similar results for loss dominant channels.

- **“FFE noise amplification” is the main effect for ‘noise dominant’ channels.**
  - Long DFE receivers may pass channels with large margin that should fail due to crosstalk or reflection. (Observed with ADC-DSP FFE receiver model).
  - **The COM difference between Mixed-signal FFE receiver and ADC-DSP FFE receiver is observable, because the ‘FFE noise amplification’ effect is considered differently.**
  - **Consistency of ADC-DSP COM and Mixed-signal COM can also be observed in FFE-lite architecture, because the ‘FFE noise amplification’ is not dominant.**

Baseline reference receivers and channels under investigation

#	Arch.	Reference Receiver	Configurations in the simulation	COM Tools
DFE	DFE-based	DFE-Only	24 taps	COM2.57 / This work
FFE-lite	FFE-based	'm-pre & 0-post' FFE + n-tap DFE	3-pre & 0-post FFE & 24-tap DFE	COM2.57 / This work
FFE-heavy	FFE-based (**Mixed-Signal**)	'm-pre & n-post' FFE + 1-tap DFE	3-pre & 24-post FFE + 1-tap DFE	COM2.57
FFE-heavy	FFE-based (**ADC-DSP**)	'm-pre & n-post' FFE + 1-tap DFE	3-pre & 24-post FFE + 1-tap DFE	This work

Channel	ID	IL fitted (dB)	ICN (mV)	FOM_ILD (dB)	COM (dB)						
					DFE b_max=0.7 MM-PD	DFE b_max=1.0 MM-PD	DFE b_max=1.0 Modified PD	FFE-lite b_max=0.7 MM-PD	FFE-lite b_max=0.7 Modified PD	FFE-lite b_max=0.6 Modified PD	FFE-heavy b_max=0.7
mellitz_3ck_adhoc_02_081518 Opt1	26	-23.79	0.56	0.23	4.19	4.53	4.53	5.03	5.15	5.06	5.13
	27	-27.59	0.42	0.26	2.53	3.28	3.28	4.09	3.99	3.86	4.06
	28	-31.36	0.33	0.29	0.49	1.67	1.61	2.67	2.36	1.90	2.41
mellitz_3ck_adhoc_02_081518 Opt2	29	-22.98	0.66	0.46	3.72	4.45	4.17	5.02	5.13	5.07	5.08
	30	-26.72	0.49	0.51	2.93	3.38	3.35	4.21	4.15	4.00	4.23
	31	-30.42	0.37	0.58	0.96	1.77	1.77	2.83	2.68	2.36	2.75
tracy_100GEL_04_0118	32	-22.94	0.36	1.28	4.73	4.99	4.99	5.33	5.39	5.34	5.22
tracy_100GEL_05_0118	33	-23.90	0.54	1.50	3.46	3.25	3.25	4.38	4.37	4.28	4.35
zambell_100GEL_02_0318	34	-27.40	0.29	0.27	2.92	2.90	2.86	4.18	4.36	4.22	4.29
mellitz_3ck_adhoc_02_072518	35	-28.01	0	0.03	3.07	4.37	4.28	5.32	4.84	4.43	4.61
	36	-27.98	0	0.00	2.88	3.81	3.81	4.55	4.34	4.07	4.33

Total **106** LR channels including 96 new channels from zambell_3ck_01_1118, kareti_3ck_01a_1118, and heck_3ck_01_1118.
Two 30mm package configurations are considered:

1. mellitz_3ck_01_090518_COM2p50 with Cd=130fF and Cp=110fF modification.
2. mellitz_3ck_adhoc_01_121918_COM2p57 Cd=110fF and Cp=87fF.

Two phase detectors are considered:

1. MM-PD : $h(ts - Tb) = h(ts + Tb) - h(ts)b(1)$, Annex(93A)
2. Modified PD : $0 = h(ts + Tb) - h(ts)b(1)$, Remove the impact of pre-1 cursor (New).

COM tool in this work implements two types of references receivers:

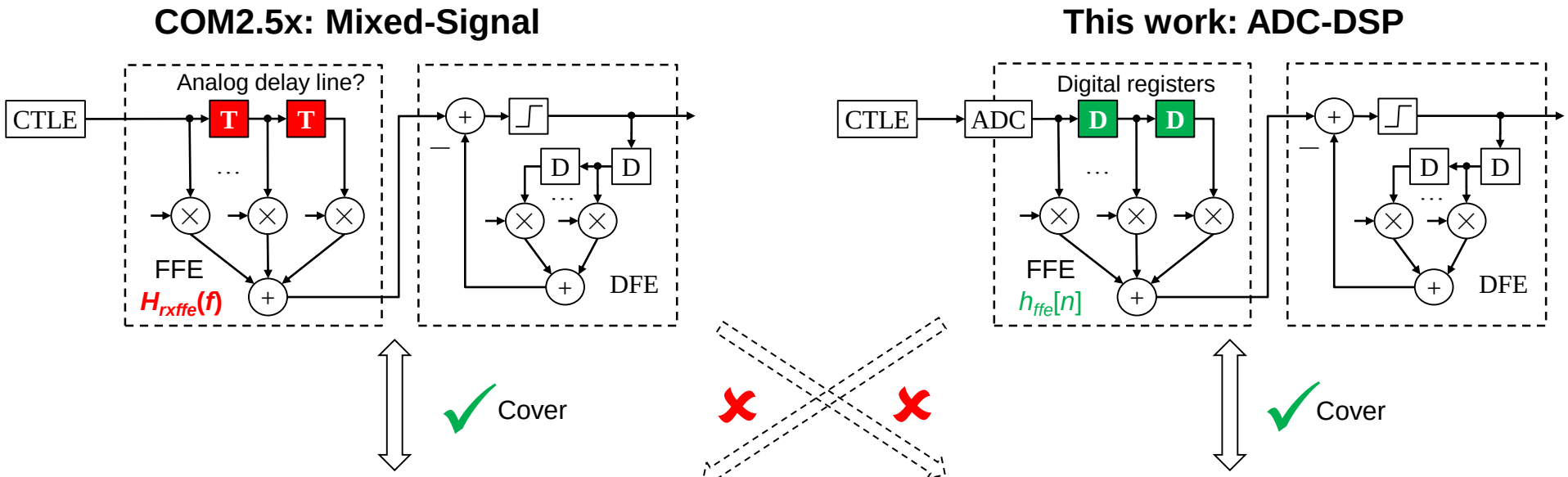
1. DFE receiver model is identical to that of COM2.5x.
2. FFE-based receivers (FFE-heavy and FFE-lite) are defined in lu_3ck_adhoc_01_082918.

COM tool in this work does not support Mixed-signal based FFE receiver.

COM2.5x tools do not support ADC-DSP based FFE receiver.

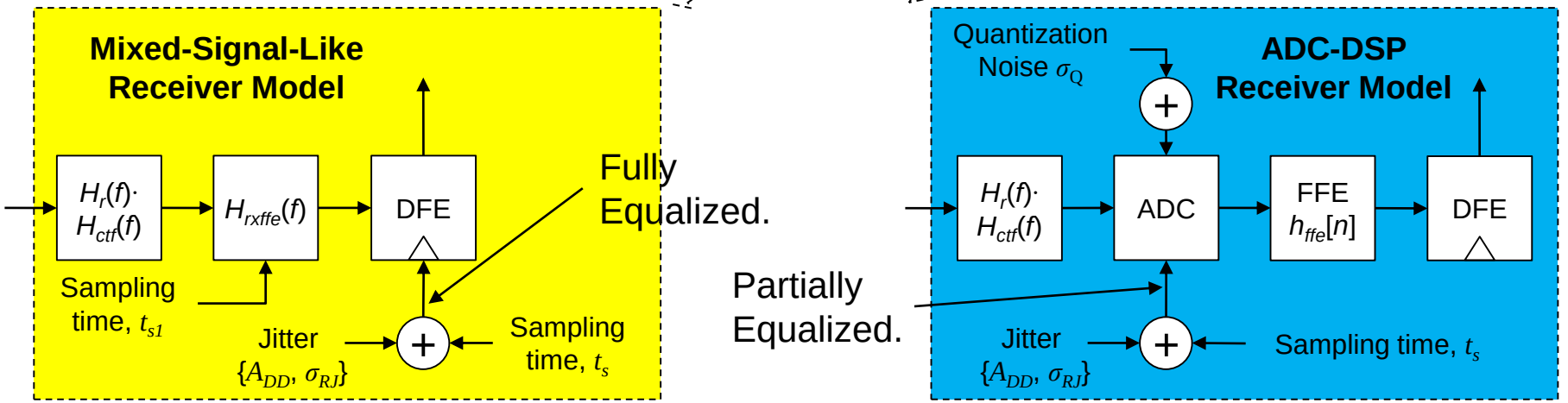
COM2.5x is simulating Mixed-Signal FFE receiver

Reference Designs



Reference Models

[lu_3ck_01_0918](#)

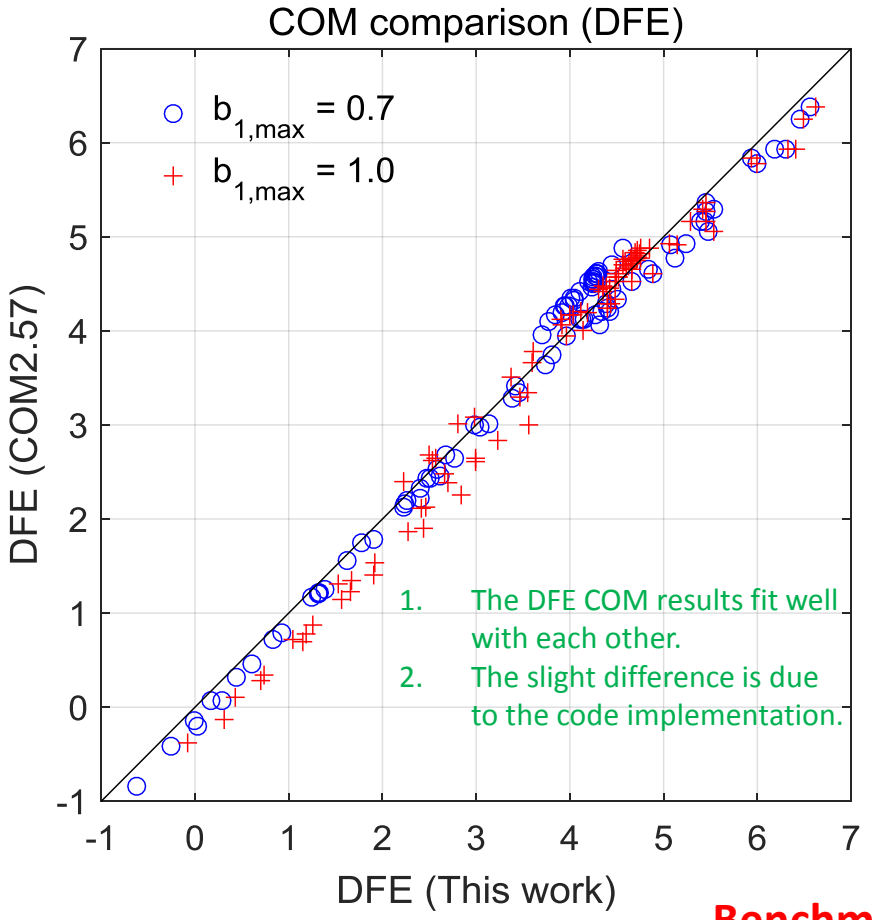


"Equalize then Slice"

"Equalize, Sample, Equalize then Slice".

