

Feasibility Study on Baud-Rate Sampling and Equalization (BRSE) for 800G-LR1

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Supporters

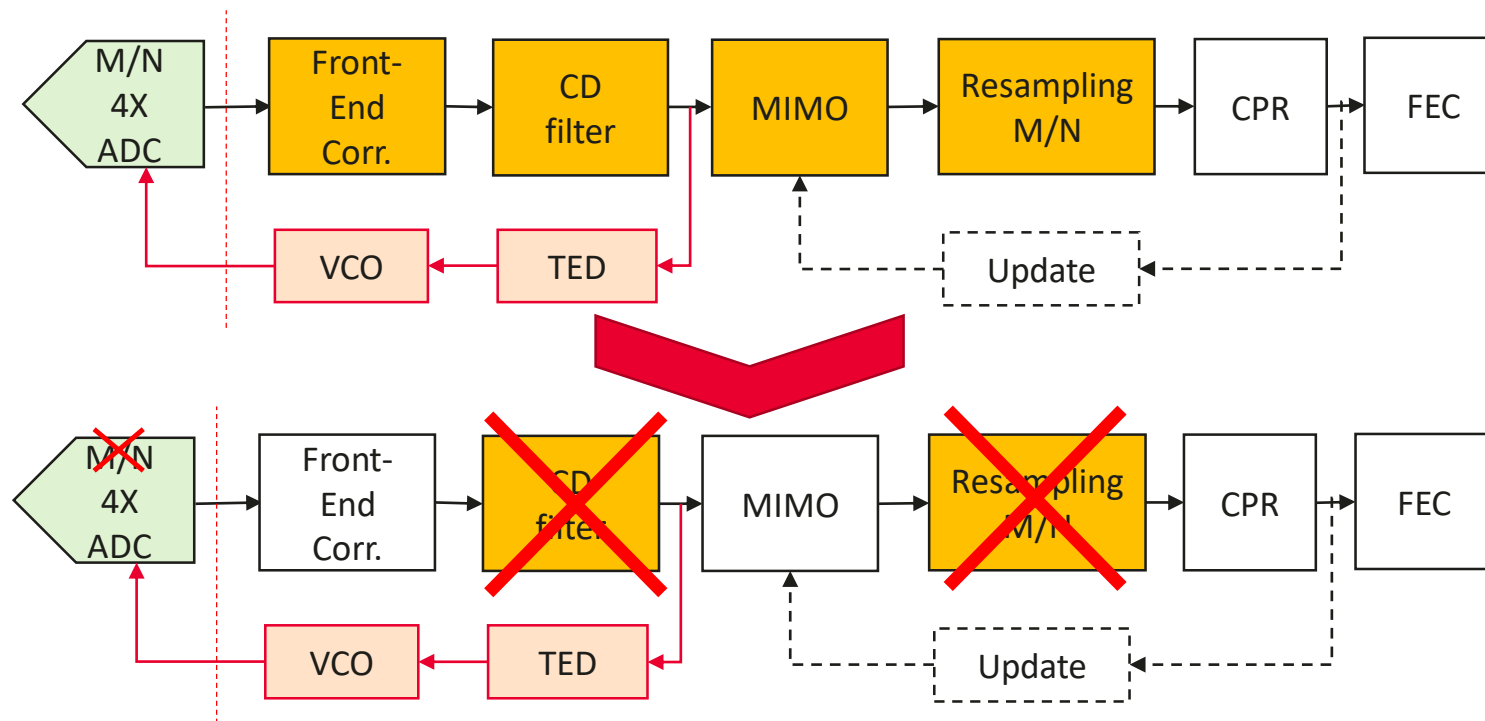
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Power saving for 800LR1

