Component BW requirement of 56Gbaud Modulations for 400GbE 2 & 10km PMD

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Fei Zhu, Yangjing Wen, Yusheng Bai
Huawei US R&D Center
Santa Clara, CA 95050

Outline

- **Introduction – recap from May interim**
- **Update on *N*x 56Gbaud alternatives**
  - *Sensitivity & Tolerance to MPI, w/ realistic ER*
- **BW requirement of *N*x 56Gbaud Alternatives**
- **Summary**

Readings from the straw polls of May 16 Norfolk Interim

- **SMF duplex is clearly preferred for 400GbE 2km and 10km** *(Stassar_01_0614)*

4A. I believe that 2km 400GbE SMF PMD will use a duplex fiber solution

Yes: 70 No: 6

4B. I believe that 10km 400GbE SMF PMD will use a duplex fiber solution

Yes: 85 No: 0

- **less number of optical carriers is clearly preferred for 400GbE 2km and 10km**

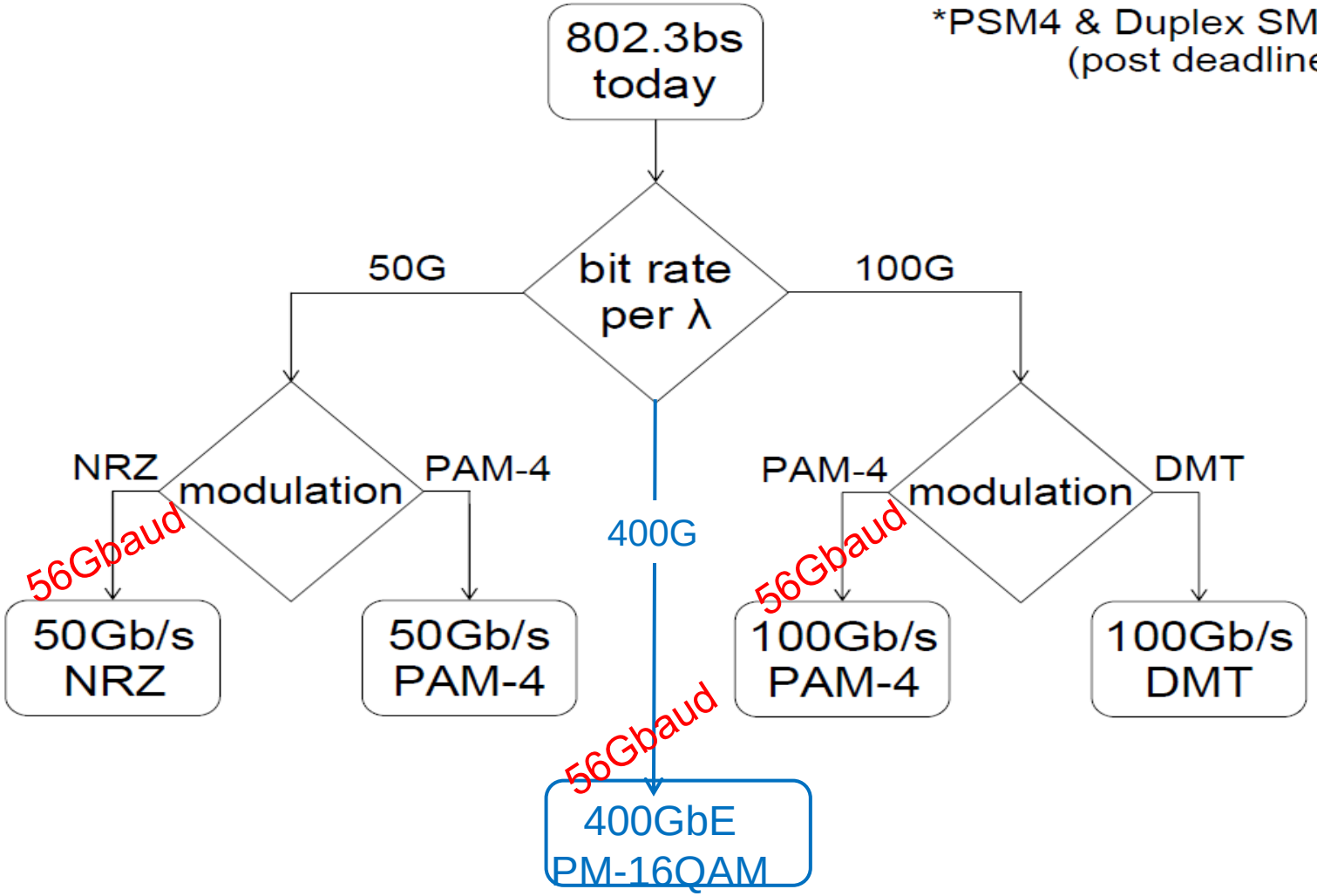
5. For 2km duplex SMF 400GbE PMD, I believe the TF should select a proposal based on an effective bit rate per wavelength per direction of

