Study on the Dependence of TDECQ on SER

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Acknowledgments:

We wish to thank Roberto Rodes, Frank Chang, Yu Xu, David Leyba, and Greg D. Le Cheminant for helpful discussions.

Introduction

- In leyba_3dj_optx_01a_230629, TDECQ measurements at high SER were made.

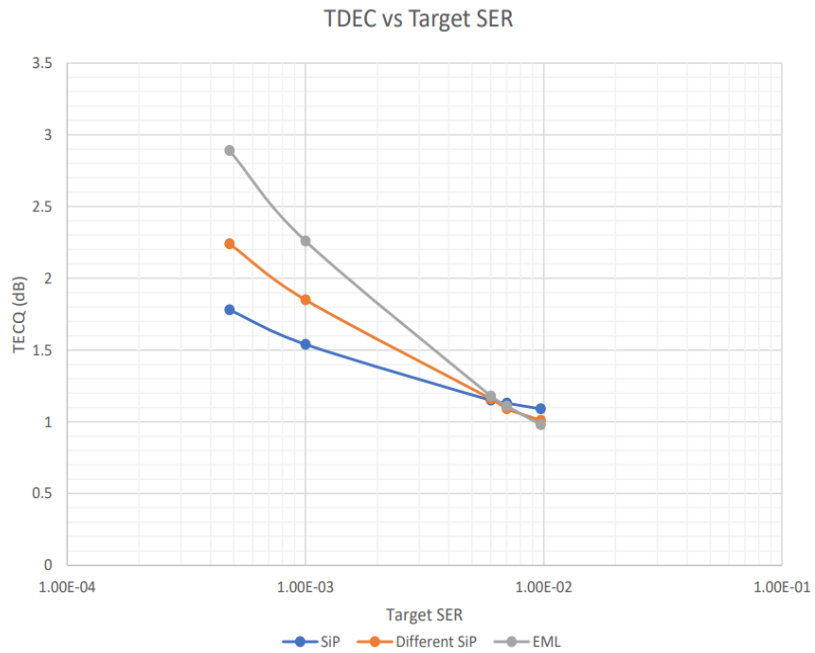
TDECQ Versus High SER Limits

David Leyba and Greg D. Le Cheminant Keysight Technologies
June 2023 IEEE 802.3dj optical ad hoc

Some observations of measured TDECQ versus SER for real transmitters

- A “strange” behavior was found, as shown on the right.

- 100G transmitters
- Two SiP and one EML
- One waveform acquired for each transmitter
- 5 tap FFE in TDECQ virtual reference receiver
- SER limit varied from 4.8 e-4 to 9.7e-3
- For the three transmitters a 1.1 dB separation in TDECQ penalty values is observed at common 4.8e-4 SER, but TDECQ converges to very similar values at high SER

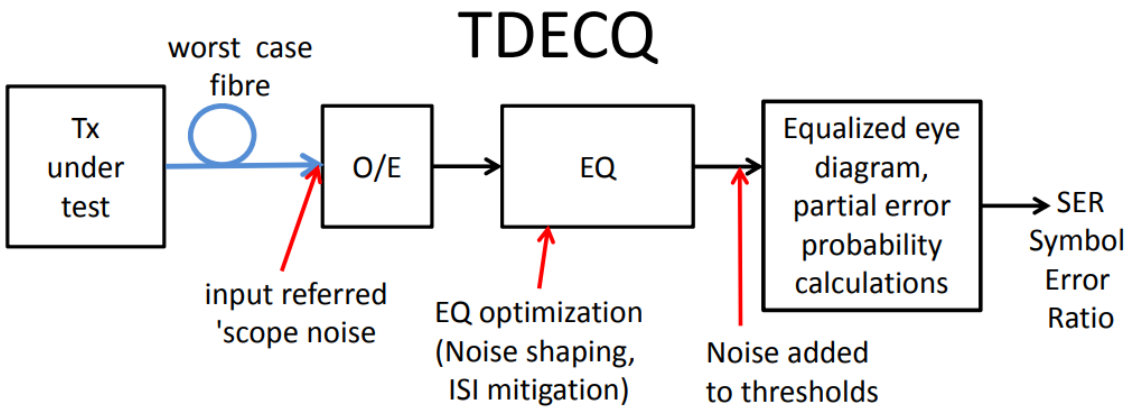


Questions raised in leyba_3dj_optx_01a_230629

Implications on specifying and testing transmitters

- Analysis performed on 100G lanes. Assume that it scales and represents what will occur for 200G lanes
  - Can be easily verified with 200G lanes by acquiring a waveform and adjusting the SER target in the TDECQ reference receiver
- Key question: Does this convergence represent behavior in real systems?
  - Does the TDECQ penalty represent the receiver sensitivity penalty observed at a high SER?
  - Would two transmitters that have different TDECQ at low SER, but similar TDECQ at high SER yield similar receiver sensitivities observed at the high SER?
- This is early work and requires further analysis and physical verification

TDECQ Introduction (1)



- In the TDECQ test, 'scope noise appears at the same point as receiver noise does in a real system.
- As part of TDECQ processing, Gaussian noise is effectively added to the signal. The amount of noise and the EQ settings are iteratively optimized to find the largest value of noise that can be added to the signal.
- TDECQ is the dB ratio of the noise that could be added to the test transmitter compared to the noise that could be added to an ideal transmitter, similar to TDEC for IEEE Clause 95 (100GBASE-SR4). 4

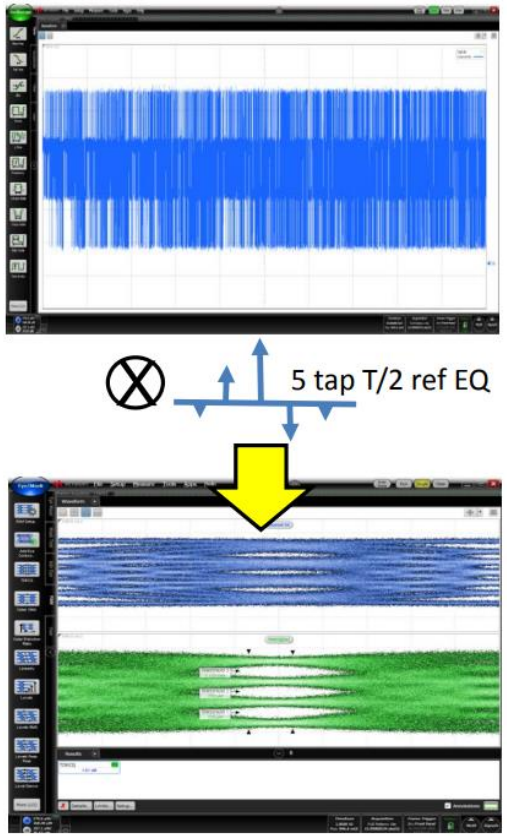
Reference: https://standards.incits.org/apps/group_public/download.php/86818/T11-2017-00102-v000.pdf