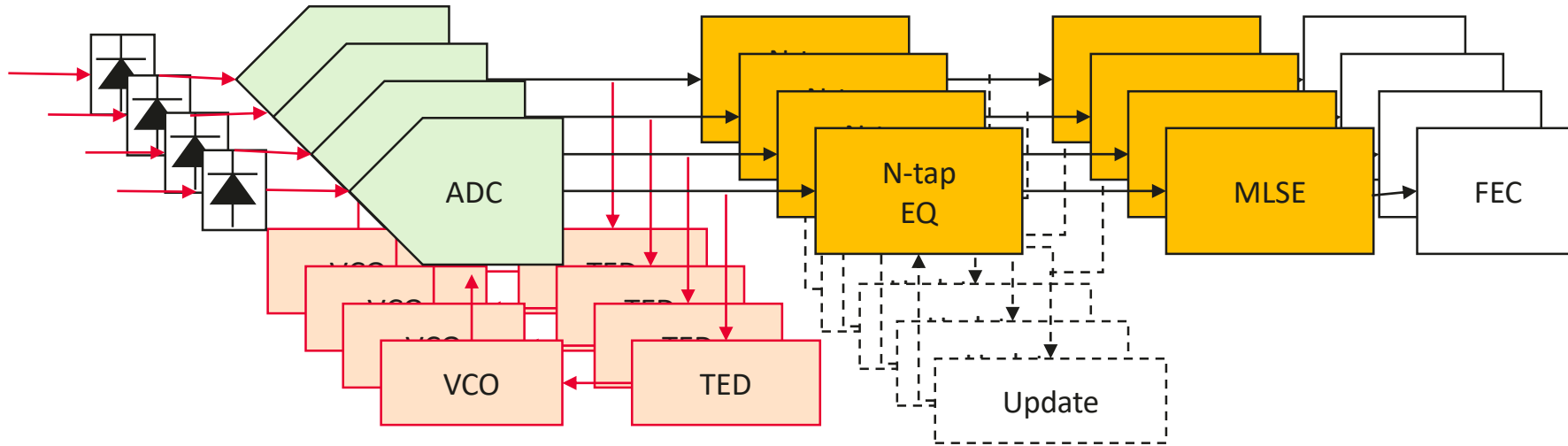
- ADC/DAC and equalization account for a large proportion of power consumption of coherent receiver ASIC [1]
- A O-Band with baud-rate sampling ADC/DAC and DSP will be a good candidate to significantly reduce the DSP power
- In this contribution, we conducted an initial feasibility study of BRSE-based 800G-LR1



TED: timing error detection; CPR: carrier phase recovery; VCO: Voltage controlled oscillator

[1] Presenter: Hongbin Zhang, Cisco Systems Inc, United States "Power Efficient Coherent Detection for Short-Reach System", OFC 2023, invited talk: M1E.1

BRSE has been used in IMDD receivers [2]



- Independent clock tracking digital timing recovery (TR) loop for each lane with low enough latency.
- Analog based clock recovery schemes with sample at the center of each signal pulse (eye open)

[2] R. Nagarajan, I. Lyubomirsky and O. Agazzi, "Low Power DSP-Based Transceivers for Data Center Optical Fiber Communications (Invited Tutorial)," in *Journal of Lightwave Technology*, vol. 39, no. 16, pp. 5221-5231, Aug.15, 2021.

