Multi-path Interference Detection for Intra-DC Links.

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Network Hardware Optics,
Meta

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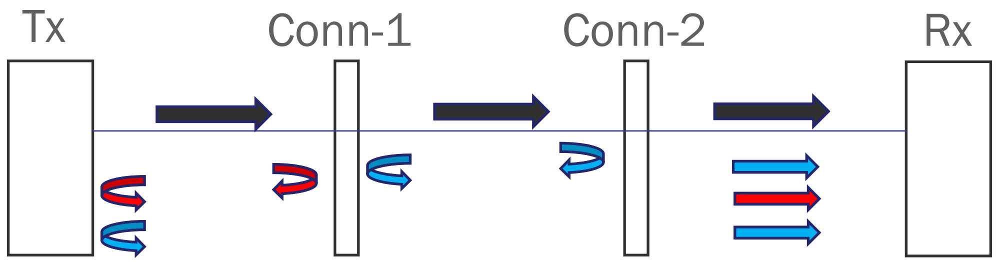
Outline

- Motivation
- Mathematical Model
- Effects on Histograms
- Detection Method
- Conclusions

Multi-path Interference

- Reflections from multiple sources coming back into the Rx



- Two or more non-ideal connectors can lead to light bouncing back-and-forth
  - Could be caused by dirt or improper connections
- For N connectors, N(N-1)/2 reflections to first order

Multi-path Interference

- Polarization alignment
- High Power penalties
- Higher order modulation formats suffer more

- Worst case: Polarization alignment between signal and reflections
- Interference (beating) with the signal leads to amplification of the impairment
- Induced power penalties rise ~exponentially with reflected optical power
- Effects become much worse going from NRZ to PAM4 and higher modulation formats
  - SNR hit is larger for multi-level formats

Detection/Cancellation

- Detection is foremost, cancellation is a bonus
- Preferred method should work in mission mode and build upon existing DSP diagnostic capabilities

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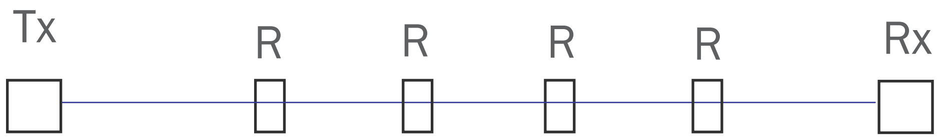
- Symptoms not visible in Tx/Rx optical powers
- SNR does not provide a unique signature
- Triaging a circuit with MPI is challenging
- For intra-DC applications, no MPI cancellation or detection exists as of present
  - Proposed cancellation schemes can mitigate MPI, however, detection is still required when mitigation is insufficient
- From a network service point of view, need a robust mechanism to ***detect*** MPI and prevent misdiagnosis

Effective MPI Level

- For an improper connection or one with dust, MPI can easily go as high as -35 — -30 dB



$$\mathrm{MPI} = 10\log_{10}\left(\sum_{i=1}^{M}\sum_{j=i+1}^{M} R_i R_j\right)$$

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Power Penalty (PP)

- MPI value = reflected power/signal power
- ER has a significant impact on power penalties

