On PMD tolerance of 200 Gb/s PAM4

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Introduction

- Differential group delay (DGD) is an important optic link parameter which has been specified in previous 802.3 series.
- Research work showed only considering 1st-order polarization mode dispersion (PMD) may under-estimate PMD impairments in both IM/DD and coherent systems [1,2].
- This contribution studies PMD tolerance of 200 Gb/s PAM4 taking into account both 1st- and 2nd-order effects.
- The methodology is applicable to PMD penalty evaluation in coherent systems.

[1] Henry H. Yaffe, et al., J. Lightwave Technol. 24(11), 4155-4161 (2006)
[2] Chongjin Xie, ECOC 2010, paper Th.10.E.6

Amendments	Scenario	DGDmax (ps)	Clause	mean DGD (ps)*
802.3ba	40G-LR4	10	87.10, Table 87-74	2.67
	100G-LR4	8	88.10, Table 88-74	2.13
	100G-ER4	10.3	88.10, Table 88-74	2.75
802.3bs	200G-DR4	2.24	121.10, Table 121-13	0.60
	200G-FR4	3	122.10, Table 121-17	0.80
	200G-LR4	8	122.10, Table 121-17	2.13
	400G-DR4	2.24	124.10, Table 124-11	0.60
	400G-FR8	3	122.10, Table 121-17	0.80
	400G-LR8	8	122.10, Table 121-17	2.13
802.3cd	50G-FR	3	139.9, Table 139-12	0.80
	50G-LR	8	139.9, Table 139-12	2.13
	100G-DR	2.24	140.9, Table 140-11	0.60
802.3cc	25G-ER	10.3	114.10, Table 114-10	2.75
802.3cn	50-ER	10.3	139.9, Table 139-12	2.75
	200G-ER4	10.3	122.10, Table 121-17	2.75
	400G-ER8	10.3	122.10, Table 121-17	2.75
802.3cu	100G-DR	2.24	140.9, Table 140-11	0.60
	100G-FR1	2.3	140.9, Table 140-11	0.61
	100G-LR1	5	140.9, Table 140-11	1.33
	400G-FR4	2.3	151.10, Table 151-13	0.61
	400G-LR4-6	4	151.10, Table 151-13	1.07

* the ratio of Max DGD to mean DGD is 3.75

PMD Characteristic Function

- The 6-D characteristic function of first- and second-order PMD vectors [3,4]

$$\Phi(\mathbf{z},\boldsymbol{\zeta}) = E\{\exp[j(\mathbf{z}\cdot\boldsymbol{\Omega}+\boldsymbol{\zeta}\cdot\boldsymbol{\Omega}')]\} = \operatorname{sech}|\boldsymbol{\zeta}|\exp\{-\frac{1}{2}[|\mathbf{z}|^2\operatorname{tanhc}|\boldsymbol{\zeta}| + \frac{(\mathbf{z}\cdot\boldsymbol{\zeta})^2}{|\boldsymbol{\zeta}|^2}(1-\operatorname{tanhc}|\boldsymbol{\zeta}|)]\} \quad (1)$$

- ($\boldsymbol{\Omega}$,$\boldsymbol{\Omega}'$) is the normalized 6-D PMD vector.

$$\boldsymbol{\Omega} = \Delta\tau\mathbf{q}/\langle\Delta\tau\rangle \qquad \boldsymbol{\Omega}' = d\boldsymbol{\Omega}/d\omega = (\Delta\tau'\mathbf{q}+\Delta\tau\mathbf{q}')/\langle\Delta\tau\rangle^2$$

- $\Delta\tau$ stands for DGD with $<\Delta\tau>$ being its mean and $\mathbf{q}$ is the unit vector in Stokes space pointing at one of the two principle states of polarization (PSP).
- From eq. (1) one can derive all the first- and second-order PMD statistics such as:
  - DGD (differential group delay)
  - PCD (polarization-dependent chromatic dispersion)
  - PSD (polarization state depolarization)
  - and their joint distributions
  - …