Why BRSE hasn't been used in coherent yet

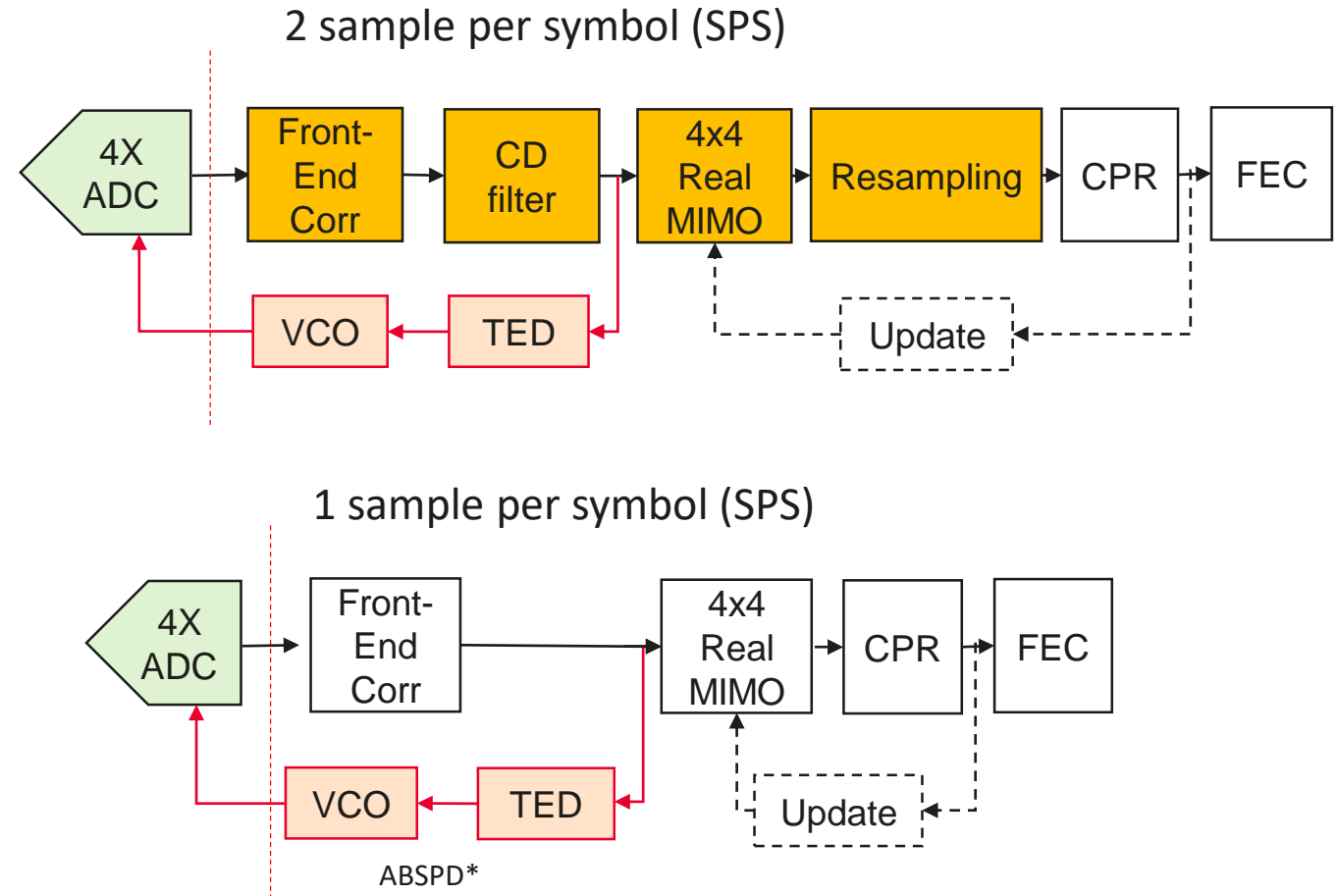
- BRSE is **sensitive to ADC sampling phase**, that results:
 - **Firstly, the timing recovery (TR) is more risk to a distorted coherent receiver**
 - The incoming signal is temporally varying due to LOFO, SOP, and so on. The analog TR with eye open cannot work.
 - The digital TR before the MIMO may fail due to the strong inter-symbol-interference (ISI) caused by CD and PMD .
 - **However, the ISI is much smaller for 800LR (especially in O band), timing error detection (TED) methods have the chance to work**
 - **Secondly, the BRSE technique is sensitive to delays or skews between the XY and IQ**
 - Coherent receiver ADCs are challenge to sample at the center of each signal pulse (with delays or skews between the XY and IQ)
 - The skews cannot be compensated by traditional coherent DSP with interpolation based digital methods under baud-rate sampling.
 - **However, a real-value 4X4 MIMO can enhance the tolerance to the skews, while implementation complexity can be simplified when the fiber CD is negligible.**
 - **What's more, the required timing delay for each of four ADC clocks could be individually or jointly optimized [3]**
 - **Thirdly, it is has a limited tolerance to fiber CD and PMD**
 - Traditional coherent is for metro and long-haul transmission in the C-band, where CD and PMD can be too high for BRSE.
 - **However, for 800LR the fiber CD and PMD are much smaller**

[3] X. Zhou, R. Urata and H. Liu, "Beyond 1 Tb/s Intra-Data Center Interconnect Technology: IM-DD OR Coherent?," in *Journal of Lightwave Technology*, vol. 38, no. 2, pp. 475-484, Jan. 15, 2020.

