Link budget study of DP-PAM4 for 800G-LR4

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Supporters

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Overview

- Initial study of practical impairments to DP-IMDD
- Outline
  - Overview of DP transmit and reception
  - Penalty assessment
  - Link budgets
  - Conclusion

Baseline links

Baseline Status as of May 17th

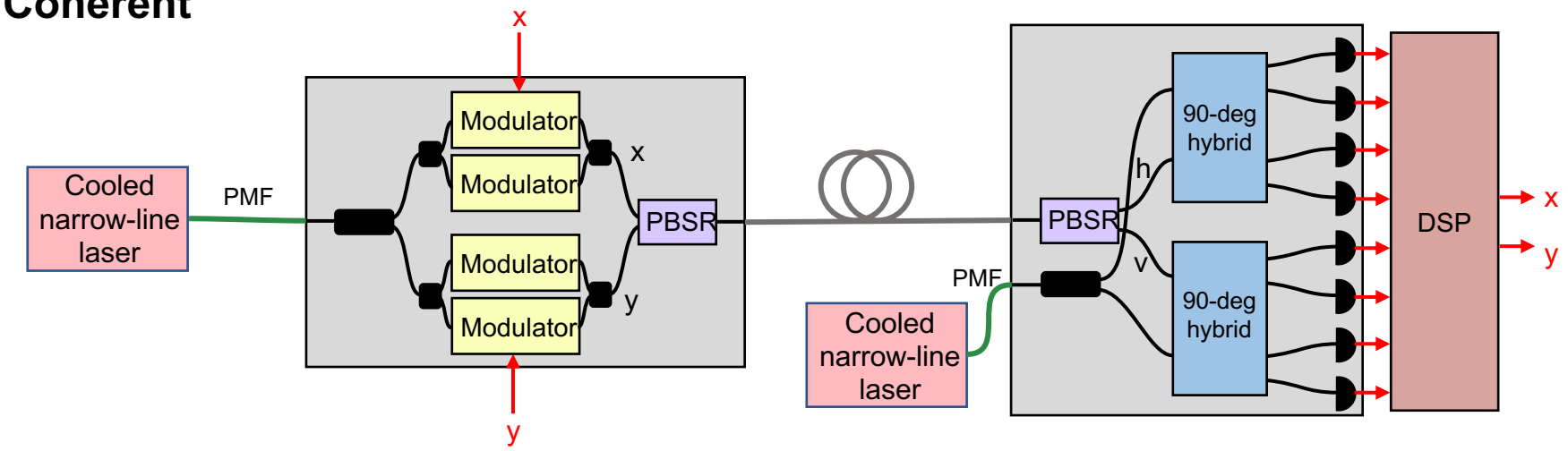
Ethernet Rate	Assumed Signaling Rate	AUI	BP	Cu Cable	MMF 50m	MMF 100m	SMF 500m	SMF 2km	SMF 10km	SMF 40km
200 Gb/s	200 Gb/s	Over 1 lane 200GAUI-1		Over 1 pair 200GBASE-CR1			Over 1 Pair TBD	Over 1 Pair TBD		
400 Gb/s	100 Gb/s							Over 4 Pair TBD		
	200 Gb/s	Over 2 lanes 400GAUI-2		Over 2 pairs 400GBASE-CR2			Over 2 Pair TBD			
800 Gb/s	100 Gb/s	Over 8 lanes 800GAUI-8	Over 8 lanes 800GBASE-KR8	Over 8 pairs 800GBASE-CR8	Over 8 pairs 800GBASE-VR8	Over 8 pairs 800GBASE-SR8	Over 8 pairs TBD	Over 8 pairs TBD		
	200 Gb/s	Over 4 lanes 800GAUI-4		Over 4 pairs 800GBASE-CR4			Over 4 pairs TBD	1) Over 4 pairs TBD 2) Over 4 λ's TBD		
	TBD								Over single SMF in each direction TBD	Over single SMF in each direction TBD
1.6 Tb/s	100 Gb/s	Over 16 lanes 1.6TAUI-16								
	200 Gb/s	Over 8 lanes 1.6TAUI-8		Over 8 pairs 1.6TBASE-CR8			Over 8 pairs TBD	Over 8 pairs TBD		

Target for this proposal

Adopted baselines

Dual polarization

Coherent

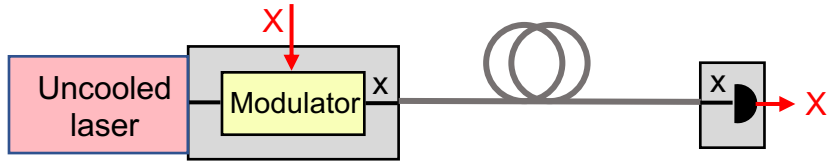


MIMO demux done in digital electronics

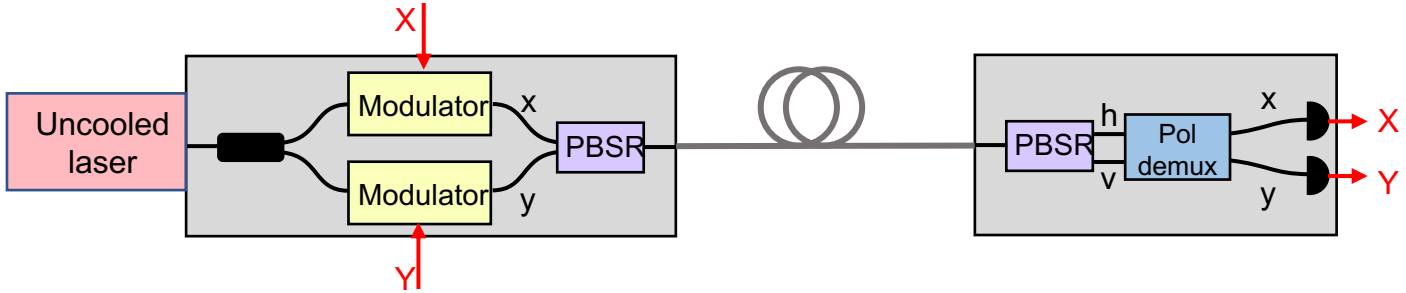
Can do MIMO demux after coherent detection because interference with LO with ppm offset provides phase information

