KEYSIGHT

TDECQ Correlation to Link Performance

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Agenda

- What TDECQ is
- What TDECQ is not
- TDECQ Correlation to Link Performance
- TDECQ Correlation to Receiver Sensitivity
- Experimental Data
- TDECQ Challenges
- Areas for Further Study

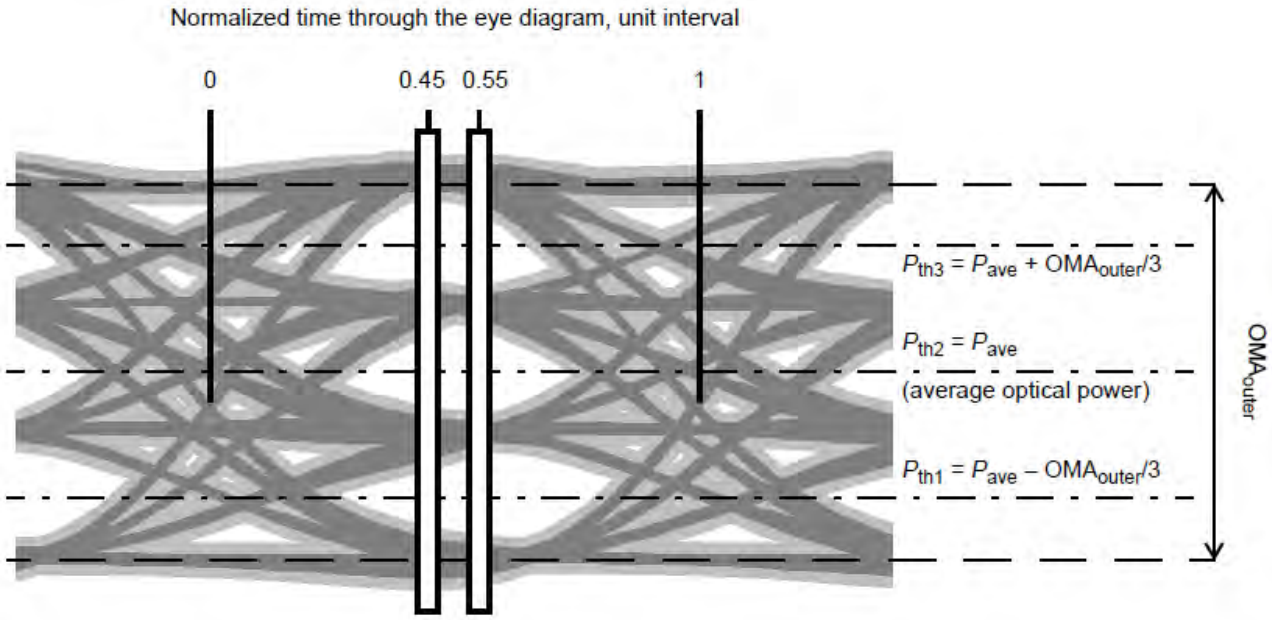
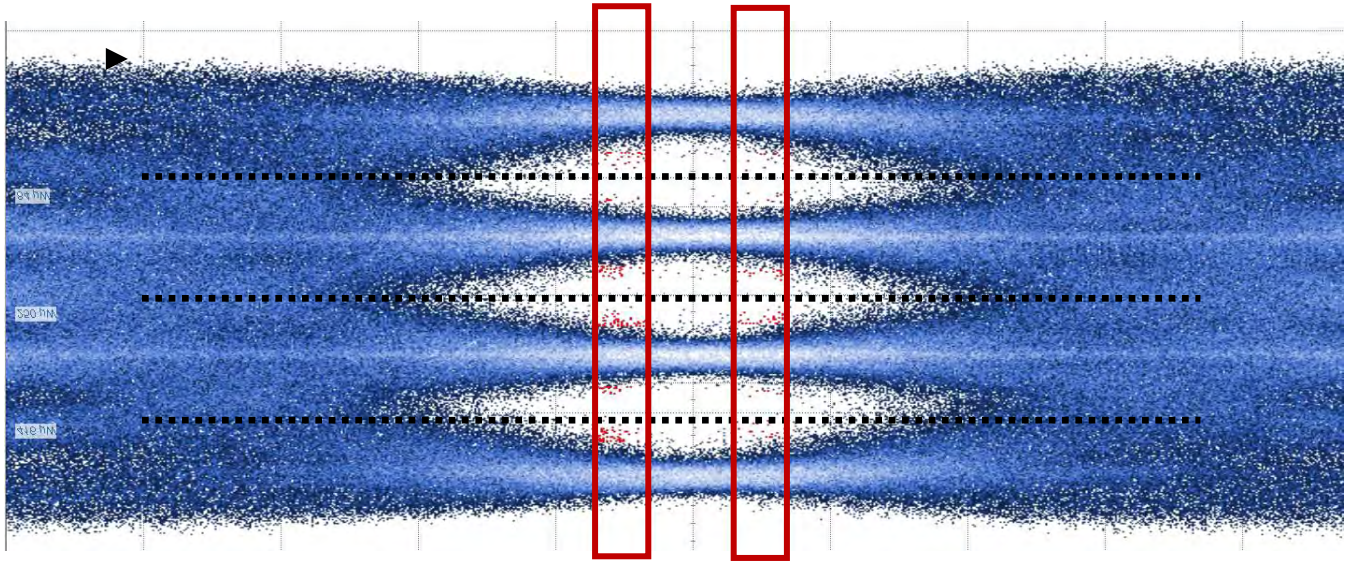