Other references: [1] G. Le Cheminant, K. Zhang, V. Houtsma, E. Harstead, and X. Liu, "TDEC (transmitter and dispersion eye closure) method for equalizer-enabled 50G-PON", Contribution D37, Q2/15 Interim Meeting, Xi'an, China, April 2019.
[2] X. Liu, "Optical Communications in the 5G Era", Academic Press, 2021.

TDECQ Introduction (2)

TDECQ measurement process

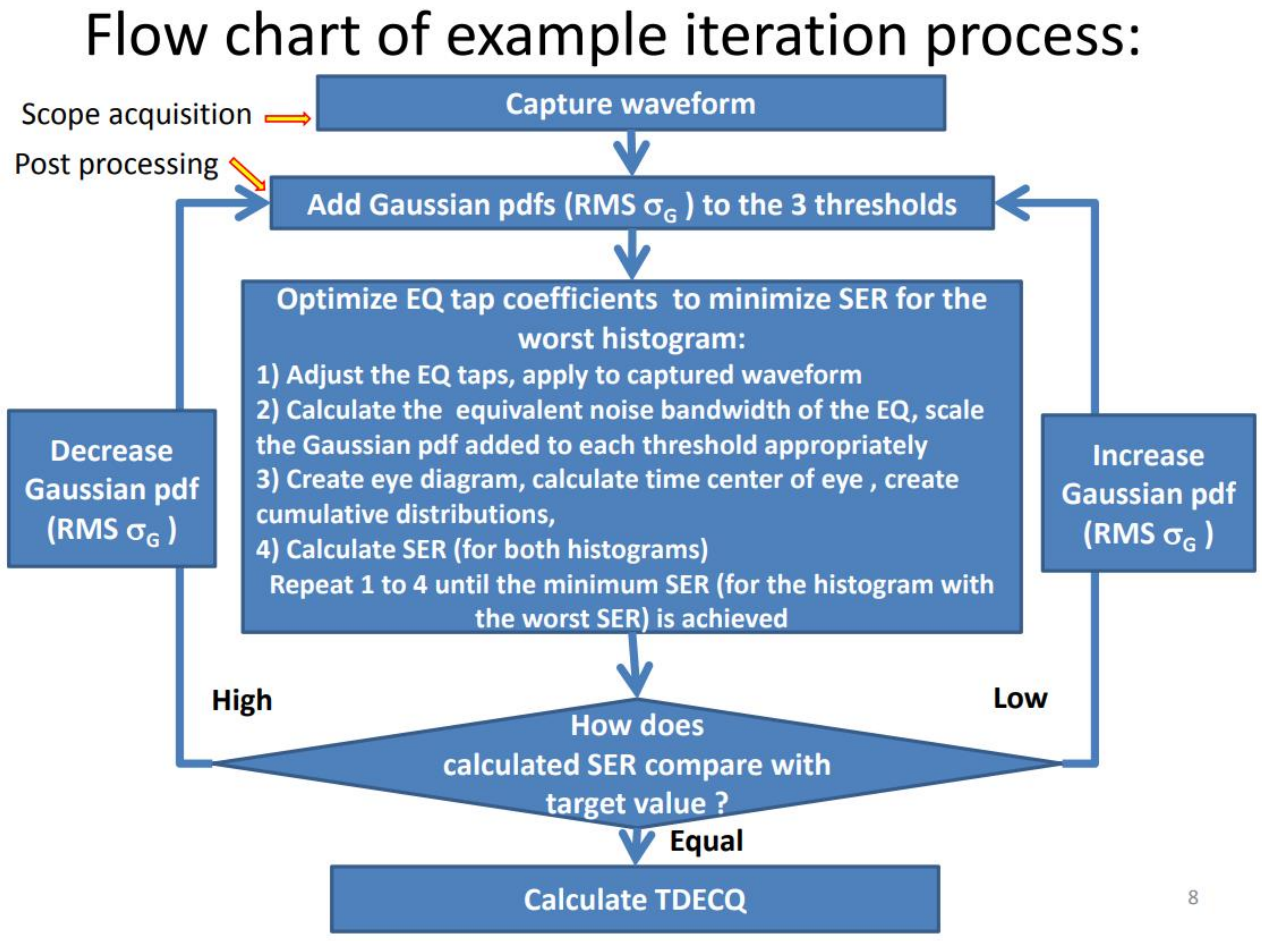
- Acquire the continuous pattern waveform from the transmitter
  - E.g. SSPRQ pattern, 2^{16}-1 length (65535 bits, designed with specific stress)
- Conceptual waveform processing
  1) Add noise to the signal
  2) Equalize the waveform with a virtual equalizer
  3) Create the PAM4 eye diagram
  4) Calculate the PAM4 symbol error (SER)
  5) Iterate the addition of noise and EQ optimization until the SER equals the target value, and the amount of noise added cannot be increased by further optimization of the equalizer tap coefficients.
- TDECQ is dB ratio of the noise that can be added to the test transmitter vs an ideal transmitter.