IM-DD

SP



DP



MIMO demux must be done in optics

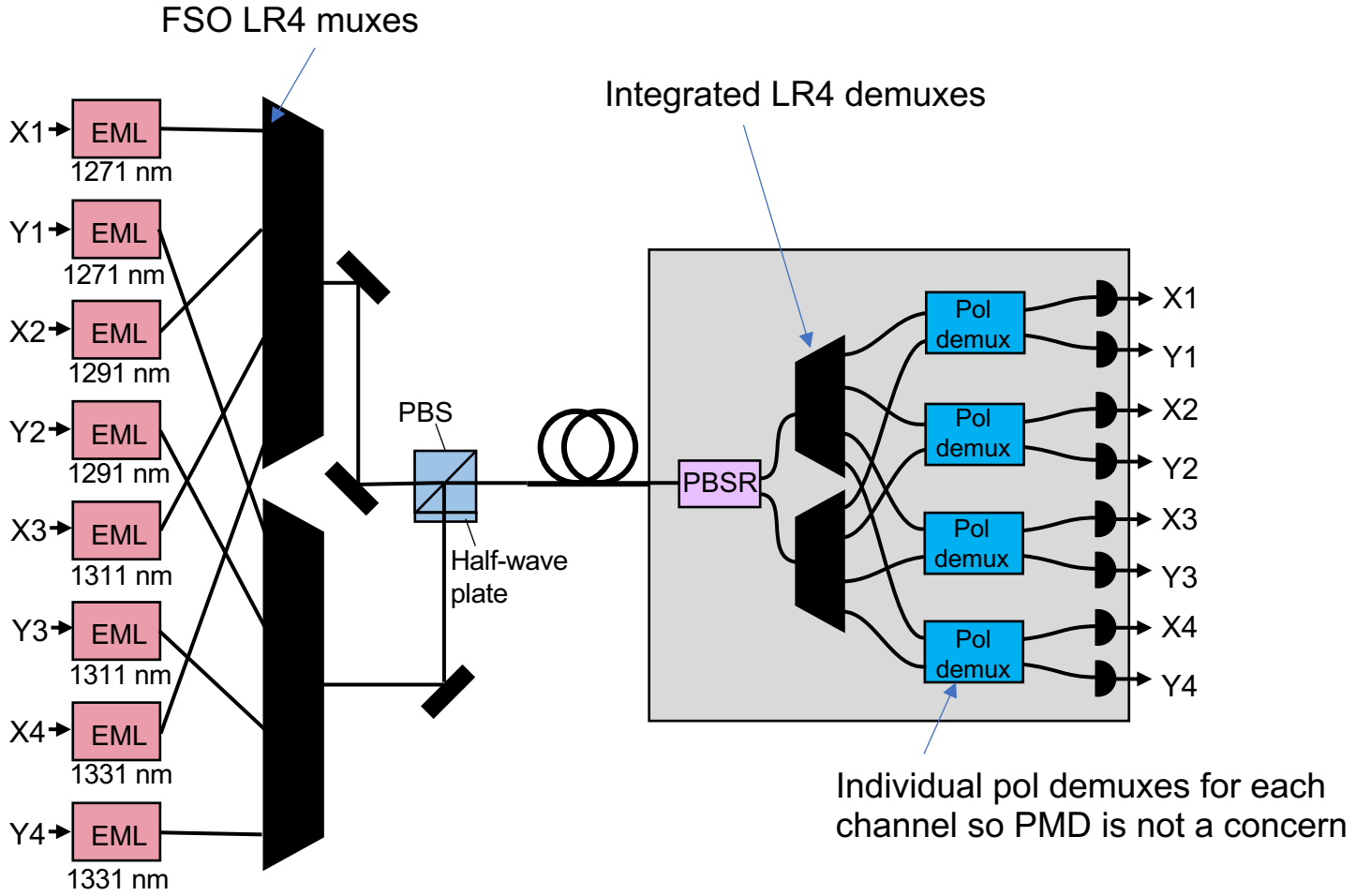
Cannot do MIMO demux after square-law detection because of loss of phase information

Some options for 800G LR (10 km)

