Modeling MPI penalty and its implication for next generation PAMx systems

Huijian ZHANG

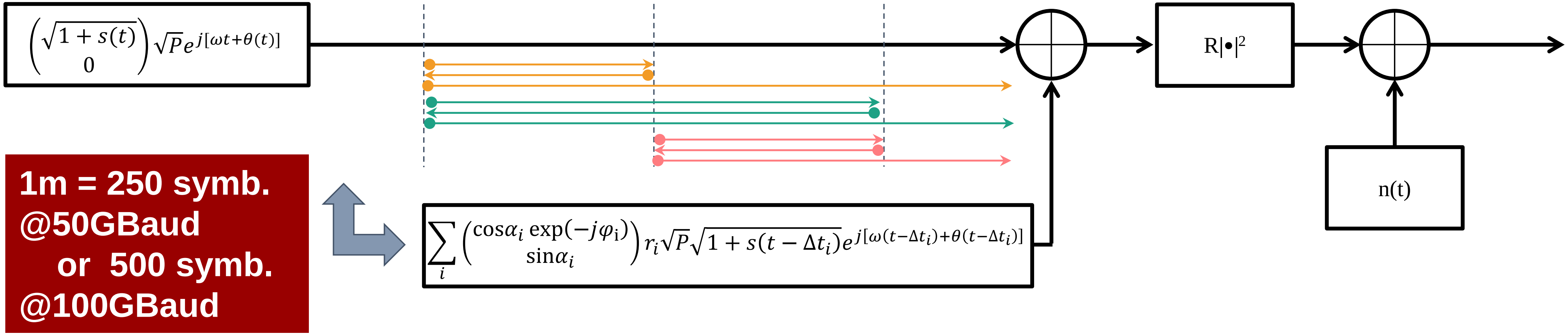
Hisilicon Optoelectronics

www.o.hisilicon.com/oe

Introduction

- Multiple path interference (MPI) has been under discussion since the emergence of optical PAM4, although its impact on NRZ signaling was studied much earlier in academia.
- Previous discussions were mainly focusing on the link engineering, such as link model, MPI statistics, link budget calculation etc.
- This contribution provides an analytical model which links MPI penalty (or tolerance) with signal characteristics: modulation formats, ER, BER floor, FEC and state of polarization.
- The model can be used as a quick reference for MPI penalty or MPI tolerance calculation.
- We will also get some implications for the next generation PAMx systems from this model.

MPI model



- s(t) is a PAMx signal with Vpp≤2 and zero mean. ω and θ are the carrier frequency and phase noise respectively.
- When the number of interfering path is large enough, MPI noise approaches circular Gaussian distribution.
- The MPI strength (dB) is defined as $10\lg(\Sigma r_i^2)$
- α_i and φ_i determine the state of polarization (SOP) of the corresponding MPI signal
- R is the responsivity of the photodiode.
- n(t) is the Gaussian distributed electrical noise.

Sensitivity penalty

- Following the same Gaussian noise approximation, we obtain similar penalty as in [1]

$$\Delta P_{dB} = -5\lg\left(1 - \frac{2\cos^2\alpha}{\mu_2\left(\frac{1}{SNR_{th}} - \frac{1}{SNR_{flr}}\right)} 10^{\frac{MPI_{dB}}{10}}\right) \quad (1)$$

- where μ_2 is the second order moment of the signal and can be calculated using Eq. (2)

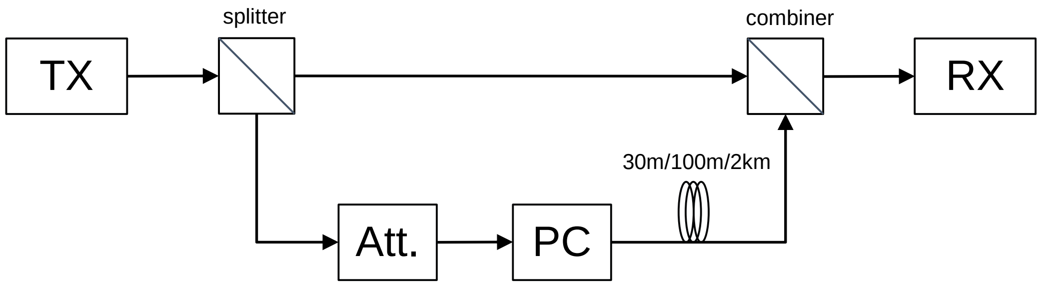
$$\mu_2 = \frac{(\gamma-1)^2}{(\gamma+1)^2} \cdot \frac{1}{M(2M-1)^2} \cdot \sum_{m=1}^{M} (2m-1)^2 \quad (2)$$

  - For PAMx signal, M=x/2. γ is the optical extinction ratio (ER).
- SNR_{th} in (1) is the required SNR at the BER threshold and SNR_{flr} is the effective SNR calculated from the BER floor (If there is no clear BER floor, it can be ignored).
- Eq. (1) doesn't show explicitly the dependence of MPI penalty on the baudrate but it reveals the strong connection between MPI penalty and signal characteristics: modulation format, ER, FEC threshold, and BER floor.