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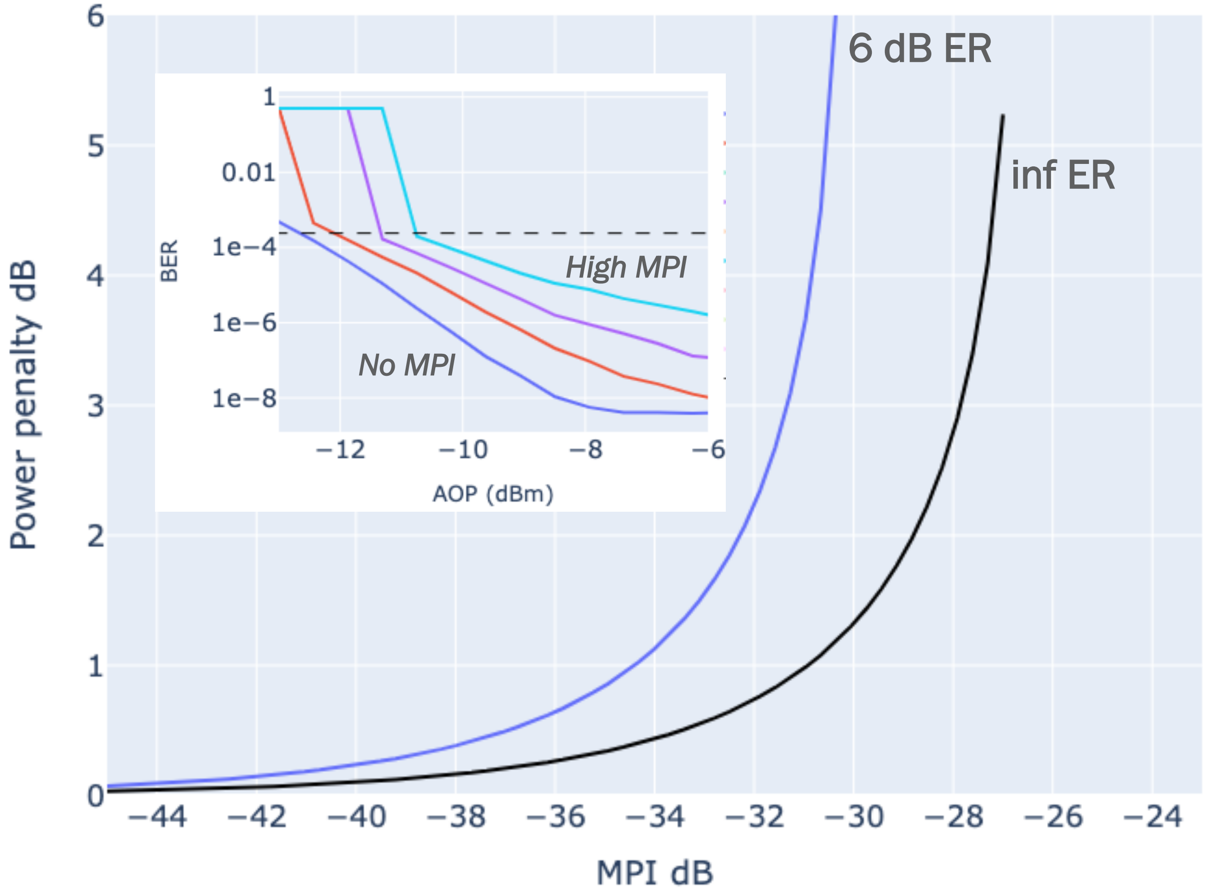


- Rx sens. at KP4 FEC level 2.4e-4
- PP: How much the sens. suffers because of MPI
- Lower ERs suffer from higher penalties

Inf. ER:

$$PP = -5\log_{10}(1 - 36\rho^2 Q^2) \quad \text{dB},$$
$$Q = 3.56 \text{ for BER} = 2.4\text{e} - 4$$

Model

- Reflected optical field comes back into Rx with a delay

$$E_{\mathrm{Rx}}(t) = E_{sig}(t)e^{i\omega_0 t}e^{i\phi(t)} + \rho E_{sig}(t-\tau)e^{i\omega_0(t-\tau)}e^{i\phi(t-\tau)}$$

$$\mathrm{MPI} : \rho^2$$

- After PD:

AWGN

$$i(t) \sim P_{sig}(t) + \rho^2 P_{sig}(t-\tau) + 2\rho\sqrt{P_{sig}(t)}\sqrt{P_{sig}(t-\tau)}\cos[\omega_0\tau + \phi(t) - \phi(t-\tau)] + n(t)$$

$$\boldsymbol{i(t) \sim P_{sig}(t) + m(t) + n(t)}$$

$$m(t) = 2\rho\sqrt{P_{sig}(t)}\sqrt{P_{sig}(t-\tau)}\cos[\omega_0\tau + \phi(t) - \phi(t-\tau)]$$

MPI term

Important Considerations

- Coherence time of laser sets a reference delay time
- MPI deals with the 'incoherent' case

- Time delay τ is larger than the coherence time of laser
- Phase fluctuations within the cosine term vary randomly: effectively treat MPI as gaussian noise
- Laser linewidth ~ 1 MHz

$$\tau_c \sim 1\ \mu s \quad \rightarrow l_c = 3e8/1.4 * \tau_c$$
$$\rightarrow l_c \sim 200\ m$$