Scope shots From OFC 2017 King Leyba LeCheminant 5

Ref.: https://standards.incits.org/apps/group_public/download.php/86818/T11-2017-00102-v000.pdf

TDECQ Introduction (3)



Ref.: https://standards.incits.org/apps/group_public/download.php/86818/T11-2017-00102-v000.pdf

TDECQ Introduction (4)

- TDECQ measurement is based on two histograms at 0.45UI and 0.55UI (according to IEEE 802.3bs):

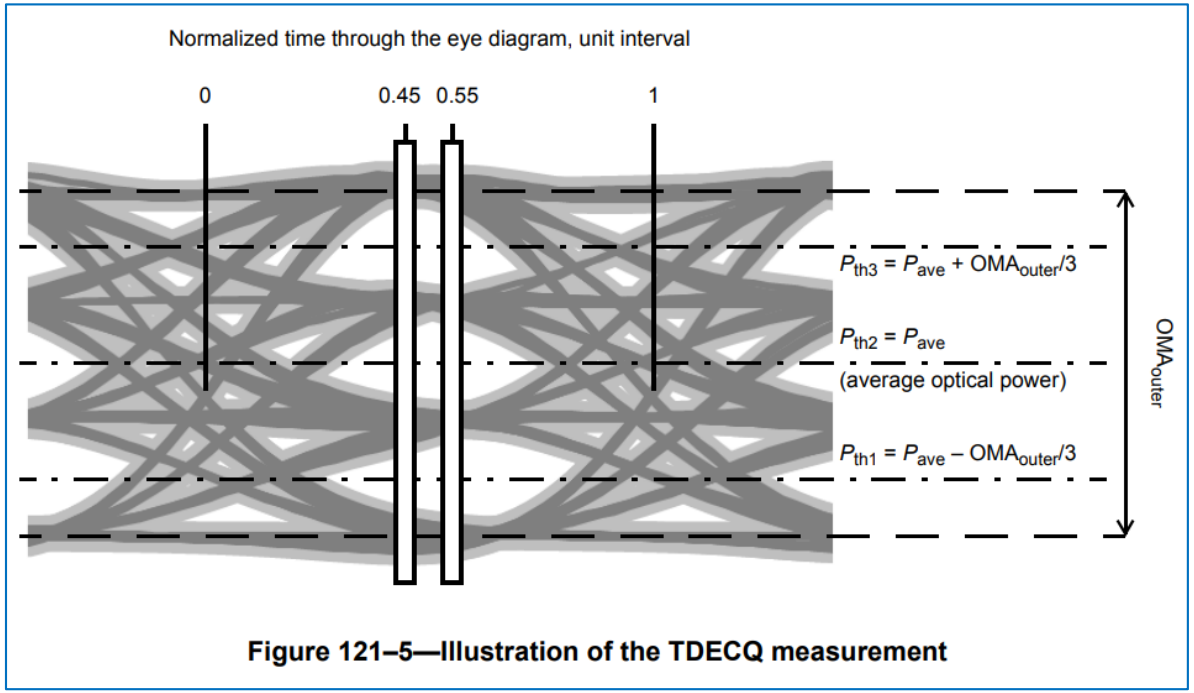


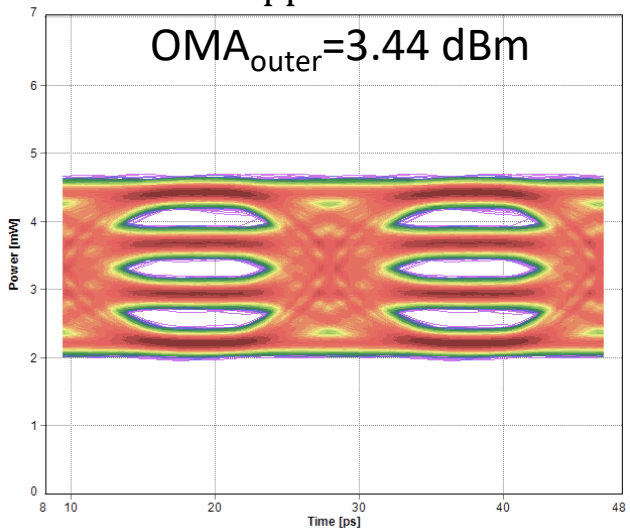
Figure 121–5—Illustration of the TDECQ measurement

- The TDECQ is calculated based on the histogram that gives the higher SER (in order to be conservative):

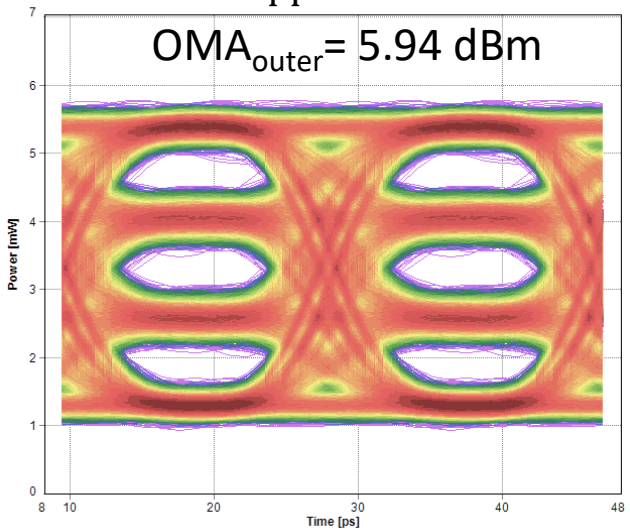
> When the larger of SER_L and SER_R is equal to the target SER of 4.8×10^{-4}, and the value of σ_G cannot be increased by further optimization of the equalizer tap coefficients, then TDECQ is calculated.

