Output specs to complement TDECQ for IM-DD PMDs

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Supporters

Abstract

- Several contributions indicate that TDECQ is not sensitive to transmitter impairments that cause bad post-FEC performance with real receivers.
    - Jitter
    - Bad pulse shaping (equalization)
    - Distortion
- This presentation suggest directions for addressing these issues.
    - At this stage of the project, we should prefer “plugging holes” using known methods (rather than revolutionize the specifications).
    - Comments against D2.0 or later are planned.
    - More research on new methods can continue in parallel.

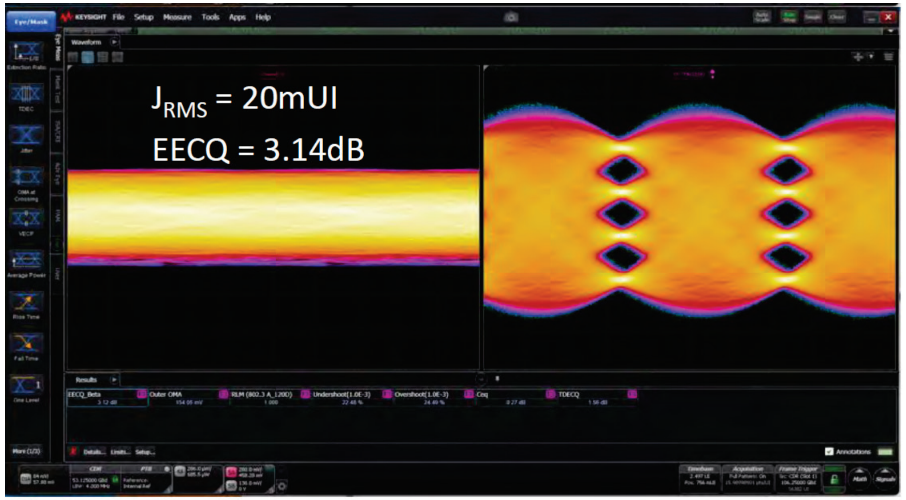
Jitter

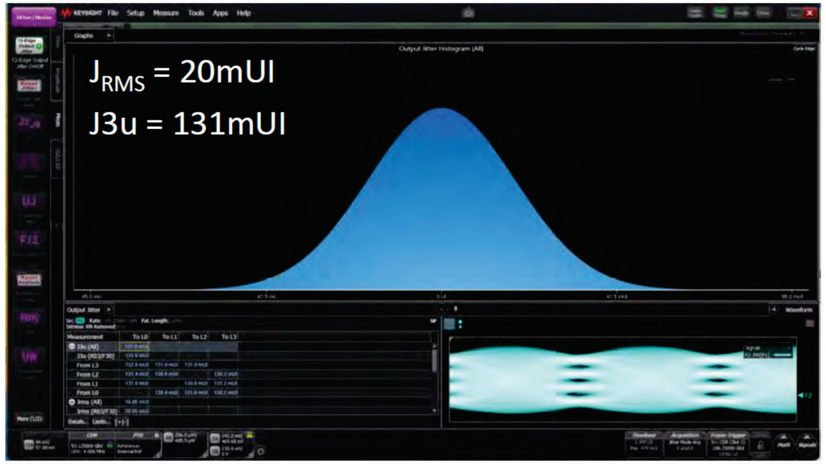
Background

- Experiments at 100 Gb/s show TDECQ does not fail with jitter profiles that cause bad post-FEC performance.
  - Originally reported in oif2024.449.02 (Marco Mazzini and Yi Tang, *Transmitter Jitter vs EECQ/TDECQ vs Post-FEC Performance*, August 2024).
- Follow up in ran_3dj_optx_01_240829 included simulation results and suggested an explanation: **low-frequency jitter can cause SNR degradation over codeword periods and correlated errors.**
  - This observation has already been made in ran_3dj_03a_2405 and led to adoption of jitter specs for C2M (see backup slide).

Background (2)

- A follow-up presentation ghiasi_3dj_01a_2409 attempted to dismiss the problem
    - “Does TDECQ/EECQ Capture Jitter Penalty <…> The short answer is – Yes”
- The data in that presentation was not really TDECQ measurements of a transmitter with jitter
    - Data was EECQ after 20 dB host channel loss – not representative of optical PMD output
    - “Adding RJ in Scope” is not equivalent to jitter in the Tx – it is likely a simulated signal
- … and the results actually showed EECQ of 3.14 dB (which, as TDECQ, would be within the PMD specs) with very high RJ
    - J3u = 131mUI would fail C2M module output specs at TP4!
- The conclusion from this presentation should have been “The long answer is – Not enough”.





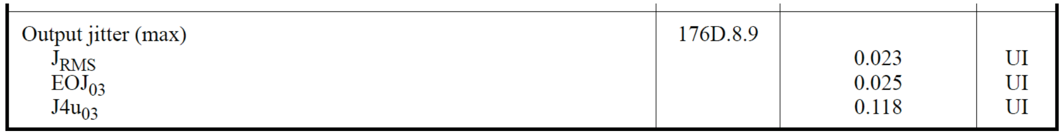
Why TDECQ is not very sensitive to jitter

- TDECQ requires a small data set, and only in an 0.1 UI region at the center of the eye
  - With SSPRQ, 1 sample per observation window, or 2 samples per UI, create the required histogram depth for a target SER of 4.8e-4! So **the jitter distribution isn't even captured**
  - In comparison, for electrical interfaces jitter is measured at the transition times, using 1000s of samples of each transition.
- TDECQ uses a reference receiver with very high bandwidth
  - E.g. 180.9.5: "3 dB bandwidth of approximately 53.125 GHz with a fourth-order Bessel-Thomson response to at least 1.3 × 106.25 GHz"
  - The large excess bandwidth diminishes the effect of jitter
  - Real receivers likely have lower bandwidth and much steeper roll-off, to reduce input noise; this creates a "narrower eye" and increases sensitivity to jitter (see backup slide).
- TDECQ does not capture spectral properties of noise/jitter
  - Low-frequency effects could cause "Block TDECQ" (as proposed in ghiasi_3dj_03a_2505) to vary with time if measured on a real-time scope.
  - However, capturing a high-jitter block requires a very long measurement time.
  - Measurement on a sampling scope cannot capture low-frequency jitter effect on an entire block.

Would jitter specs solve the problem?

