Technical Feasibility of Single Wavelength 400GbE 2km &10km application

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  - for 400GbE 2km & 10km
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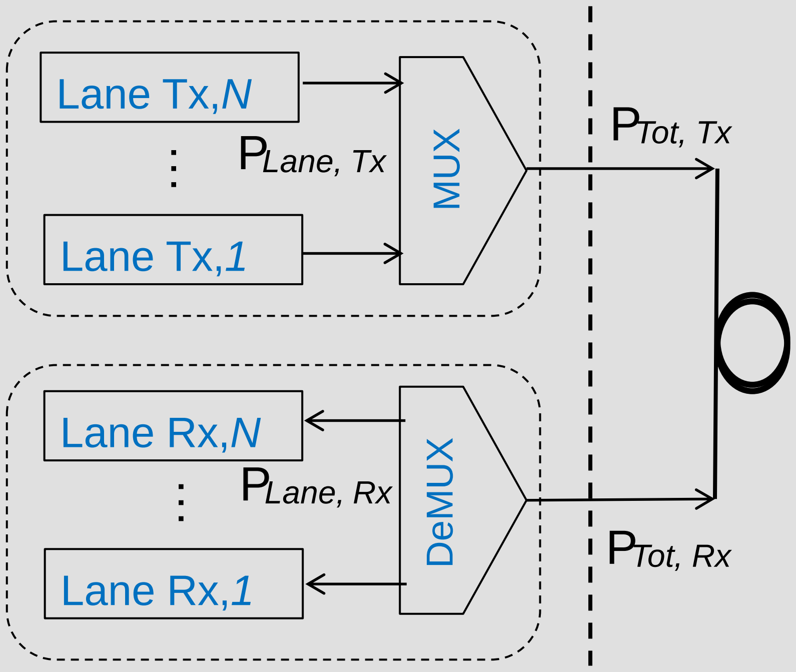
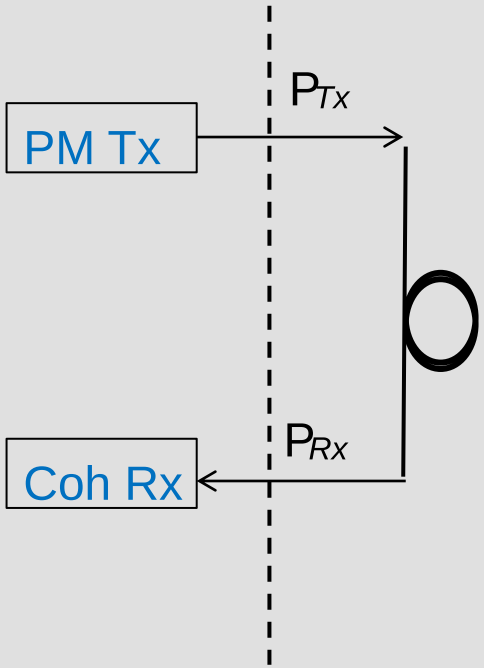
N x 56Gbaud Alternatives for 400GbE 2km

Modulation /Detection	400GbE Scheme	Rx Sensitivity per Lane (intrinsic)	Rx Sensitivity aggregated (extrinsic)
NRZ, IM-DD	8 x56 Gbps	X dBm	X + (9+3) dBm
PAM4, IM-DD	4 x112 Gbps	X+ 4.5 dBm	X+4.5 +(6+1.5) dBm
PM-16QAM, IQ -CohRx	1x 448 Gbps	X- 3 dBm	X-3 dBm