a) 25G: 5; b) 50G: 51; c) 100G: 77; d) 400G: 10

6. For 10 km duplex SMF 400GbE PMD, I believe the TF should select a proposal based on an effective bit rate per wavelength per direction of

a) 25G: 5; b) 50G: 53; c) 100G: 74; d) 400G: 11

The 400GbE 2km and 10km PMD candidates



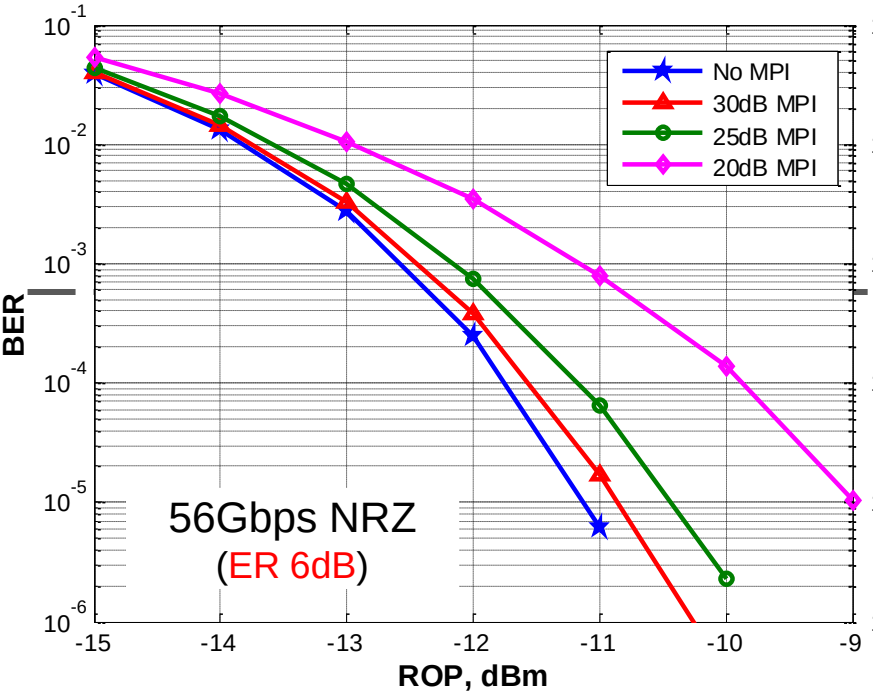
Notes:

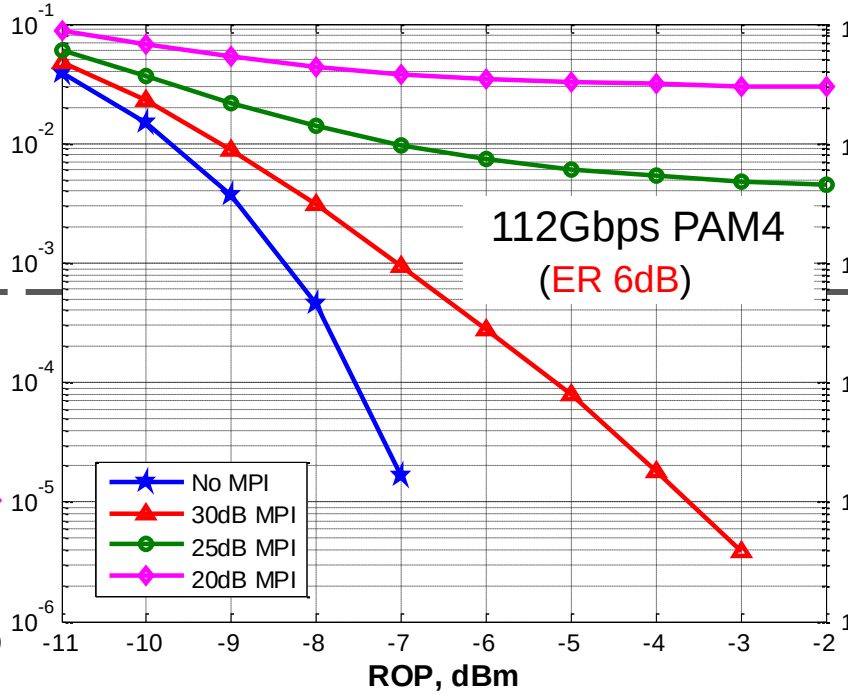
1) "the Decision tree" (in black) from:
   Cole_3bs_01a_0514