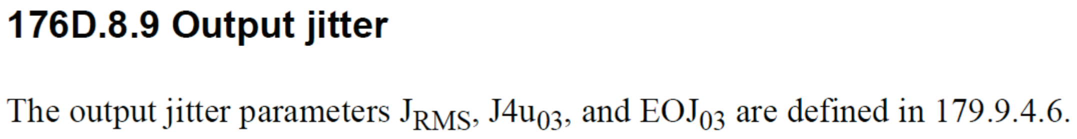
- Specifications for electrical interfaces (e.g. C2M module output) include jitter parameters $J4u_{03}$, J_{RMS}, and EOJ.
  - Based on PRBS13Q with per-transition timing histograms.
- These specs effectively limit jitter above the reference CDR bandwidth of 4 MHz.
  - This matches the jitter profile used in jitter tolerance tests – also in SRS for optical receivers.
  - **The combination is the correct way to specify for interoperability (at the expected FLR).**
- Measurements of these parameters are implemented in test equipment, including sampling scopes, and can be done in a few seconds.
  - No challenges are expected for using the same method for optical signals.
  - PRBS13Q is widely available in modules.
  - Bandwidth and SNR of optical DUT and test equipment is expected to be similar to (and likely higher than) electrical specs – so measurement noise should not be an issue.
- Is it a silver bullet?
  - Probably not, but it is a low-hanging fruit and likely good enough!
  - More detailed specs (e.g., using jitter spectral analysis) could be explored as future steps

C2M jitter specs



Output jitter (max)	176D.8.9		
J_{RMS}		0.023	UI
EOJ_{03}		0.025	UI
$J4u_{03}$		0.118	UI

From **Table 176D–3—Summary of module output specifications at TP4**



176D.8.9 Output jitter

The output jitter parameters J_{RMS}, $J4u_{03}$, and EOJ_{03} are defined in 179.9.4.6.

- Note that the definitions at 179.9.4.6 are also applicable to optical signals.
- The following additional considerations should be made…
  - Tx equalization: the sentence "These parameters are calculated from measurements with a single transmit equalizer setting to compensate for the loss of the host channel. The equalizer setting is chosen to minimize any or all of the jitter parameters." is irrelevant for optical PMDs.
  - Clocking: as in TDECQ specifications (e.g., 180.9.5), the clock source for the transmitted test pattern should be derived from the clock recovered from the xAUI-n input signal.

Concerns raised about optical jitter specs

… and responses

Jitter is captured by TDECQ by means of two sampling phases ±0.05 UI from the center.

- That separation mainly captures the bandwidth effect of the reference receiver (BT-filter and equalizer), which affects the slopes and "eye shape". By this effect, TDECQ is sensitive to the bandwidth of the transmitter.
- One sample at each phase per UI with SSPRQ (64k samples per phase) is enough to calculate TDECQ at SER=4.8e-4. With such a small data set, the distribution of Tx jitter is not captured.

It might cause false failures, e.g. with high-frequency jitter.

- The proposed jitter measurement method is the same as what is used for electrical interfaces.
- The measured jitter is a property of the driving clock – and is expected to be similar to what is seen on electrical signals (optical components should not affect it).
- False failures due to jitter are not a known issue in electrical specifications (on the contrary, jitter is known to be correlated with link performance).

Jitter measurement is longer than TDECQ, possibly prohibitive for volume testing.

- 802.3 is not a test specification. Vendors can choose what to test and how.
- Tx jitter affects interoperability (Rx performance), as was demonstrated, so it needs to be specified.

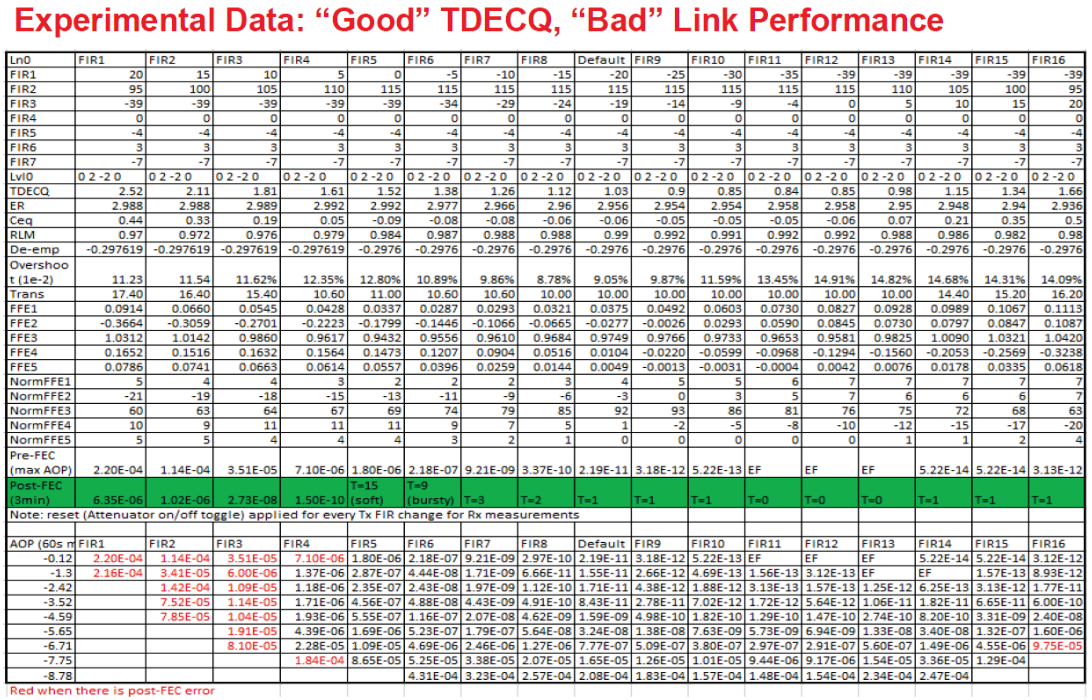
Jitter – summary

- Problem statement:
  - Transmitters with high jitter can meet current specifications (TDECQ and other) while causing post-FEC performance degradation with real receivers.
- Proposed direction:
  - Add jitter specifications at TP2 using the metrics defined for C2M (and other electrical interfaces).
    - Add a requirement, as in TDECQ, that the clock source for the PRBS13Q test pattern is derived from the clock recovered from the xAUI-n input signal.
    - Limit values should be similar to those of C2M module output (may be changed if data shows these are not feasible).

