

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

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IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet

# Supporters

- Atul Srivastava (NEL)
- Frank Chang (Source)
- Chongjin Xie (Alibaba)
- Gerald Wong (CIG)

# 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

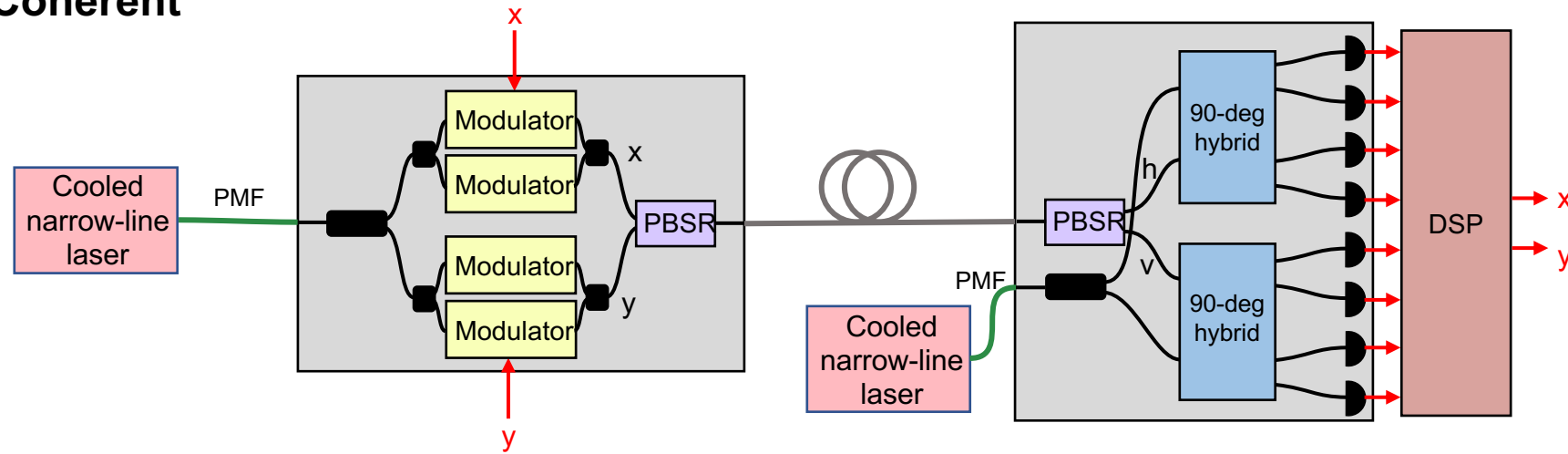
Ethernet Rate	Assumed Signaling Rate	AUI	BP	Cu Cable	MMF 50m	MMF 100m	SMF 500m	SMF 2km	SMF 10km	SMF 40km
200 Gb/s	200 Gb/s	Over 1 lane 200GAUI-1		Over 1 pair 200GBASE-CR1			Over 1 Pair TBD	Over 1 Pair TBD		
400 Gb/s	100 Gb/s							Over 4 Pair TBD		
	200 Gb/s	Over 2 lanes 400GAUI-2		Over 2 pairs 400GBASE-CR2			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