Our simulation results (1): SiP (MZM) Transmitters

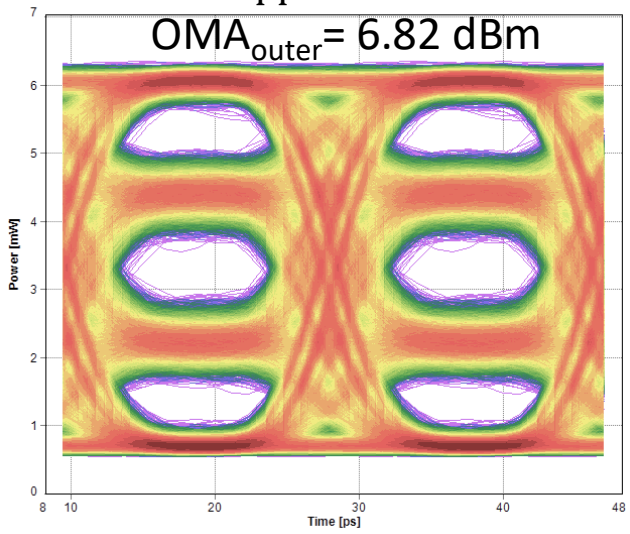
$v_{pp} = 0.15v_\pi$



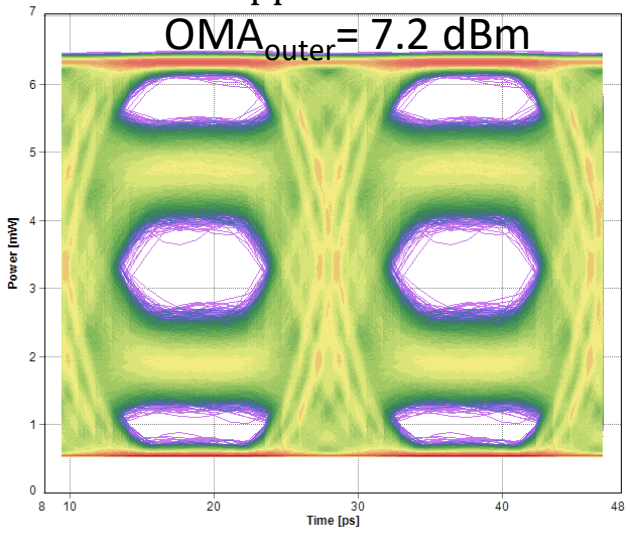
$v_{pp} = 0.3v_\pi$



$v_{pp} = 0.45v_\pi$



$v_{pp} = 0.6v_\pi$

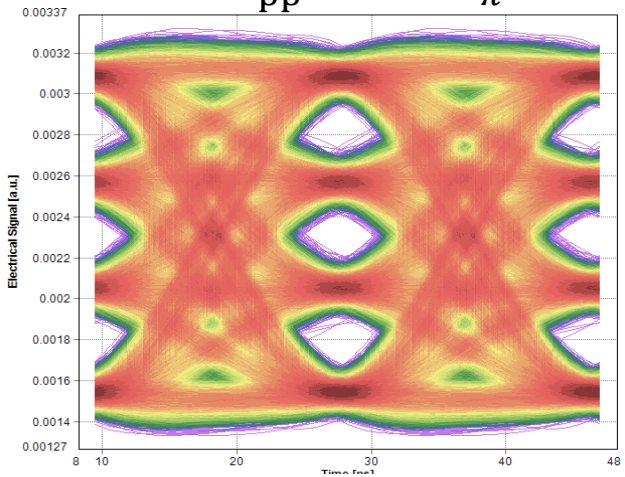


- At high drive voltage (to achieve high OMA), SiP-based MZM suffers from nonlinear distortion of the MZM transfer function.

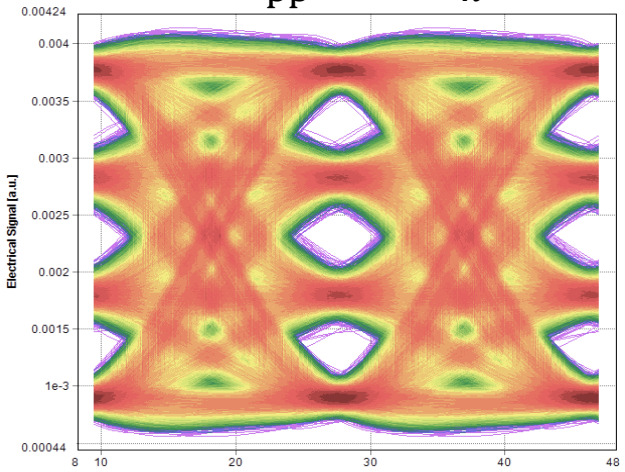
Our simulation results (2): Received eyes after EQ at OMAouter=3.5dBm

SiP (MZM)