Poor Tx pulse shaping / equalization

Background

- Data presented in chayeb_3dj_01_2505 shows the effect of pulse shaping (using Tx FFE) on existing spec parameters (TDECQ, ER, Ceq) and on link performance
- The receiver (available 100G module implementation) is highly sensitive to Tx FFE setting.
    - This is a specific receiver implementation – but the results are likely representative
    - And no other data has been contributed…
- Existing Tx specs are less sensitive to the Tx FFE.
    - TDECQ is affected but passes even in the extreme bad cases.
- The next slides illustrate the table data graphically.



Experimental Data: “Good” TDECQ, “Bad” Link Performance

Ln0	FIR1	FIR2	FIR3	FIR4	FIR5	FIR6	FIR7	FIR8	Default	FIR9	FIR10	FIR11	FIR12	FIR13	FIR14	FIR15	FIR16
FIR1	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-39	-39	-39	-39	-39
FIR2	95	100	105	110	115	115	115	115	115	115	115	115	115	110	105	100	95
FIR3	-39	-39	-39	-39	-39	-34	-29	-24	-19	-14	-9	-4	0	5	10	15	20
FIR4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FIR5	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4
FIR6	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
FIR7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7	-7
Lvl0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0
TDECQ	2.52	2.11	1.81	1.61	1.52	1.38	1.26	1.12	1.03	0.9	0.85	0.84	0.85	0.98	1.15	1.34	1.66
ER	2.988	2.988	2.989	2.992	2.992	2.977	2.966	2.96	2.956	2.954	2.954	2.958	2.958	2.95	2.948	2.94	2.936
Ceq	0.44	0.33	0.19	0.05	-0.09	-0.08	-0.08	-0.06	-0.06	-0.05	-0.05	-0.05	-0.06	0.07	0.21	0.35	0.5
RLM	0.97	0.972	0.976	0.979	0.984	0.987	0.988	0.988	0.99	0.992	0.991	0.992	0.992	0.988	0.986	0.982	0.98
De-emp	-0.297619	-0.297619	-0.297619	-0.297619	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976	-0.2976
Overshoot (1e-2)	11.23	11.54	11.62%	12.35%	12.80%	10.89%	9.86%	8.78%	9.05%	9.87%	11.59%	13.45%	14.91%	14.82%	14.68%	14.31%	14.09%
Trans	17.40	16.40	15.40	10.60	11.00	10.60	10.60	10.00	10.00	10.00	10.00	10.00	10.00	10.00	14.40	15.20	16.20
FFE1	0.0914	0.0660	0.0545	0.0428	0.0337	0.0287	0.0293	0.0321	0.0375	0.0492	0.0603	0.0730	0.0827	0.0928	0.0989	0.1067	0.1113
FFE2	-0.3664	-0.3059	-0.2701	-0.2223	-0.1799	-0.1446	-0.1066	-0.0665	-0.0277	-0.0026	0.0293	0.0590	0.0845	0.0730	0.0797	0.0847	0.1087
FFE3	1.0312	1.0142	0.9860	0.9617	0.9432	0.9556	0.9610	0.9684	0.9749	0.9766	0.9733	0.9653	0.9581	0.9825	1.0090	1.0321	1.0420
FFE4	0.1652	0.1516	0.1632	0.1564	0.1473	0.1207	0.0904	0.0516	0.0104	-0.0220	-0.0599	-0.0968	-0.1294	-0.1560	-0.2053	-0.2569	-0.3238
FFE5	0.0786	0.0741	0.0663	0.0614	0.0557	0.0396	0.0259	0.0144	0.0049	-0.0013	-0.0031	-0.0004	0.0042	0.0076	0.0178	0.0335	0.0618
NormFFE1	5	4	4	3	2	2	2	3	4	5	5	6	7	7	7	7	7
NormFFE2	-21	-19	-18	-15	-13	-11	-9	-6	-3	0	3	5	7	6	6	6	7
NormFFE3	60	63	64	67	69	74	79	85	92	93	86	81	76	75	72	68	63
NormFFE4	10	9	11	11	11	9	7	5	1	-2	-5	-8	-10	-12	-15	-17	-20
NormFFE5	5	5	4	4	4	3	2	1	0	0	0	0	0	1	1	2	4
Pre-FEC (max AOP)	2.20E-04	1.14E-04	3.51E-05	7.10E-06	1.80E-06	2.18E-07	9.21E-09	3.37E-10	2.19E-11	3.18E-12	5.22E-13	EF	EF	EF	5.22E-14	5.22E-14	3.13E-12
Post-FEC (3min)	6.35E-06	1.02E-06	2.73E-08	1.50E-10	T=15 (soft)	T=9 (bursty)	T=3	T=2	T=1	T=1	T=1	T=0	T=0	T=0	T=1	T=1	T=1

Note: reset (Attenuator on/off toggle) applied for every Tx FIR change for Rx measurements