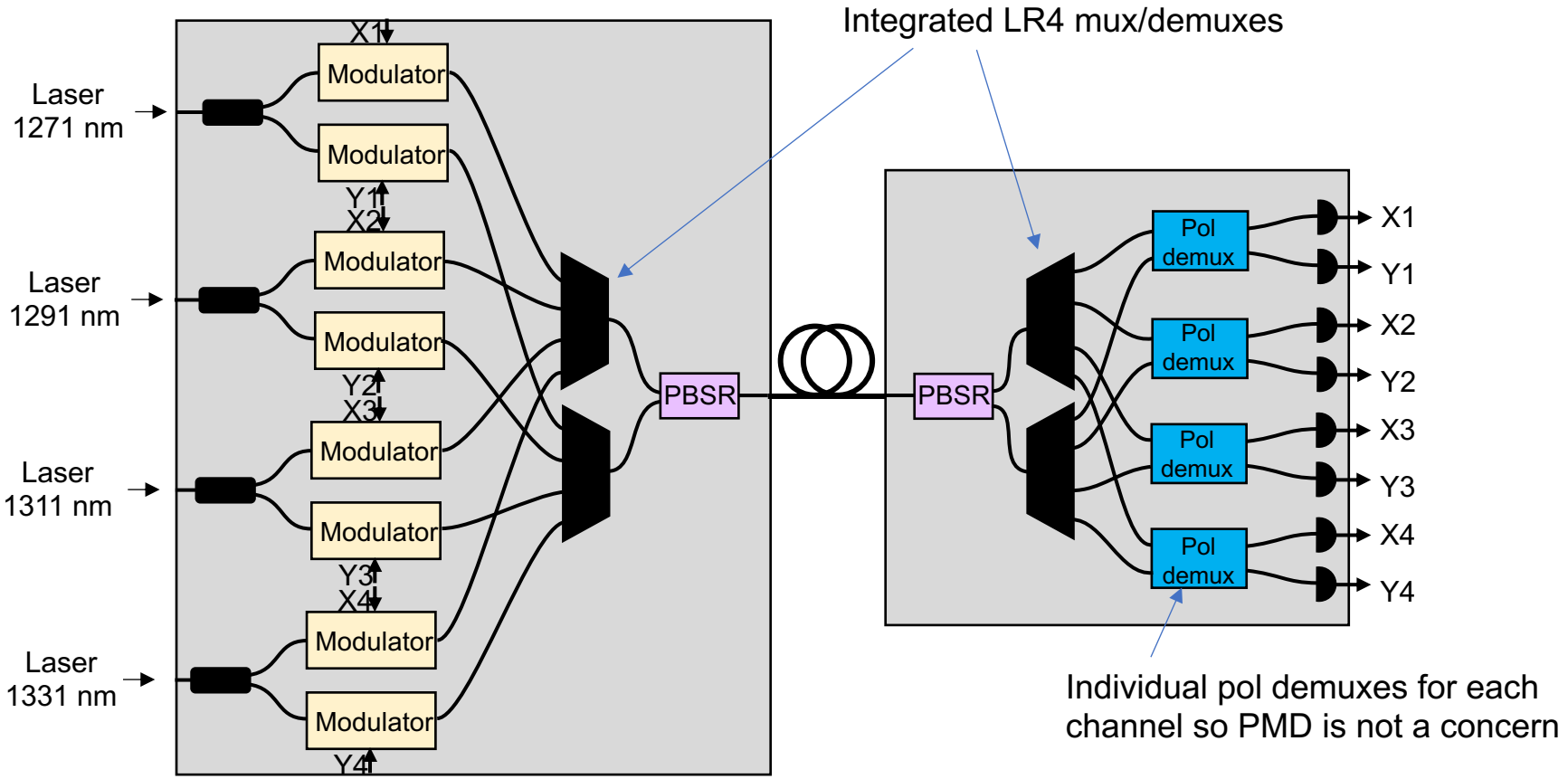
λ qty	λ spacing	Baud rate	Format	Laser qty	Laser pwr	Cooled laser	Backward compatibility	KP4 FEC	Disp.	FWM	Time to market
8	20 nm	56 Gbaud	PAM4								
8	800 GHz	56 Gbaud	PAM4								
4	20 nm	112 Gbaud	PAM4								
4	10 nm	112 Gbaud	PAM4								
4	20 nm	56 Gbaud	DP-PAM4								