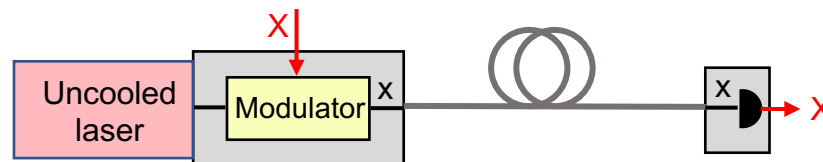
## Coherent



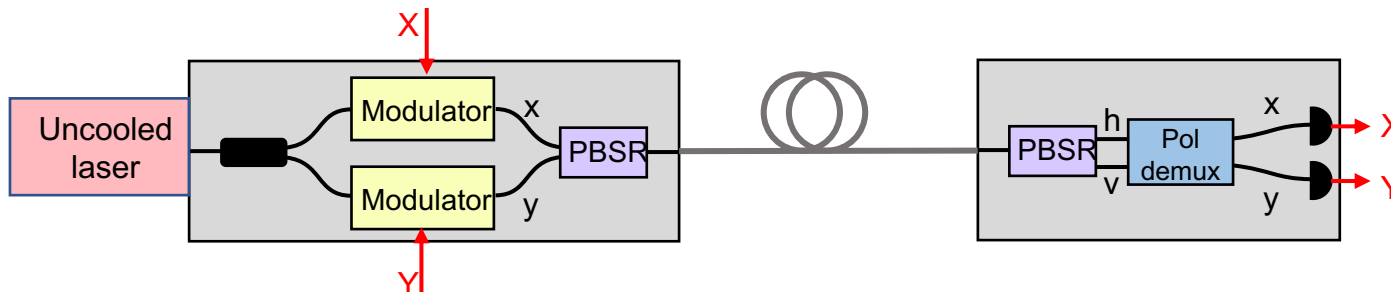
MIMO demux done in digital electronics

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

## IM-DD SP



## DP

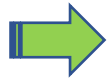


MIMO demux must be done in optics

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

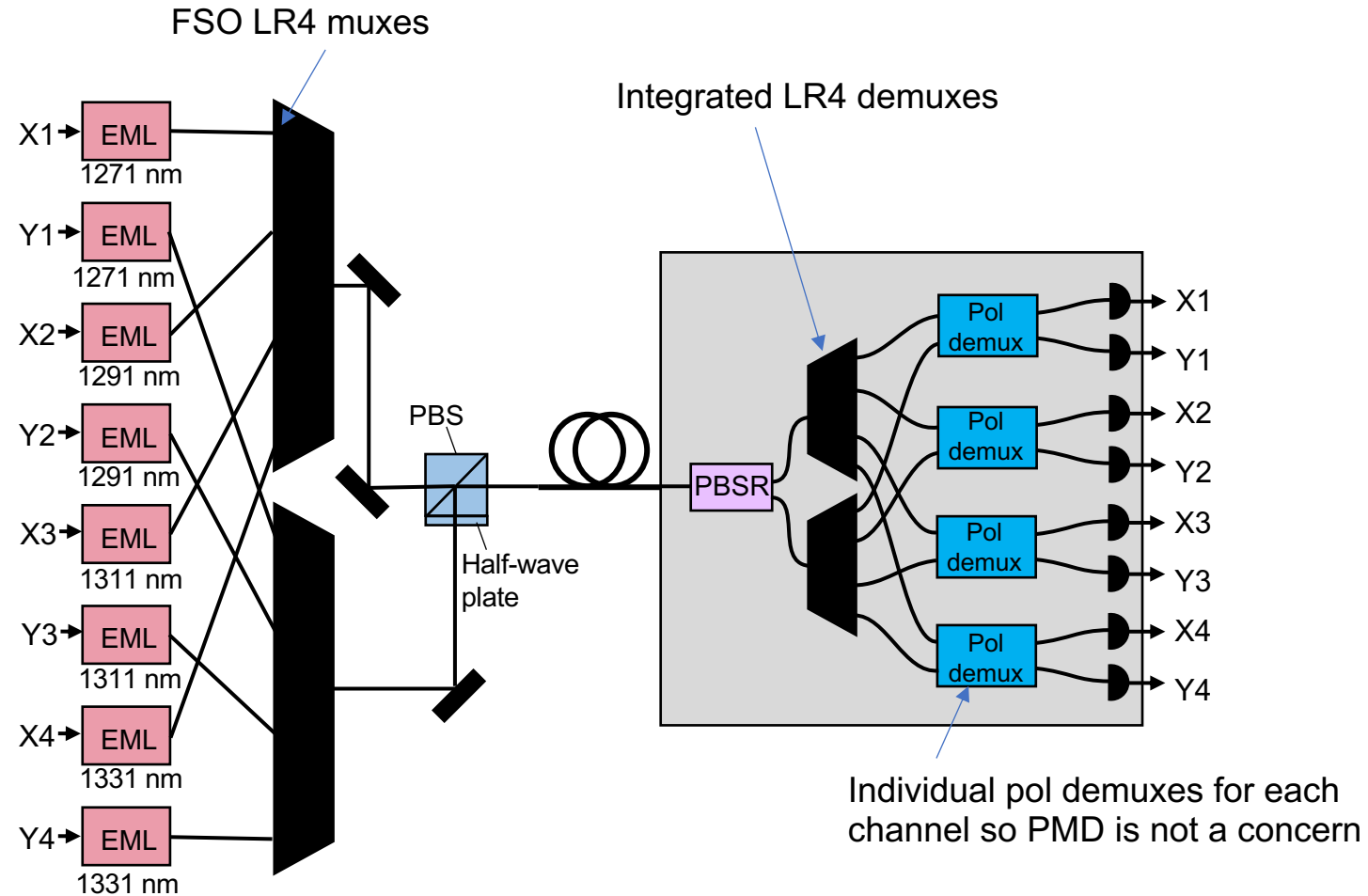
# Some options for 800G LR (10 km)