Simulation for BRSE

- Simulation model and DSP flow

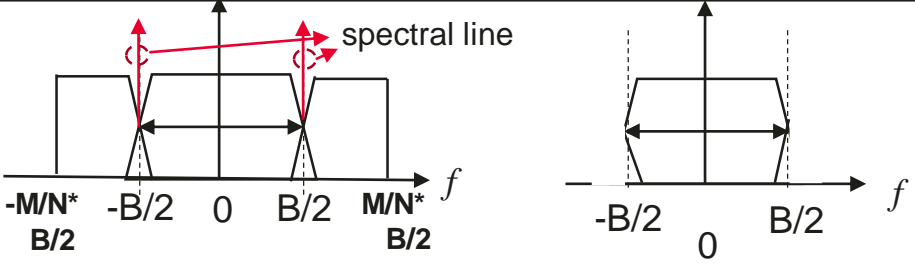
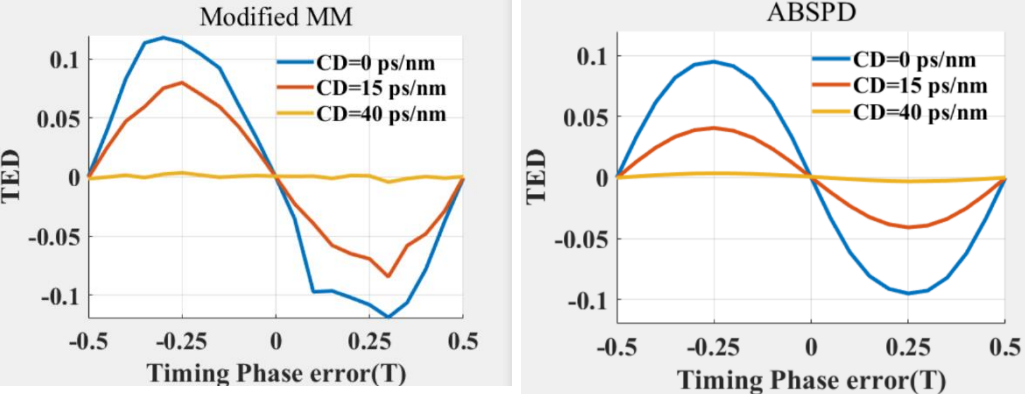
Simulation Parameters	value
Baud-Rate	123.6GBaud
Modulation format	16QAM
FEC threshold	1.1e-2 (Based on KP4+BCH)



TED: timing error detection; TD-MIMO: time domain MIMO; CPR: carrier phase recovery; ABSPD: abs timing phase detector [4]

[4] N. Stojanovic, T. Rahman, S. Calabrò, J. Wei and C. Xie, "Baud-Rate Timing Phase Detector for Systems with Severe Bandwidth Limitations," 2020 OFC, paper M4J.5.

CD tolerance to TR of ADC under Baud-Rate Sampling

TED Algorithm Example	Note	
<p>Gardner/Godard [5]</p>	<ul style="list-style-type: none"> Normally used, can suffer uncompensated CD and PMD Cannot work under baud-rate sampling (without distinct spectral line at the baud-rate) 	
<p>4th power-based PD[6] ABSPD [4] Sign MM [7]</p>	<ul style="list-style-type: none"> Can deal with small Roll-off Factor values without distinct spectral line But sensitive to the CD and PMD Expected CD tolerance smaller than <u>40ps/nm</u> 	 <p>Example: S curves under different CD</p>

[5] F.M. Gardner, "A BPSK/QPSK Timing Error Detector for Sampled Receivers", IEEE Trans. Comm., vol. 34, pp.423-429, May 1986.