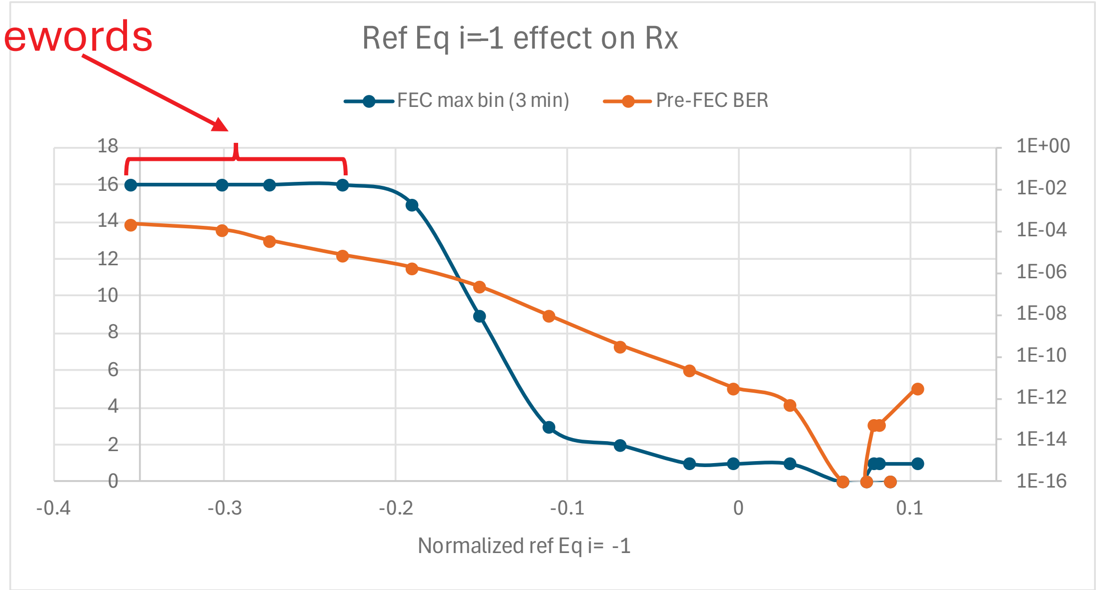
AOP (60s m	FIR1	FIR2	FIR3	FIR4	FIR5	FIR6	FIR7	FIR8	Default	FIR9	FIR10	FIR11	FIR12	FIR13	FIR14	FIR15	FIR16
-0.12	2.20E-04	1.14E-04	3.51E-05	7.10E-06	1.80E-06	2.18E-07	9.21E-09	2.97E-10	2.19E-11	3.18E-12	5.22E-13	EF	EF	EF	5.22E-14	5.22E-14	3.12E-12
-1.3	2.16E-04	3.41E-05	6.00E-06	1.37E-06	2.87E-07	4.44E-08	1.71E-09	6.66E-11	1.55E-11	2.66E-12	4.69E-13	1.56E-13	3.12E-13	EF	EF	1.57E-13	8.93E-12
-2.42		1.42E-04	1.09E-05	1.18E-06	2.35E-07	2.43E-08	1.97E-09	1.12E-10	1.71E-11	4.38E-12	1.88E-12	3.13E-13	1.57E-13	1.25E-12	6.25E-13	3.13E-12	1.77E-11
-3.52		7.52E-05	1.14E-05	1.71E-06	4.56E-07	4.88E-08	4.43E-09	4.91E-10	8.43E-11	2.78E-11	7.02E-12	1.72E-12	5.64E-12	1.06E-11	1.82E-11	6.65E-11	6.00E-10
-4.59		7.85E-05	1.04E-05	1.93E-06	5.55E-07	1.16E-07	2.07E-08	4.62E-09	1.59E-09	4.98E-10	1.82E-10	1.29E-10	1.47E-10	2.74E-10	8.20E-10	3.31E-09	2.40E-08
-5.65			1.91E-05	4.39E-06	1.69E-06	5.23E-07	1.79E-07	5.64E-08	3.24E-08	1.38E-08	7.63E-09	5.73E-09	6.94E-09	1.33E-08	3.40E-08	1.32E-07	1.60E-06
-6.71			8.10E-05	2.28E-05	1.09E-05	4.69E-06	2.46E-06	1.27E-06	7.77E-07	5.09E-07	3.80E-07	2.97E-07	2.91E-07	5.60E-07	1.49E-06	4.55E-06	9.75E-05
-7.75				1.84E-04	8.65E-05	5.25E-05	3.38E-05	2.07E-05	1.65E-05	1.26E-05	1.01E-05	9.44E-06	9.17E-06	1.54E-05	3.36E-05	1.29E-04	
-8.78						4.31E-04	3.23E-04	2.57E-04	2.08E-04	1.83E-04	1.57E-04	1.48E-04	1.54E-04	2.34E-04	2.47E-04		

Red when there is post-FEC error

Source: chayeb_3dj_01_2505, page 8

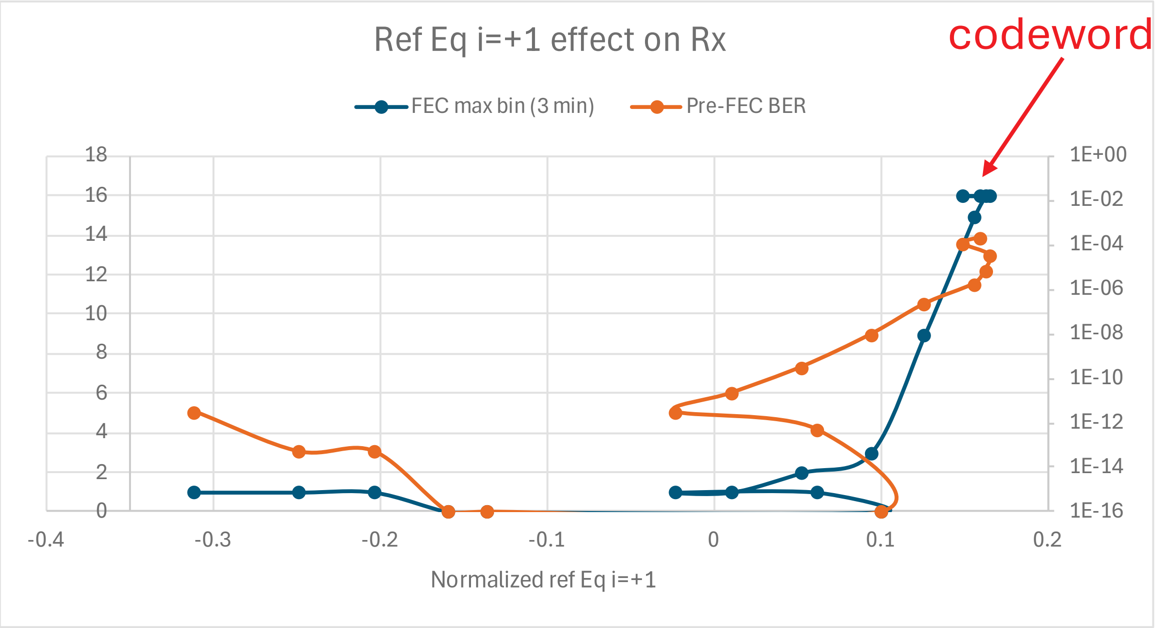
Observations

- Tx equalization can be characterized by the reference FFE precursor FFE(2) (i=-1) and postcursor FFE(4) (i=+1)
- Strong Rx equalization (in any of the two) corresponds to poor Tx equalization
- When strong Rx equalization is required, the receiver shows bad BER and high FEC bins.