Our proposal

DP-PAM4 implementation of 800G LR4: EML Tx, SiPh Rx

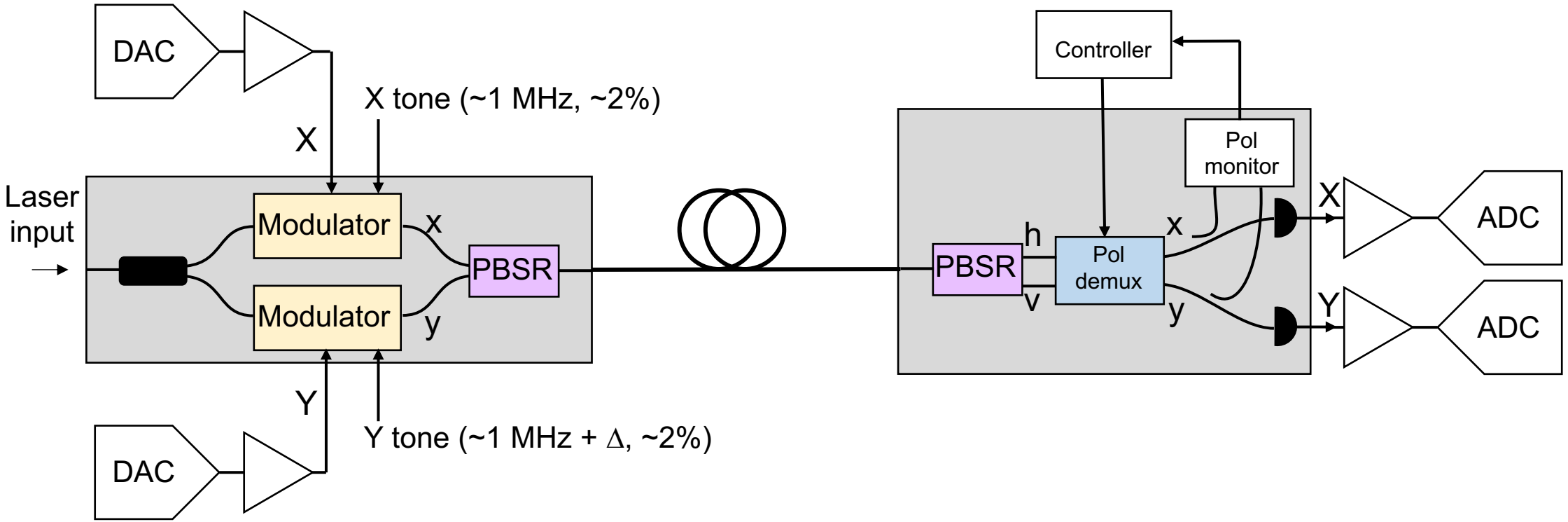


DP-PAM4 implementation of 800G LR4: SiPh Tx, SiPh Rx



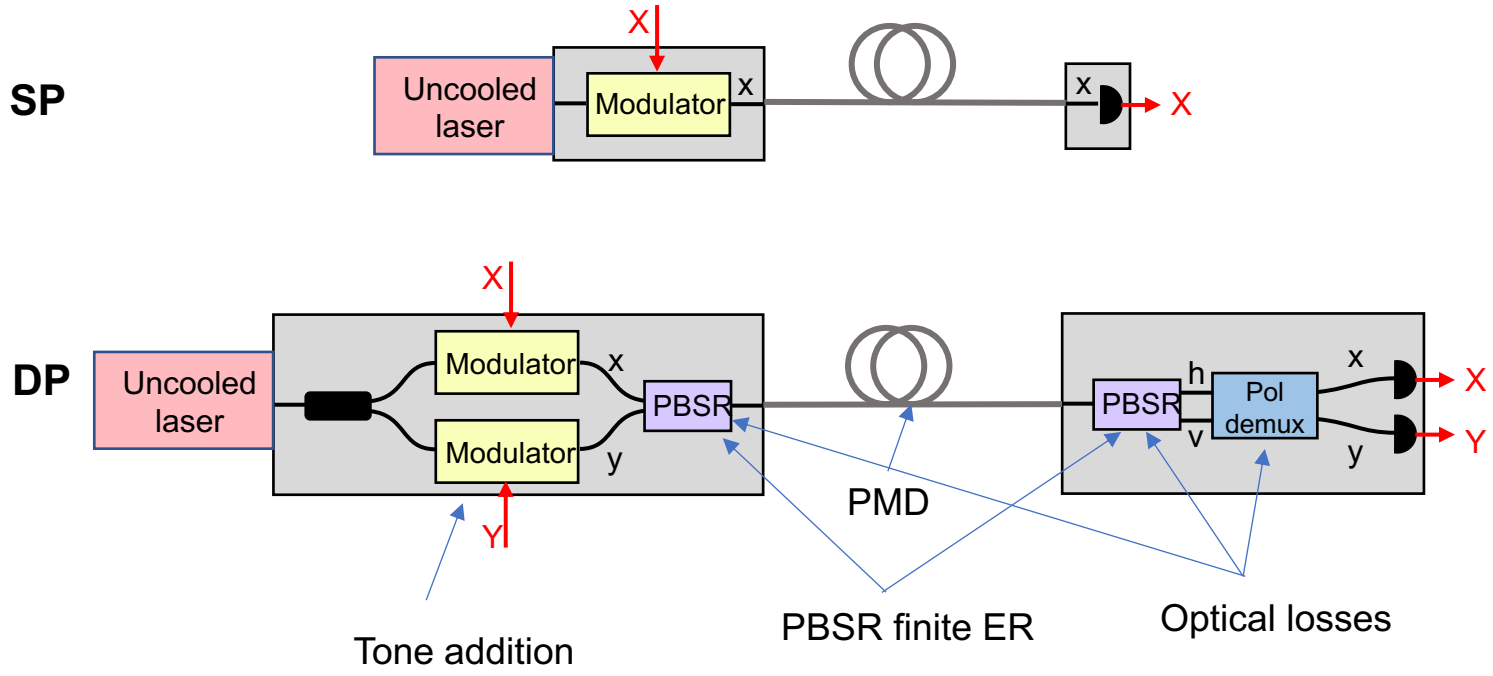
Marker tones

Two simple low-frequency marker tones are added at the transmitter to identify and aid in separating the X and Y polarizations in the receiver.

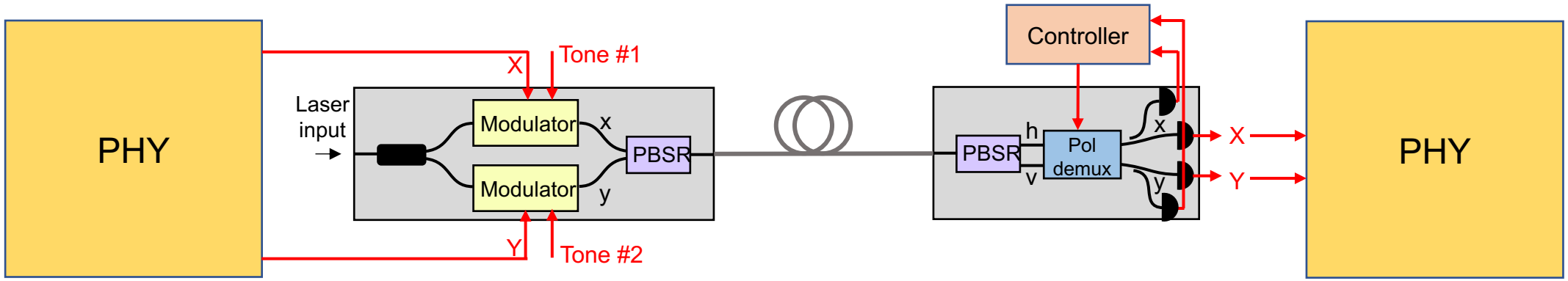


DP system is entirely agnostic to PHY and PCS

DP penalty assessment



DP-PAM4 simulation: setup



PDL compensation

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = DP_{\mathrm{Rx}}FP_{\mathrm{Tx}} \begin{bmatrix} x \\ y \end{bmatrix}$$

P_{Tx} = Tx rotator, PBS, and output coupling
F = fiber
P_{Rx} = Rx input coupling, PBS, and rotator
D = MIMO demux

If P_{Tx}, F, and P_{Rx} are all unitary (lossless) then D can be unitary
However, if not, they can be viewed as having polarization-dependent loss (PDL)
In such a case, D must also be non-unitary