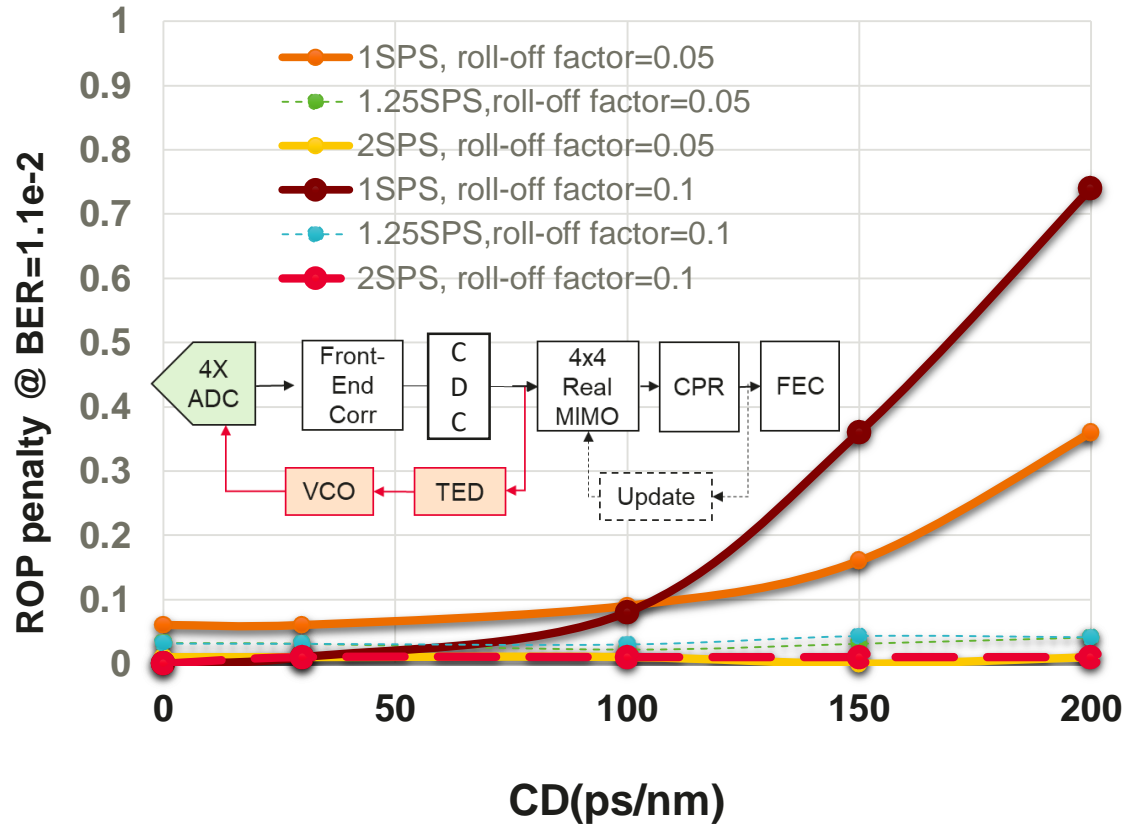
[6] T. T. Fang and C. F. Liu, "Fourth-power law clock recovery with prefiltering", in Proc. ICC, Geneva, Swiss, May 1993, vol. 2, pp. 811-815.