ADC-DSP and Mixed-Signal FFE receivers were used as benchmarks

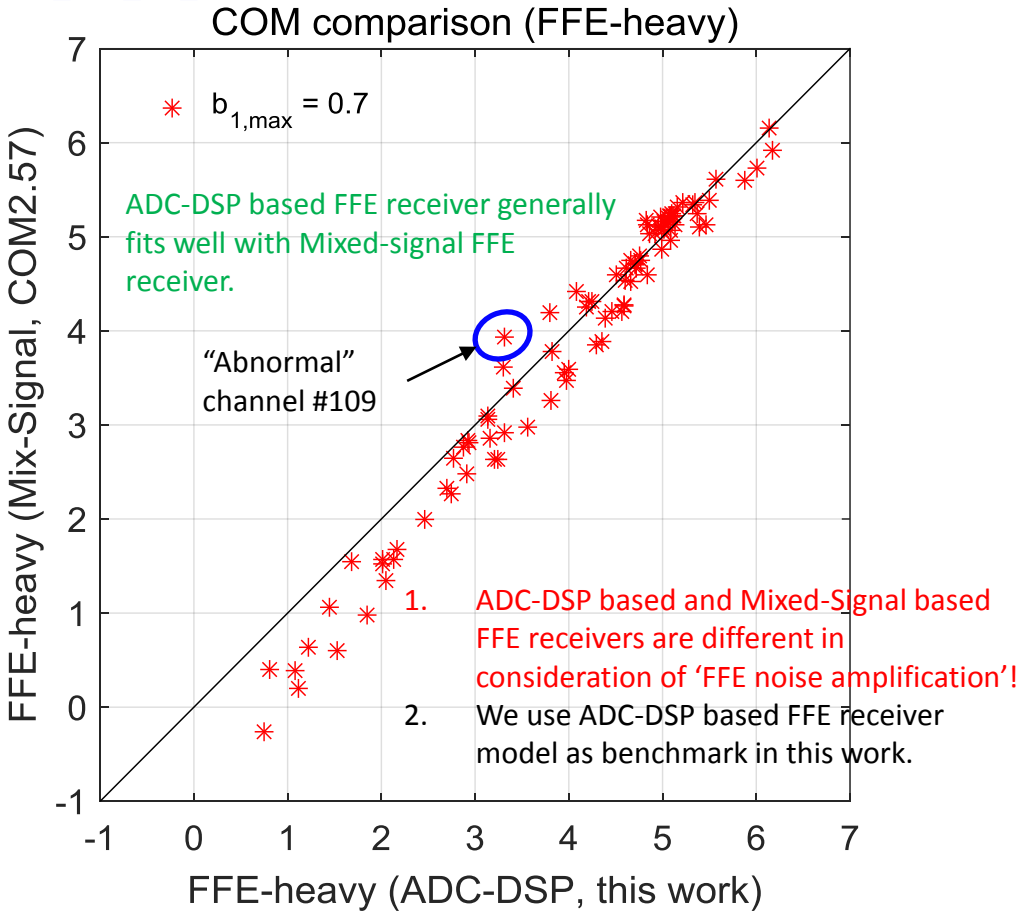
Good correlations can be observed for DFE receiver model for independent implementations.



Spreadsheet in COM2.57 is used in the simulation.

Benchmark in sun_3ck_adhoc_01a_120518.

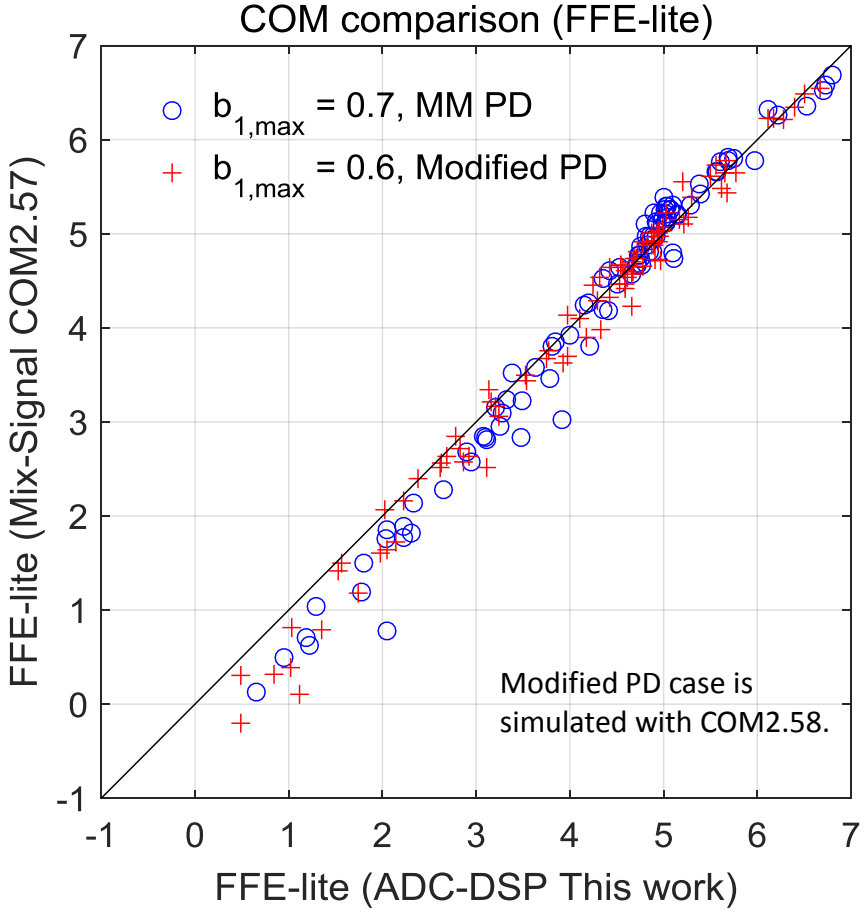
'FFE noise amplification' consideration is the main difference of ADC DSP FFE receiver and Mixed-signal FFE receiver!
lu_3ck_01_0918



Benchmark in this work.

FFE-lite minimizes the difference between ADC-DSP and Mixed-Signal FFE

Good correlations can be observed from ADC-DSP and Mixed-signal FFE-lite receiver model, because the 'FFE noise amplification' is not dominant in this receiver architecture (only pre-FFE taps are applied).

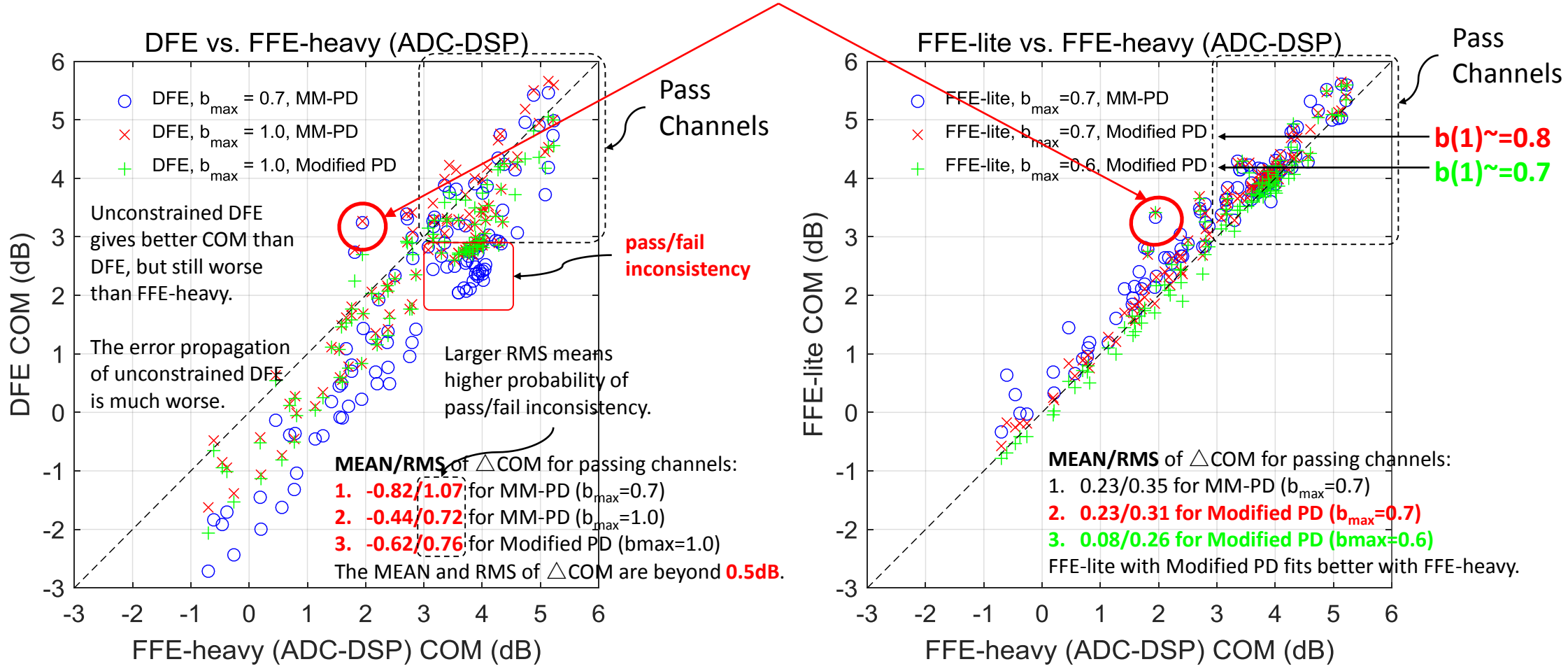


- Good correlation can be observed between ADC-DSP and Mixed-signal COM FFE-lite receiver.
- FFE-lite uses long DFE, the "FFE noise amplification" is not dominant. Implementations of ADC-DSP based and Mixed-Signal based FFE-lite receivers give similar COM.
- If FFE-lite receiver is applied, the difference between ADC-DSP and Mixed-signal COM FFE receiver implementations can be ignored.

Spreadsheet in COM2.57 is used in the simulation.