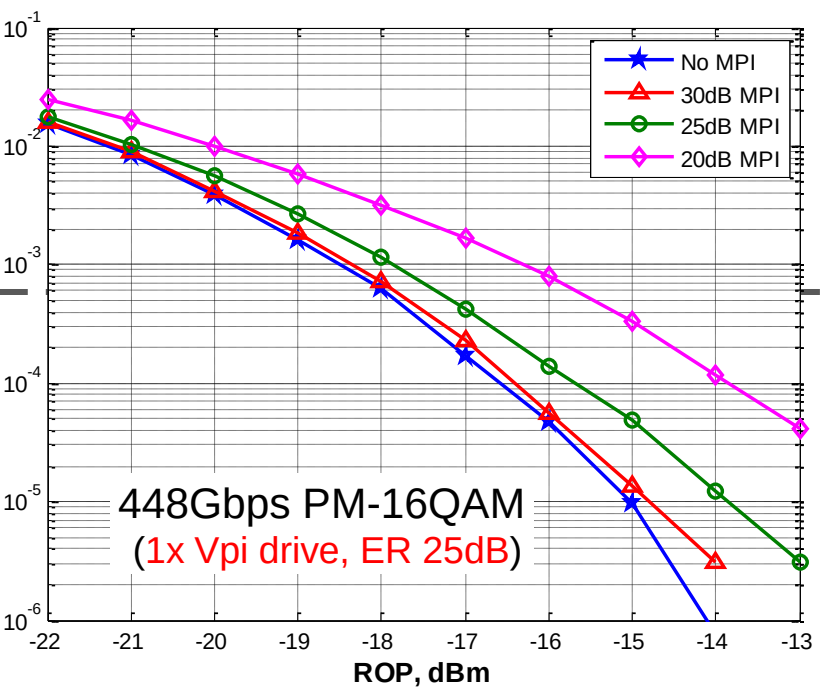
2) 400G per λ PM-16QAM option (in blue) is proposed in
   Zhu_3bs_0X_0514

3) Symbol rate (in red) is added to highlight the focus of this presentation --- Tx and Rx BW requirement of Nx56Gbaud 400GbE alternatives