Uncorrectable codewords

Under-equalized Bad region

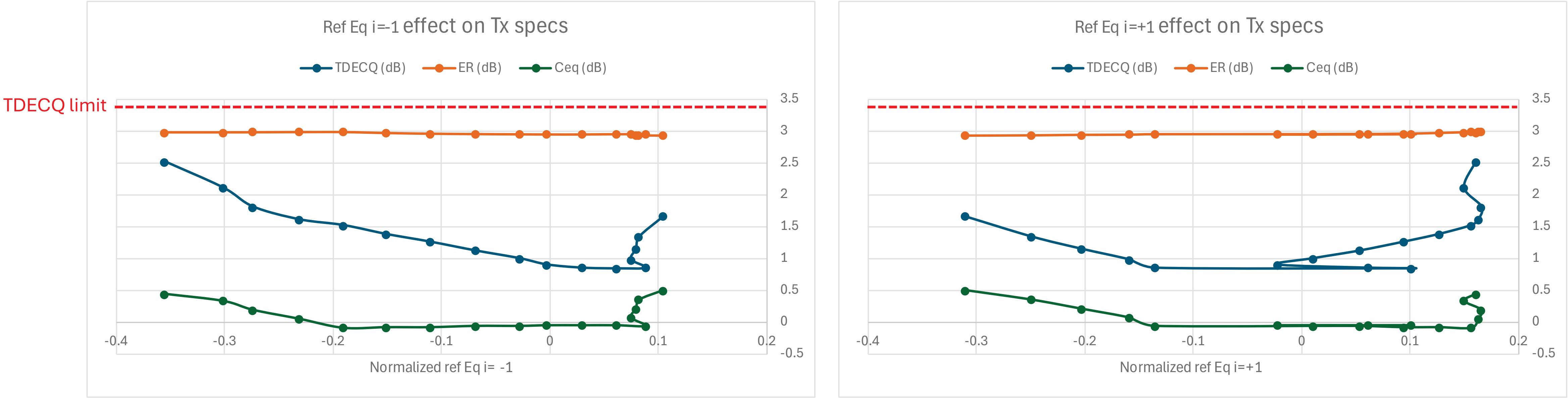


Uncorrectable codewords

Under-equalized Bad region

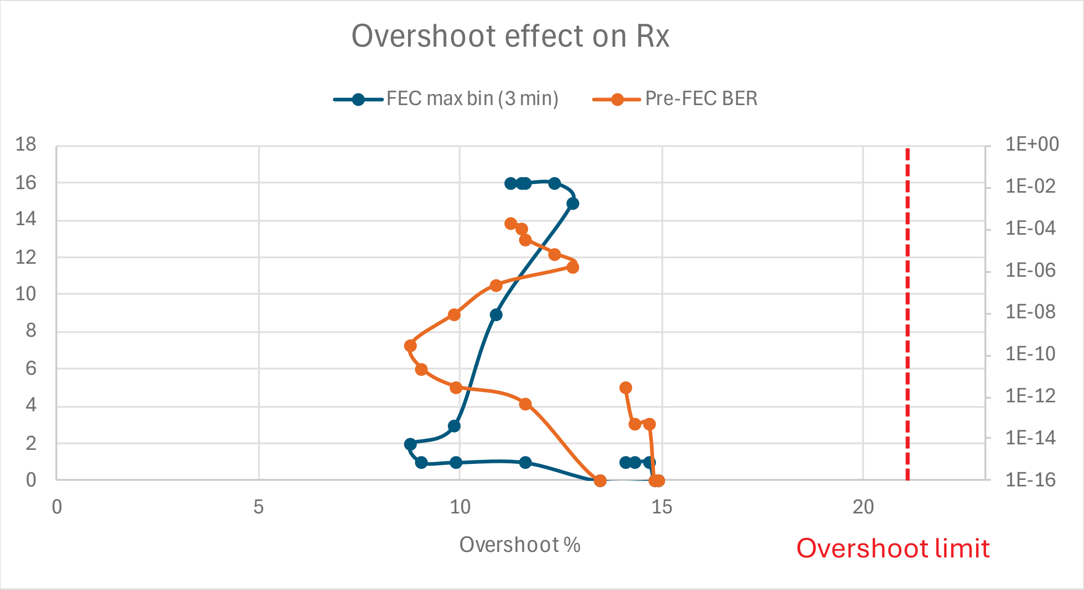
Observations (2)

- TDECQ is affected by the equalization, but spec is <3.4 dB – met in all cases.
- Ceq is weakly sensitive to equalization (it is not a spec parameter).
- ER is constant across the data set.



Observations (3)

- Overshoot is affected by the equalization, but has no correlation to Rx performance. Spec (<22%) is met in all cases.