Figure 121–5—Illustration of the TDECQ measurement

IEEE 802.3bs – Clause 121.8.5.1

What a Transmitter Dispersion Eye Closure Quatenary (TDECQ) Is

- TDECQ is a power penalty metric to assess the quality of a PAM4 optical transmitter.
- TDECQ aggregates various transmitter impairments including non-ideal waveforms and dispersion
- TDECQ describes how much extra is required to compensate for the transmitter's non-ideal performance.
- TDECQ is measured on an oscilloscope used as a virtual receiver with an equalizer and decision circuit.
- TDECQ is intentionally pessimistic using a "worst-case" reference receiver and "mistimed" sample locations



Transmitter under test

TDECQ According to the Standard

Goal of TDECQ: Find the maximum intrinsic receiver noise that still achieves the desired error performance (currently specified as SER).

The methodology specified in the standards:

- Combines samples from each level, l, into histograms which represent an estimated pdf,

$$f_{y_k|L}(y_k|L=l)$$

- Let $n \sim N(0,\sigma^2)$ be a normal gaussian, then the SER is a function of σ defined as:

$$SER(\sigma) = \sum_{l=0}^{l=3} \Pr\{L=l\} f_{y_k|L}(y_k|L=l) \left[Q\left(\frac{y_k - th_{l-1}}{\sigma}\right) + Q\left(\frac{th_l - y_k}{\sigma}\right) \right]$$

- The maximum σ is found such that $SER(\sigma) \leq SER_{target}$

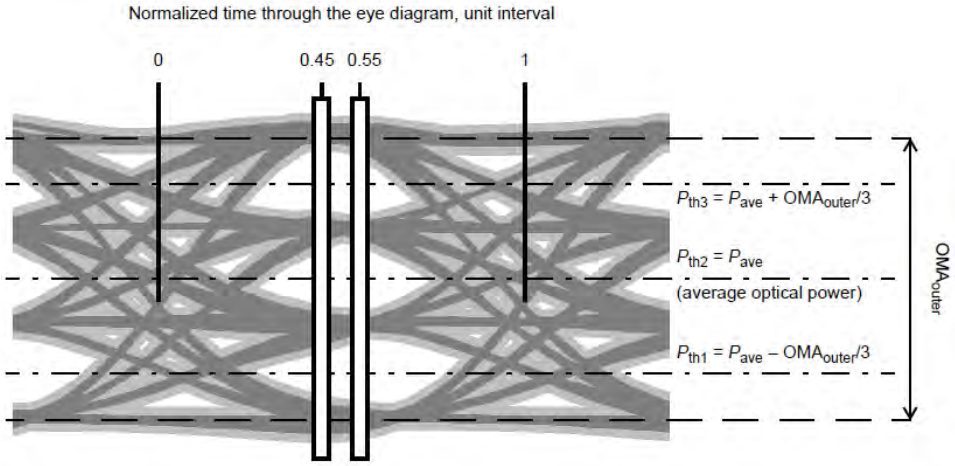
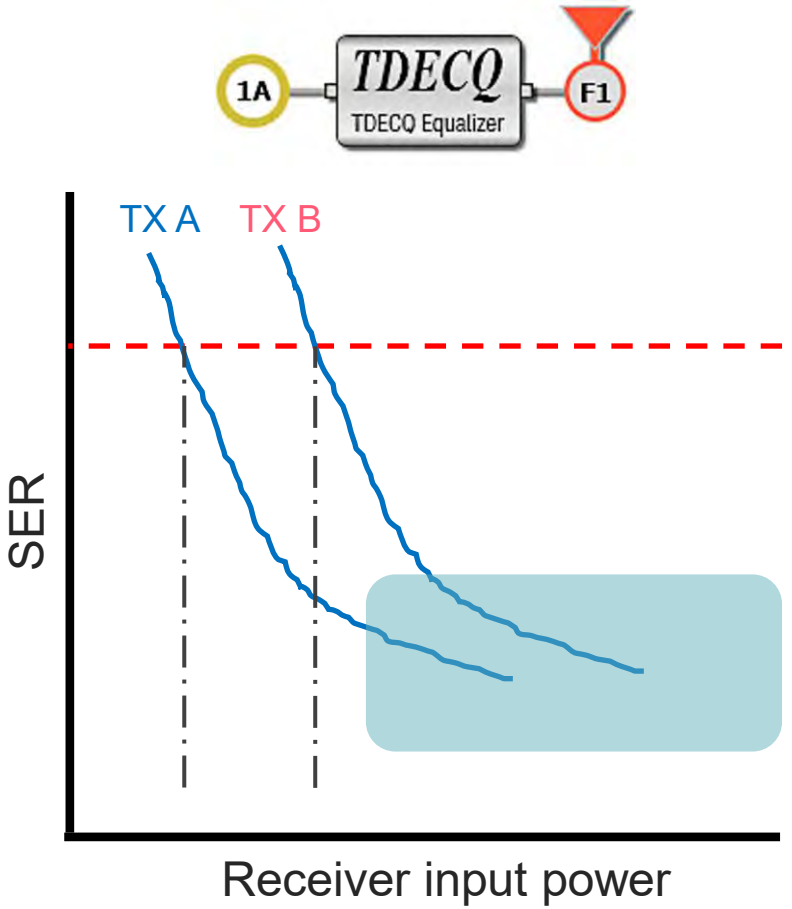