$\lambda$ qty	$\lambda$ 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								

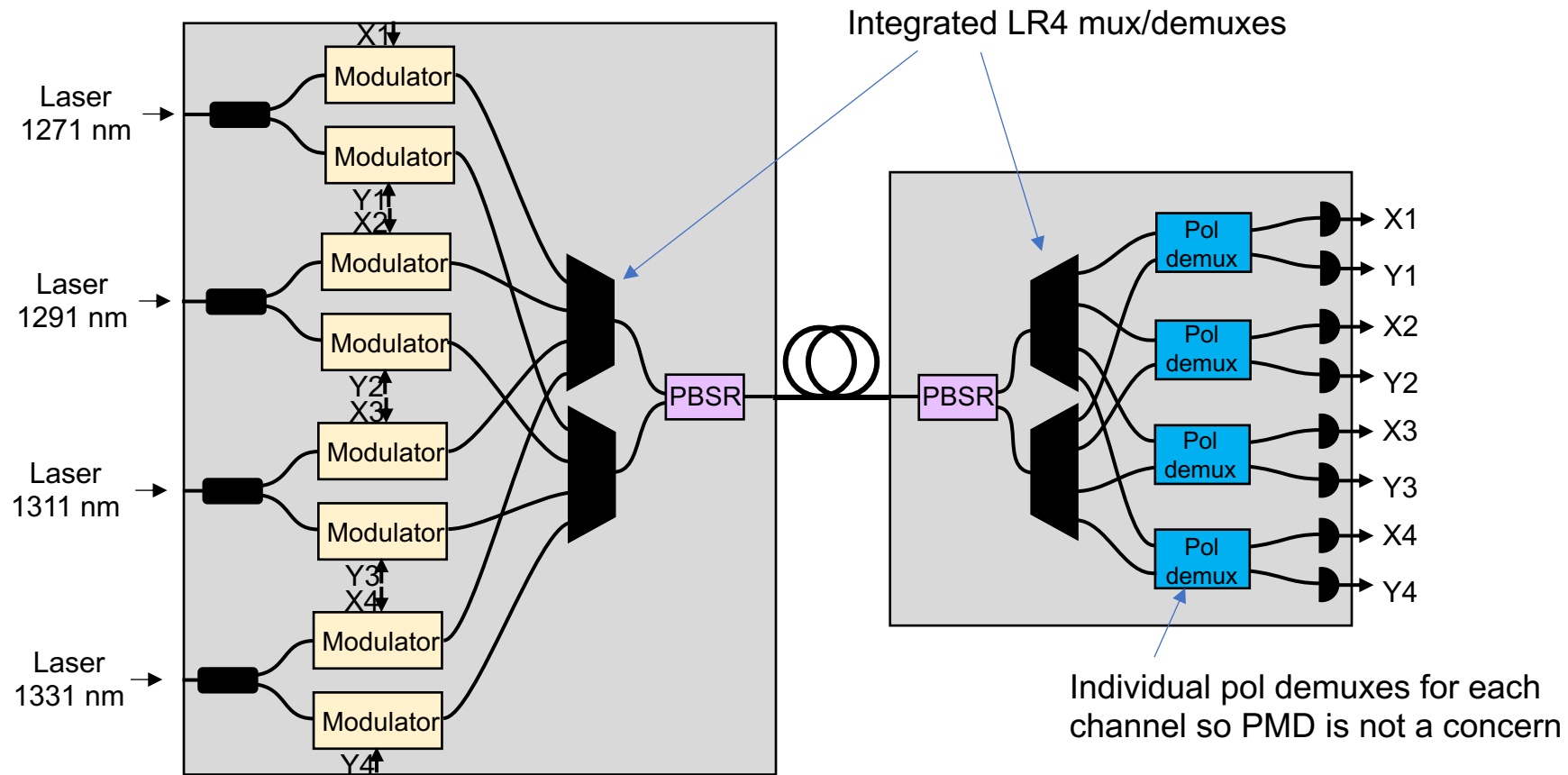


Our proposal

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



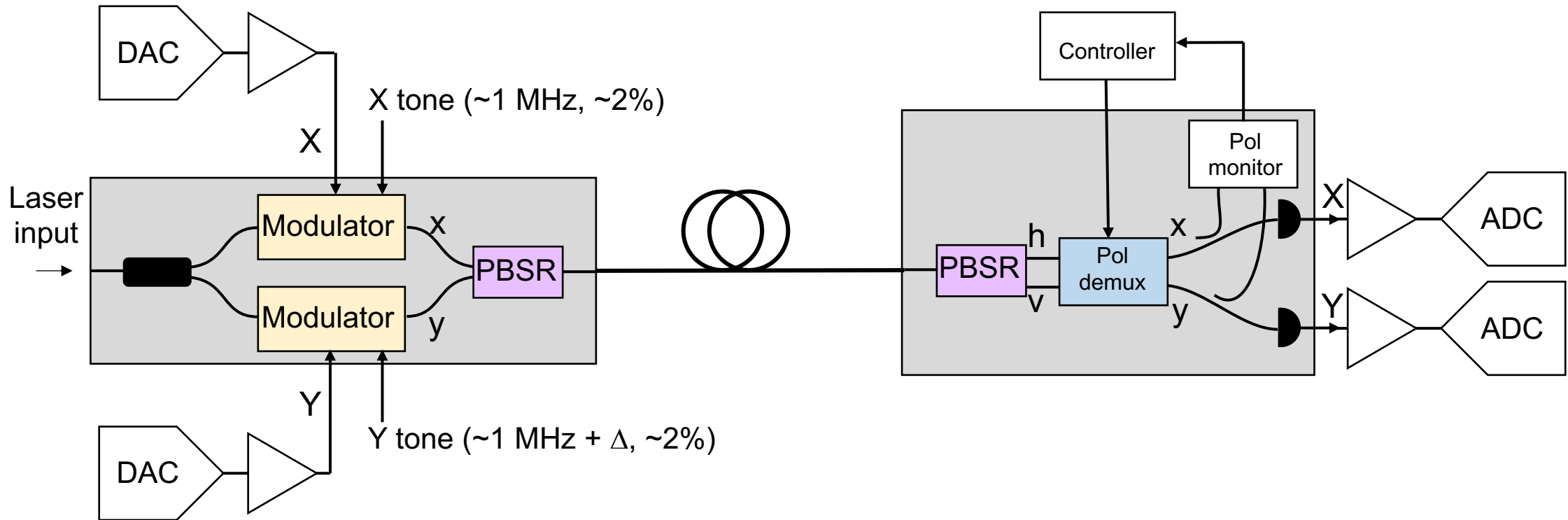
# DP-PAM4 implementation of 800G LR4: SiPh Tx, SiPh Rx