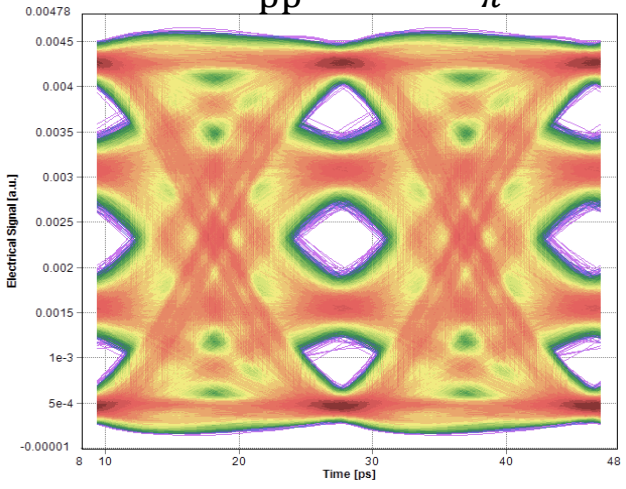
$v_{pp} = 0.15v_\pi$



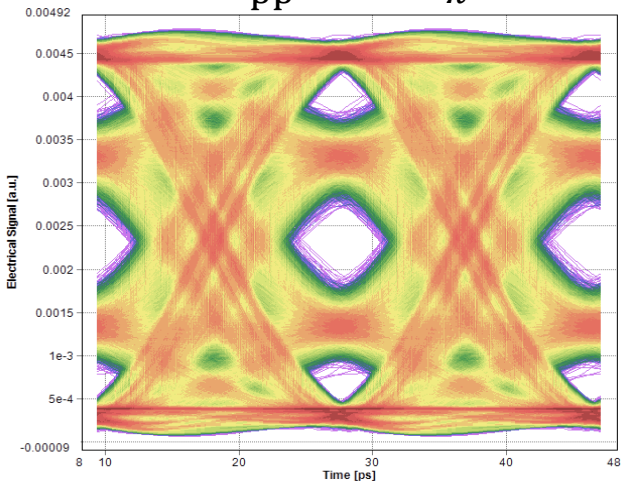
$v_{pp} = 0.3v_\pi$



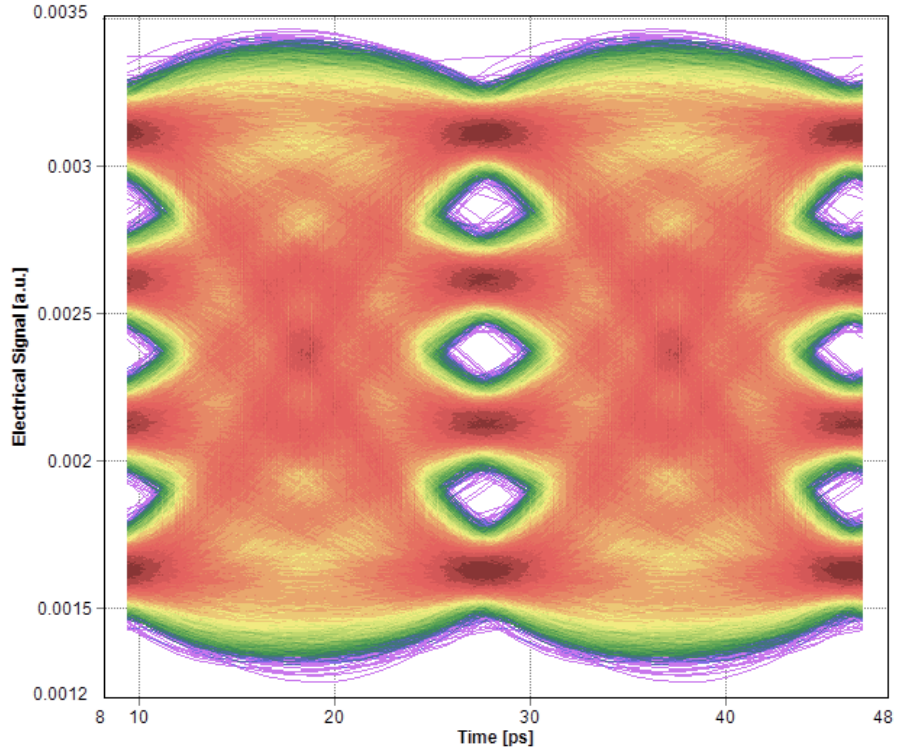
$v_{pp} = 0.45v_\pi$



$v_{pp} = 0.6v_\pi$



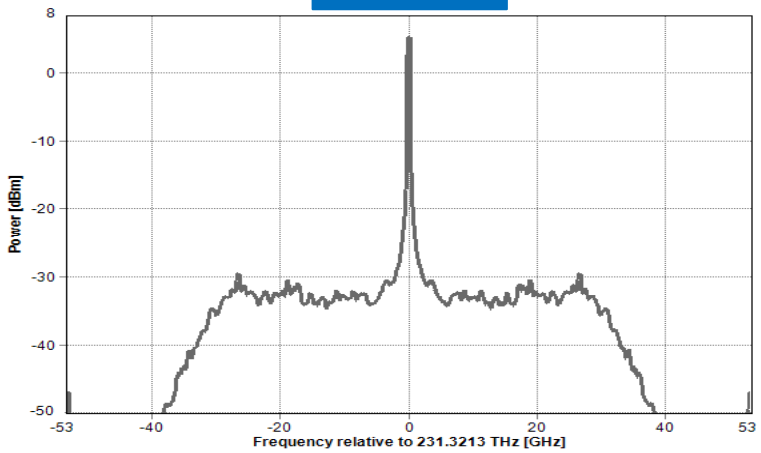
EML



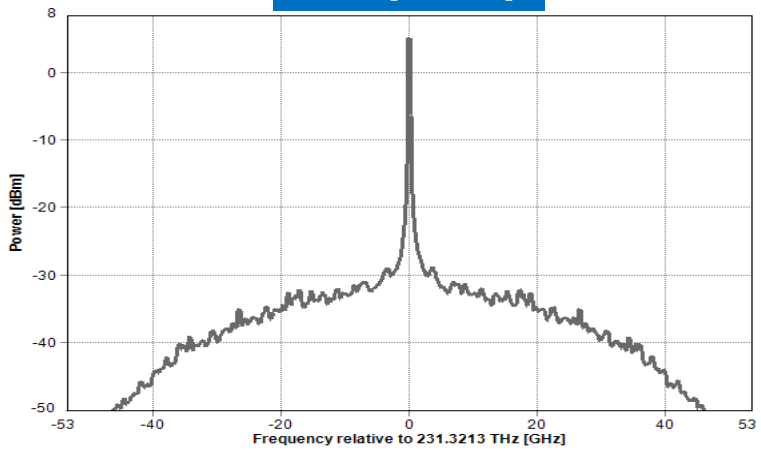
- EML has a moderate overshoot (~12%) and some rare ISI instances, which cause a higher error floor and degrade TDECQ more at low SER.