Tone penalty

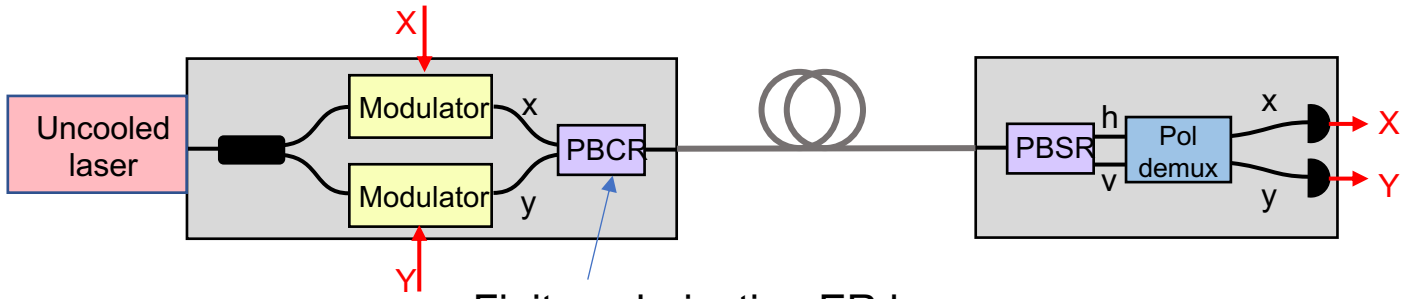
Tone frequency = 1-3 MHz

Low-frequency cut-off maximum = 100 kHz, thus tone is in the signal bandwidth

Tone amplitude = 2%

Calculated penalty @ 1e-6 BER < 0.05 dB

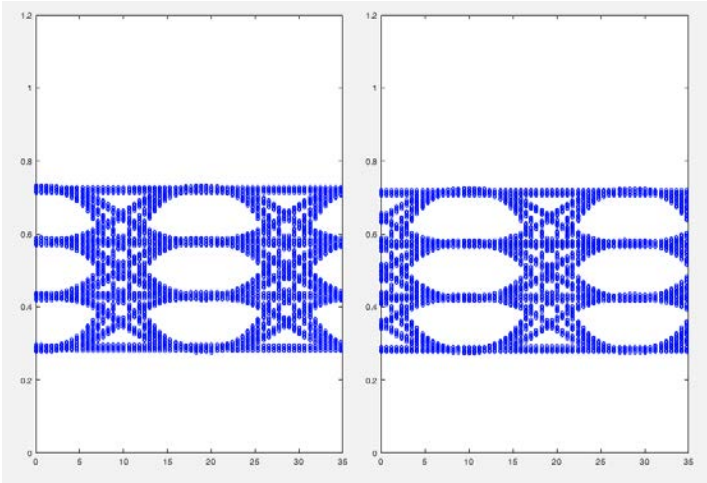
Tx PBC finite extinction ratio



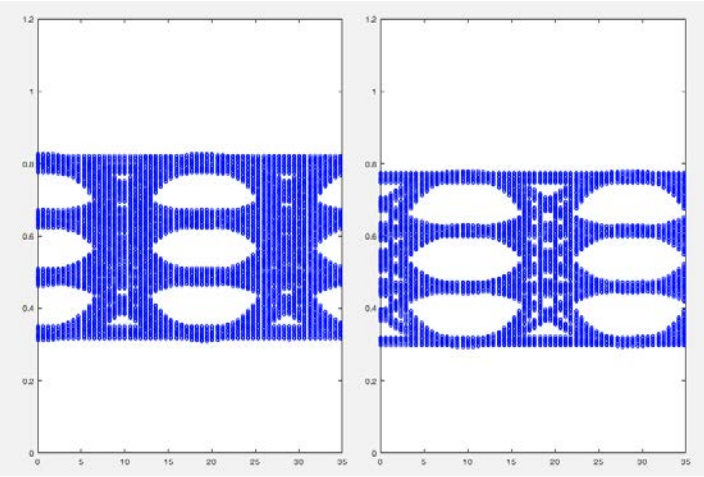
Finite polarization ER here
Typical spec. for polarization splitter = 23 dB

Finite ER is equivalent to PDL (non-unitary transfer matrix)

50 dB ER

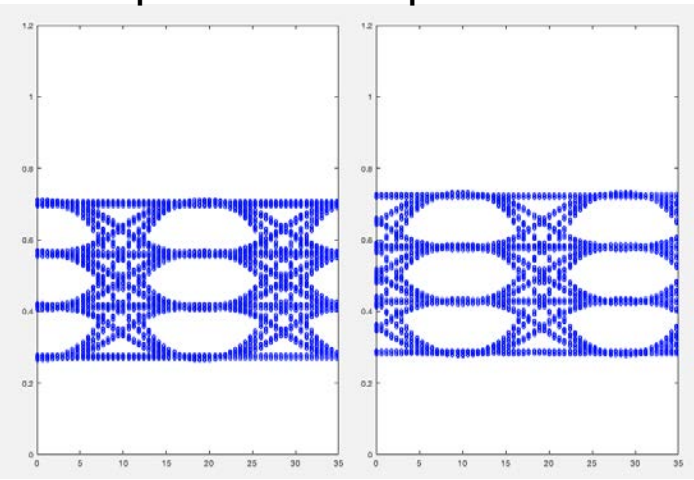


20 dB ER



Penalty ~1.0 dB

20 dB ER w/ PDL compensation in pol demux



Penalty ~0.0 dB

DGD

Table 151–13—Fiber optic cabling (channel) characteristics

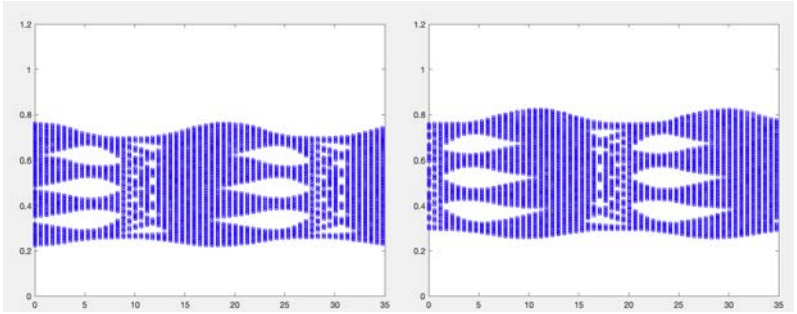
Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Operating distance (max)	2	6	km
Channel insertion loss[a, b] (max)	4	6.3	dB
Channel insertion loss (min)	0	0	dB
Positive dispersion[b] (max)	6.6	19.9	ps/nm
Negative dispersion[b] (min)	–11.7	–35.2	ps/nm
DGD_max[c]	2.3	4	ps
Optical return loss (min)	25	22	dB

IEEE Std 802.3cu-2021

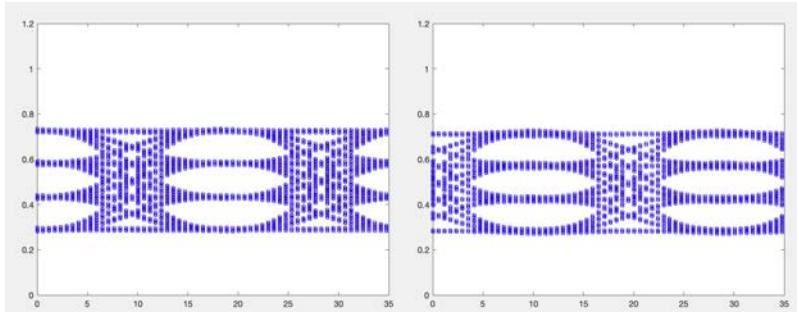
DGD causes different frequency components to have a different polarization, reducing the effectiveness of optical polarization demultiplexing