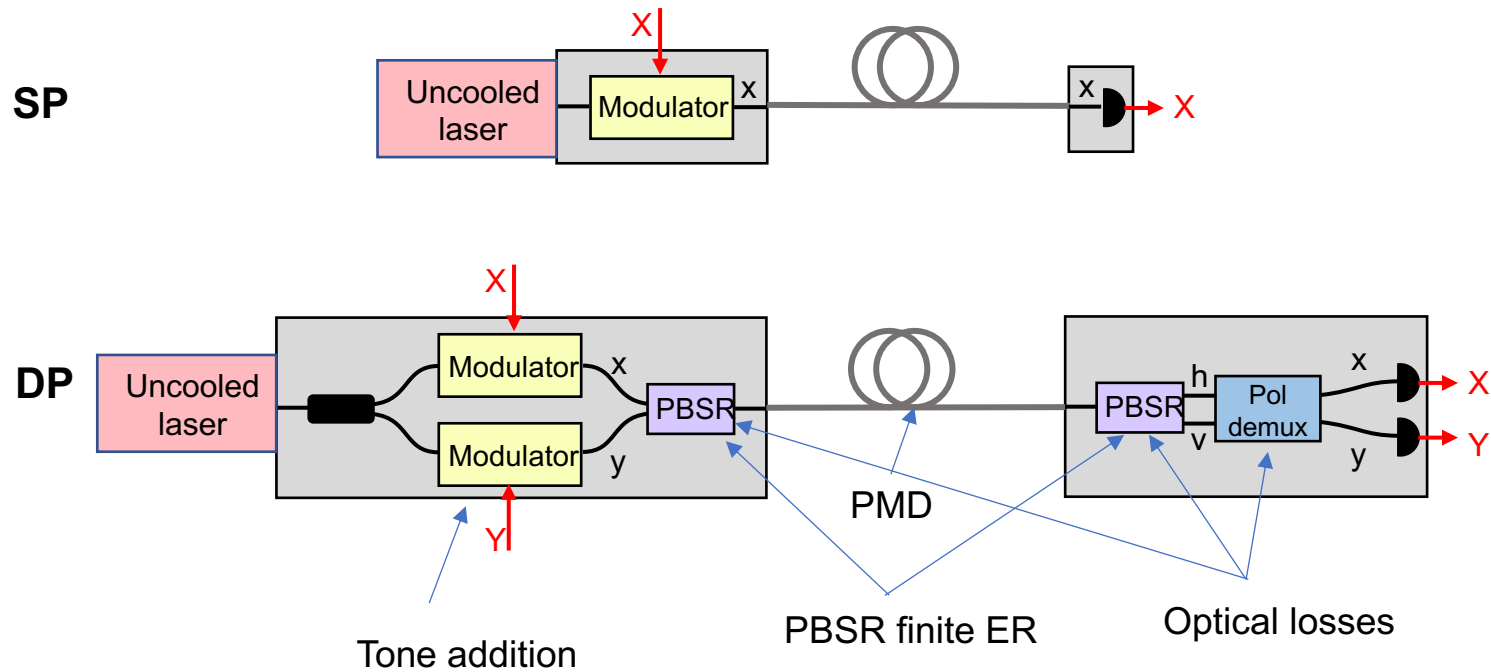
# Marker tones

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.

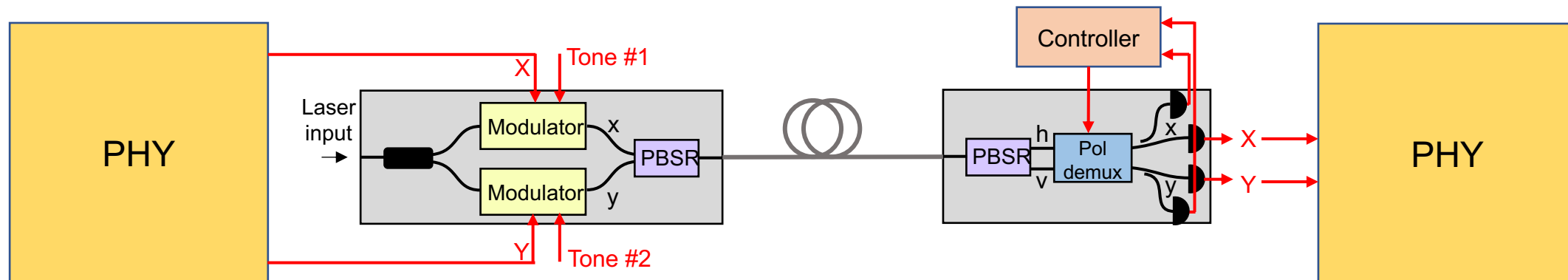


DP system is entirely agnostic to PHY and PCS

# DP penalty assessment



# DP-PAM4 simulation: setup



# PDL compensation

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

$P_{\text{Tx}}$  = Tx rotator, PBS, and output coupling

$F$  = fiber

$P_{\text{Rx}}$  = Rx input coupling, PBS, and rotator

$D$  = MIMO demux

If  $P_{\text{Tx}}$ ,  $F$ , and  $P_{\text{Rx}}$  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