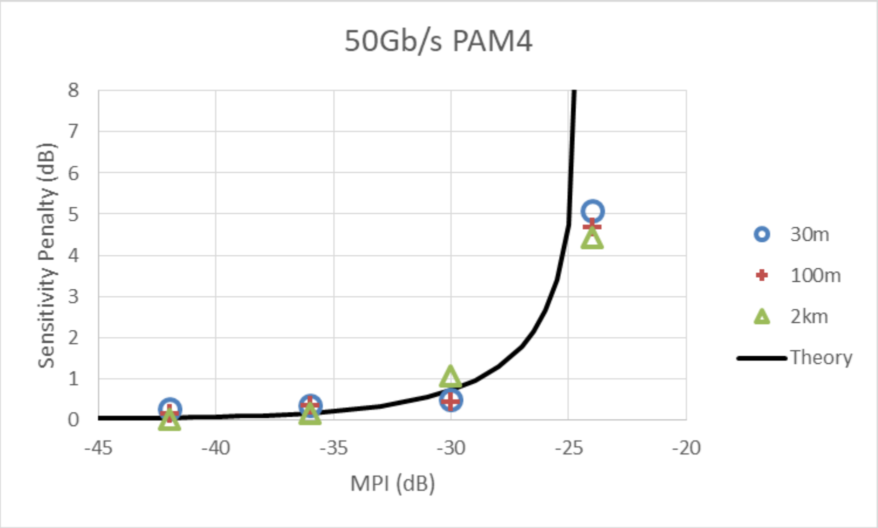
[1] James L. Gimlett, et al., JLT, Vol. 7, No. 6, 1989, page 888-895.

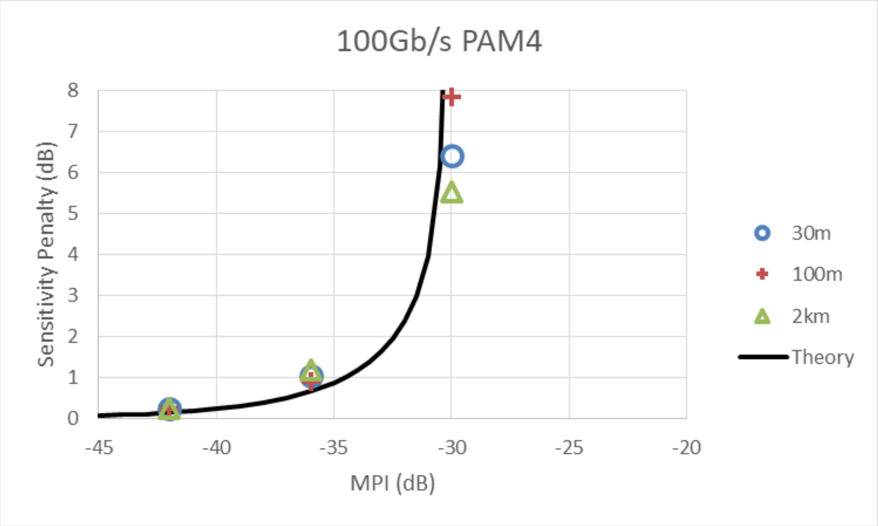
Model validation

- MPI is emulated in a split-and-combine manner where PC is to align the MPI component's SOP with that of the main signal. Strength and delay are tunable.
- The proposed model fits experimental results pretty well with ER and BER floor set accordingly.
- $\cos^2\alpha$ being 0.70 instead of 1.0 can be attributed to manual alignment of polarization controller and non-Gaussianity of the MPI noise.