- Incoherent interference: Roundtrip delay (distance) for MPI > ~100m

P. Legg et al, JLT, VOL. 14, NO. 9, SEPTEMBER 1996

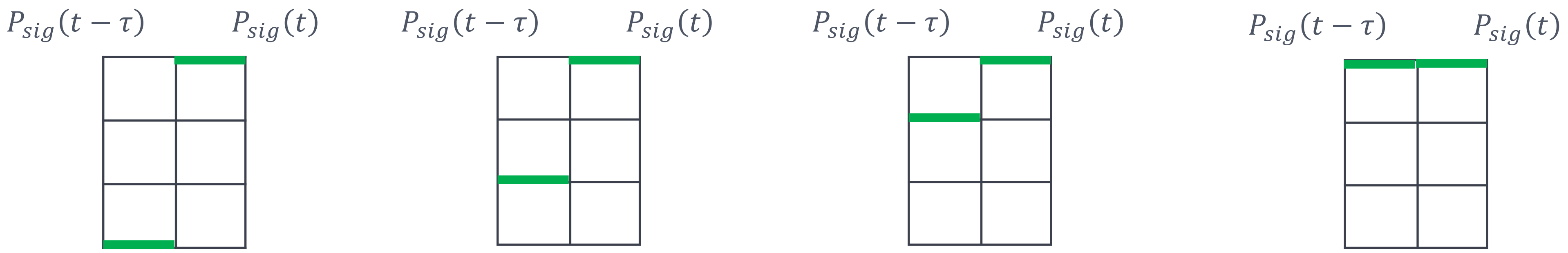
MPI: Level Dependent Noise

$$m(t) = 2\rho\sqrt{P_{sig}(t)}\sqrt{P_{sig}(t-\tau)}\cos[\Psi(t)]$$

- Considering PAM-4 signaling, we can separately analyze this for each of the four ideal signal levels:

$$\mu_l = \langle m_l(t)\rangle = 2\rho\left\langle\sqrt{P_{sig}(t)}\right\rangle_l\left\langle\sqrt{P_{sig}(t-\tau)}\right\rangle_l\langle\cos[\Psi(t)]\rangle \;\rightarrow 0$$

$$\sigma_l^2 = \langle m_l^2(t)\rangle = 4\rho^2\,\langle P_{sig}(t)\rangle_l\,\langle P_{sig}(t-\tau)\rangle_l\,\langle\cos^2[\Psi(t)]\rangle$$