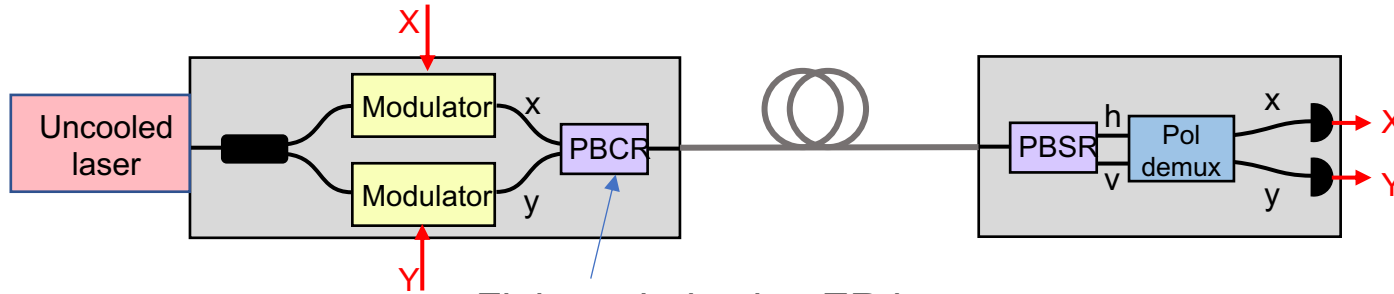
Tone frequency = 1-3 MHz

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

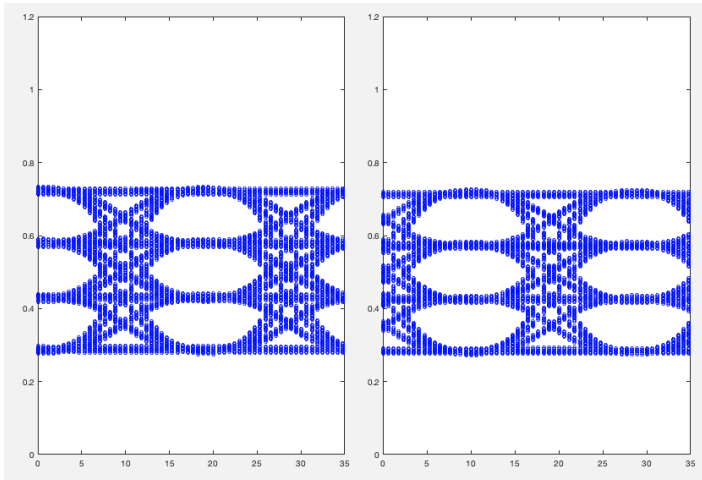


Finite polarization ER here

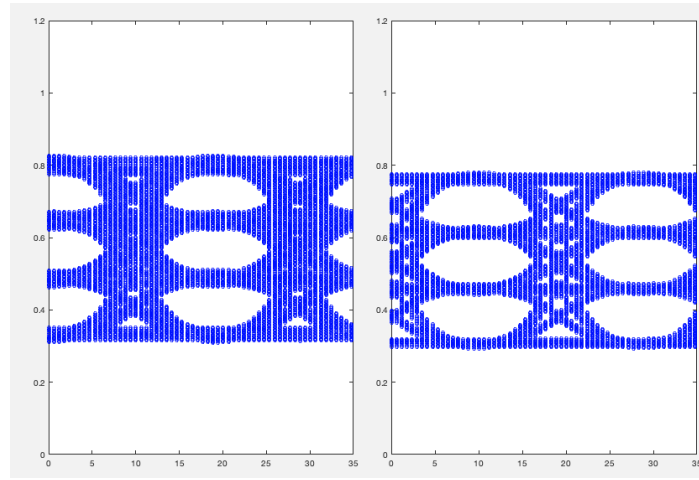
Typical spec. for polarization splitter = 23 dB

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

50 dB ER

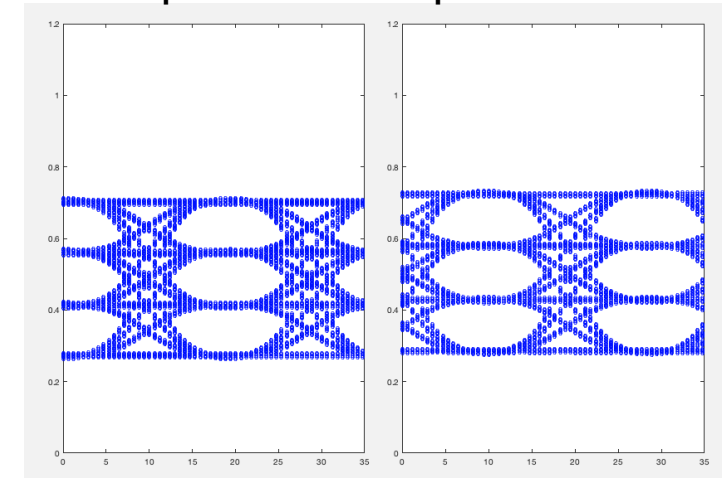


20 dB ER



Penalty ~1.0 dB

20 dB ER w/ PDL  
compensation in pol demux

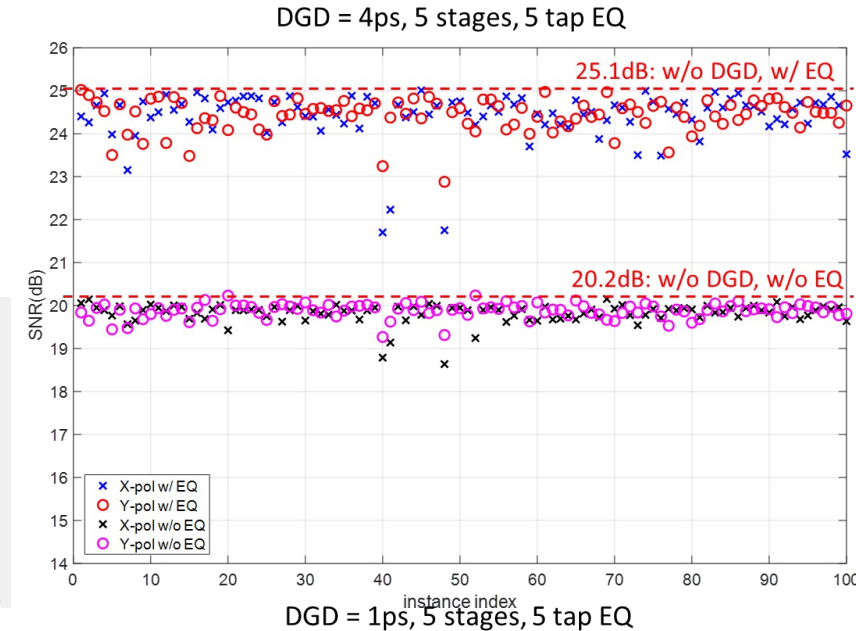
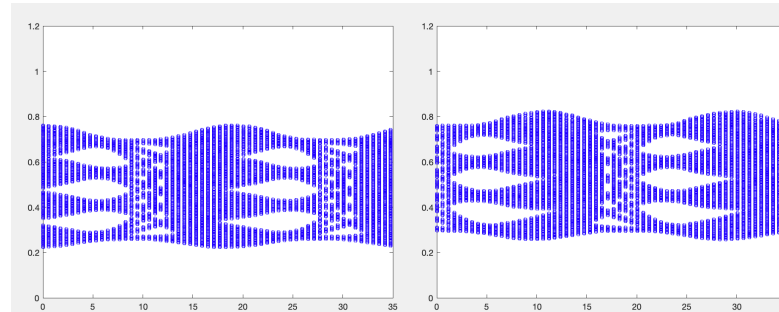