[7] A. Gorshtein, D. Sadot, and G. Dorman. "MIMO equalization optimized for baud rate clock recovery in coherent 112 Gbit/sec DP-QPSK metro systems." Optical Fiber Technology 22 (2015): 23-27

CD Influence to Baud-Rate Sampling Equalizer

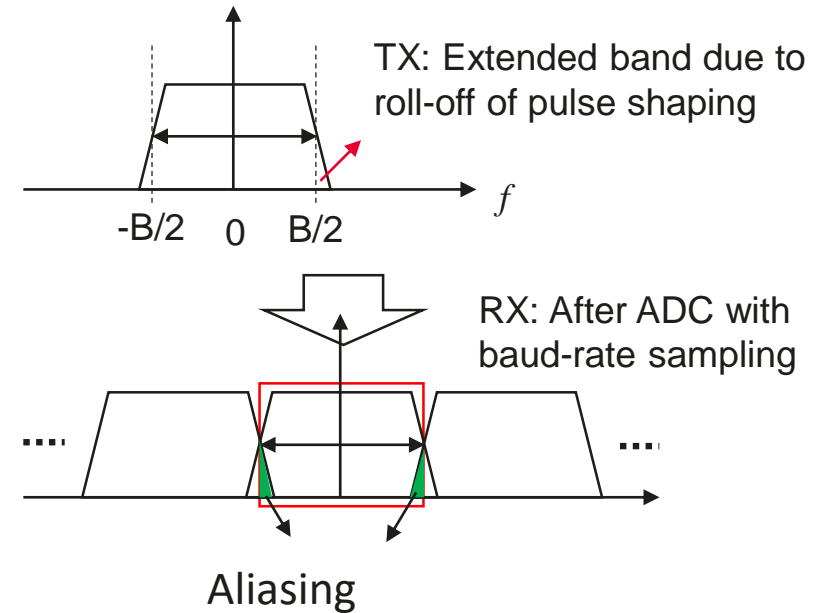
- The CD tolerance can be improved to >150 ps/nm.

Note: An extra CD compensation before TR has done for those cases



- Why CD brings extra penalty to BRSE?