[3] G. J. Foschini, et al., J. Lightwave Technol. 9(11), 1439-1456 (1991)
[4] G. J. Foschini, et al., J. Lightwave Technol. 17(9), 1560-1565 (1999)

Distribution and Outage Probability of DGD

- It's well known that DGD, the first-order PMD, follows Maxwellian distribution.

$$f_{\Delta\tau}(x) = \frac{32x^2}{\pi^2\langle\Delta\tau\rangle^3}\exp\left(-\frac{4x^2}{\pi\langle\Delta\tau\rangle^2}\right), x > 0$$

- Mean DGD is related to the r.m.s. DGD by

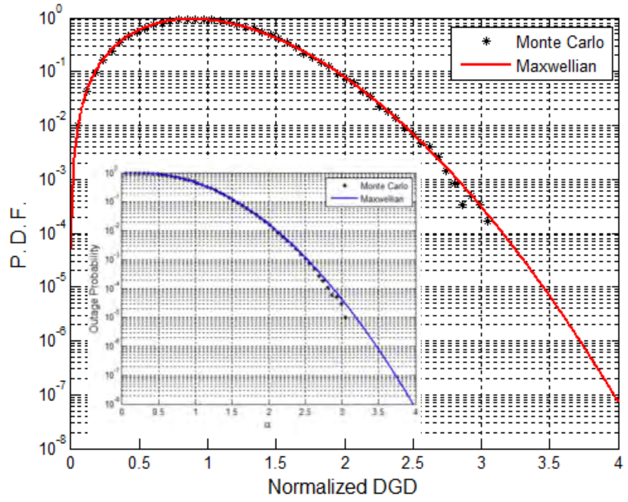
$$\langle\Delta\tau\rangle = \sqrt{8/3\pi}\Delta\tau_{rms}$$

  - Note: the fiber PMD coefficient might be defined using mean DGD or r.m.s. DGD

- The outage probability is

$$P_{outage} = \int_{\alpha\langle\Delta\tau\rangle}^{+\infty} f_{\Delta\tau}(x)dx$$

$$= \frac{4\alpha}{\pi}\exp\left(-\frac{4\alpha^2}{\pi}\right) + \mathrm{erfc}\left(\frac{2\alpha}{\sqrt{\pi}}\right)$$



α	P_{outage}	α	P_{outage}
3.00	4.20E-05	3.50	7.74E-07
3.05	2.90E-05	3.55	5.00E-07
3.10	1.99E-05	3.60	3.22E-07
3.15	1.36E-05	3.65	2.05E-07
3.20	9.19E-06	3.70	1.30E-07
3.25	6.19E-06	3.75 [5]	8.21E-08
3.30	4.14E-06	3.80	5.14E-08
3.35	2.75E-06	3.85	3.20E-08
3.40	1.81E-06	3.90	1.98E-08
3.45	1.19E-06	3.95	1.21E-08

[5] https://www.ieee802.org/3/cu/public/May19/anslow_3cu_01_0519.pdf

Distribution and Outage Probability of DGD and PCD

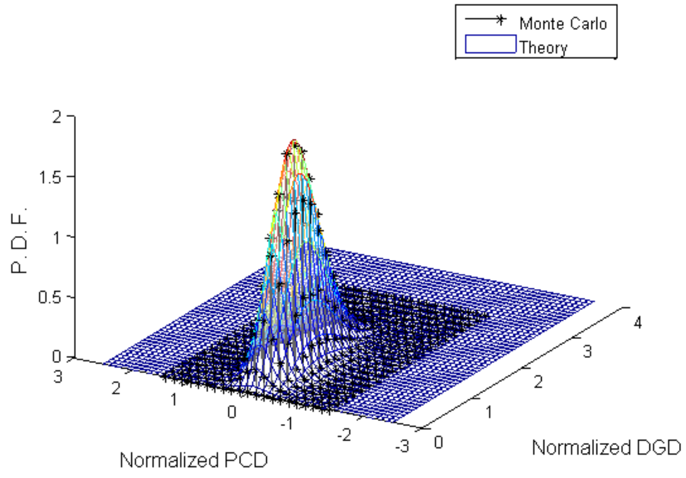
- The joint distribution of DGD and PCD is shown below. DGD and PCD are independent.