Penalty ~0.0 dB

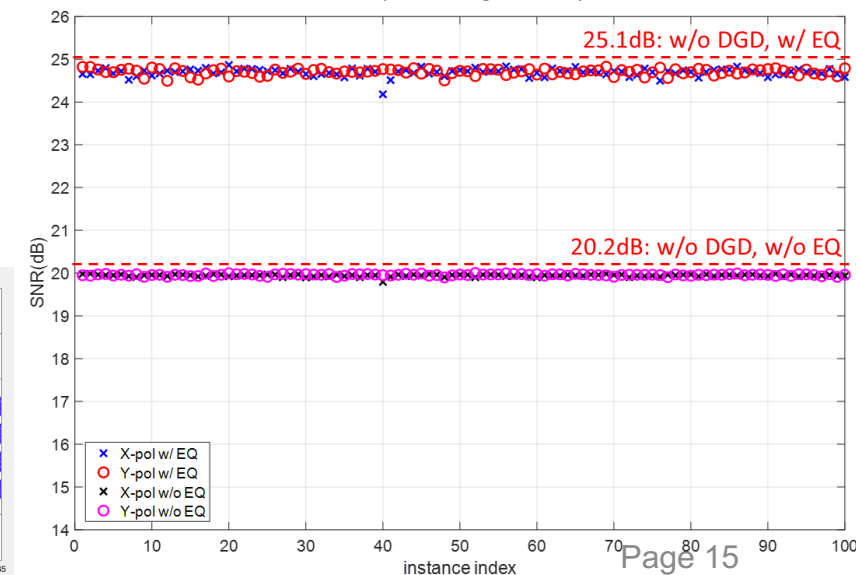
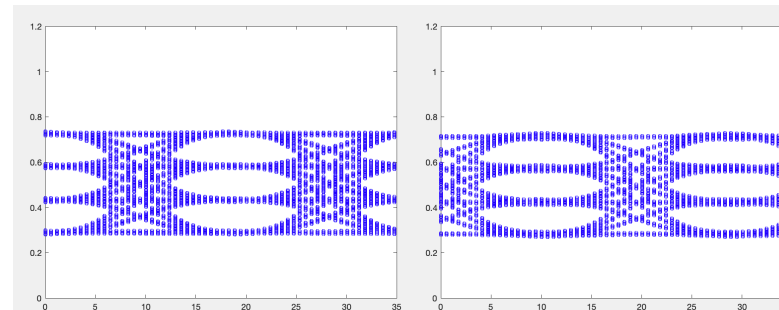
Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Operating distance (max)	2	6	km
Channel insertion loss <sup>a, b</sup> (max)	4	6.3	dB
Channel insertion loss (min)	0	0	dB
Positive dispersion <sup>b</sup> (max)	6.6	19.9	ps/nm
Negative dispersion <sup>b</sup> (min)	-11.7	-35.2	ps/nm
DGD_max <sup>c</sup>	2.3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

IEEE Std 802.3cu-2021

4 ps DGD



1 ps DGD



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

# 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
<b>Total</b>	<b>1.1</b>	<b>0.5</b>	

## Assumptions:

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

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

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
<b>Total</b>	<b>0.6</b>	

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
<b>Total</b>	<b>1.1</b>	<b>1.5</b>	