TX: PAM4 transmitter
RX: PAM4 receiver
Att.: Tunable attenuator
PC: Polarization controller





MPI tolerance and link budget for MPI

- Given MPI penalty, we can get the MPI tolerance from eq. (1)

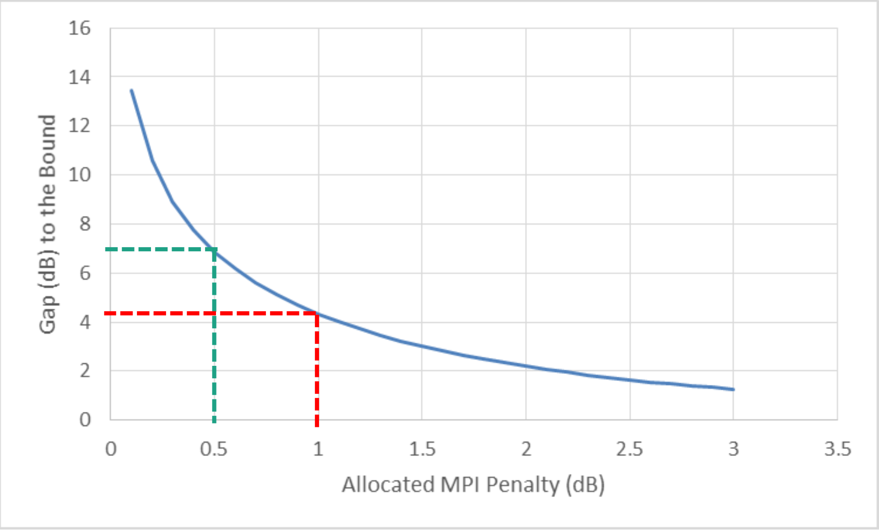
$$MPI_{tolerance} = 10\lg\left[\mu_2\left(\frac{1}{SNR_{th}} - \frac{1}{SNR_{flr}}\right)/(2cos^2\alpha)\right] + 10\lg(1 - 10^{\frac{-\Delta P_{dB}}{5}}) \quad (3)$$

- Apparently there exist a bound for MPI tolerance

$$MPI_{tolerance} = 10\lg\left[\mu_2\left(\frac{1}{SNR_{th}} - \frac{1}{SNR_{flr}}\right)/(2cos^2\alpha)\right] \quad (4)$$

- The gap between MPI tolerance at given penalty and the bound is

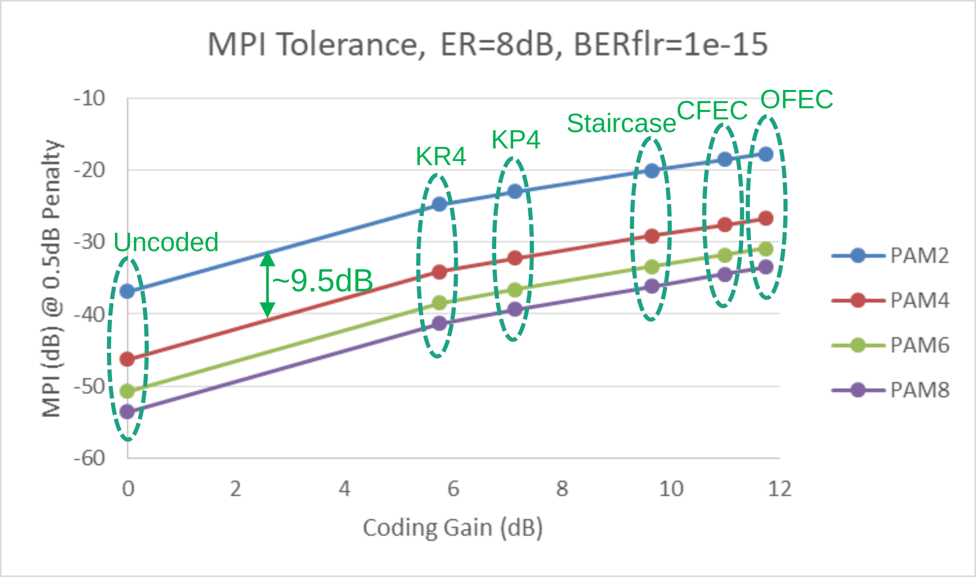
$$GAP(\Delta P_{dB}) = -10\lg(1 - 10^{\frac{-\Delta P_{dB}}{5}}) \quad (5)$$



- The gap decrease rapidly with MPI penalty, for example Gap reduces from 7dB to 4.3dB when penalty increase from 0.5dB to 1dB.
- It implies smaller MPI budget is preferred so that the system can work robustly.