Existing Reference Equalizer limits

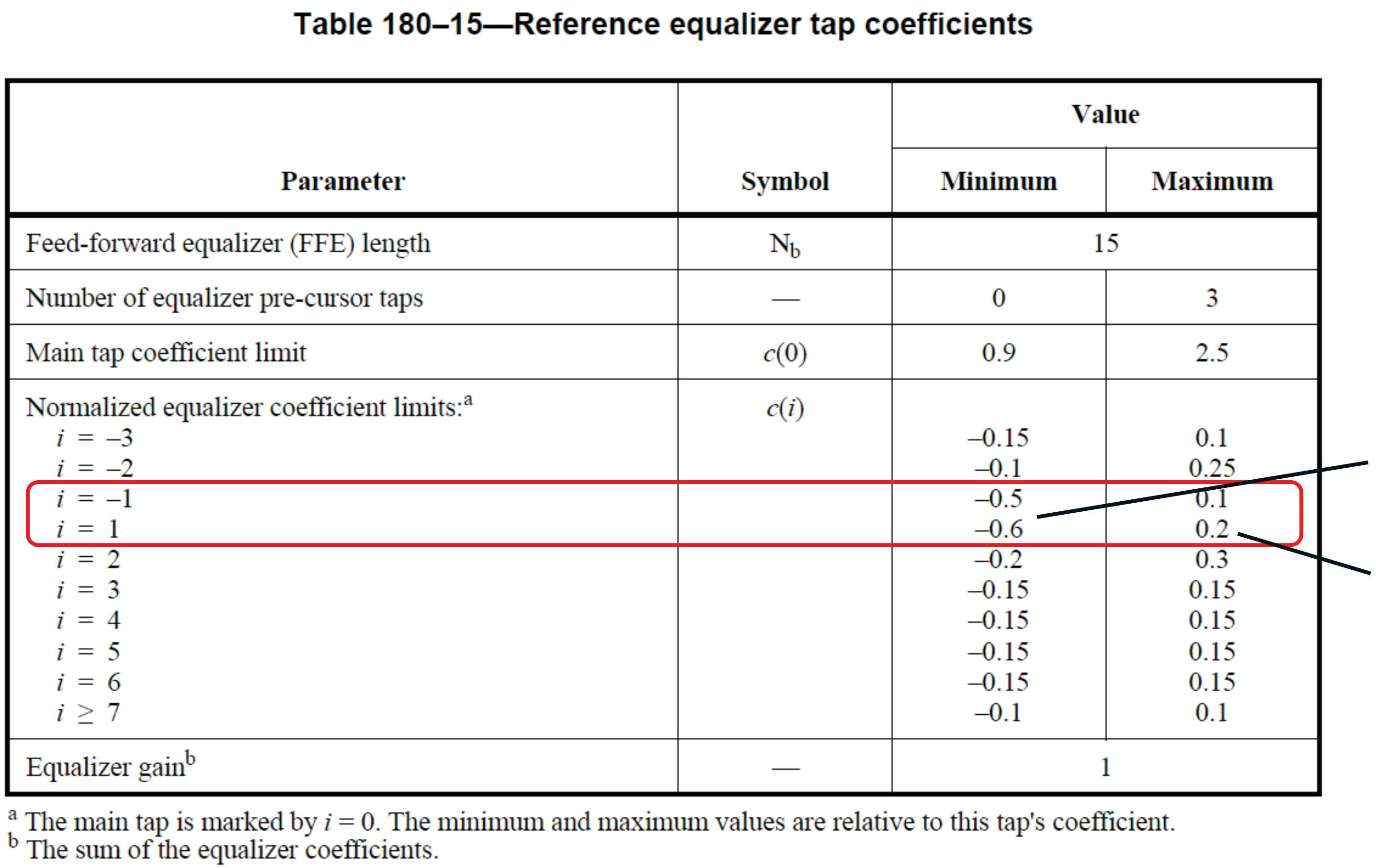


Table 180–15—Reference equalizer tap coefficients

Parameter	Symbol	Value	
		Minimum	Maximum
Feed-forward equalizer (FFE) length	N_b	15	
Number of equalizer pre-cursor taps	—	0	3
Main tap coefficient limit	$c(0)$	0.9	2.5
Normalized equalizer coefficient limits:[a]	$c(i)$		
$i = -3$		–0.15	0.1
$i = -2$		–0.1	0.25
$i = -1$		–0.5	0.1
$i = 1$		–0.6	0.2
$i = 2$		–0.2	0.3
$i = 3$		–0.15	0.15
$i = 4$		–0.15	0.15
$i = 5$		–0.15	0.15
$i = 6$		–0.15	0.15
$i \geq 7$		–0.1	0.1
Equalizer gain[b]	—	1	

[a] The main tap is marked by $i = 0$. The minimum and maximum values are relative to this tap's coefficient.
[b] The sum of the equalizer coefficients.

Change both to -0.3

Change to 0.1

The allowed ranges of c(-1) and c(+1) are very wide. All tested cases are within these ranges.

To rule out the bad cases, it is suggested to tighten the limits as shown.

The suggested ranges match most of the contributed transmitter data (see backup slide).