$$f_{\Delta\tau,\Delta\tau'}(x,y) = \frac{64x^2}{\pi^2\langle\Delta\tau\rangle^5}\exp\left(-\frac{4x^2}{\pi\langle\Delta\tau\rangle^2}\right)\mathrm{sech}^2\left(\frac{4y}{\langle\Delta\tau\rangle^2}\right), x > 0$$

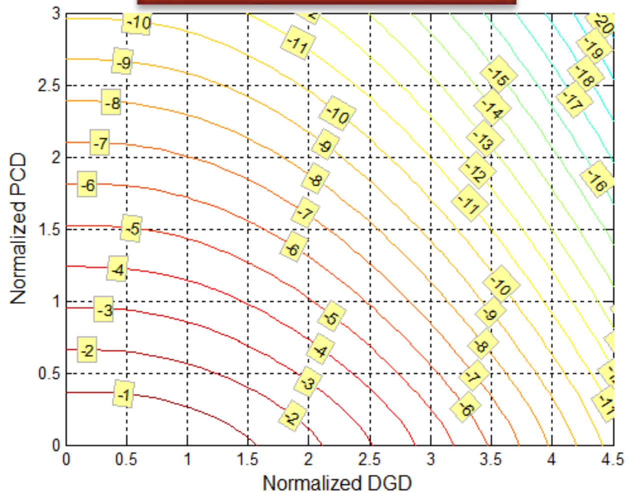
- The 2-D outage probability has a closed form solution.

$$P_{outage} = 2\int_{\beta\langle\Delta\tau\rangle^2}^{+\infty} dy \int_{\alpha\langle\Delta\tau\rangle}^{+\infty} f_{\Delta\tau,\Delta\tau'}(x,y)dx = \frac{2}{\exp(8\beta)+1}\left[\frac{4\alpha}{\pi}\exp\left(-\frac{4\alpha^2}{\pi}\right) + \mathrm{erfc}\left(\frac{2\alpha}{\sqrt{\pi}}\right)\right]$$

2-D P.D.F



2-D Poutage



Distribution and Outage Probability of DGD and PSD

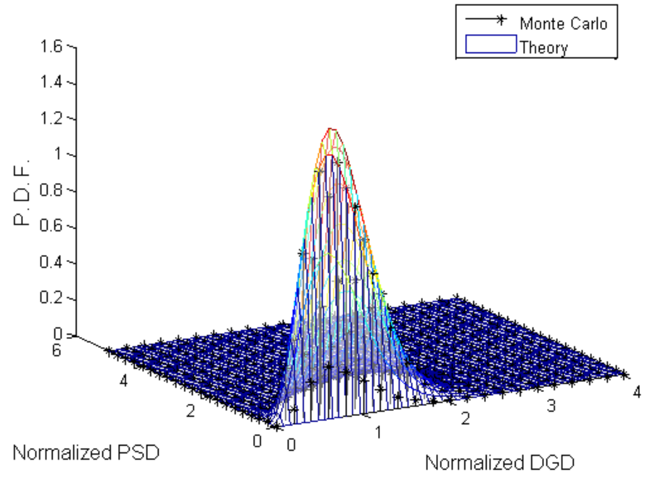
- DGD and PSD have strong correlation. The joint distribution is shown below.

$$f_{\Delta\tau,|\Delta\tau\mathbf{q}'|}(x,y)=\frac{2048x^2y}{\pi^4\langle\Delta\tau\rangle^7}\int_0^{+\infty}\mathrm{J}_0\left(\frac{8yt}{\pi\langle\Delta\tau\rangle^2}\right)t^2\mathrm{csch}(t)\exp\left[-\frac{4x^2}{\pi\langle\Delta\tau\rangle^2\mathrm{tanhc}(t)}\right]dt\,,x>0,y>0$$