Figure 121–5—Illustration of the TDECQ measurement

IEEE 802.3bs – Clause 121.8.5.1

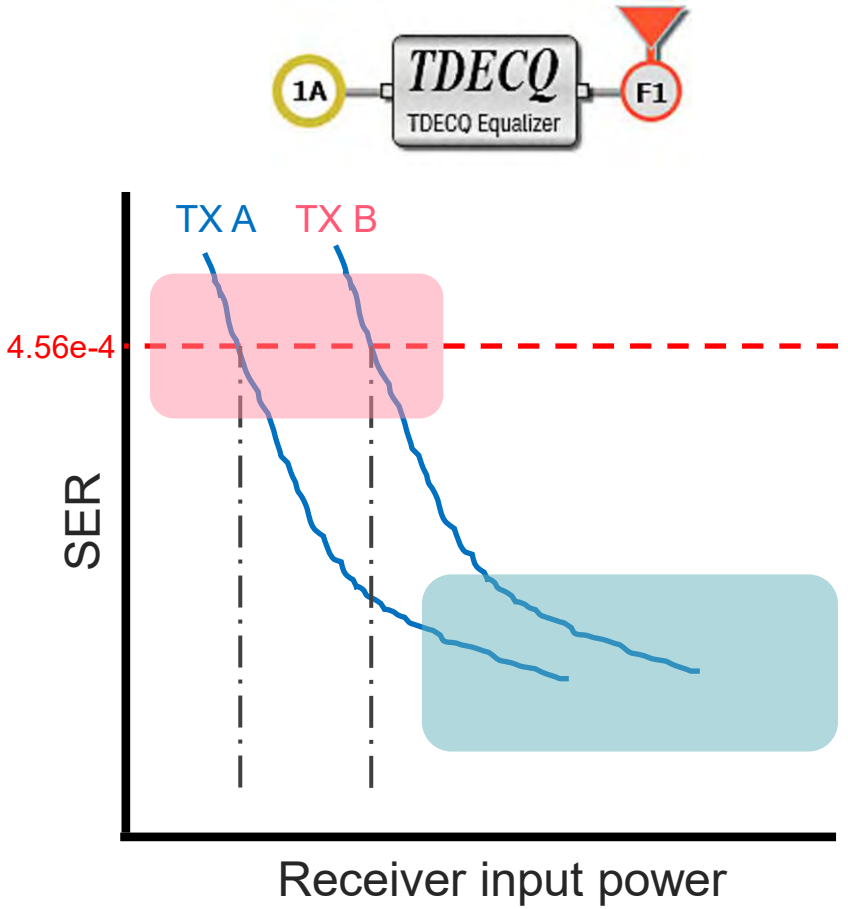
TDECQ Correlation to Link Performance (BER)

- TDECQ is a transmitter quality metric measured on an oscilloscope used as a virtual worst-case reference receiver
- Transmitters does not make bit errors; BER (Bit Error Ratio) is a system level metric
- TDECQ is designed to target the minimum power/highest error rate transceiver setup
- The target SER for TDECQ is a theoretical pre-FEC BER value that assumes errors are not correlated and randomly distributed
- TDECQ **is not intended to correlate** to BER or BER floor (blue area)