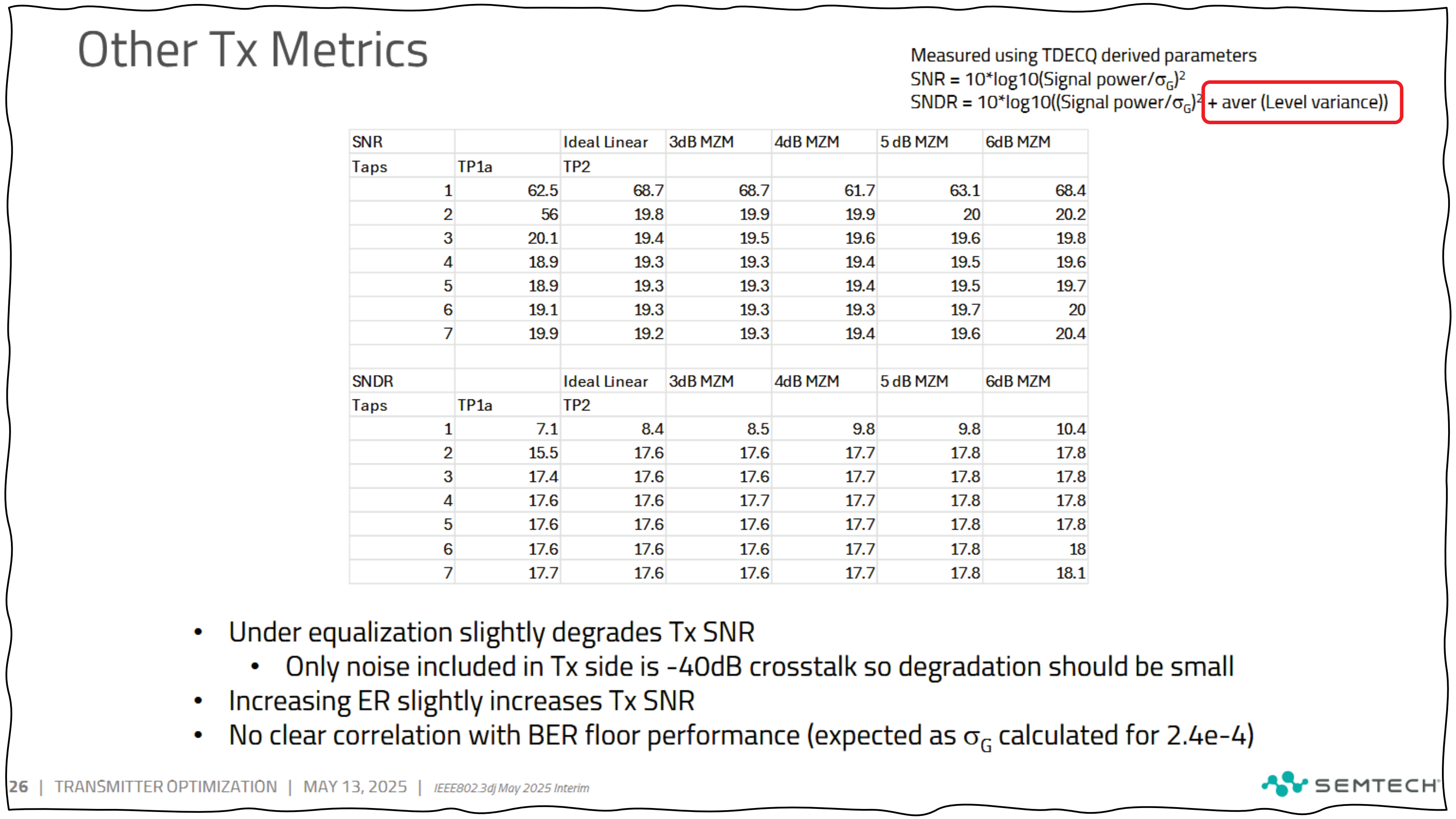
Pulse shaping – summary

- Problem statement:
  - Transmitters with poor pulse shaping can meet current specifications (including TDECQ with the existing tap limits) while causing post-FEC performance degradation with real receivers.
- Proposed direction: Tighten the normalized equalizer coefficient limits as follows
  - i=-1: min = ~~-0.5~~ -0.3, max = 0.1
  - i=1: min = ~~-0.6~~ -0.3, max = ~~0.2~~ 0.1

Distortion

Background

- kimber_3dj_01a_2505 recently analyzed TDECQ dependence on Tx equalization (in an LPO environment, both simulation and measurement).
  - Test cases were different from those of chayeb_3dj_01_2505 and individual coefficients were not reported.
- It was observed (page 25 and on) that equalization can affect Tx distortion and thus Rx performance.
- SNDR was discussed on slide 26 but the bottom line was “No clear correlation with BER floor performance”
  - However, the definition used for SNDR was only based on level variance.



Other Tx Metrics

Measured using TDECQ derived parameters

$\text{SNR} = 10^{*}\log10(\text{Signal power}/\sigma_G)^2$

$\text{SNDR} = 10^{*}\log10((\text{Signal power}/\sigma_G)^2 + \text{aver (Level variance)})$

SNR		Ideal Linear	3dB MZM	4dB MZM	5 dB MZM	6dB MZM
Taps	TP1a	TP2				
1	62.5	68.7	68.7	61.7	63.1	68.4
2	56	19.8	19.9	19.9	20	20.2
3	20.1	19.4	19.5	19.6	19.6	19.8
4	18.9	19.3	19.3	19.4	19.5	19.6
5	18.9	19.3	19.3	19.4	19.5	19.7
6	19.1	19.3	19.3	19.3	19.7	20
7	19.9	19.2	19.3	19.4	19.6	20.4
SNDR		Ideal Linear	3dB MZM	4dB MZM	5 dB MZM	6dB MZM
Taps	TP1a	TP2				
1	7.1	8.4	8.5	9.8	9.8	10.4
2	15.5	17.6	17.6	17.7	17.8	17.8
3	17.4	17.6	17.6	17.7	17.8	17.8
4	17.6	17.6	17.7	17.7	17.8	17.8
5	17.6	17.6	17.6	17.7	17.8	17.8
6	17.6	17.6	17.6	17.7	17.8	18
7	17.7	17.6	17.6	17.7	17.8	18.1

- Under equalization slightly degrades Tx SNR
  - Only noise included in Tx side is -40dB crosstalk so degradation should be small
- Increasing ER slightly increases Tx SNR
- No clear correlation with BER floor performance (expected as σ_G calculated for 2.4e-4)

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Source: kimber_3dj_01a_2505, page 26

Observation

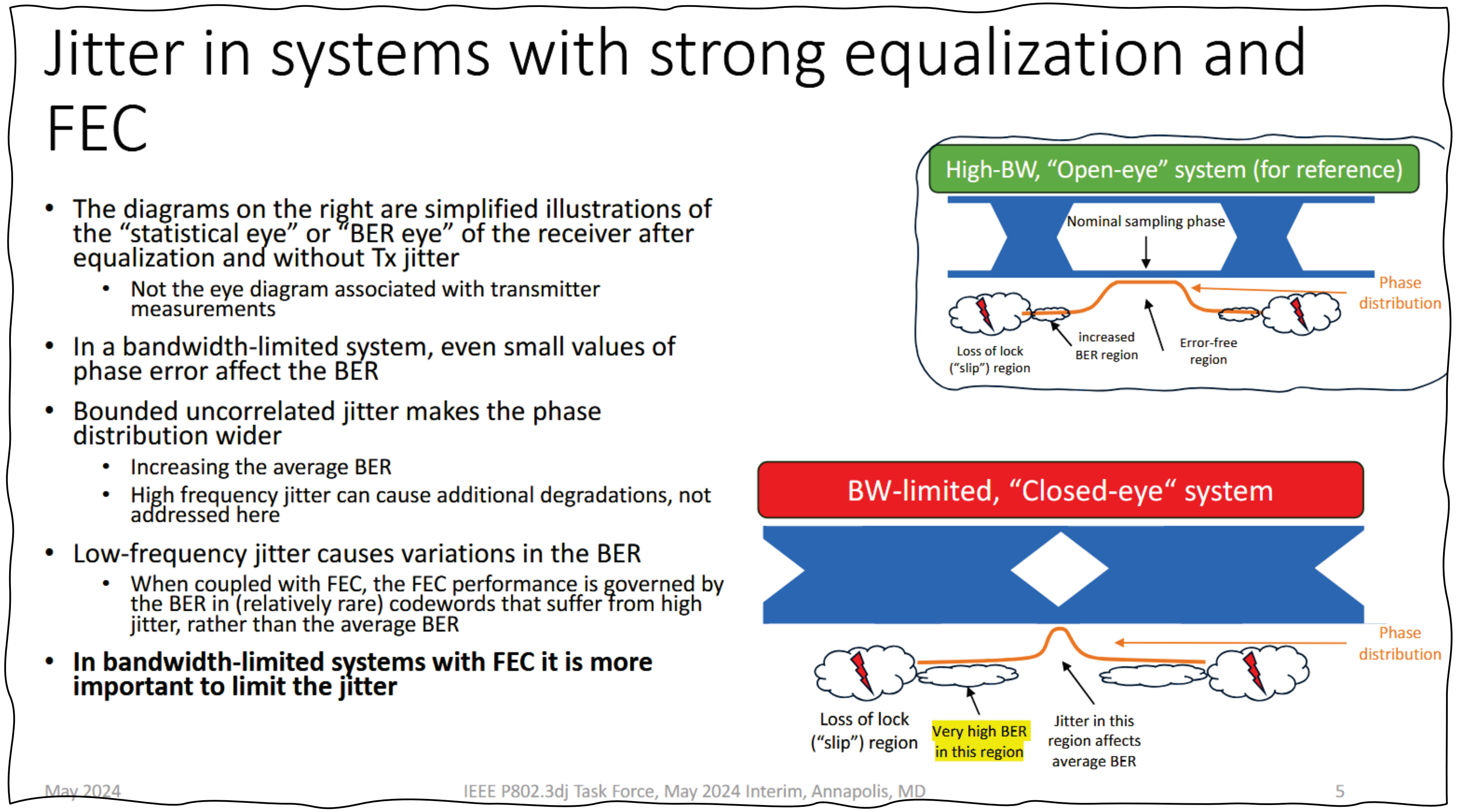
- Distortion is measured as part of SNDR in the electrical specifications, using the linear fit pulse response (with level mismatch removed) and the std of the linear fit error, σ_e.
  - σ_e normalized to OMA is likely a better metric for the dynamic distortion that receivers cannot easily handle.
  - The other component, σ_n, may be sensitive to scope noise and is perhaps less relevant for optics.
- SDR (the distortion part of electrical SNDR, using σ_e only) should be considered as an additional specification.
  - Data is needed…
  - No proposal at this time, but joint work to measure SDR and correlate with link performance is encouraged.