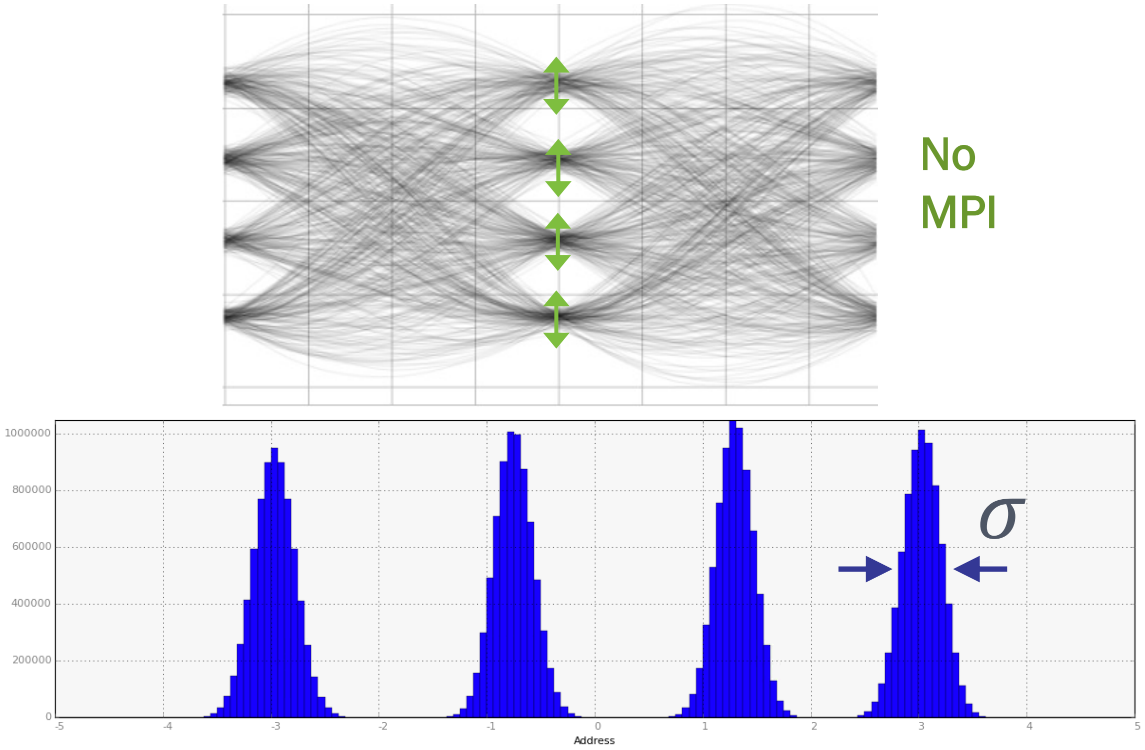
$$\sigma_l^2 = 2\rho^2 P_l P_{avg}$$

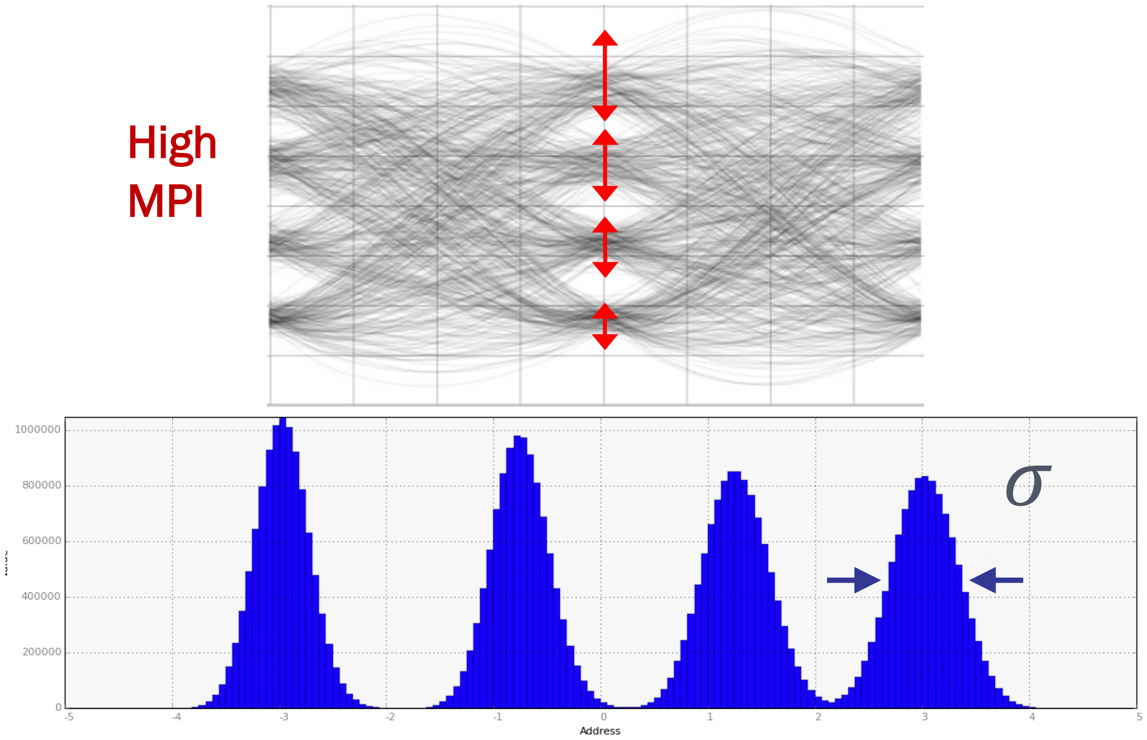
- **Variance of each PAM level is proportional to its optical power level**

ρ^2	:	MPI
τ	:	Time Delay Between Signal and Reflection
μ_l	:	Mean of Noise at l_{th} PAM Level
σ_l^2		Variance of Noise at l_{th} PAM Level
P_l	:	Optical Power of l_{th} PAM Level
P_{avg}	:	Average Optical Power of Signal

PAM-4 Histograms

- Histograms captured before the slicer in the DSP Equalizer
- Upper eyes are more closed