Impact of Rx sensitivity on 400GbE 2km Link budget

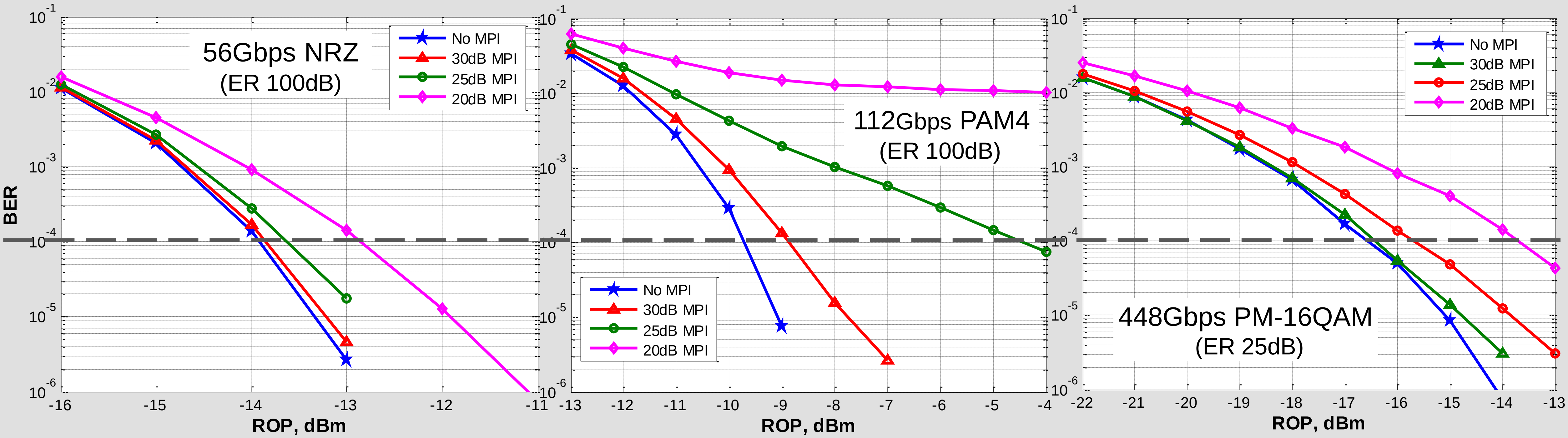
	8 x 56Gbps NRZ	4 x 112Gbps PAM4	1x 448Gbps PM-16QAM
Max Rx Sensitivity per lane, $P_{Lane, Rx}$ (@ BER of $1x10^{-4}$)	**-13.8 dBm**	**-9.8 dBm**	**-16.6 dBm**
DeMUX IL	3 dB	1.5 dB	N/A
Total Margin (for MPI, *etc.*)	2 dB	2 dB	2 dB
SMF 2km Loss Budget	4 dB		
Min Tx Output Power into SMF per Lane	-4.8 dBm	-2.3 dBm	-10.6 dBm
Min Tx Output Power into SMF Aggregated, $P_{tot, Tx}$	**4.2 dBm**	**3.7 dBm**	**-10.6 dBm**
MUX IL	3 dB	1.5 dB	N/A
Min Tx output power per Lane *before* MUX, $P_{Lane, Tx}$	**-1.8 dBm**	**-0.8 dBm**	**-10.6 dBm**

- **Tx parameters:**
  - 3dB BW: 0.75xBaudrate;
  - RIN: -145 dB/Hz;
  - Linewidth: 0.7 MHz for NRZ & PAM4, 0.1 MHz for PM-16QAM;
  - Ideal intensity modulation for NRZ & PAM4;
  - I/Q modulator for PM-16QAM with 25 dB ER (Extinction Ratio)
- **Rx parameters:**
  - 3dB BW: 0.75 x Baudrate
  - Responsibility: 0.85 A/W for NRZ & PAM4; 0.05 A/W for PM-16QAM (incld. ICR IL)
  - Receiver Noise: 30 pA/sqrt(Hz)