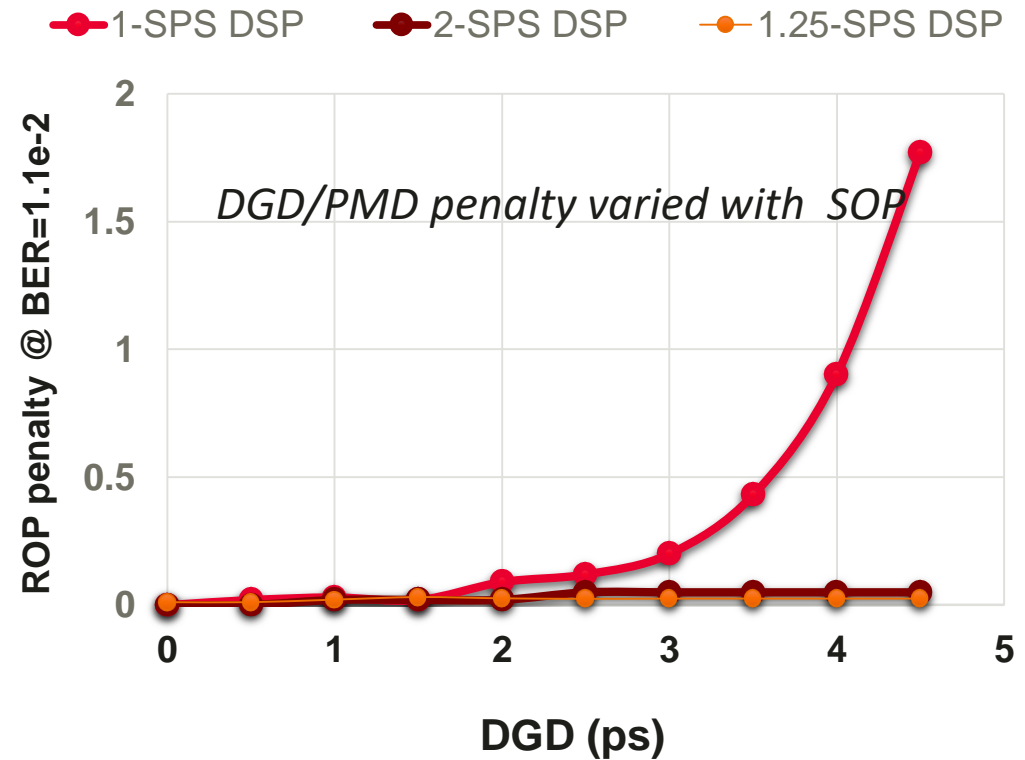
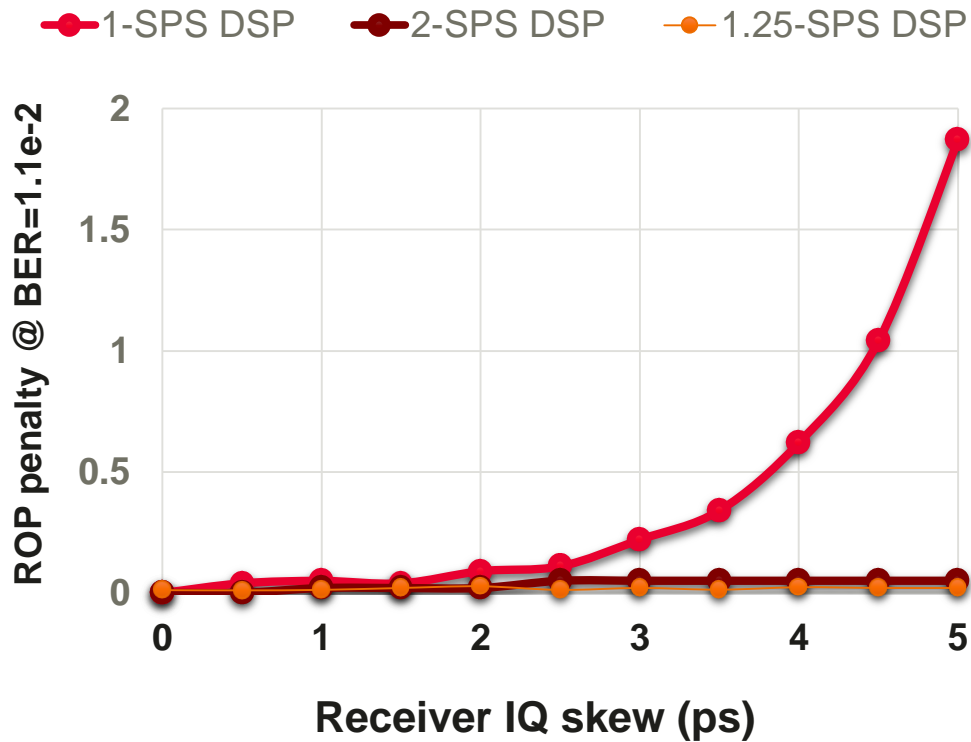
- Out-of-band spectral components are mixed in-band under baud-rate sampling, causing colored noise
- The effect of aliasing could be enhanced by CD [9,10]