*N*x 56Gbaud Alternatives: Sensitivity & Tolerance to MPI



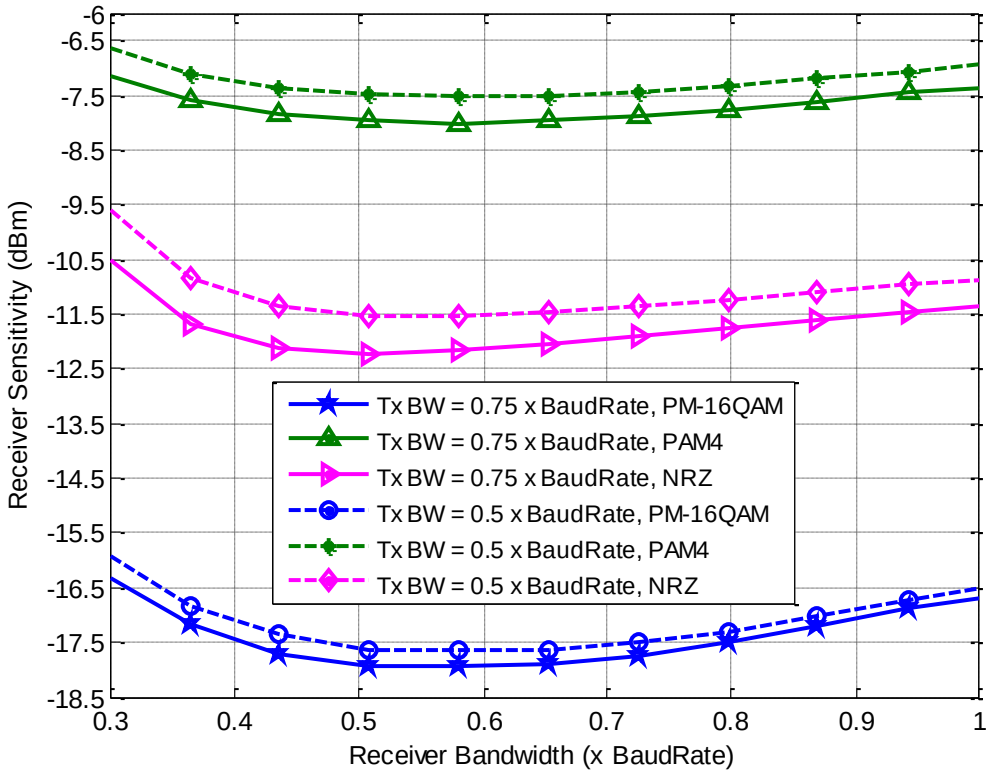




	Rx Sensitivity (@ BER of 1e-3, Tx/Rx 3dB BW=0.75x Baudrate, 5th order Bessel)		
	56Gbps NRZ	**112Gbps PAM4**	**448Gbps PM-16QAM**
No MPI	-12.6 dBm	- 8.4 dBm	- 18.4 dBm
-30dB MPI	-12.5 dBm	- 7.1 dBm	-18.3 dBm
-25 dB MPI	- 12.2 dBm	?	- 17.9 dBm

The difference from *Zhu_3bs_0X_0514: realistic ER of 6dB is applied in simulation for IM format NRZ and PAM4.*