Components for Nx 56Gbaud Alternatives

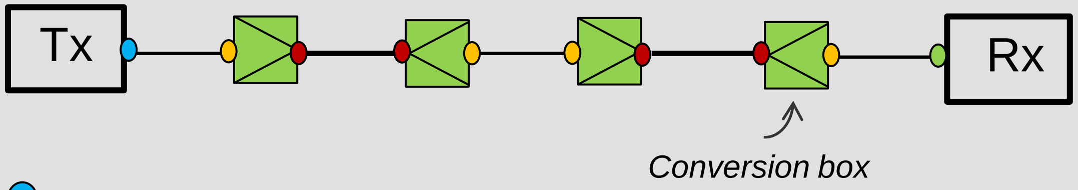
	8 x 56Gbps NRZ	4 x 112Gbps PAM4	1x 448Gbps PM-16QAM
Lasers	8 (DML?) *(can DML still make it at 56Gbaud?)*	4 (EML)	1 (shared LO) (Linewidth ~300kHz)
Modulators	IM in DML or EML	IM in EMLs	PM-IQM
Drivers	8 (limiting)	4 (linear)	4 (linear)
Receivers & TIAs	8 (DD: single-ended pin w/ limiting TIA)	4 (DD: single-ended pins w/linear TIAs)	1 ICR (CohDet: Optical Hybrid, 4 balanced pins w/ linear TIAs)
MUX & DeMUX optics	Yes (8:1 & 1:8) extra loss	Yes (4:1 & 1:4) extra loss	N/A
DSP ASIC (/ASSP)	Not needed (sensitive to residual CD in 1310nm)	Needed (4 A/Ds + DSP) (more tolerant to BW limit, *but* still sensitive to residual CD in 1310nm)	Needed (4 A/Ds + DSP) (more tolerant to BW limit & residual CD in 1310nm)
Scalability	?? (>8 lanes lead to large CD Penalty)	?? (more lanes more MUX/DeMUM IL)	Yes (readily scalable to 1.6TbE)

Modulation Formats & Tolerance to MPI

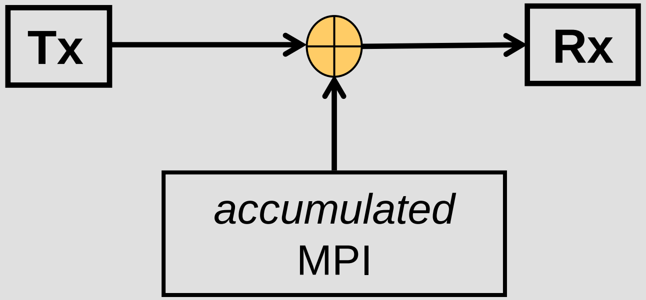


MPI effects modeled as incoherent Xtalk	MPI Power Penalty (@ BER of 1x10^{-4})		
	56Gbps NRZ	**112Gbps PAM4**	**448Gbps PM-16QAM**
-30 dB	0.1 dB	0.8 dB	0.2 dB
-25 dB	0.3 dB	5.6 dB	1 dB

Modeling MPI effect – 2km Link Configuration



- (blue) Tx reflectance: -12 dB
- (yellow) LC to MPO connector reflectance: -26 dB
- (red) MPO to MPO connector reflectance: APC (~ return loss)
- (green) Rx reflectance: -26 dB



$$E(t) = E_S(t) + \sqrt{\varepsilon} E_{MPI}(t)$$

Modeling MPI effect:

- Dominated by the reflection between Tx and other connectors (LC to MPO) as well as Rx;
  - For dual trunk, max total MPI between Tx and other reflection points could be as high as -24dB;
  - Total MPI rms value between Tx and other reflection points, and RX could be ~ -30dB;
- **Total MPI-induced Xtalk could be in the range of -24 ~ -30dB:**
  - The MPI between Tx and the first connector (and also MPI between last connector and Rx) is likely coherent;
  - The MPI between other reflection points are likely incoherent; For 1MHz linewidth, the coherence length is 200m, which corresponds to 100m fiber due to the double pass of MPI;
- **If there is a dirt connector, MPI could shot up. That's why simulation considers 20, 25, and 30dB cases**