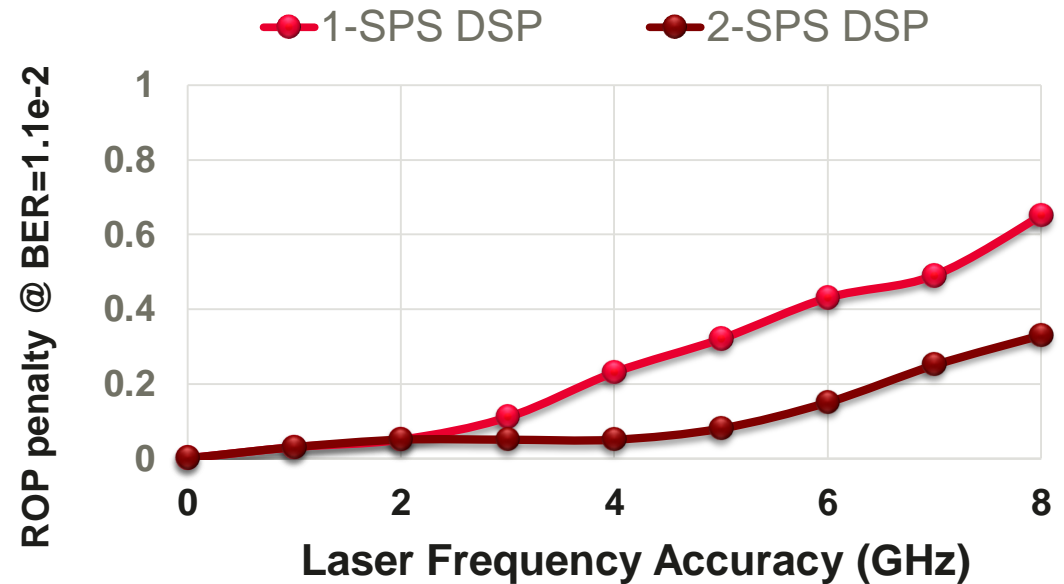
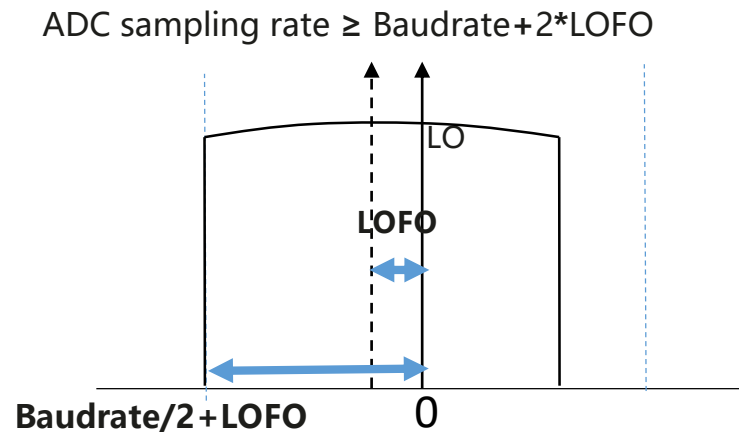
[8] D. S. Millar, D. Lavery, R. Maher, B. C. Thomsen, P. Bayvel and S. J. Savory, "A baud-rate sampled coherent transceiver with digital pulse shaping and interpolation," in OFC 2013, paper OTu21.2.
 [9] Q. Xiang, Y. Yang, T. Zuo, Q. Zhang, T. Zhang, S. Zhang, L. Liu, and Y. Yao, "Hardware Efficient and Chromatic Dispersion Tolerant Symbol-Rate Equalization Scheme for Short-Reach Coherent Transmission System," J. Lightwave Technol. 40, 5450-5456 (2022)

Improve Tolerance to IQ Skew and PMD

- Normal 2x2MIMO cannot work with Skew >1 ps.
- DGD/PMD distortion may one of the top problems of BRSE, and four ADC clocks with individually optimizing may help to future increase the tolerance.
- A real-value 4X4 MIMO, can enhance the tolerance to both IQ skew and DGD (to 3 ps).



Performance Degradation of BRSE due to LOFO



- BRSE is relatively sensitive to local oscillator frequency offset (LOFO), with ~ 3 GHz tolerance.
- Thus, the LOFO should have a proper constraint.

Summary

- We have conducted an initial feasibility study on the use of **baud-rate sampling and equalization (BRSE)** to achieve **low power consumption** in 800G-LR1.
- The simulation results show that **BRSE is feasible to achieve for 800G-LR1 (123GBd DP16QAM) without a CDC module**
 - Non-decision aided TR is expected to tolerate $<40\text{ps/nm}$ dispersion.
 - The 4x4 MIMO based Baud rate equalizer is expected to tolerate, 3.5ps IQ skew, 3.5ps DGD, and $\pm 3\text{GHz}$ Laser frequency accuracy, respectively.
- With a CDC module prior to TR, **$>150\text{ps/nm}$ CD can be tolerated.**
- Due to its multiple benefits, **BRSE is a promising coherent-lite approach** for further evaluation, especially for **O-band 800G-LR1 (even for O-band 800G-ER1).**

Thank you!