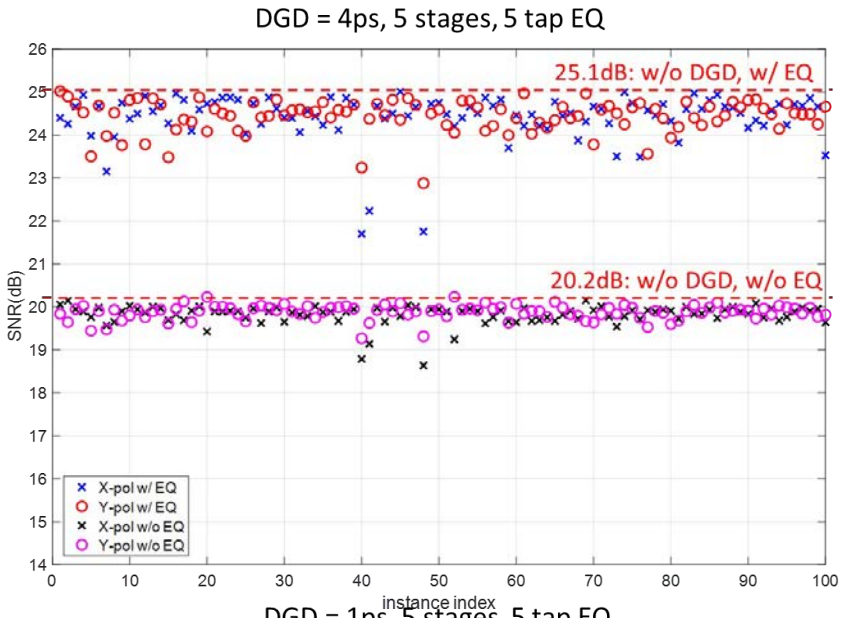
SSMF is specified at 0.04 ps/sqrt(km). This gives DGD of only 0.1 ps for 6 km

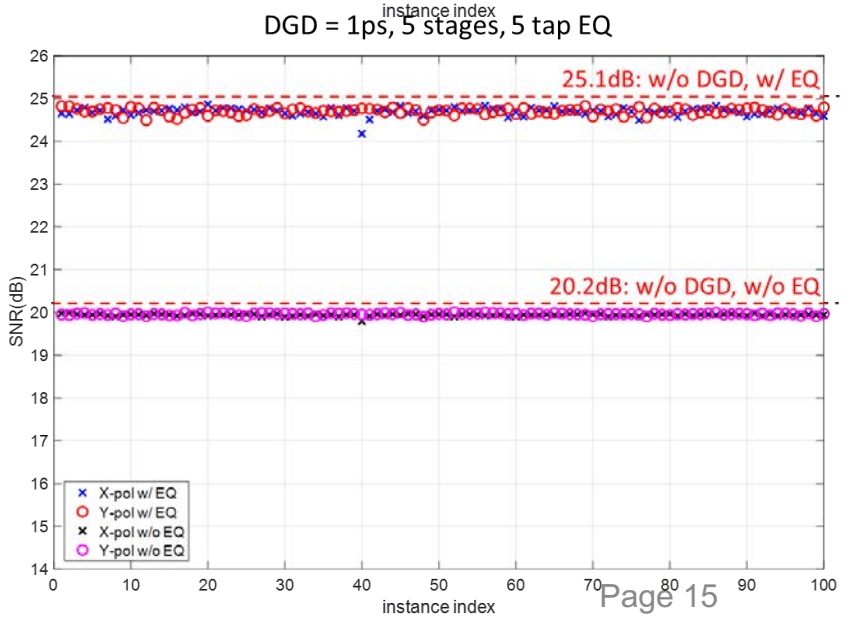
4 ps DGD



1 ps DGD







Performance penalties

Item	Penalty w/out PDL comp (dB)	Penalty w/ PDL comp (dB)	Comments
Tx PBC ER	0.7	0.0	23 dB ER
Rx PBS ER	0.7	0.0	23 dB ER
Tone	0.05		2%
DGD	0.5		1 ps DGD
Total	**1.1**	**0.5**	

Lower than IEEE spec for 6 km (4 ps), but SSMF is specified at 0.04 ps/sqrt(km), which gives DGD of only 0.1 ps for 6 km, so 1 ps is still very conservative

Assumptions:

- Penalty is at 10^{-4} BER
- Power imbalance < 3 dB between X and Y at launch
- Penalties are uncorrelated

Note: coherent Tx & Rx also have penalties from imperfect ERs

Tx loss penalties

Item	Penalty (dB)	Comments
Tx PBC insertion loss	0.2	
Tx fiber coupling loss to TM	0.4	Does not apply to EML-based Tx
Total	**0.6**	

Note: a coherent Tx has the same loss penalty

Rx loss penalties

Item	Penalty w/out PDL comp (dB)	Penalty w/ PDL comp (dB)	Comments
Rx fiber coupling loss to TM	0.4	0.4	
Rx PBS insertion loss	0.2	0.2	
Rx MIMO demux insertion loss	0.5	0.5	
PDL compensation	0.0	0.4	Non-unitary controller requires more optical elements
Total	**1.1**	**1.5**	