That’s all

Questions?

Backup

Why jitter affects post-FEC performance



Jitter in systems with strong equalization and FEC

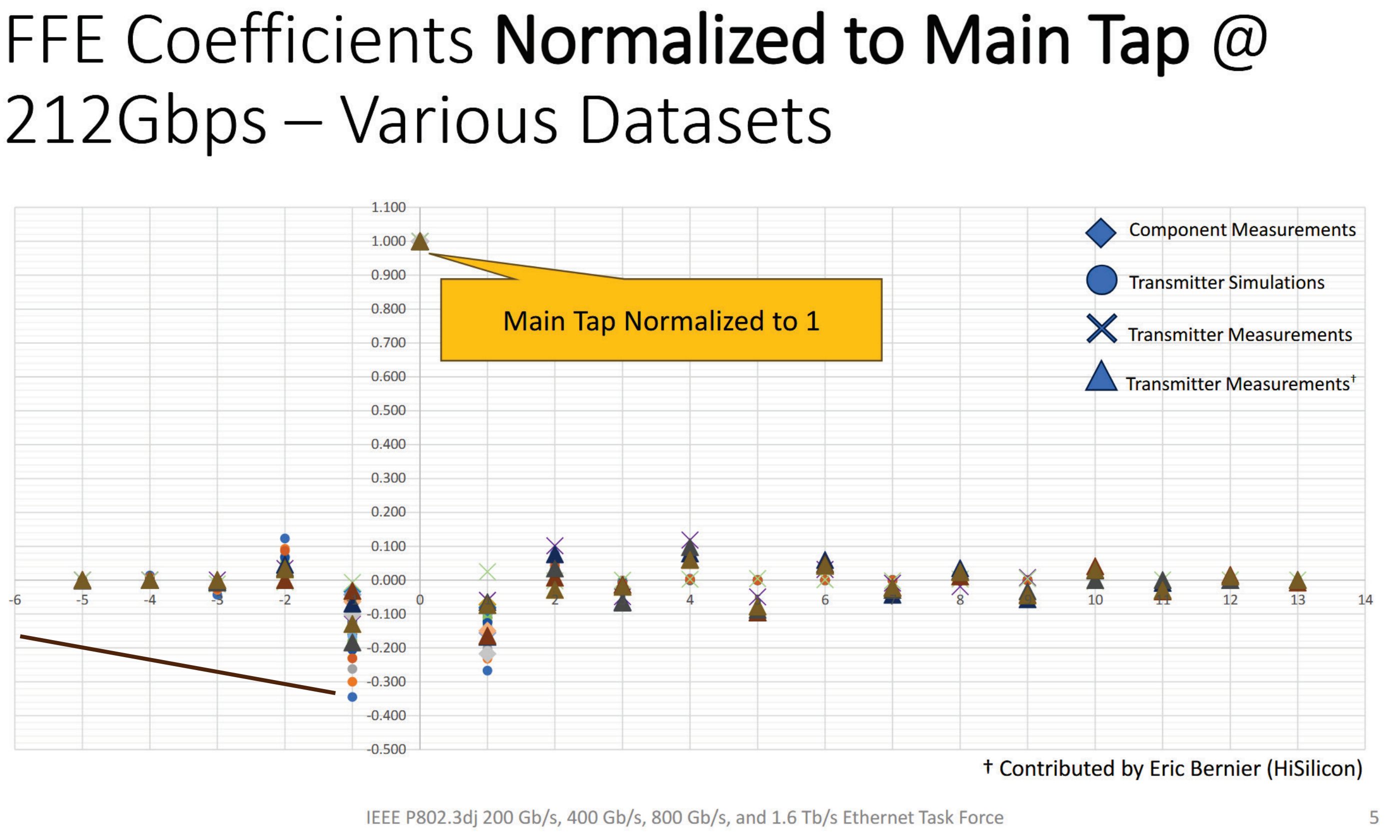
- The diagrams on the right are simplified illustrations of the “statistical eye” or “BER eye” of the receiver after equalization and without Tx jitter
  - Not the eye diagram associated with transmitter measurements
- In a bandwidth-limited system, even small values of phase error affect the BER
- Bounded uncorrelated jitter makes the phase distribution wider
  - Increasing the average BER
  - High frequency jitter can cause additional degradations, not addressed here
- Low-frequency jitter causes variations in the BER
  - When coupled with FEC, the FEC performance is governed by the BER in (relatively rare) codewords that suffer from high jitter, rather than the average BER
- **In bandwidth-limited systems with FEC it is more important to limit the jitter**

May 2024 IEEE P802.3dj Task Force, May 2024 Interim, Annapolis, MD 5

Source: ran_3dj_03a_2405

Contributed data for FFE coefficients

Source: welch_3dj_01_2405



FFE Coefficients **Normalized to Main Tap** @ 212Gbps – Various Datasets

Main Tap Normalized to 1

† Contributed by Eric Bernier (HiSilicon)

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Only one dataset is slightly out of the suggested limits.