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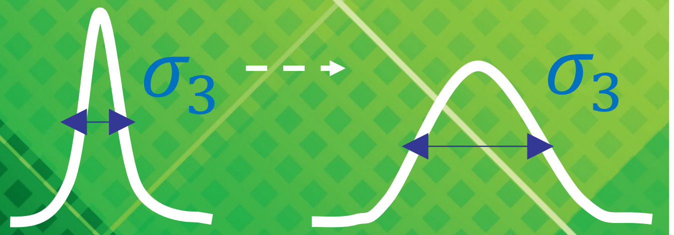
- Case for a new MPI detection method
- Leverage existing capabilities of the DSP



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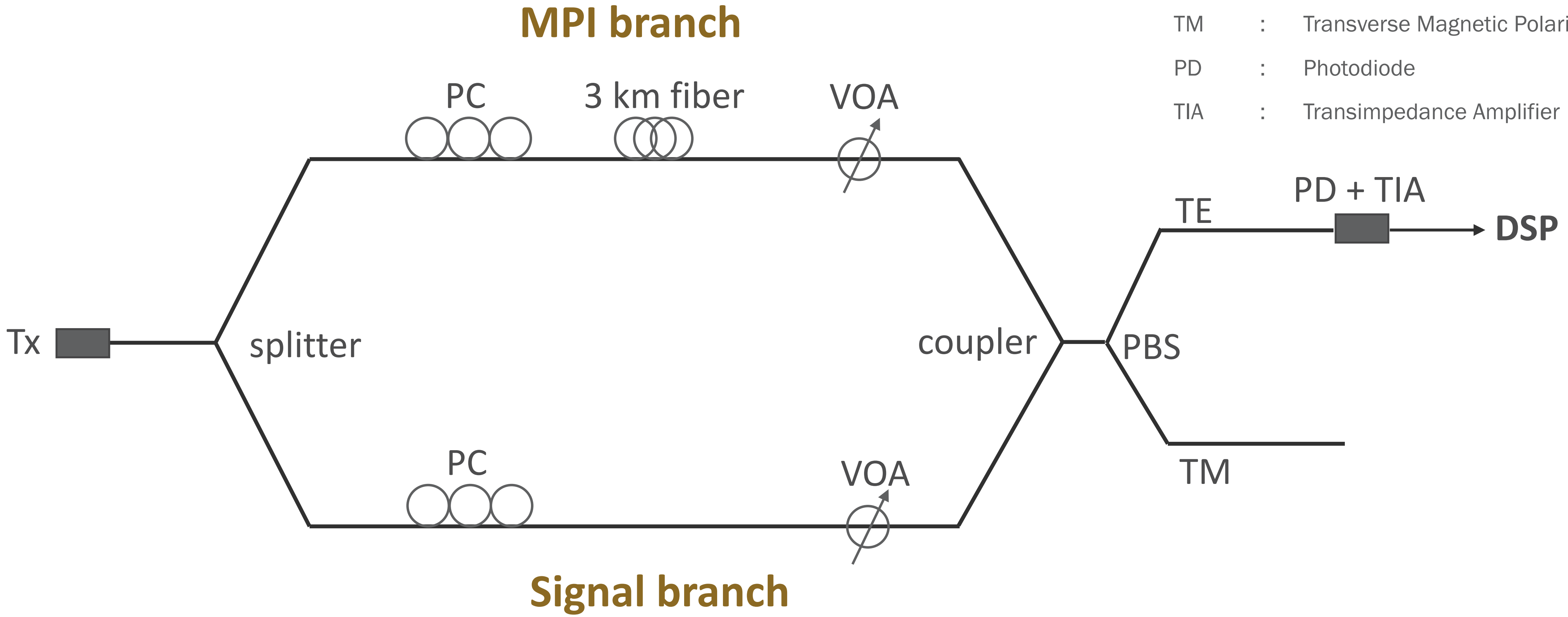
Histogram based MPI detection

- MPI leaves a unique signature on the statistics of PAM levels at the Rx
- Most ISI is mitigated by the Equalizer
  - Histograms are clean
- RIN and FWM have similar effects:
  - Assume Tx is within RIN spec
  - FWM has a much lower probability
- Method:
  - Set standard deviation (SD) of level 0 (σ_0) as baseline
  - Compare SD of level 3 (σ_3) with reference
  - For ratios beyond a certain threshold, raise a flag
- **Works in mission mode, diagnostics can be easily supported in the DSP and defined in CMIS**