Note: a coherent Rx has the same loss penalty as the first two rows

Total penalties due to DP

Tx

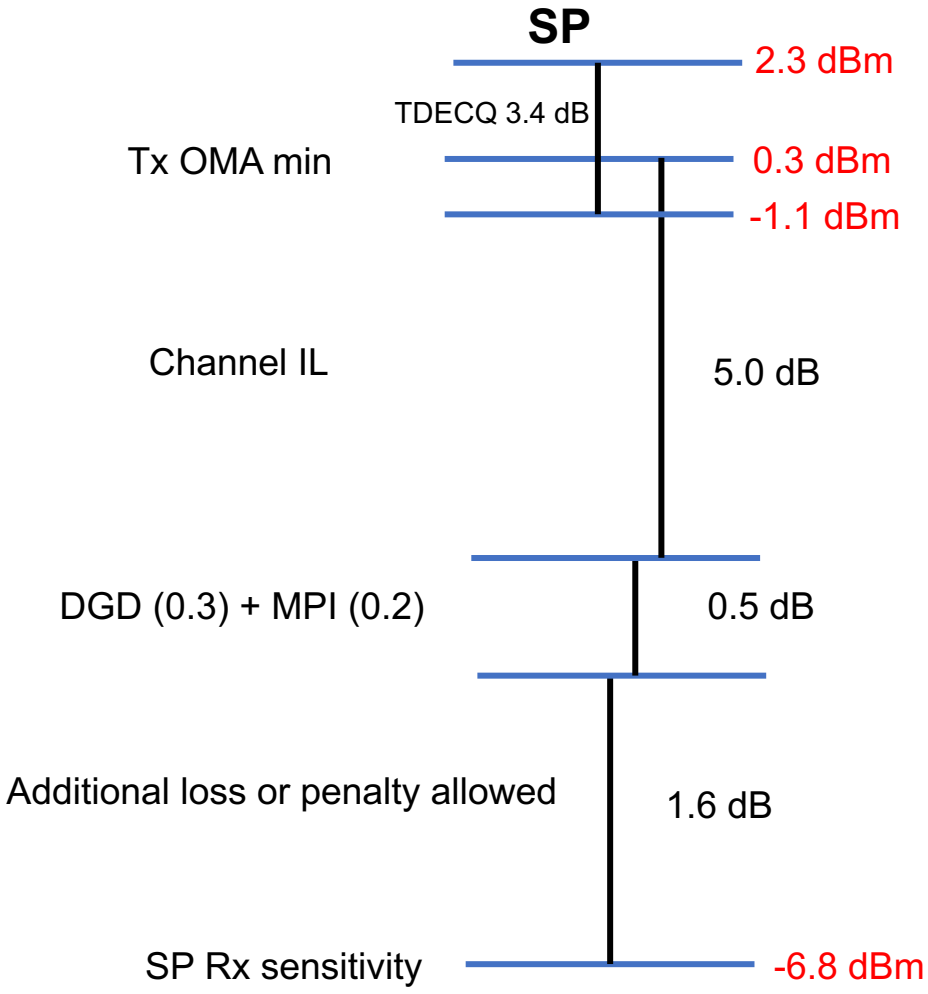
Item	Penalty (dB)
Loss penalty	0.6
Total	**0.6**

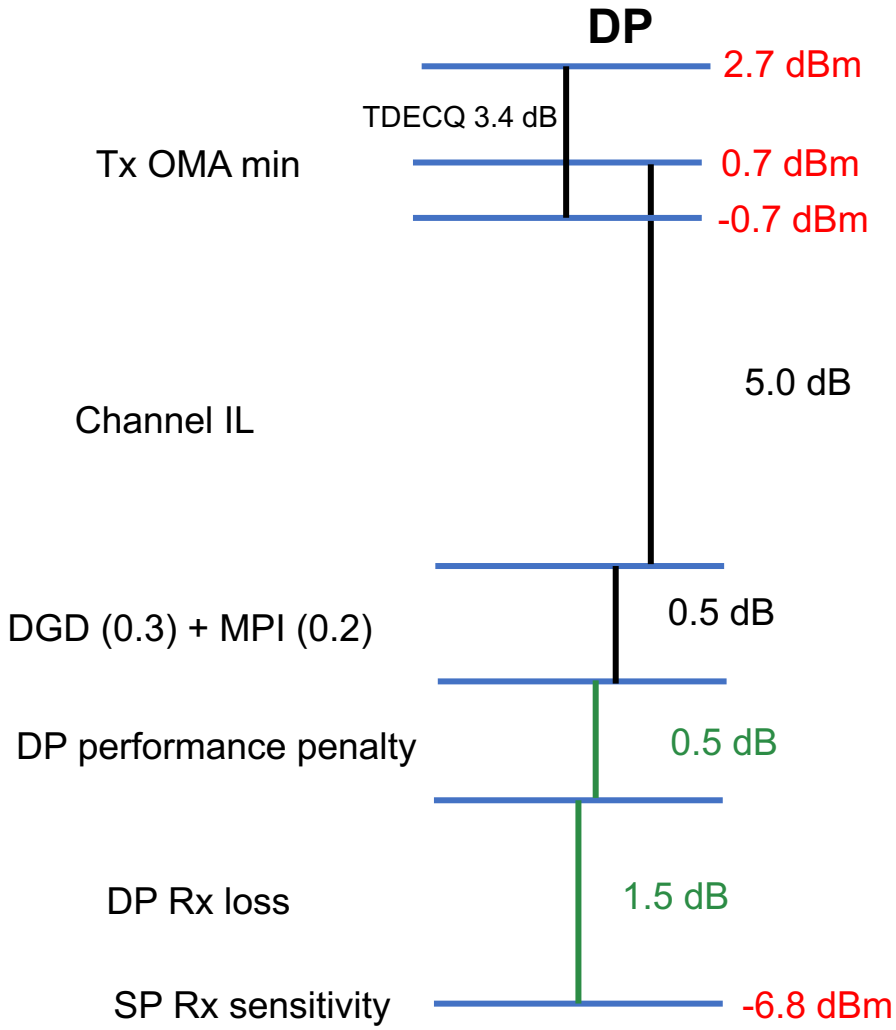
Rx

Item	Penalty w/out PDL comp (dB)	Penalty w/ PDL comp (dB)
Performance penalty	1.1	0.5
Loss penalty	1.1	1.5
Total	**2.2**	**2.0**