New concerns with long DFE receivers (COM2.50 with Cd=130fF, Cp=110fF and 2.5% TX FFE)

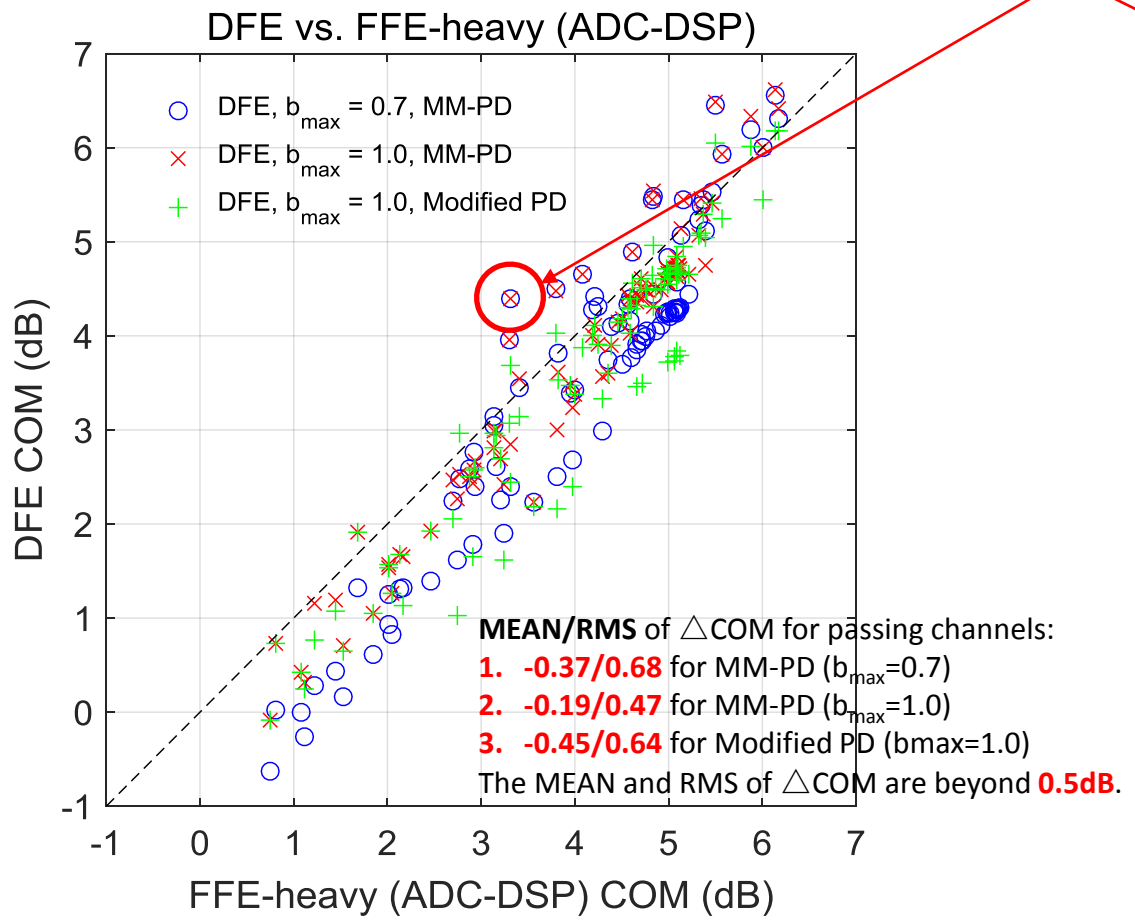
Long DFE receivers may pass channels with large margin which is not supported by FFE-heavy receiver!

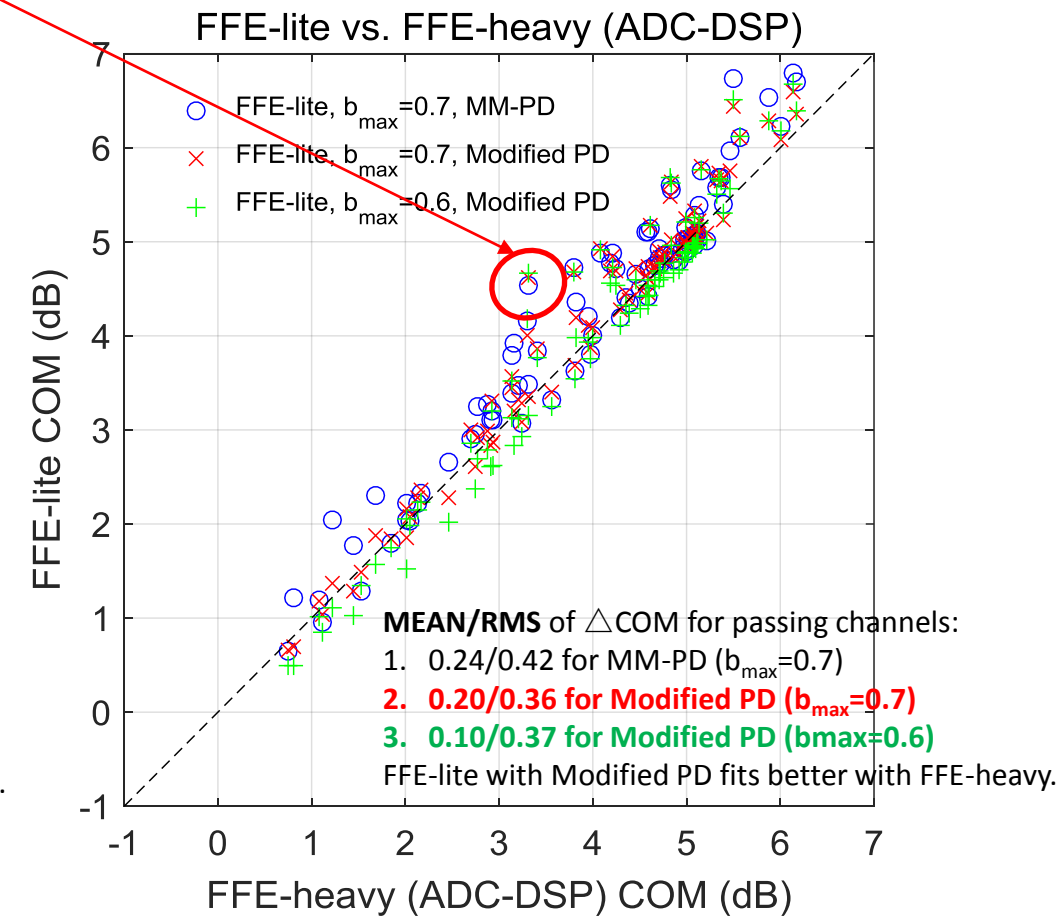


Total 106 channels including 96 new channels from zambell_3ck_01_1118, kareti_3ck_01a_1118 and heck_3ck_01_1118.
Unconstrained DFE results are consist with kareti_3ck_01a_1118 (Cisco). FFE-lite results are consist with li_3ck_02a_1118 (Intel) & wu_3ck_01_1118 (MediaTek).

New concerns with long DFE receivers (COM2.57 with Cd=110fF, Cp=87fF and 2.0% TX FFE)

Using better package and 2.0% resolution TX FFE does not help, “abnormal” channels still exist.



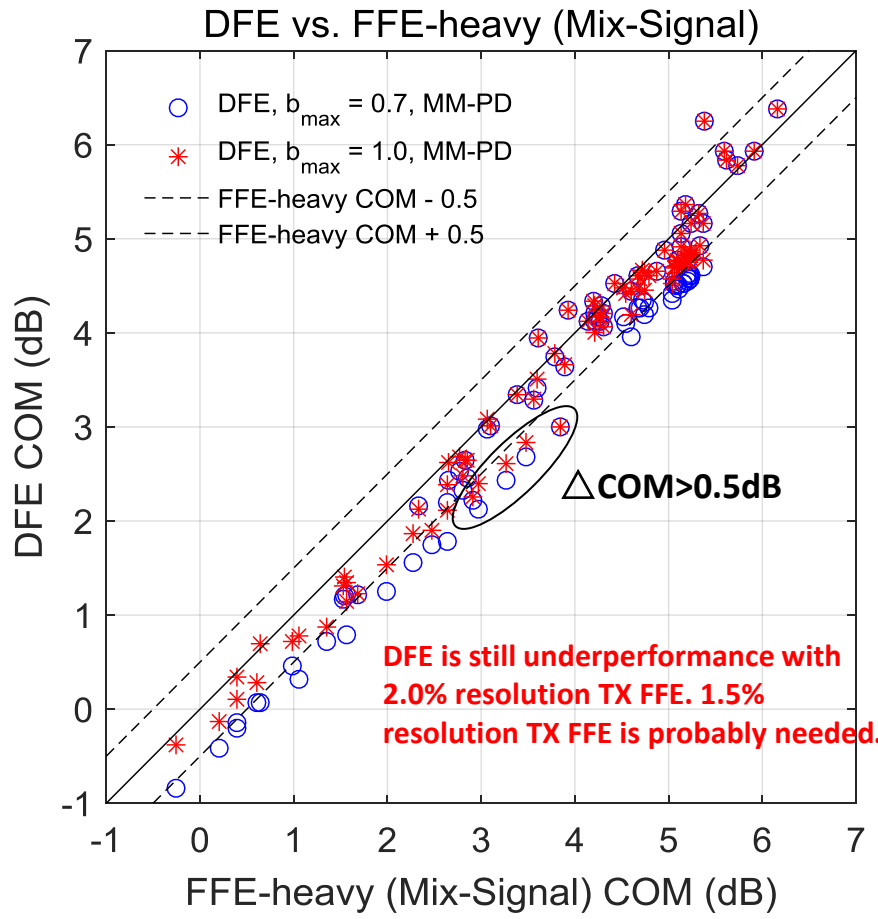


DFE generally has lower performance and large △COM deviation compared with FFE-heavy.

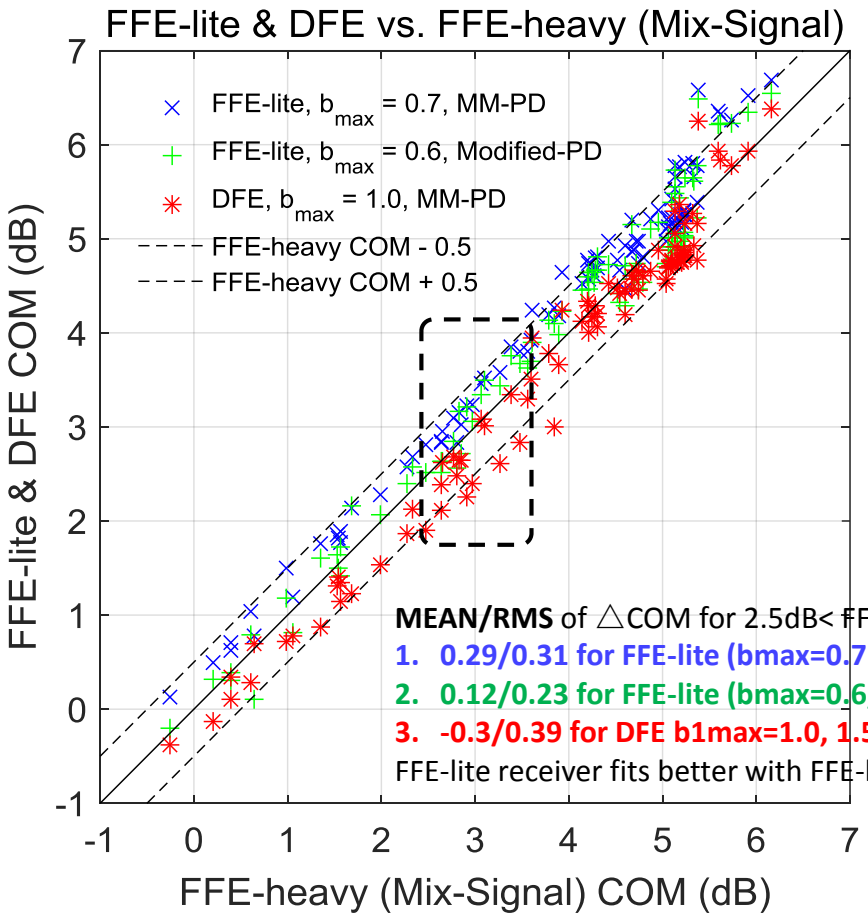
FFE-lite generally has similar performance and small △COM deviation compared with FFE-heavy.