Our simulation results (3): EQ-induced noise enhancement

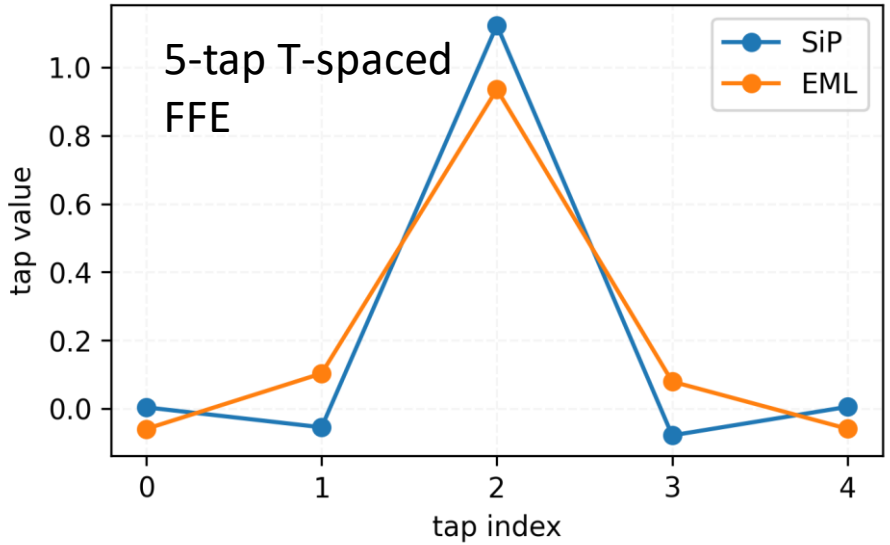
EML

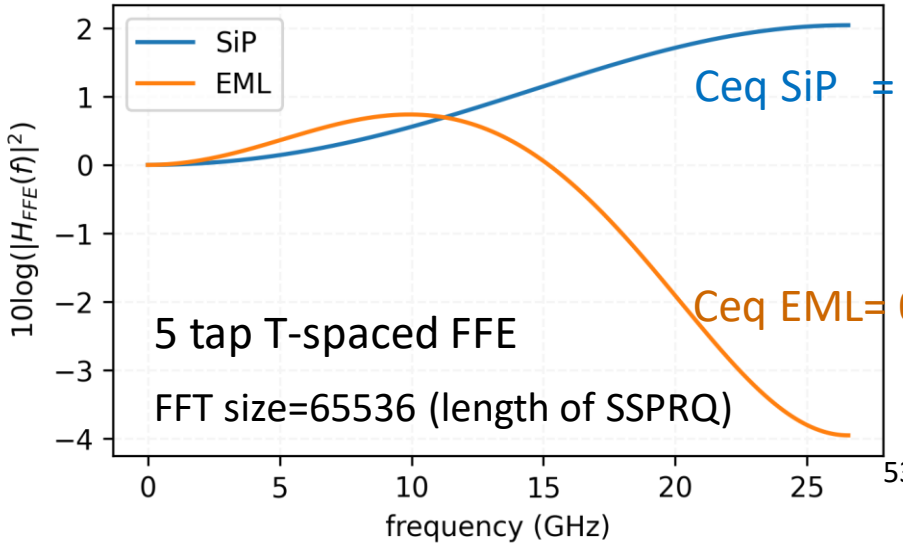


SiP (MZM)



FFE





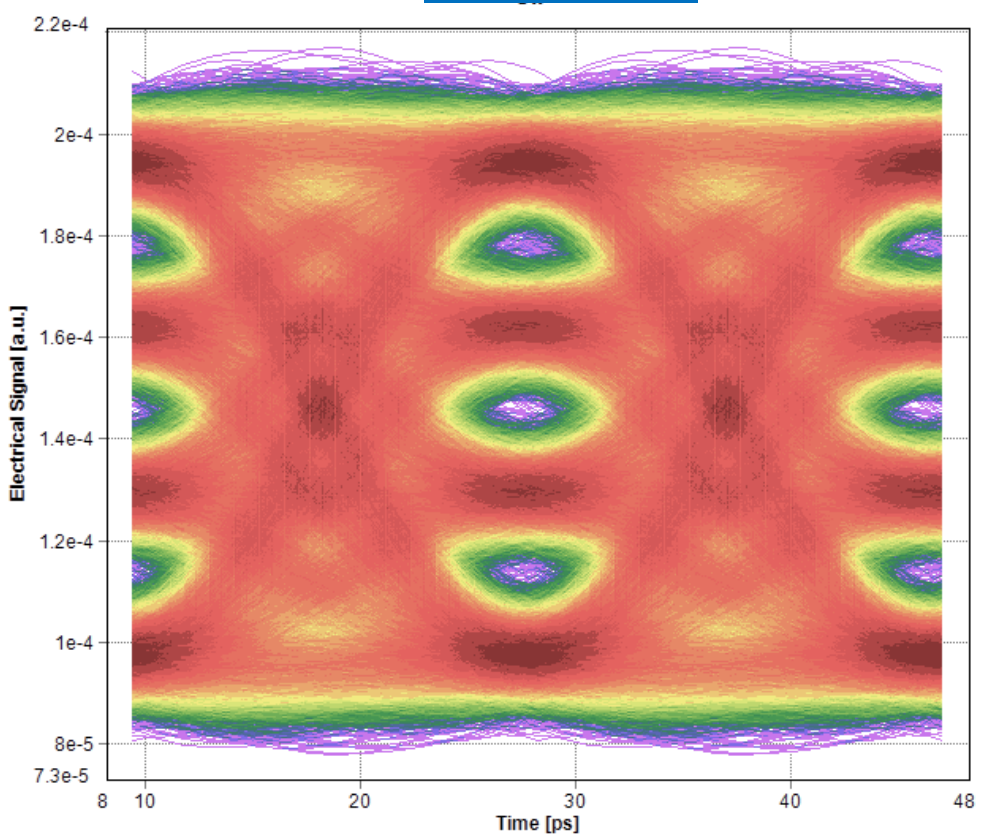
Ceq SiP = 1.109 (**0.45** dB)

Ceq EML= 0.972 (**-0.12** dB)

53.125/2 GHz

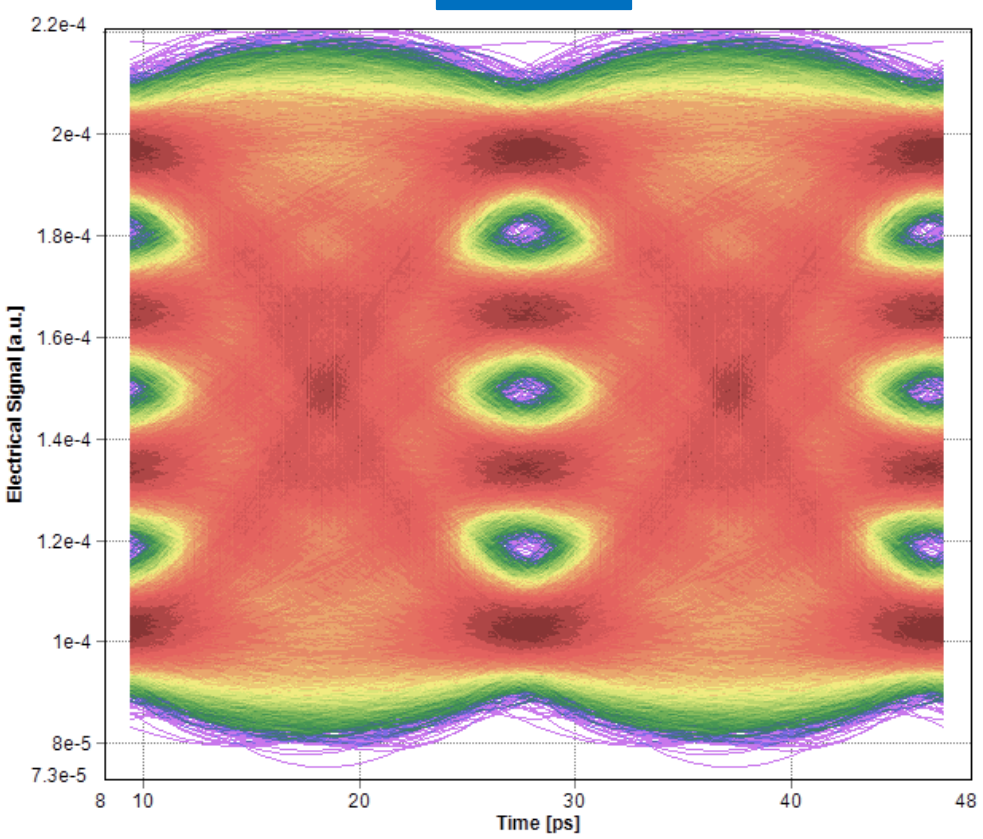
Our simulation results (4): Received eyes after EQ at OMAouter=-8.6dBm