Link budget for 6 km

Assuming PDL compensation



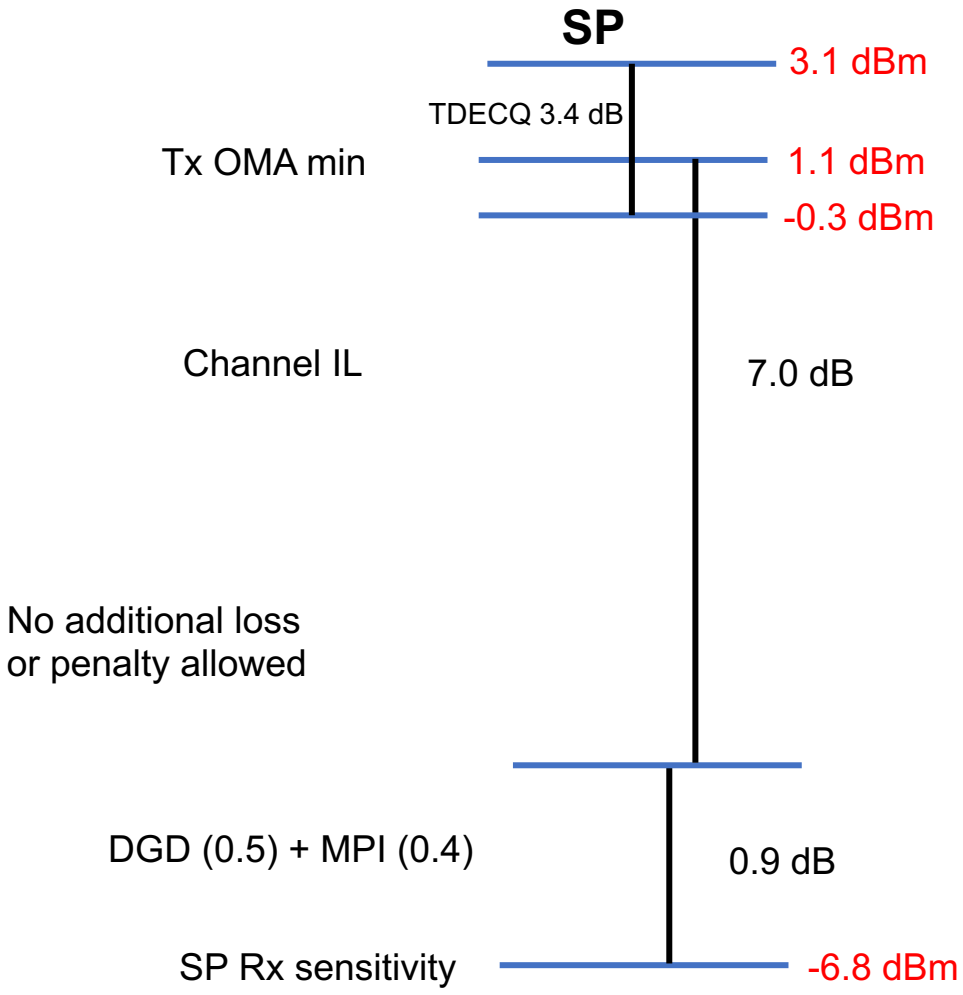


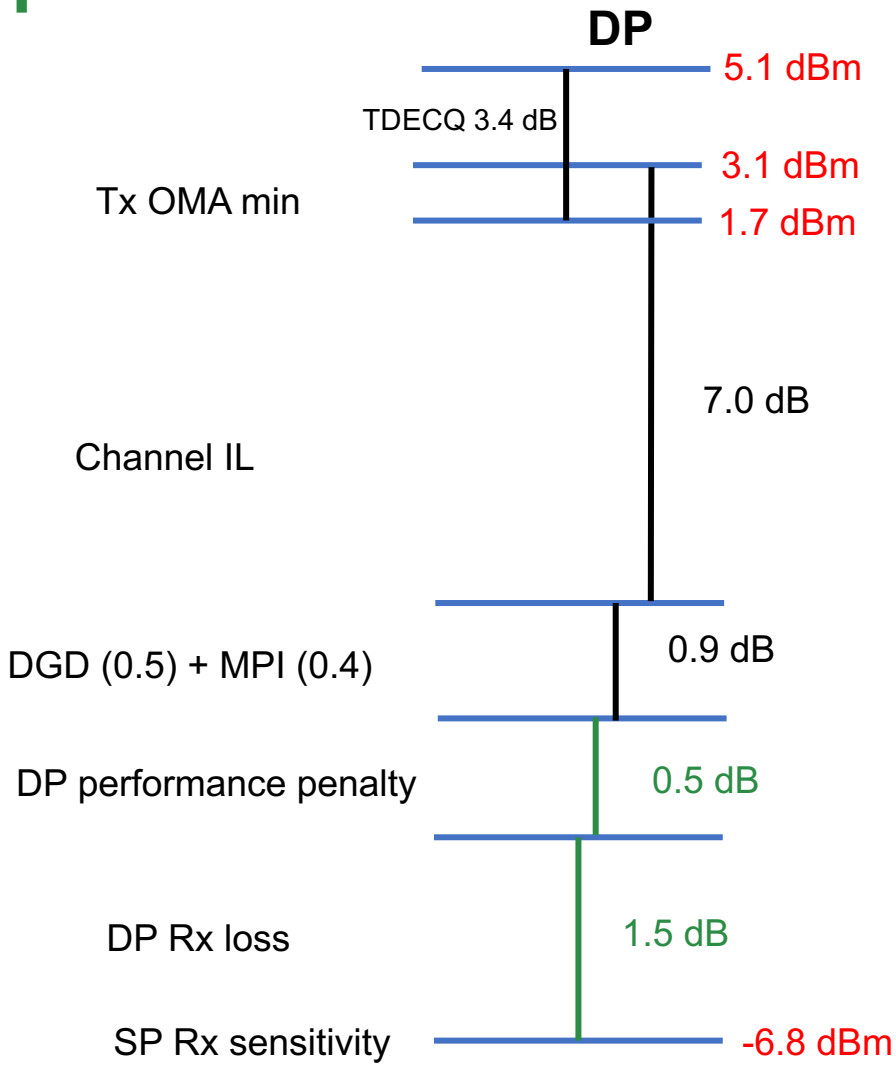
No additional loss or penalty allowed

https://www.ieee802.org/3/cu/public/May19/yu_3cu_01a_0519.pdf

Link budget for 10 km

Assuming PDL compensation





https://www.ieee802.org/3/cu/public/May19/yu_3cu_01a_0519.pdf

Conclusions

- Performed initial study of DP-PAM4 implementation penalties
- Rx will likely need PDL (non-unitary) compensation
- 6-km link appears reasonable
  - Requires ~0.4 dB higher launch OMA per polarization
  - Requires smaller maximum DGD (1 ps instead of 4 ps)
    - Today's fiber are specified for < 0.1 ps DGD for 6 km
- 10-km link appears challenging with current technology
- Many of these DP penalties are not unique to IMDD and are present in coherent links, as well