Simulation results of COM2.57 code and spreadsheet (2.0% TX FFE)

FFE-lite fits better with FFE-heavy Mixed-signal receiver. No "abnormal" channels are observed with COM2.57 code.



"1.5% resolution TX FFE" and "b1max=1.0" are probably needed, even compared with Mixed-signal FFE receiver.



MEAN/RMS of △COM for 2.5dB< FFE-heavy COM<3.5dB:

1. **0.29/0.31 for FFE-lite (bmax=0.7)**
2. **0.12/0.23 for FFE-lite (bmax=0.6, Modified PD)**
3. **-0.3/0.39 for DFE b1max=1.0, 1.5% TX FFE is needed.**

FFE-lite receiver fits better with FFE-heavy receiver.

COM2.58 is used in the simulation of modified PD cases. (Thanks! Rich)

Unresolved Issue tracking

COM2.5x

This work

#	A: DFE	B: FFE-lite	C1: FFE-heavy (Mixed-Signal, COM2.5x)	C2: FFE-heavy (ADC-DSP, lu_3ck_adhoc_01_082918)
	n-tap DFE	'm-pre & 0-post' FFE + n-tap DFE	'm-pre & n-post' FFE + 1-tap DFE	'm-pre & n-post' FFE + 1-tap DFE
Pre cursor equalizer	TX FFE	TX FFE + RX Pre-tap FFE	TX FFE + RX Pre-tap FFE	TX FFE + RX Pre-tap FFE
Post cursor equalizer	Long DFE	Long DFE	Long FFE + 1-tap DFE	Long FFE + 1-tap DFE
Additional Requirements	1. 2% or finer TX FFE resolution. 2. b1max=0.85 or higher. 3. Only good package is verified,	None	None	None
Known Unresolved Issues	**May pass channels that should fail due to crosstalk or reflection.**			None
	1. Lower performance in general. Large △COM deviation with respect to long FFE receivers. 2. Feasibility of fine resolution TX FFE should be studied.	None	1. Noise amplification is not fully considered (transmitter noise and jitter noise) and may not fully cover ADC DSP receiver design. 2. Different jitter noise insertion point. 3. Low simulation efficiency.	

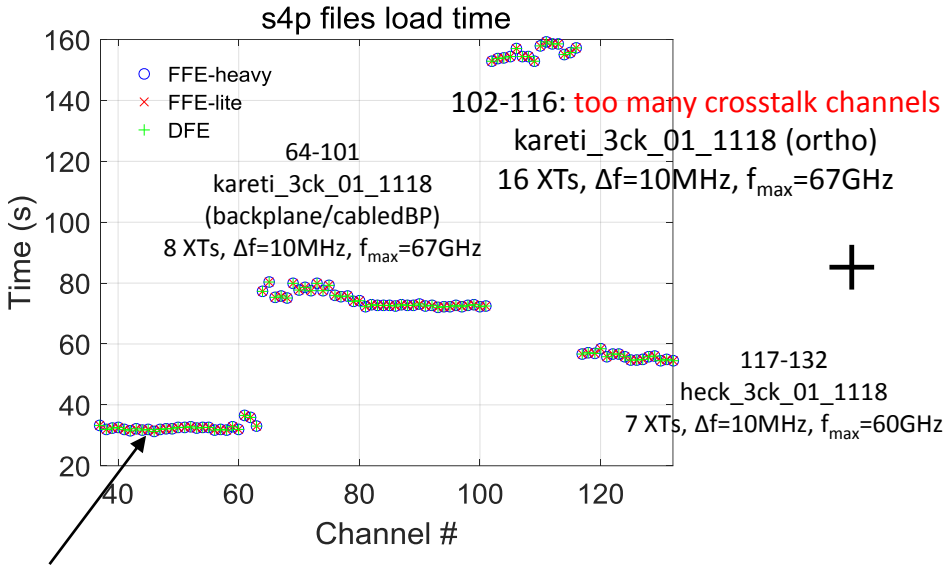
Thoughts on Mixed-signal and ADC-DSP FFE receiver models

- The COM2.5x is emulating FFE receiver under mixed-signal architecture, which cannot fully reproduce the behavior of an ADC-DSP FFE receiver. Simulation results verify the original concern proposed in lu_3ck_01_0918.
  - FFE noise amplification effect is not fully considered. (transmitter noise and jitter noise)
  - The jitter is added in the different place.
  - The DFE COM is greater than FFE COM for the ‘abnormal’ channels.
  - All the ‘abnormal’ channels passed the ERL test.
  - For LR channels, both architectures are usable, they have good correlation in COM results.

- Why does COM2.5x MS-based FFE receiver generally generate similar results as ADC-DSP FFE receiver?
  - Most of the channels are insertion loss dominant channels.
  - The ‘precursor cancellation’ is the dominant effect which dwarfs ‘FFE noise amplification’ effect.

- Why is COM2.5x Mixed-signal FFE receiver slow?
  - The FFE noise amplification is considered in frequency domain, integral of crosstalk noise for each TX FFE and CTLE settings. 8 aggressors need to calculate the integral 8 times!
  - Speeding up is possible! Consider the FFE noise amplification effect in time domain. Pre-calculate the crosstalk RMS for all the CTLE settings in advance, move the integration calculation out of the FOM optimization loop.

Simulation time of DFE and FFE-based reference receivers



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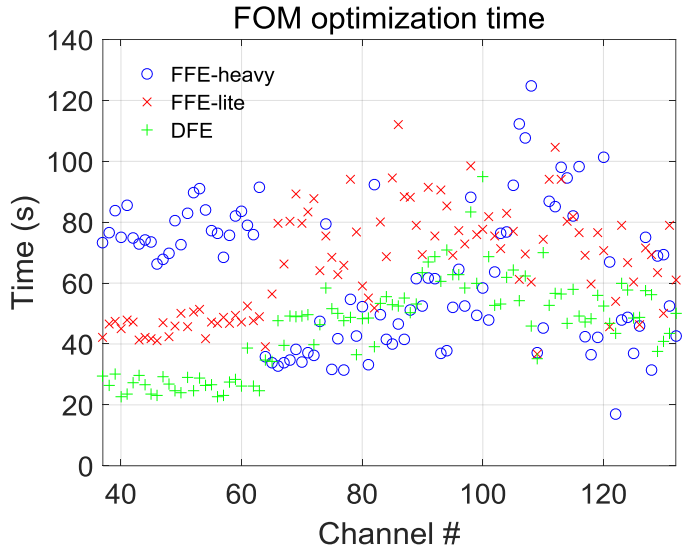
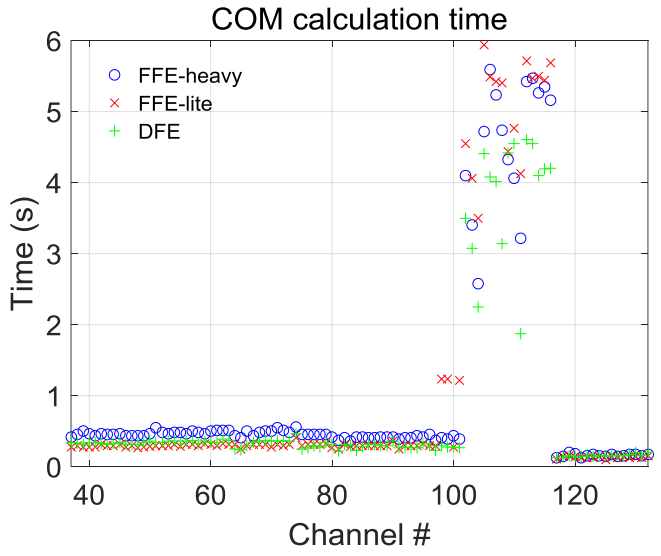


37-63: low bandwidth
zambell_3ck_01_1118
8 XTs, Δf=10MHz, fmax=35GHz



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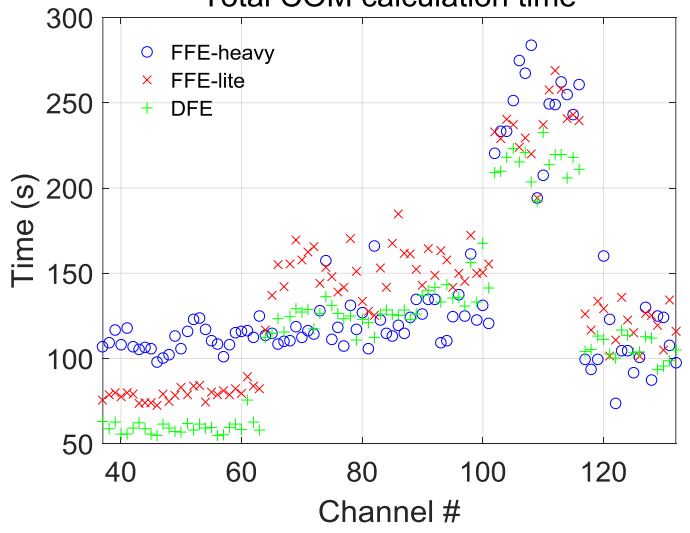
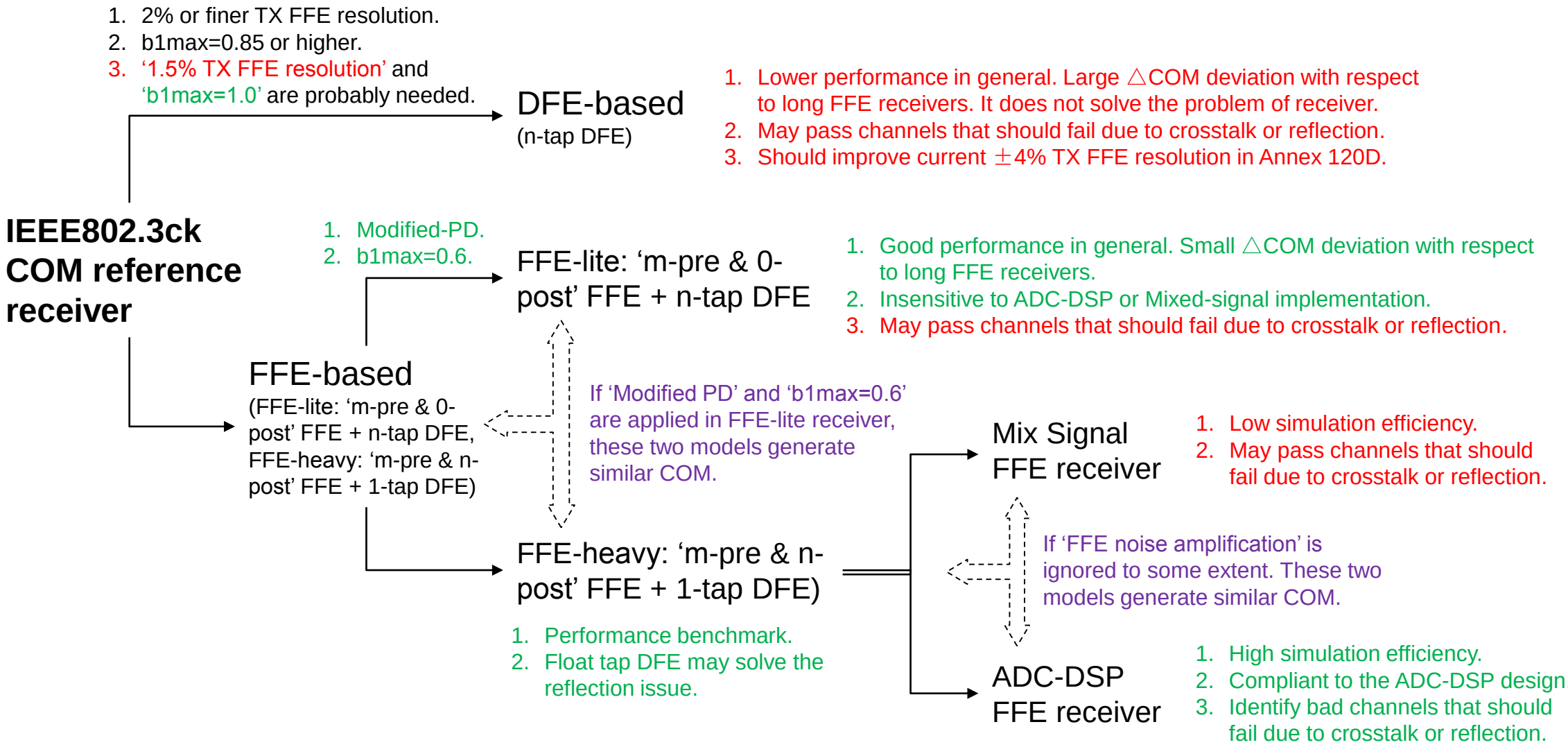