Why single wavelength coherent solution for 400GbE 2km & 10km PMD

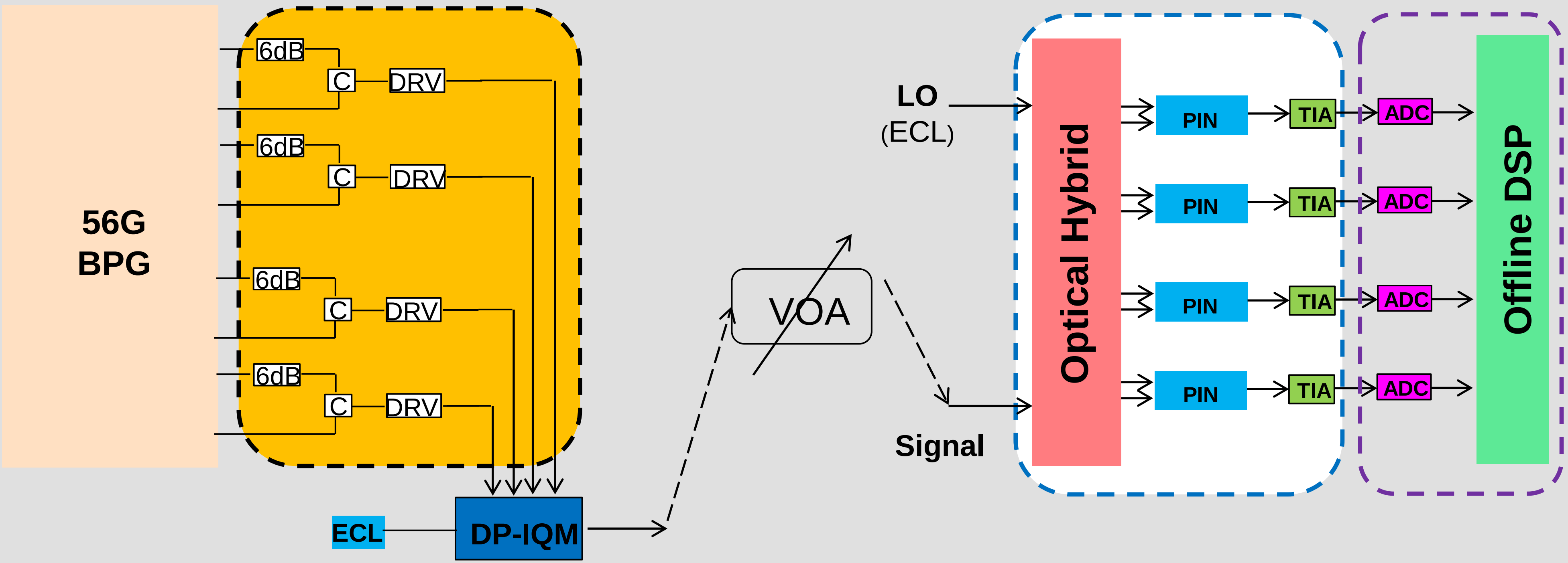
- **High Receiver Sensitivity**
  ~3dB better than NRZ;
  ~7.5dB better than PAM4;
  much less (>10dB less) optical power onto fiber connectors
- **More Tolerant to MPI**
  - slightly worse than NRZ, but much better than PAM4
- **Scalable**
  1x 448Gbps for 400GbE
  4x 448Gbps for 1.6 TbE in the future

1x448Gbps (56Gbaud) PM-16QAM 400GbE 2km &10km Link Budget Estimate

Operating spectral band: 1310 nm	56Gbaud PM-16QAM 400GbE 2km and 10km link budget estimate		
	SMF 2km (shared LO)	SMF 10km (shared LO)	SMF 10km (not shared)
Laser output power	15 dBm	15 dBm	13 dBm
available to Tx / LO	11.5 dBm	11.5 dBm	13 dBm
PM-IQM IL + Modulation Loss	16 dB	16 dB	16 dB
SMF Loss Budget	4 dB	6.3 dB	6.3 dB
Receiving power (@ BER $1x10^{-4}$)	-8.5 dBm	-10.8 dBm	-9.3 dBm
Min Rx Sensitivity, balanced PINs	-15.5 dBm (at LO power 11 dBm)	-15.5 dBm (at LO power 11 dBm)	-16.5 dBm (at LO power 13dBm)
Total Margin	**7 dB**	**4.7 dB**	**7.2 dB**
MPI penalty (@BER $1x10^{-4}$) (at MPI power -25dB)	1 dB	1 dB	1 dB
Margin available for others*	**6 dB**	**3.7 dB**	**6.2 dB**