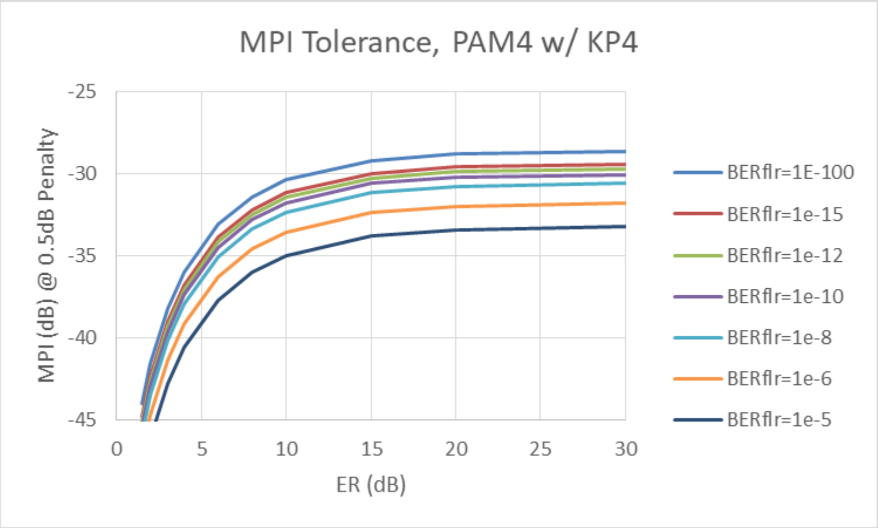
MPI tolerance vs. modulation formats and FEC schemes

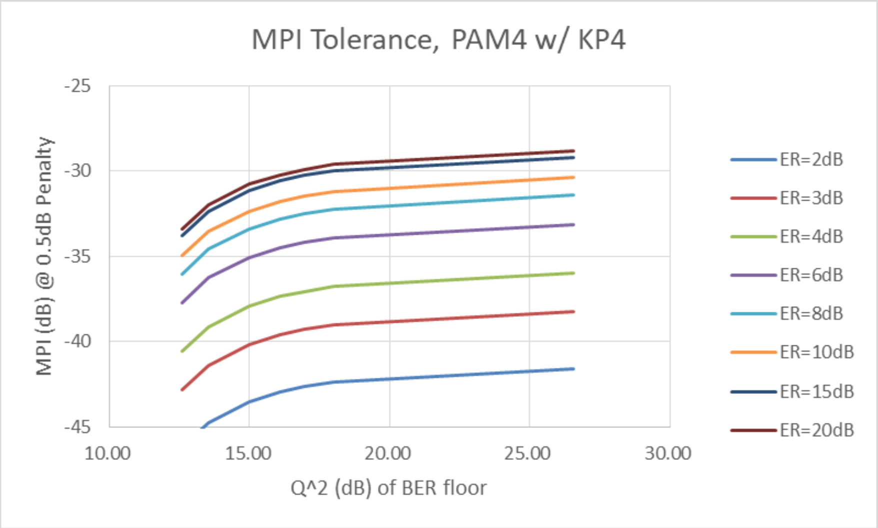
- ER and BER floor are assumed to be 8dB and 1e-15 respectively.
- MPI tolerance @ 0.5dB sensitivity penalty is calculated for PAM2 PAM4 PAM6 and PAM8 with various FEC schemes.
- As expected, MPI tolerance strongly depends on the modulation, for example, the well-know 9.5dB gap between PAM2 and PAM4.
- MPI tolerance also strongly depends on the FEC coding gain. If BER floor = 0, they are 1:1 proportional.



MPI tolerance vs. ER and BER floor

- PAM4 with KP4 is assumed.
- Higher ER is helpful to increase the MPI tolerance, especially when ER is smaller than 10dB. This is because at given optical power, ER corresponds to the swing of the received electrical signal.
- Strong correlation with BER floor is also observed. Lower BER floor shows better MPI tolerance because of larger system margin.





Implication for next generation PAMx systems

- 200Gbps per lane is regarded as the mainstream optical data rate for next generation Ethernet.
- Implications from the analytical model for 200Gbps:
  - Modulation formats selection
    - In terms of MPI tolerance, PAM4 is a better choice than PAM6 or higher order modulation formats which is already a consensus.
  - Link budget for MPI
    - If MPI budget needs to be specified, smaller value (≤0.5dB) is suggested due to the fast decay of the gap to the MPI bound.
  - Constraints on signal characteristics
    - 200Gbps PAM4 is likely to have lower ER and poorer BER floor than its 50Gbps or 100Gbps counterparts which will result in poorer MPI tolerance.
    - On the other hand, new FEC with higher coding gain is under discussion which will increase MPI tolerance depending on the coding gain.
- In summary, signal characteristics and FEC should be jointly considered to close the target MPI link budget when 200Gbps PAM4 is considered for longer distance applications such FR or LR.

THANK YOU