FOM optimization can be finished ~1min.

The difference of simulation efficiency for different architecture is small.

There is not obvious difference in simulation efficiency of different receiver architectures under ADC-DSP FFE receiver model.

Decision tree for IEEE802.3ck COM reference receiver



Summary of the reference receiver candidates

- **FFE-heavy** receiver **has already been used as a benchmark**.
  - ADC-DSP model replays all the receiver behaviors.
    - Consist with Mixed-signal receivers in loss dominant channels.
    - Replay the FFE noise amplification in noise dominant channels.
  - Mixed-Signal model cannot fully cover ADC-DSP receiver design since it fails to replay the 'FFE noise amplification' effect. **It may pass channels that should fail due to crosstalk or reflection**.
  - Reflection issues may be solved by ADC-DSP receiver with float-tap DFE.
- **FFE-lite** receiver is a good compromise for various implementations.
  - It generally gives similar COM compared with FFE-heavy and has small mean/deviation of △COM.
  - Most of the concerns have been resolved, including the 'b(1) control' and 'outperform' issue.
  - **Insensitive to ADC-DSP or Mixed-signal implementation.**
  - **It may pass channels that should fail due to crosstalk or reflection.**
- **DFE** receivers have the following concerns:
  - Low performance in general. Large △COM deviation with respect to FFE receiver.
  - **'1.5% TX FFE resolution' and 'b1max=1.0' are probably needed.**
  - **It may pass channels that should fail due to crosstalk or reflection.**
  - Some prerequisites to make DFE receiver work.
    - 2% or finer TX FFE resolution (Cannot pass COM with 2.5% TX FFE resolution for some 28dB channels).
    - Relax the "b1max=0.7" constrain to 0.85 or higher (Introduces more severe burst errors).
  - 2.5%→1.5% TX FFE needs extra TX power, area and latency without obvious benefits.
  - Feasibility of changing TX FFE resolution from 2.5% to 1.5% is questionable and should be demonstrated.

Summary

- Since COM 2.5x is implemented under the Mixed-signal architecture, it cannot fully simulate the FFE noise amplification effect, which results some COM differences between itself and ADC-DSP FFE-heavy receiver.

- FFE-based receivers (FFE-lite or FFE-heavy) have good correlations in COM because most LR channels are loss dominant. Also, the COM difference between ADC-DSP and Mixed-signal implementations of FFE-lite receiver can be ignored.

- DFE-based receiver generally has lower performance. To reach the objective of 28dB, it needs ‘2% or even finer TX FFE’ and ‘b1max=0.85’ or higher (probably ‘1.5% TX FFE’ and ‘b1max=1.0’).

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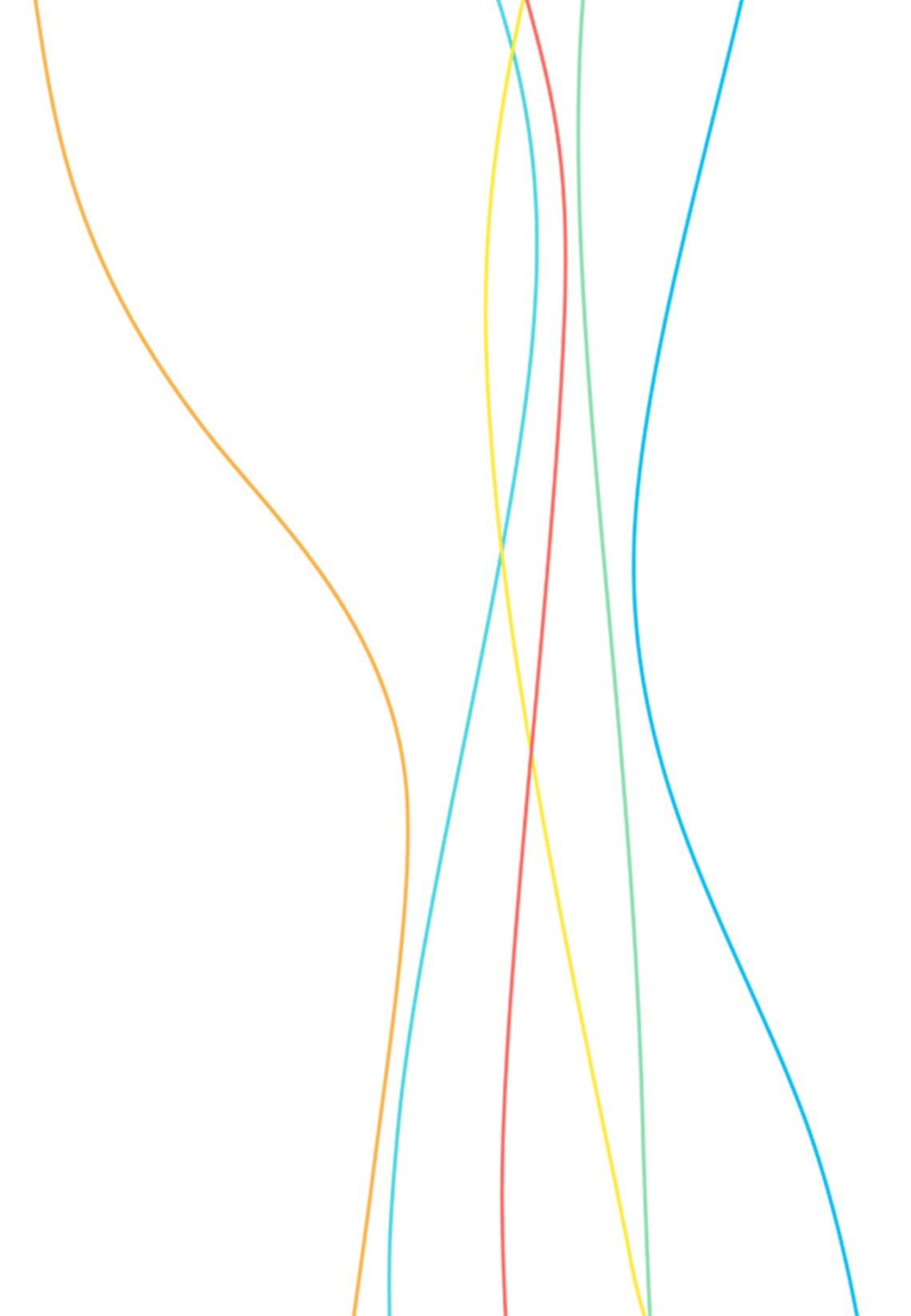
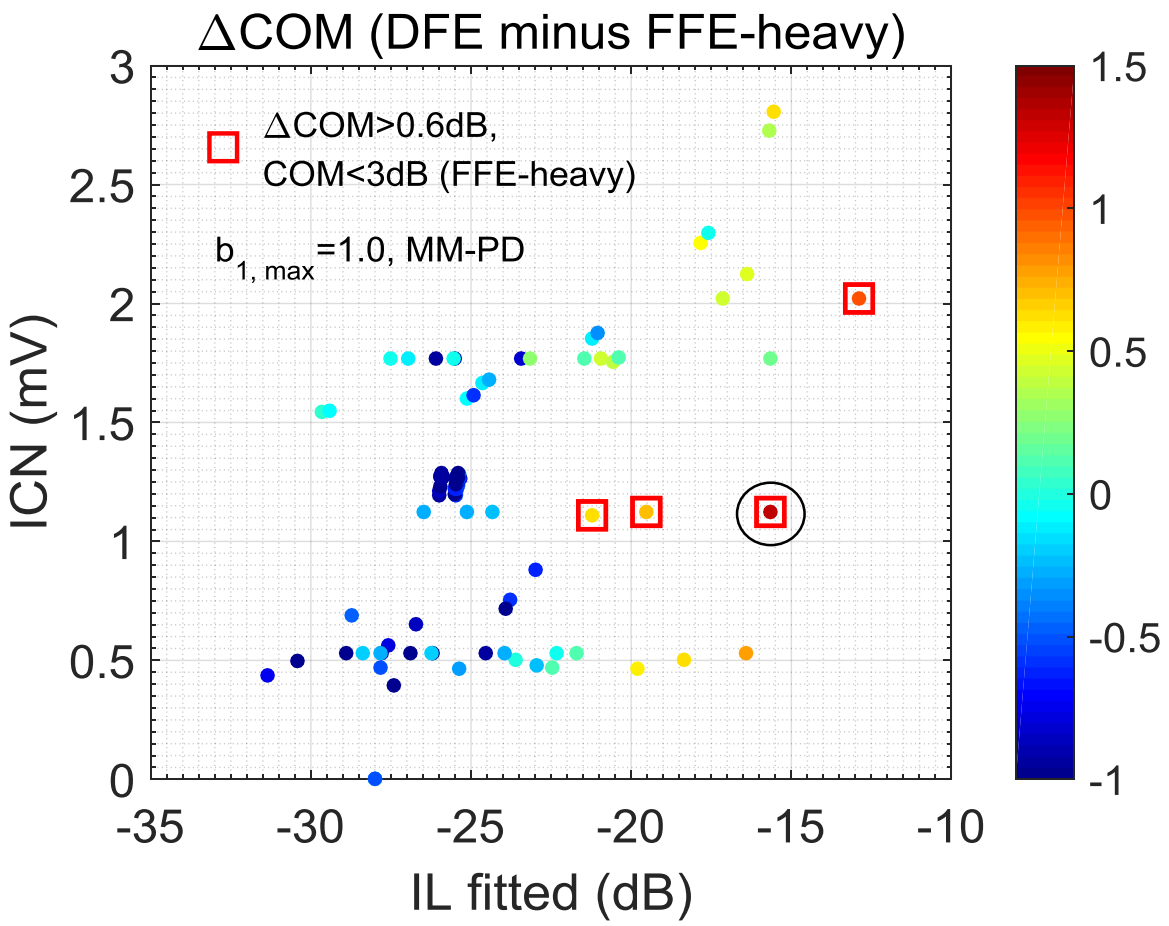
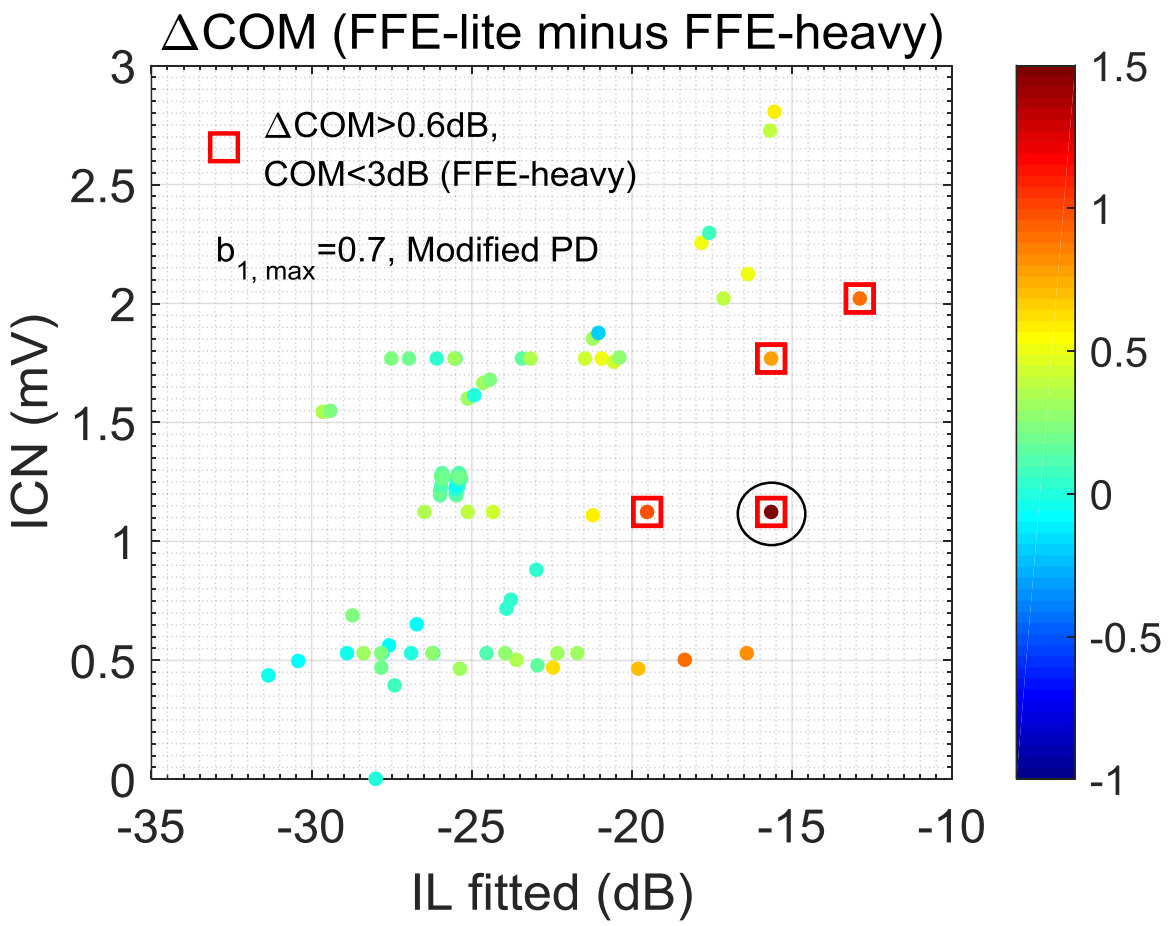
THANK YOU