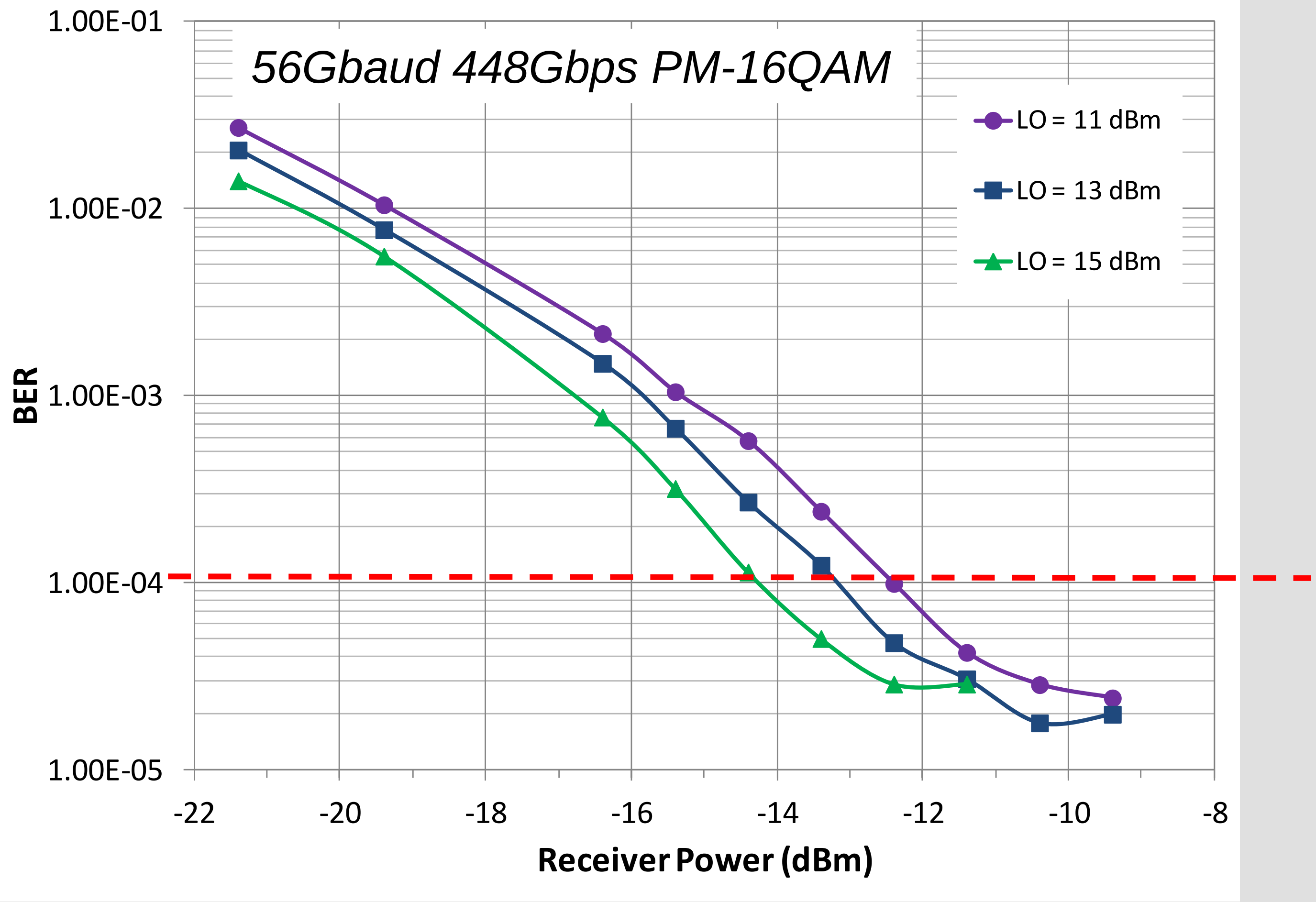
*Potential other penalties such as ASIC implementation, aging, etc.