Experimental setup

PC : Polarization Controller
VOA : Variable Optical Attenuator
PBS : Polarization Beam Splitter
TE : Transverse Electric Polarization
TM : Transverse Magnetic Polarization
PD : Photodiode
TIA : Transimpedance Amplifier



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- Principle holds over a wide optical power range, covering usual optical Rx power levels in DC

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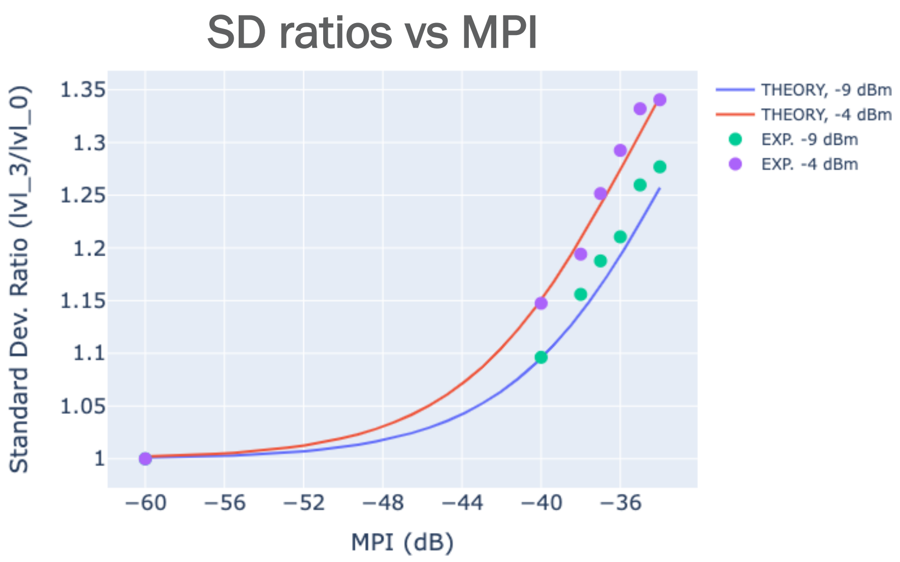
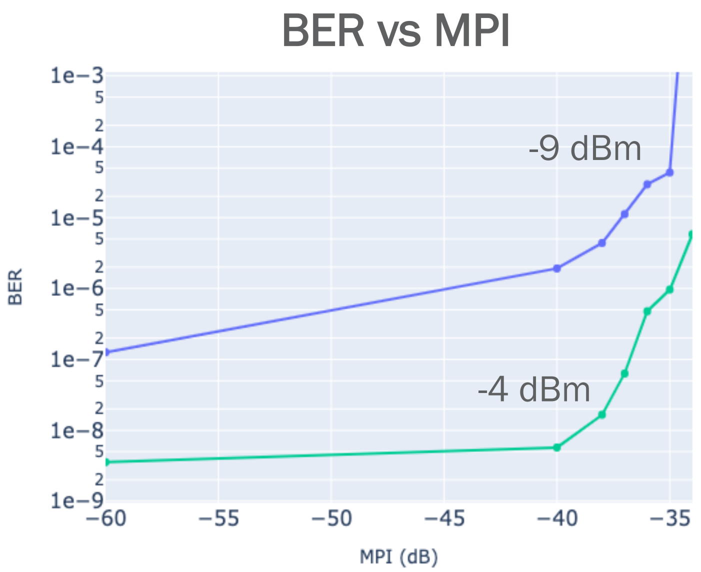
Results

- Data (σ_3/σ_0) collected for various input power levels, as low as -9 dBm
- BER jumps by more than a decade when SD ratio reaches ~1.2
- Threshold could be chosen around this value
- As soon as σ_3/σ_0>1.2: raise a flag for high MPI





Summary

- MPI can cause significant power penalties for PAM-4 intra-DC links
- For efficient link triaging, need a reliable method to detect a high value of MPI
- MPI has a unique effect on histograms before the slicer
- Use ratios of variances of PAM levels to raise a flag for MPI
- Proposed scheme works in mission mode and over wide optical powers