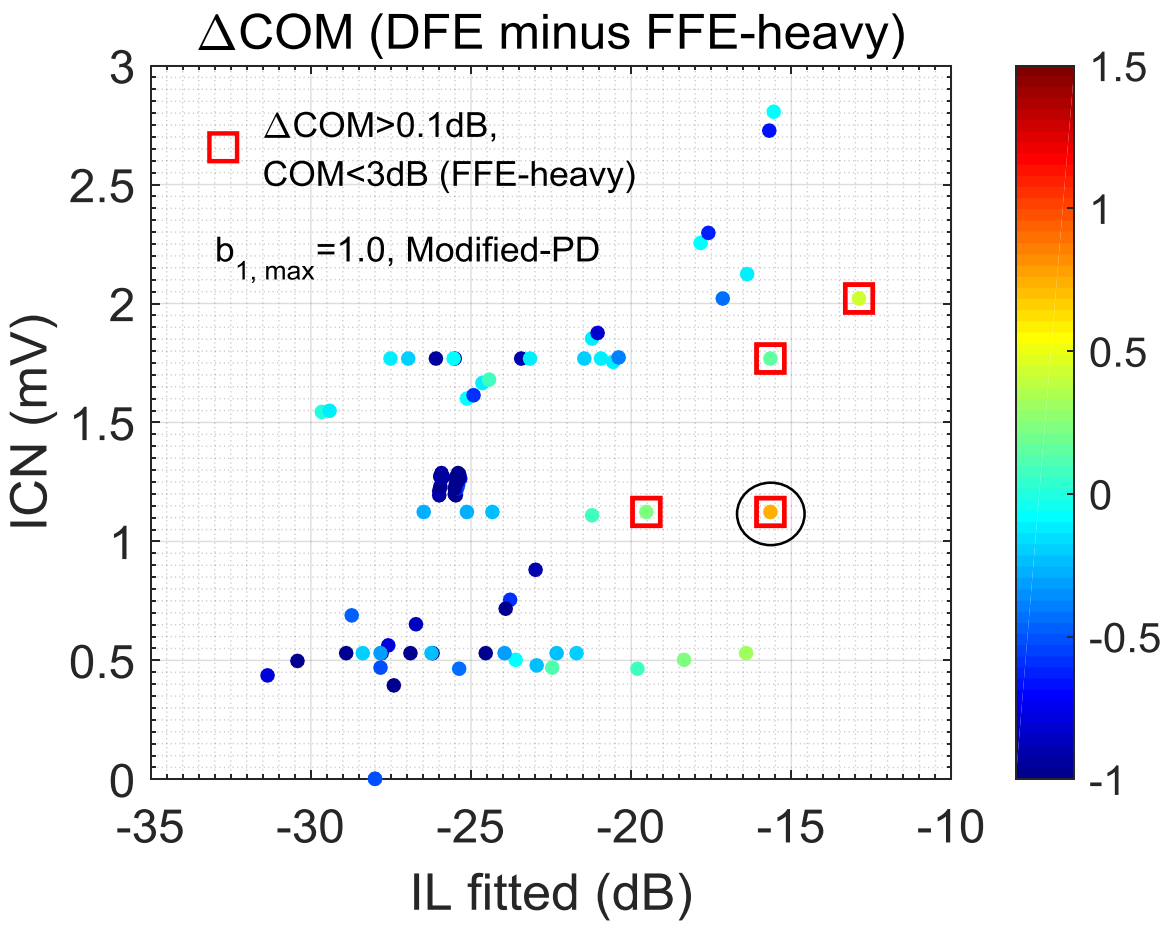
Insertion loss and crosstalk of the “abnormal” channels

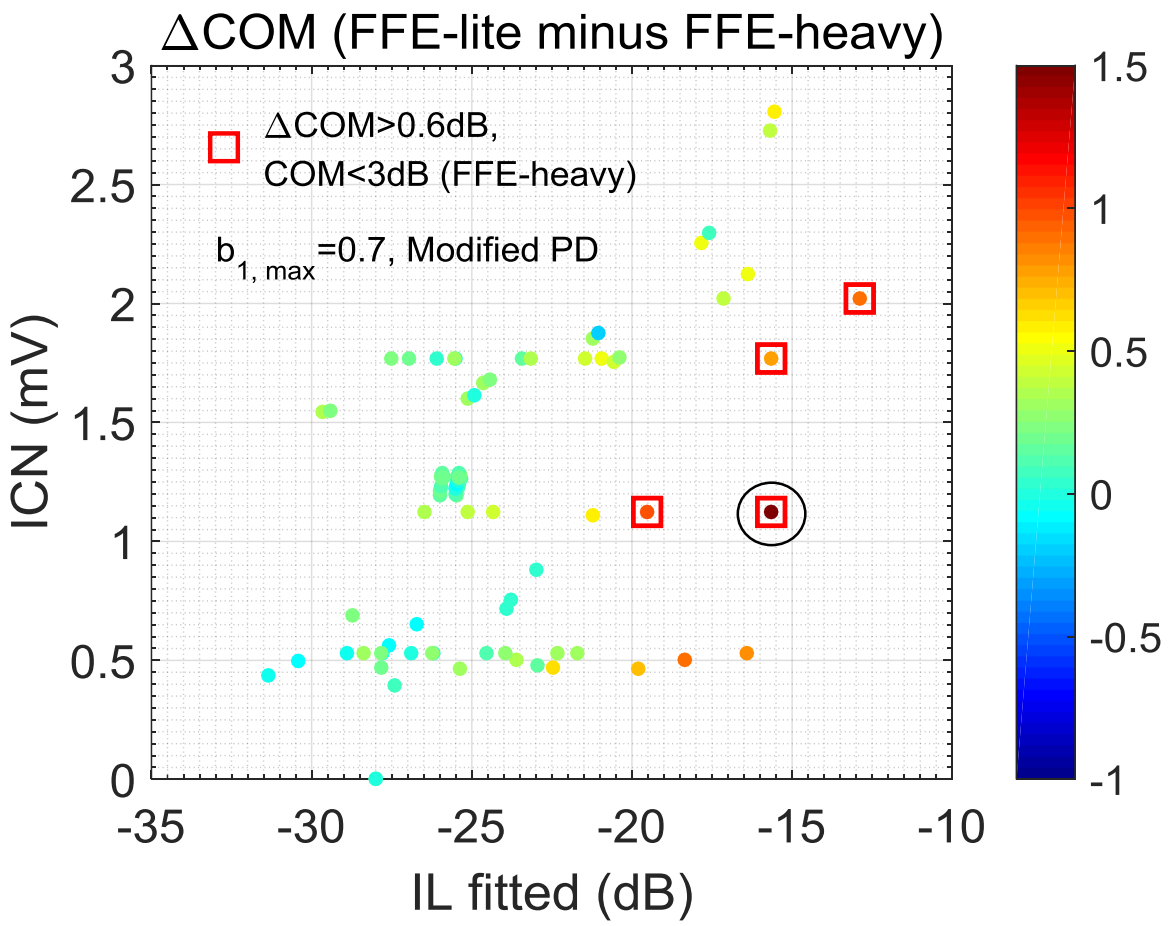




- DFE may pass the same channels as FFE-lite with large margins which can not be supported by FFE-heavy receivers. This is due to the long DFE that exists in both receivers.