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

# Total penalties due to DP

## Tx

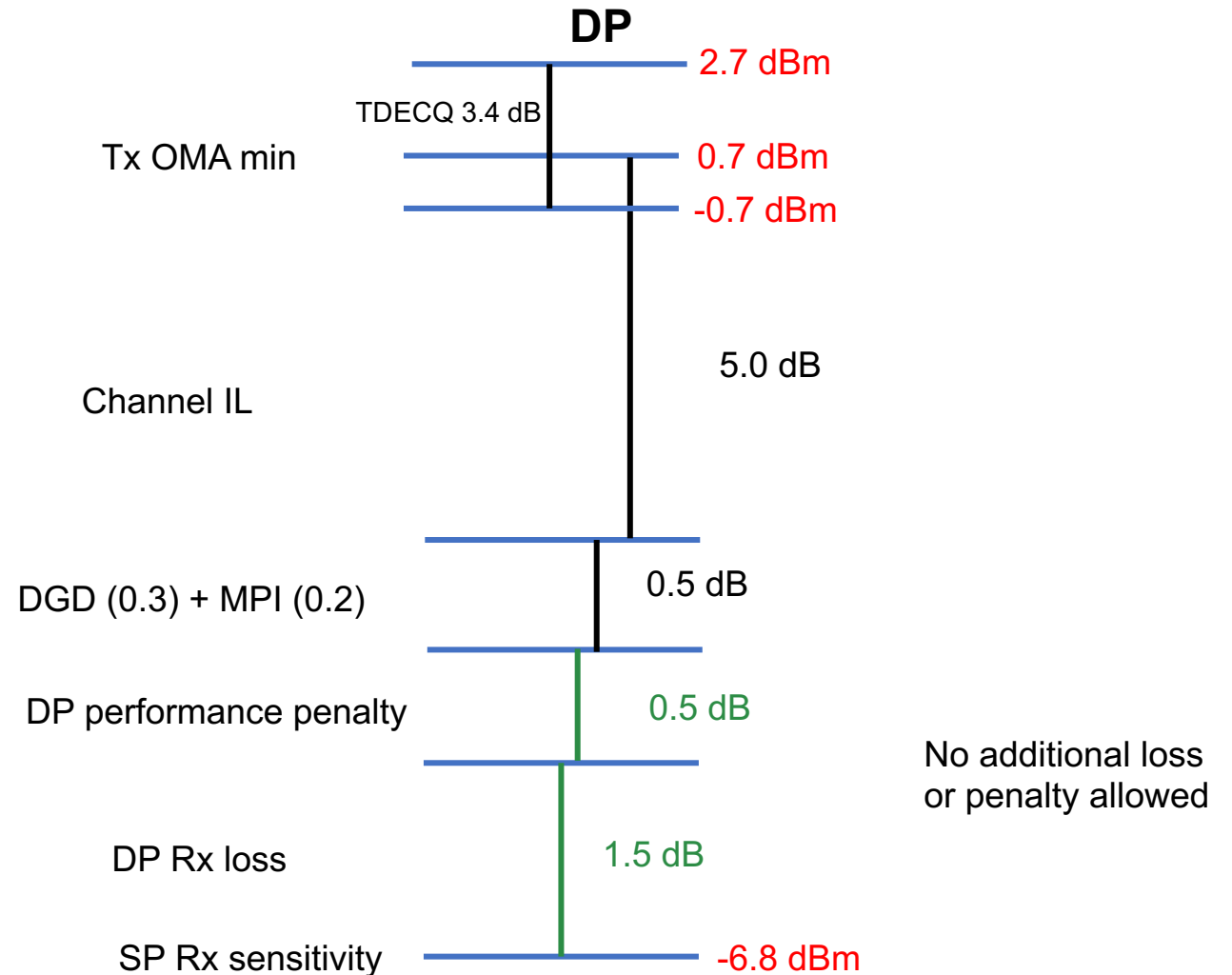
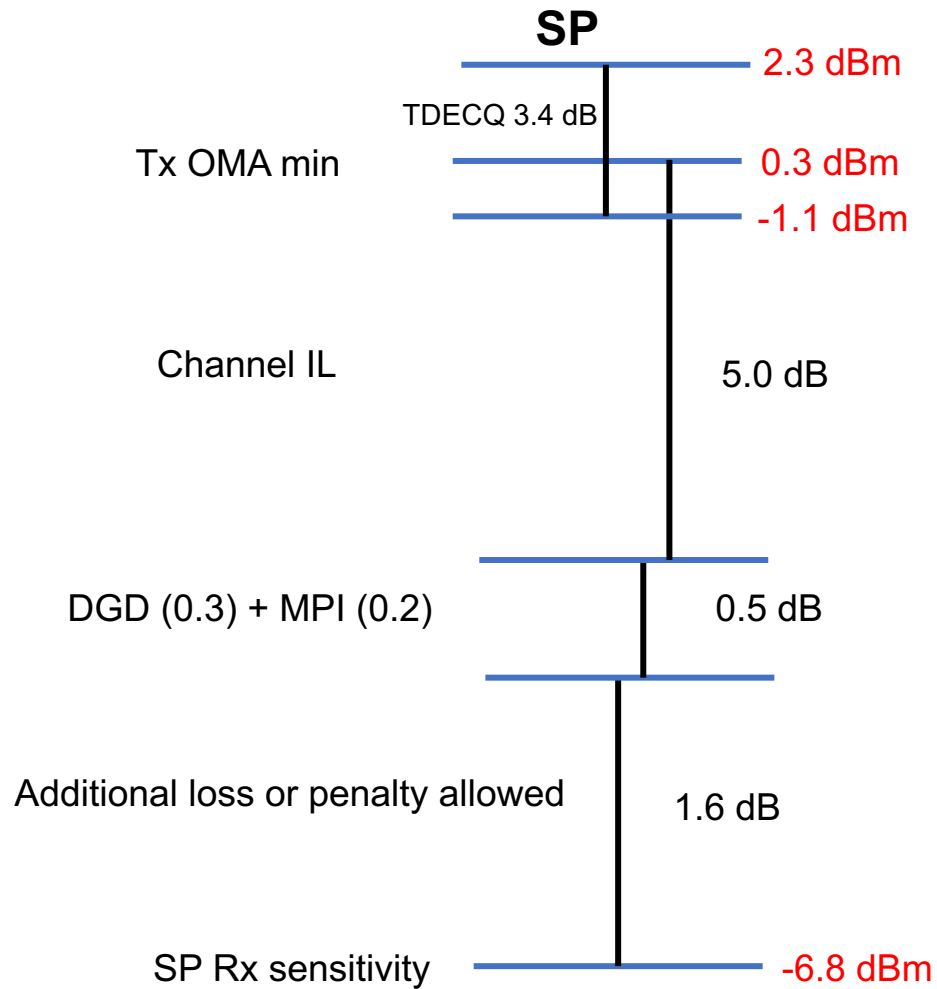
Item	Penalty (dB)
Loss penalty	0.6
<b>Total</b>	<b>0.6</b>