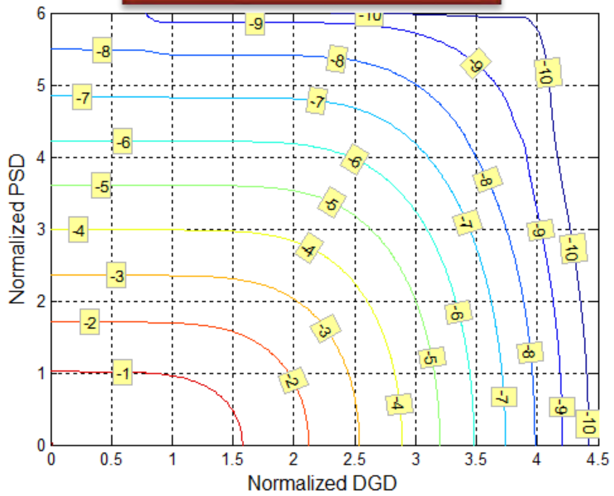
- The 2-D outage probability has to be evaluated using numerical integral.

$$P_{outage}=\int_{\gamma\langle\Delta\tau\rangle^2}^{+\infty}dy\int_{\alpha\langle\Delta\tau\rangle}^{+\infty}f_{\Delta\tau,|\Delta\tau\mathbf{q}'|}(x,y)dx$$

2-D P.D.F



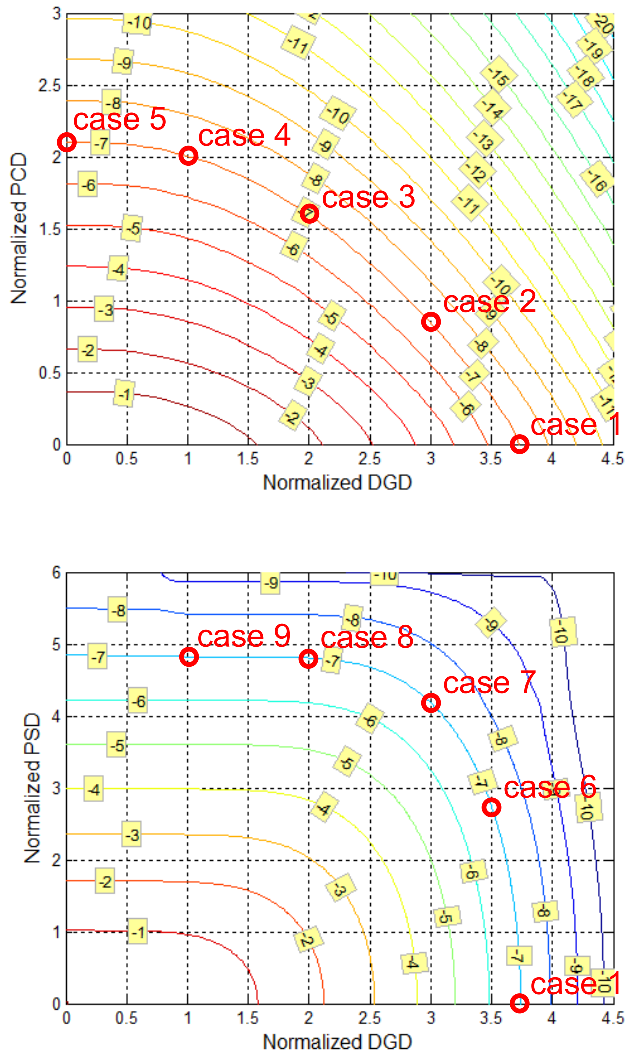
2-D Poutage



Proposed Simulation Cases

Simulation Case #	(α, β, γ)
1	(3.75, 0.0, 0.0)
2	(3.0, 0.84, 0.0)
3	(2.0, 1.59, 0.0)
4	(1.0, 2.01, 0.0)
5	(0.0, 2.10, 0.0)
6	(3.5, 0.0, 3.73)
7	(3.0, 0.0, 4.17)
8	(2.0, 0.0, 4.80)
9	(1.0, 0.0, 4.85)
...	...