SiP (MZM)



SER=0.00037

EML

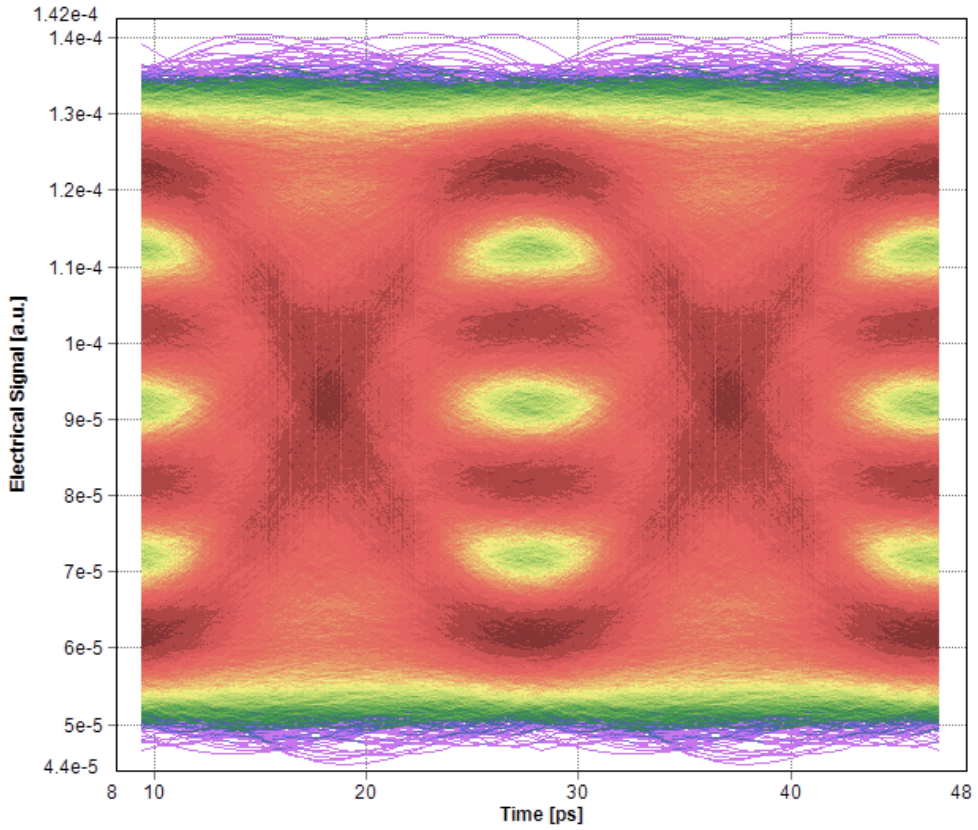


SER=0.00046

❖ At low SER, SiP (MZM) performs better.

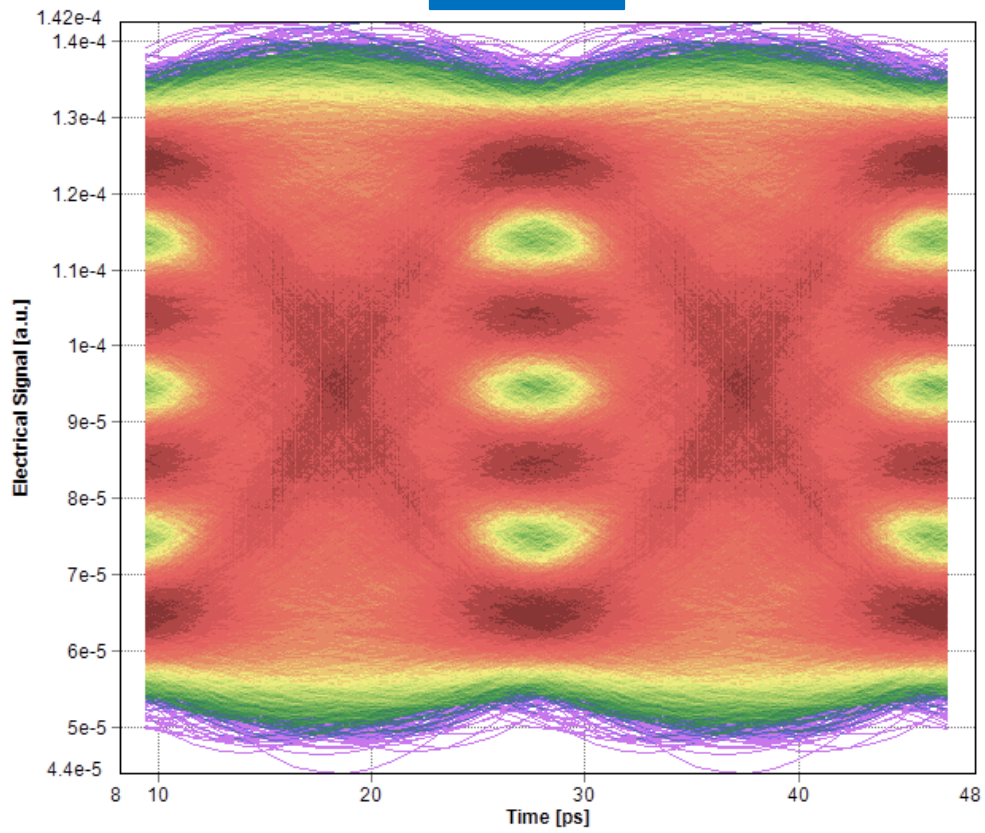
Our simulation results (5): Received eyes after EQ at OMAouter=-10.6dBm

SiP (MZM)