## 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
<b>Total</b>	<b>2.2</b>	<b>2.0</b>

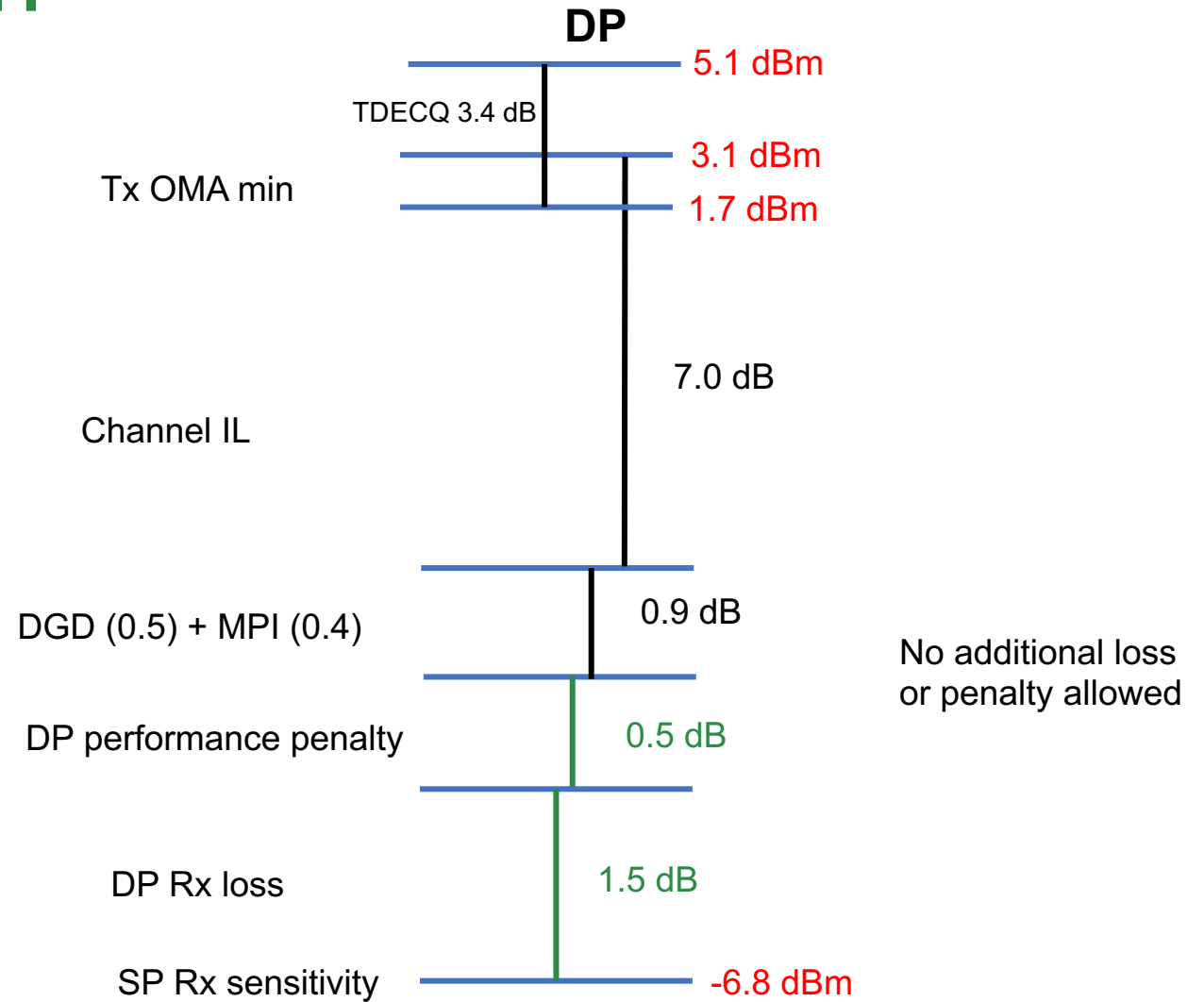
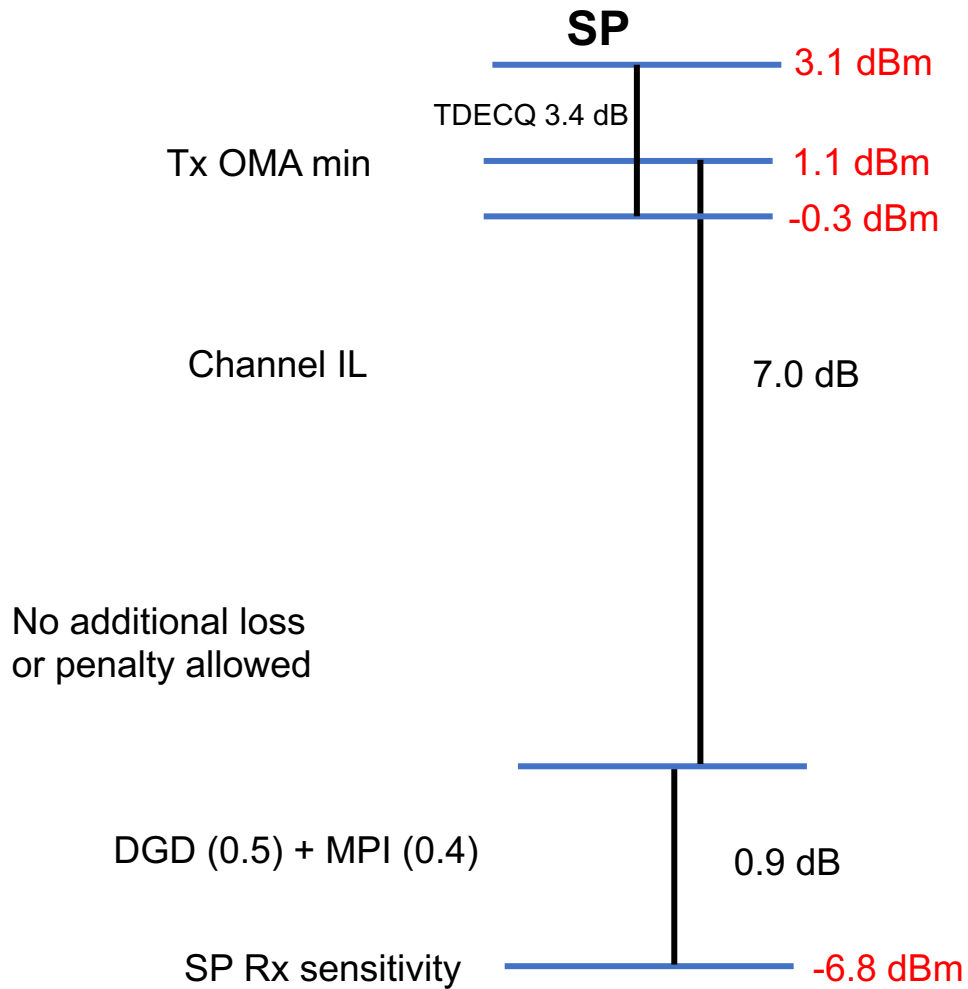
# Link budget for 6 km

Assuming PDL compensation



# Link budget for 10 km

Assuming PDL compensation



# Conclusions

- Performed initial study of DP-PAM4 implementation penalties
- Rx will likely need PDL (non-unitary) compensation
- 6-km link appears reasonable
  - Requires  $\sim 0.4$  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