Preliminary Testbed Verification – Lab Setup



- Tx side: integrated PM-IQM (3dB BW 33GHz) with 4 SHF limiting driver (3dB BW 55GHz) were used in lab setup;
- Rx side: single-ended PINs were used in lab setup. Balanced PINs are preferred for ~3dB better receiver sensitivity;
- ADCs are located inside a 80 GS/s DSO. Offline DSP processing in floating –point was applied for lab verification. Digital compensation of driver nonlinear response is applied.

Preliminary Testbed Verification – Rx Sensitivity Results



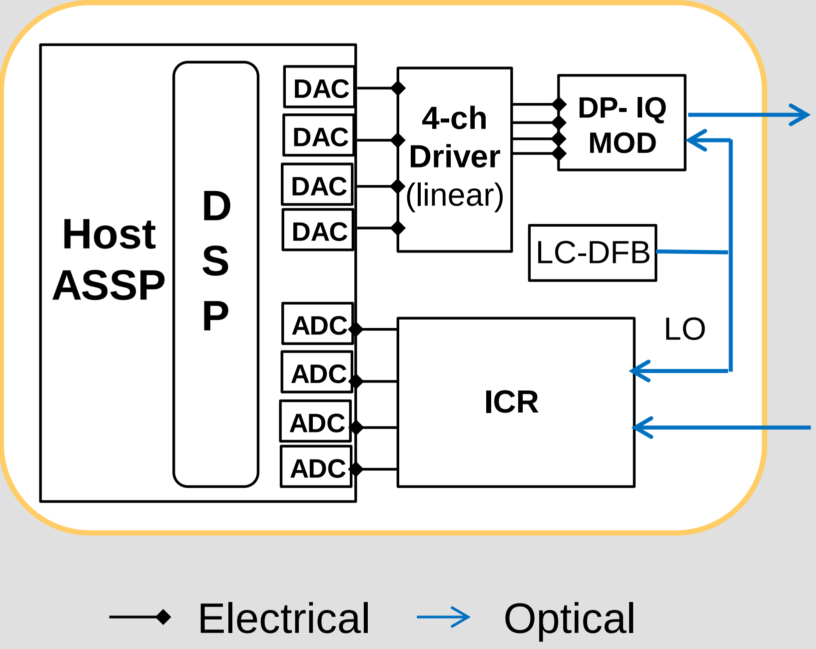
@ moderate LO power 11dBm, Min Rx sensitivity at BER of 1x10^{-4}:

- 12.5 dBm, single-ended PINs

Expected Rx sensitivity with balanced PINs should be 3dB better (*i.e.*, -15.5 dBm).

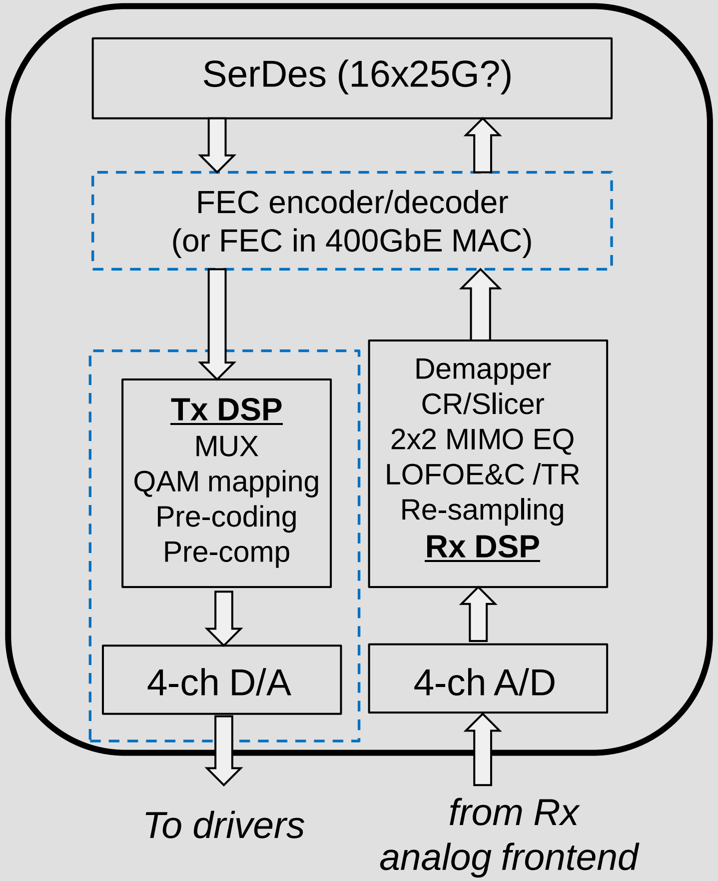
More powerful FEC would be preferred to ease the design requirement of DSP ASIC / ASSP.