- These simulation cases are equivalent in the sense that they share the same Poutage (1e-7)



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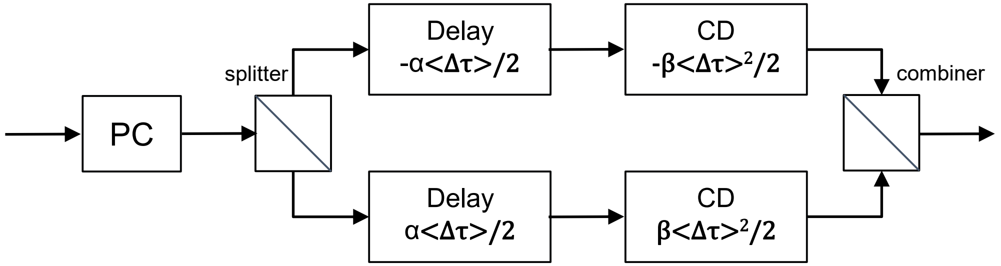
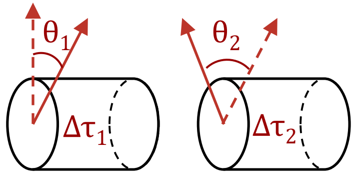
PMD Emulators and Validation

- DGD and PCD emulator



PC: Polarization controller
PBS: Polarization beam splitter
PBC: Polarization beam combiner

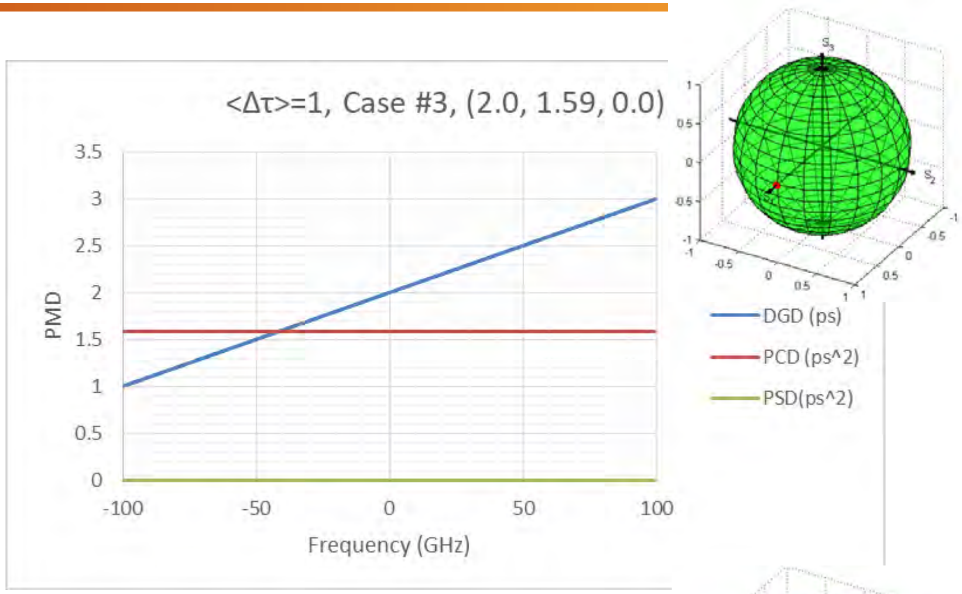
- DGD and PSD emulator [6]