Insertion loss and crosstalk of the “abnormal” channels





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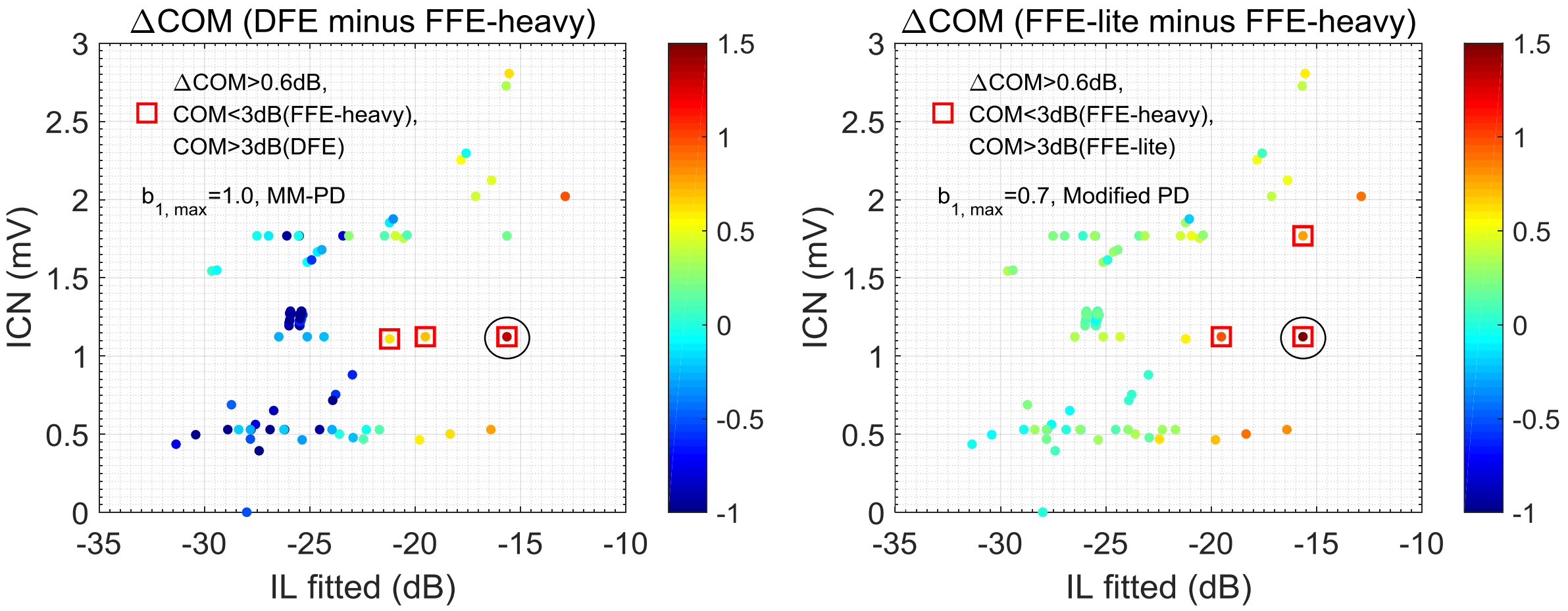
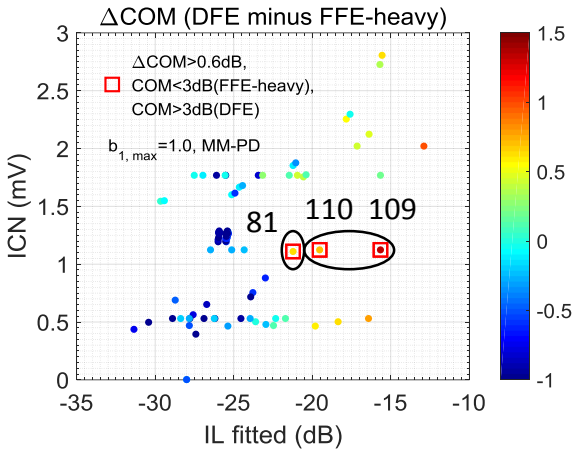


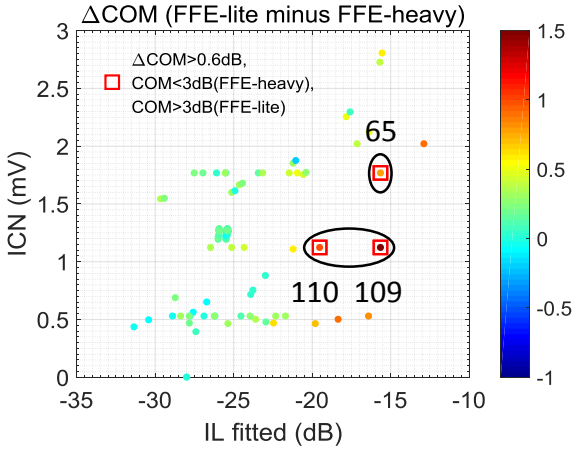
- DFE may pass the same channels as FFE-lite with large margins which can not be supported by FFE-heavy receivers. This is due to the long DFE that exists in both receivers.

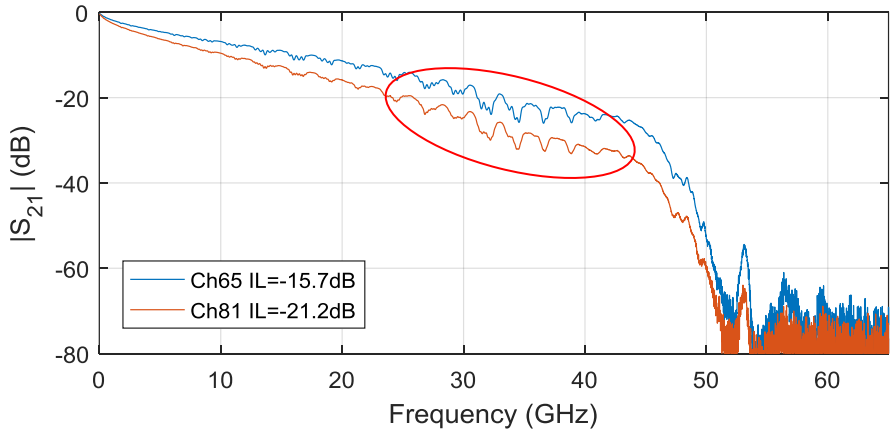
Details of the “abnormal” channels

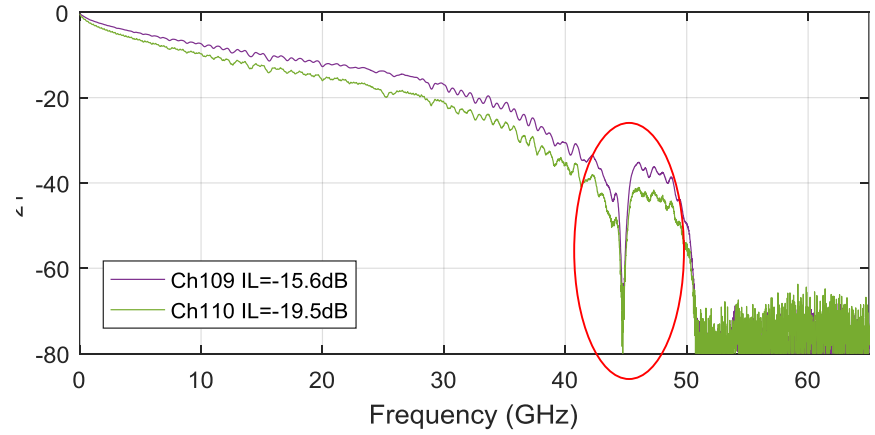


Channel		ID	IL fitted (dB)	ICN (mV)	FOM_ILD (dB)	COM (dB)			
						DFE b_max=0.7 MM-PD	DFE b_max=1.0 MM-PD	FFE-lite b_max=0.7 Modified PD	FFE-heavy b_max=0.7
kareti_3ck_01_1118 backplane	Bch2_7	65	-15.65	1.77	0.47	3.31	2.91	3.50	2.73
	Bch3_14	81	-21.21	1.11	0.45	2.99	3.41	3.40	2.80
kareti_3ck_01_1118 ortho	Och1	109	-15.65	1.12	0.69	3.24	3.27	3.42	1.94
	Och2	110	-19.52	1.12	0.73	3.39	3.39	3.69	2.70

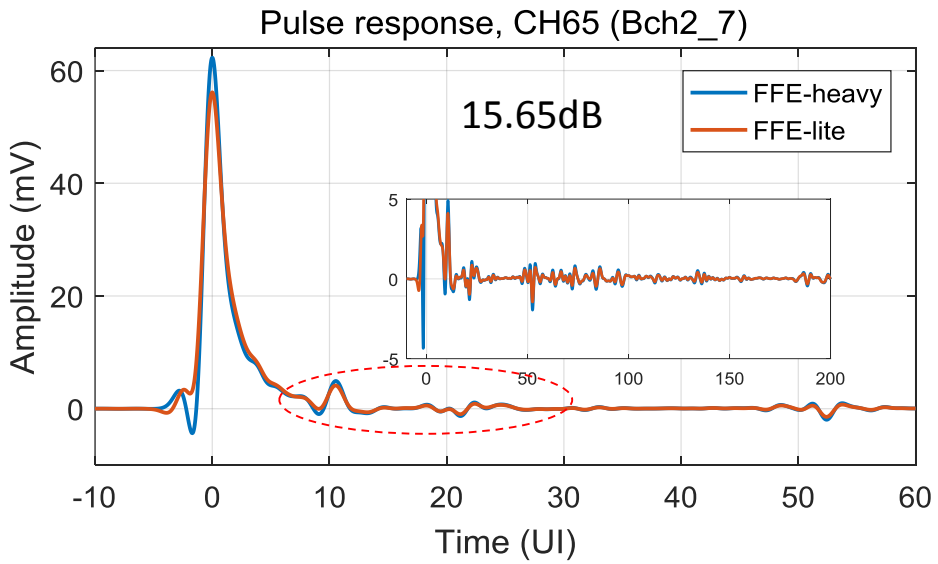
Ch 110 and 81 are not VSR channels, these two channels cannot rule out by other metrics such as ILD.