SER=0.0097

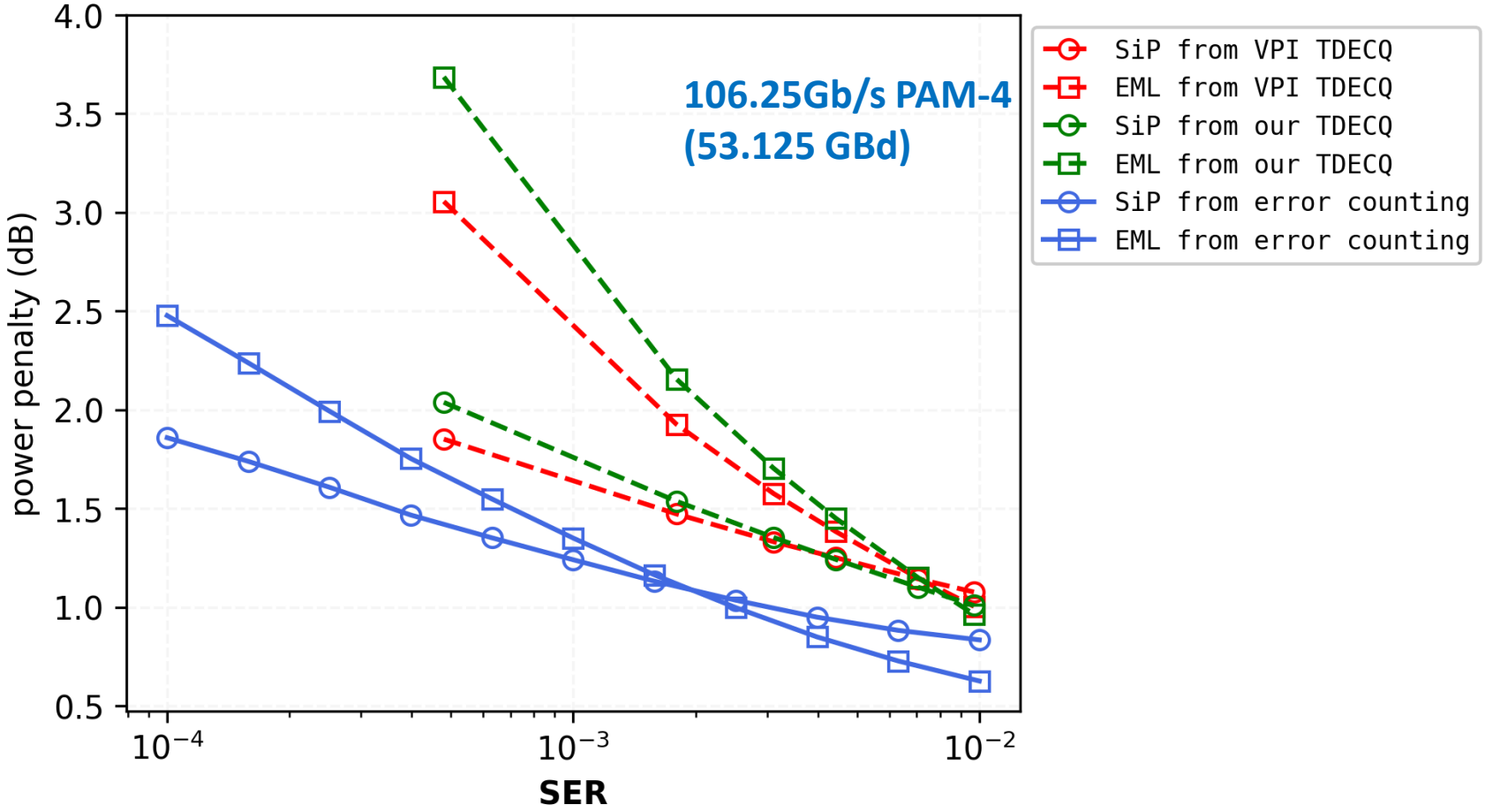
EML



SER=0.0068

❖ At high SER, SiP (MZM) suffers more due to EQ-induced noise enhancement.

Our simulation results (6): TDECQ vs. direct-error-counting



- ✓ At high SER, TDECQ penalty still represents the receiver sensitivity penalty observed.
- ✓ A “worse” transmitter at low SER can become a “better” transmitter at high SER.
- ✓ The physical reason is because of different nonlinear distortion, ISI, and EQ-induced noise enhancement behaviors of these two types of transmitters.

Our simulation results (7): TDECQ at different SER

	MZM $V_{pp} = 0.45V_\pi$	MZM $V_{pp} = 0.50V_\pi$	EML
$\mathbf{OMA_{outer}}$ (dBm)	6.82	6.98	6.80
$\mathbf{TDECQ@4.8 \times 10^{-4}}$ (dB)	2.49	2.99	3.69
$\mathbf{TDECQ@1 \times 10^{-2}}$ (dB)	1.17	1.36	0.96
$\mathbf{OMA_{outer} - TDECQ@4.8 \times 10^{-4}}$	4.33	3.99	3.11
$\mathbf{OMA_{outer} - TDECQ@1 \times 10^{-2}}$	5.65	5.62	5.84

Note: Based on common practices in our industry, MZM is driven at $\sim \mathbf{0.45}V_\pi$, without overshooting, while EML is driven with a moderate overshooting (of up to 22%).

- ✓ At high SER, TDECQ penalty still represents the receiver sensitivity penalty observed.
- ✓ A "worse" transmitter at low SER can become a "better" transmitter at high SER.
- ✓ The physical reason is because of different nonlinear distortion, ISI, and EQ-induced noise enhancement behaviors of these two types of transmitters.

Discussion & Conclusion

1) Key question: Does this convergence represent behavior in real systems? >> Yes.
   - Does the TDECQ penalty represent the receiver sensitivity penalty observed at a high SER? >> Yes.
   - Would two transmitters that have different TDECQ at low SER, but similar TDECQ at high SER yield similar receiver sensitivities observed at the high SER?

   >> Yes, and could even be reversed (in performance comparison).

2) This is early work and requires further analysis and physical verification

   >> Based on our analysis, some physical explanations have been provided.

We have shown that the dependence of TDECQ on symbol error rate (SER) is different for different optical transmitter types, and a "worse" transmitter at low SER can become a "better" transmitter at high SER. Some physical explanations are also provided. Overall, TDECQ is expected to continue to be a viable performance metric for PAM4 at high SER.

Thank you!