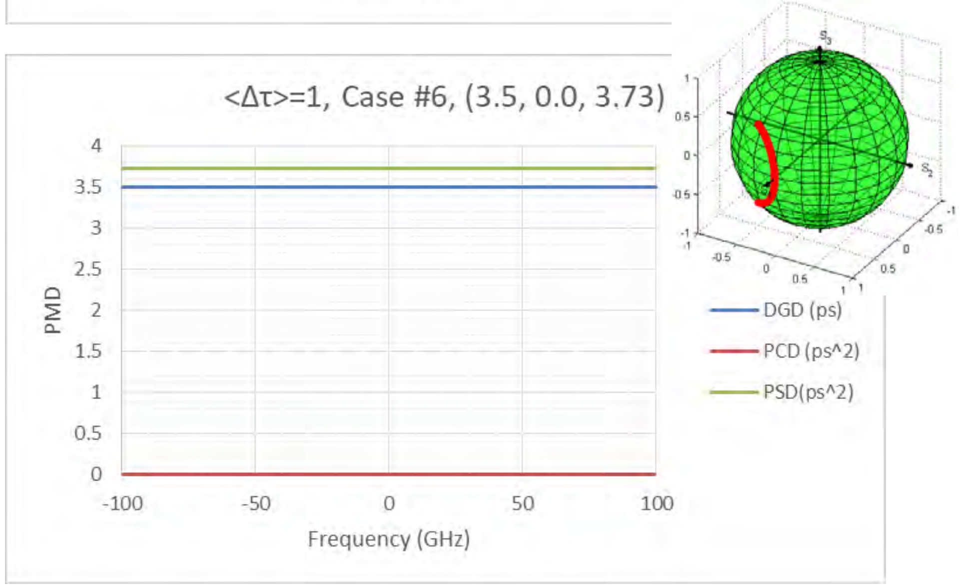


$$\varphi = \theta_2 - \theta_1 = \mathrm{atan}(2\gamma/\alpha^2)$$

$$\Delta\tau_1 = \Delta\tau_2 = \alpha\langle\Delta\tau\rangle/\sqrt{2[1+\cos(2\varphi)]}$$

- PMD values are accurately emulated.
- Insets show the input PSP on Poincaré sphere.

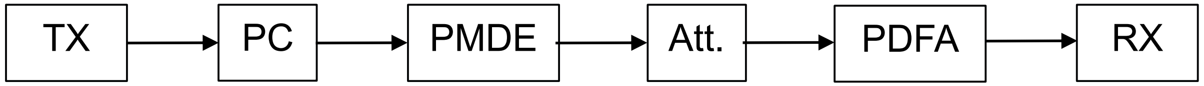




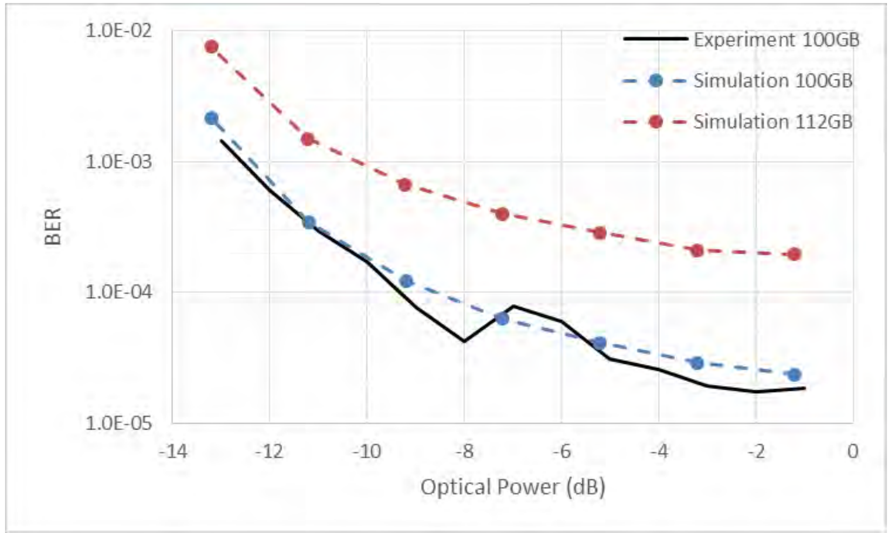
[6] M. Wegmuller, et al., Photonics Technol. Letters, 14(5), 630-632 (2002)

Simulation Parameters

- Simulator is calibrated using 100 GBaud experimental data.
- The PC makes sure that the 112 GBaud PAM4 launches the PMDE in the worst state of polarization (SOP).
- Due to the availability of some components, a PDFA is used before RX.
- 25-tap FFE is used in the Rx to equalize the signal.
- Power penalty is measure at BER threshold of 2e-3.