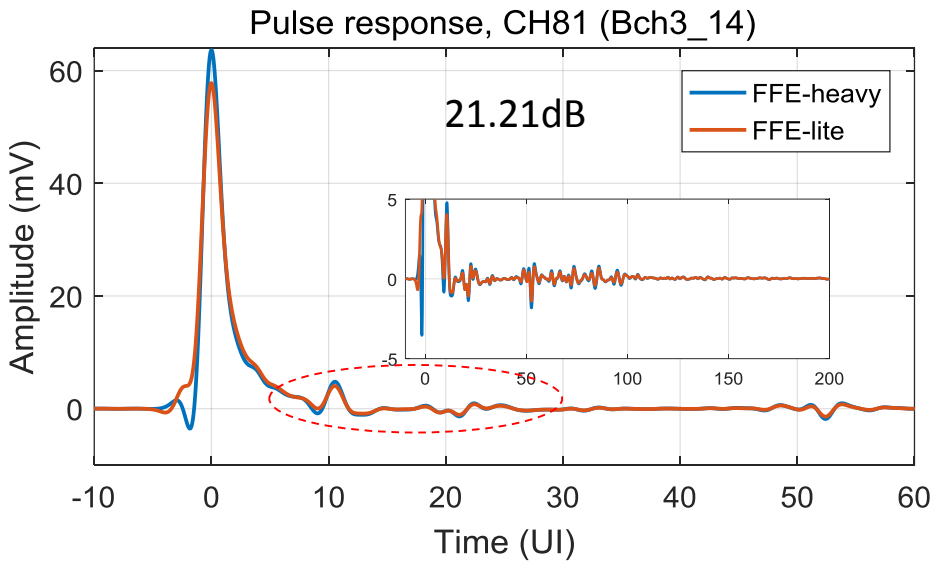


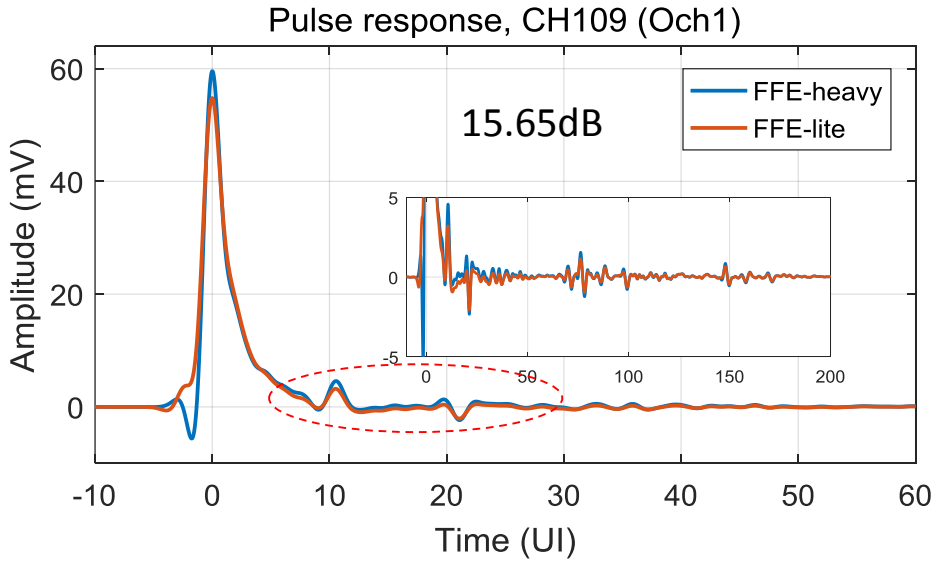


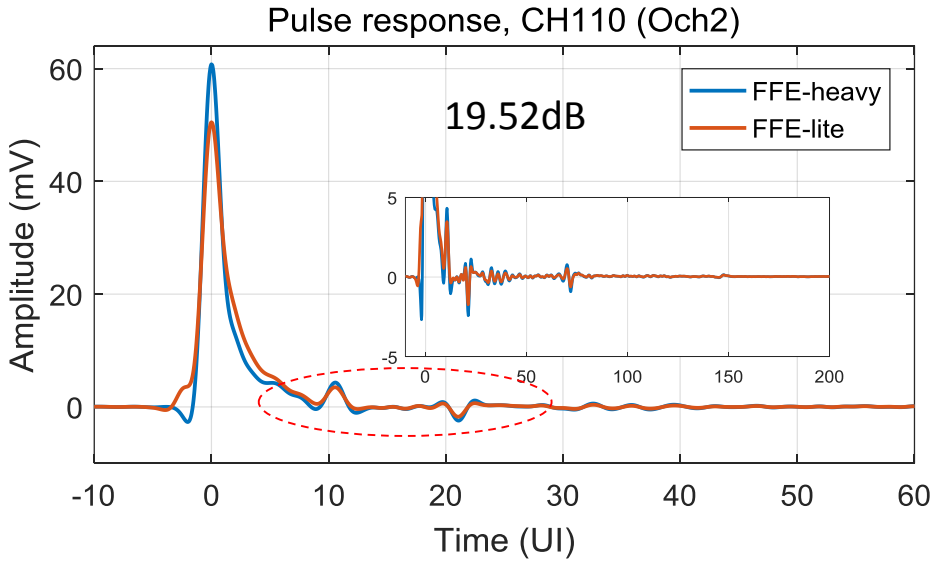


Time domain analysis of the “abnormal” channels: Pulse Response

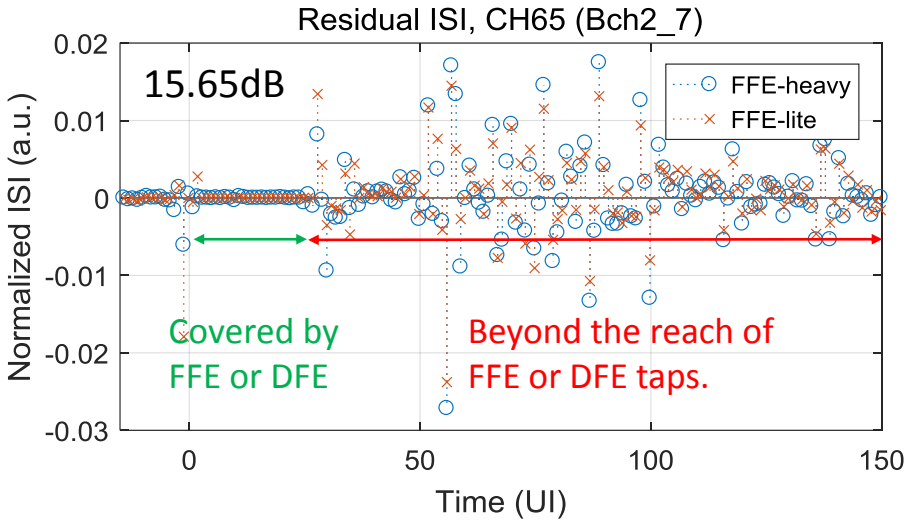


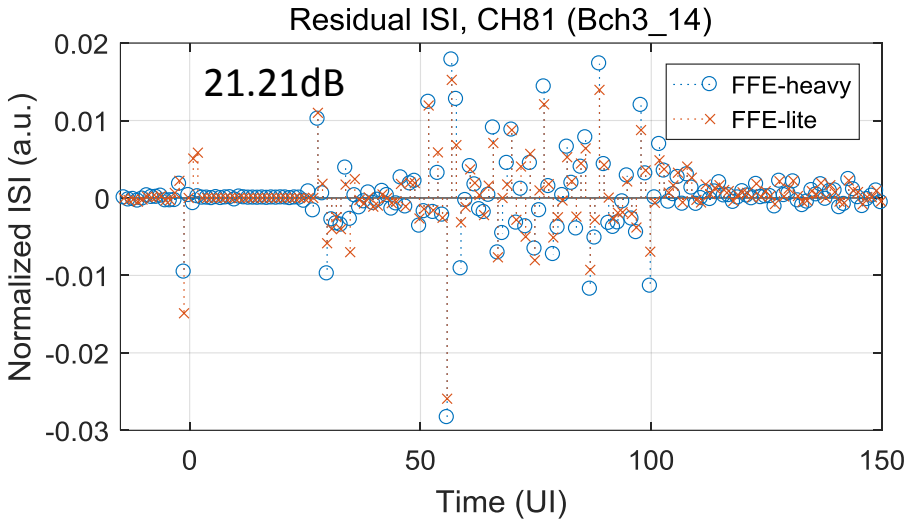


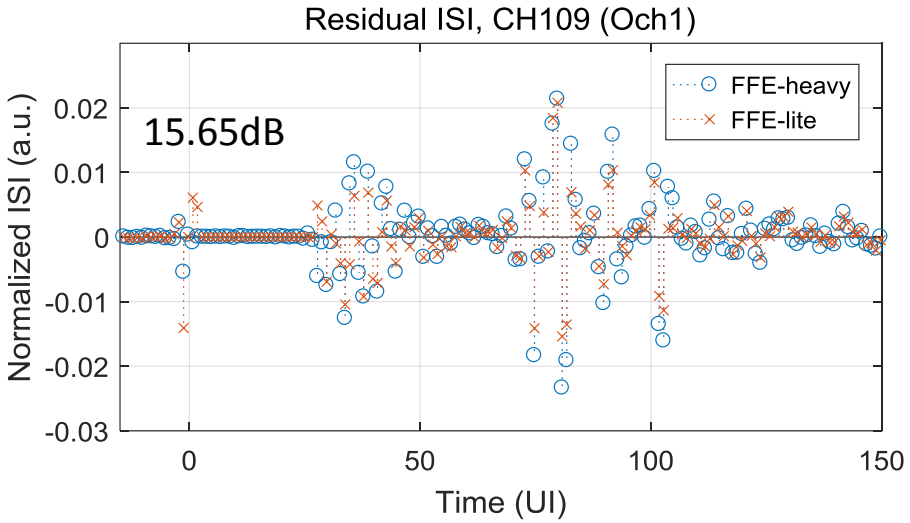


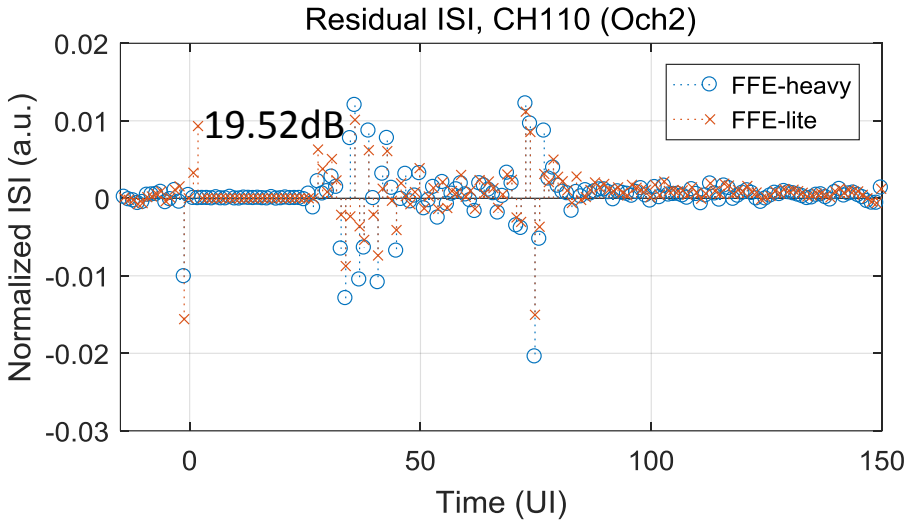


Time domain analysis of the “abnormal” channels: Residue ISI









Main cursor is normalized to 1.