Consideration of Components for 1x448Gbaud PM-16QAM for 400GbE Clients



Key O/E Components	Availability	Notes
LC (long cavity)- DFB laser (output 13~15dBm, linewidth 300kHz)	available	ECL (100kHz) is not necessary for 56Gbaud 16QAM
DP-IQM (3dB BW ~ 40 GHz)	Samples available	InP, SiP-based may be preferred for small size
Linear driver (3dB BW ~ 40 GHz)	under development	Linear drivers also needed for 56Gbaud PAM4
ICR (3dB BW ~ 35GHz)	under development	large BW balanced pins are available
High Speed A/D & D/A (ENOB>5bit, sampling > 75GSps)	under development	D/As are not necessary. But if used, Tx component specs (skew, BW) could be relaxed.
DSP ASIC / ASSP	to be specified & developed	Low power version can be designed from the current work for LH. May require some standards work to establish proper handshaking.

Consideration of DSP algorithm for 1x448 Gbps PM-16QAM for 400GbE 2km & 10km



Tx side:

- *D/As are not necessary. A 16:8 gear box could be used instead and QAM symbols may be formed in analog domain, too; However*
- Tx DSP plus DACs could be useful for pre-equalization, spectral shaping, and skew control, in order to relax Tx components specs;

Rx side:

- *Since in1310nm, separate CD compensation block may not be needed; Residual CD could be compensated in MIMO FIR;*
- 2x2 complex MIMO FIR is for polarization tracking and demultiplexing;
- *While polarization separation can be done blindly using constrained CMA, training would be needed to resolve phase ambiguity;*
- One way to avoid training is to use differential pre-coding, and pay a diff coding penalty. Penalty is small at BER of $1x10^{-4}$;
- *However, considering potential implementation penalties, stronger FEC with higher perFEC BER limit above $1x10^{-3}$ should be actively considered;*
- Both pre-data training and in data training have been considered in other standards, and could be considered here too.

Summary

- ✓ **Technical feasibility of Nx56Gbaud alternatives for 400GbE 2km /10km are analyzed, with simulation data, in terms of**
  - intrinsic & extrinsic Rx sensitivities, and aggregated power to SMF;
  - MPI tolerance - ***PAM4's poor tolerance to MPI should be taken seriously***
  - Scalability

Modulation Generation/Detection	400GbE Scheme	Max Rx Sensitivity/Lane (@ BER 1x10^{-4})	Required Min Power Aggregated onto fiber (after MUX)	Tolerance to MPI	Scalability to TbE
NRZ, IM-DD (*ideal ER*)	8 x56 Gbps	-13.8 dBm/Lane	4.2 dBm	Excellent	??
PAM4, IM-DD (*ideal ER*)	4 x112 Gbps	-9.8 dBm/Lane	3.7 dBm	Very poor	??
PM-16QAM, IQ –CohRx (*ER 25dB*)	1x 448 Gbps	-16.6 dBm	-10.6 dBm	Good	Yes

- ✓ **Link budget of 1x448Gbps PM-16QAM 400GbE 2km & 10km are estimated using simulation and testbed data;**
- ✓ **Considerations of component availability and DSP algorithm are provided**

THANK YOU