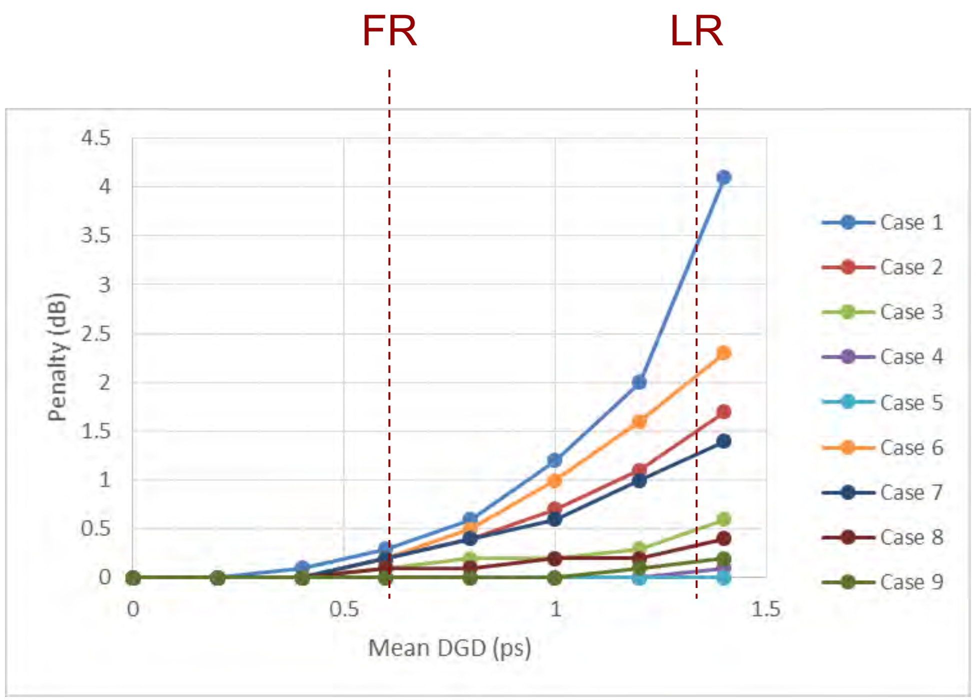


TX: PAM4 transmitter
RX: PAM4 receiver
PC: Polarization controller
PMDE: PMD emulator
Att.: Tunable attenuator



PMD Tolerance

- Simulation case 1 exhibits the worst performance which means for 200 Gb/s PAM4 with relatively small mean DGD, the 1st-order effect still dominants.
- If we take the same DGDmax as defined in IEEE 802.3cu, we need to allocate ~3.4dB link budget for PMD for LR application with FFE only.
- For FR application, ~0.3dB link budget needs to be reserved for PMD.



Summary

- This contribution reviewed the PMD basics and proposed a few test cases to simultaneously evaluate the impact of 1st- and 2nd-order PMD.
- Simulation results show that the 1st-order effect dominants the PMD penalty in 200 Gb/s PAM4 systems and notable DGD penalties were observed with FFE:
  - ~3.4dB for LR (DGDmax=5ps);
  - ~0.3dB for FR (DGDmax=2.3ps);
- It will be more problematic when combined with other link impairments such as dispersion, laser chirp and multi-path interference (MPI). More study is needed here.
- More advanced Rx algorithms such as MLSE/SOVA/BCJR might be helpful to reduce the penalty and are under investigation.
- The methodology can be applied to coherent system design and higher order effects might have more impacts.

THANK YOU