TDECQ Correlation to Receiver Sensitivity

- TDECQ was designed to correlate with receiver sensitivity by targeting the minimum power/highest error rate (red area)
- TDECQ describes the power penalty for a transmitter under test compared to an ideal reference transmitter at the target SER (4.56e-4)
- By design, TDECQ does not have a 1:1 correlation with receiver sensitivity
- TDECQ is intentionally pessimistic using a “worst case” reference receiver and “mistimed” sample locations
- Improving TDECQ correlation to receiver sensitivity is an area for further study



Experimental Data: Test Setup

- Setup: Module TX => Keysight (Line rate is PAM4 100Gbit/sec)
  - Module is 400-DR4, One lane sends SSPRQ pattern to N1092C
  - Another lane generates a clock trigger for N1092C.
- Pattern Gen: On chip SSPRQ pattern generator
- AOP for TDECQ measurement is about +1.5dBm
- Rise Time is 20-80%
- Ceq is measured by Keysight scope using the IEEE 802.3 draft option from pulldown menu

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

BROADCOM

Experimental Data: “Bad” TDECQ, “Good” BER

Ln0	TECQ1	TECQ2	TECQ3	TECQ4	TECQ5
FIR1	0	0	0	0	0
FIR2	168	158	148	138	128
FIR3	0	10	20	30	40
FIR4	0	0	0	0	0
FIR5	0	0	0	0	0
FIR6	0	0	0	0	0
FIR7	0	0	0	0	0
Lvl0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0	0 2 -2 0
TDECQ	3.96	4.02	4.33	5.09	6.73
ER	6.952	6.925	6.908	6.992	7
Ceq	1.85	2.12	2.46	2.92	3.36
RLM	0.947	0.963	0.962	0.967	0.979
De-emp	0	0	0	0	0
Overshoot (1e-2)	1.82%	2.18%	2.51%	2.90%	2.85%
Trans time	15.80	17.60	18.20	22.8	23.8
FFE1	0.0437	0.0460	0.0597	0.05492	0.07337
FFE2	-0.2885	-0.3006	-0.3539	-0.36748	-0.44484
FFE3	1.5176	1.6055	1.7189	1.87493	2.03389
FFE4	-0.2537	-0.3420	-0.4340	-0.6253	-0.7858
FFE5	-0.0191	-0.0089	0.0093	0.06293	0.12341
NormFFE1	2	2	2	2	2
NormFFE2	-14	-13	-14	-12	-13
NormFFE3	71	70	67	63	59
NormFFE4	-12	-15	-17	-21	-23
NormFFE5	-1	0	0	2	4
Pre-FEC (max AOP)	EF	EF	6.15E-13	1.85E-13	1.34E-10
Post-FEC (3min)	T=0	T=0	T=1	T=1	T=1

TDECQ Challenges

- Appears to be some lack of correlation between test methodology (TDECQ) and actual performance (post FEC errors).
- Reference receiver does not match real receiver
  - CDR loop bandwidth, sampler bandwidth, “mistimed” and “jittered” sample timing, equalizer configuration
- Reference receiver does not try to emulate non-linearities, overload conditions, or other imperfections in a real receiver
- Any post processing/FEC is ignored, **assumed to be covered by target SER**
- Lots of ways to get the same TDECQ value; All impairments are treated equally.
  - SRS testing may not accurately predict performance
  - SRS repeatability/reliability can be an issue depending on impairments used to achieve target SECQ

Areas for Further Study

- **Improving the "Bad" TDECQ but "Good" Transmitter Case:**
  - **Improve the "worst-case" reference receiver to more closely match real receiver capabilities**
    - More equalization (more FFE taps, add DFE, etc)
    - Reduce mistiming of sampling locations (bring the histograms closer together)

- **Improving the "Good" TDECQ but "Bad" Transmitter Case:**
  - **Better Specification of the CDR and transmitted jitter characteristics**
    - Current specification is limited to loop bandwidth
    - ran_3dj_02a_2407 and oif2024.449.02 demonstrated receivers with performance issue related to bandlimited random jitter in OIF
    - There are currently no specs related to jitter
  - **Model Non-linearities and overload conditions of real receivers**
    - Not really a feasible option
    - Most likely too specific to individual receivers; not really fit for a standard
  - **Use Codeword Error Rate (CER) instead of SER for TDECQ targets**
    - Variations of this have been proposed separately in ghiasi_3dj_03_2501
    - Removes the need to assume uncorrelated codeword symbol errors
    - Captures correlation of errors due to effects that are present in the waveform

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Thank you