*N*x 56Gbaud Alternatives: Dependence on Rx BW

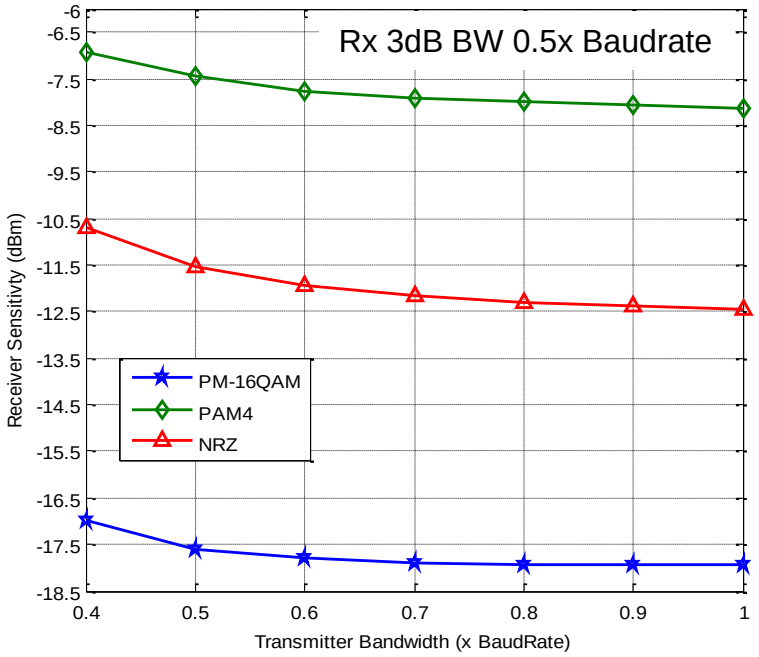


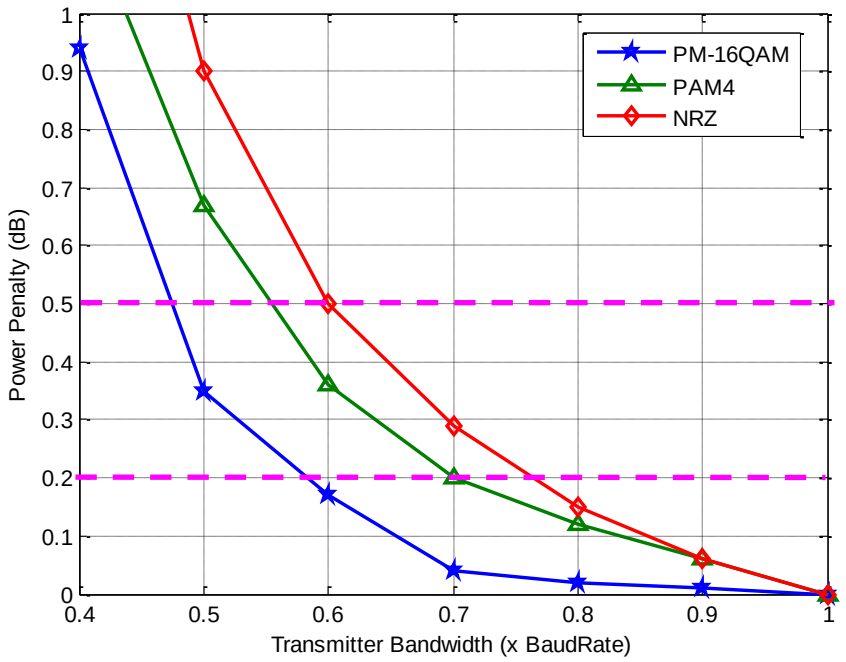
Observations:

- **Given a Tx BW, an optimal receiver bandwidth exists for each format;**
- **Optimal Rx BW for PM-16QAM, PAM4 and NRZ are similar: ~ 0.5x Symbol rate** *(i.e., 3dB BW 28GHz),* **whether Tx 3dB BW is set at 0.75x or 0.5x BaudRate;**
- **PM-16QAM is less sensitive to Tx BW, due to the nature of phase modulation.**

- **Dashed lines: Tx 3dB BW (5th order Bessel) setting = 0.5x Baudrate, (***or* 28GHz**);**
- **Solid lines: Tx 3dB BW setting = 0.75x Baudrate , (***or, 42GHz***)**

Nx 56Gbaud Alternatives: Impact of Tx BW





Notes:

1) At optimal Rx BW of 0.5x Symbol rate (*i.e.*, 28GHz);
2) Rx sensitivity is defined @ BER 1e-3;
3) Power Penalty (PP) is referenced to Tx 3dB BW of 1x Baudrate;
4) No Rx EQ is applied in case of NRZ;
5) No Tx pre-emphasis in all formats considered.

***Nx* 56Gbaud Alternatives**	**Required Tx BW** (@ Rx 3dB BW = 0.5x Baudrate)	
	@ 0.2dB PP	@ 0.5dB PP
448 Gbps PM-16QAM	0.58x (*or* 32 GHz)	0.47x (*or* 26 GHz)
112 Gbps PAM4	0.70x (*or* 39 GHz)	0.56x (*or* 31 GHz)
56 Gbps NRZ (No Rx EQ)	0.76x (*or* 43 GHz)	0.60x (*or* 34 GHz)

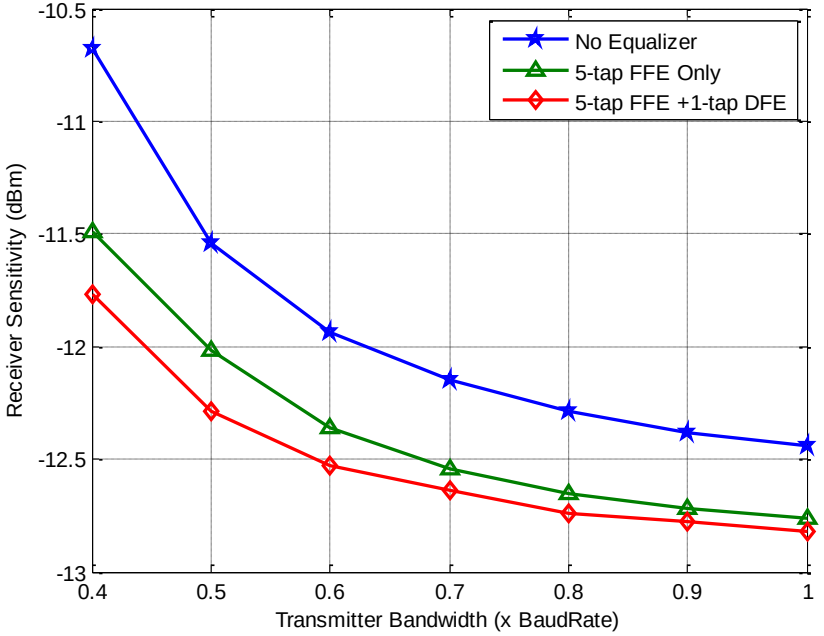
Transmitter BW decomposed

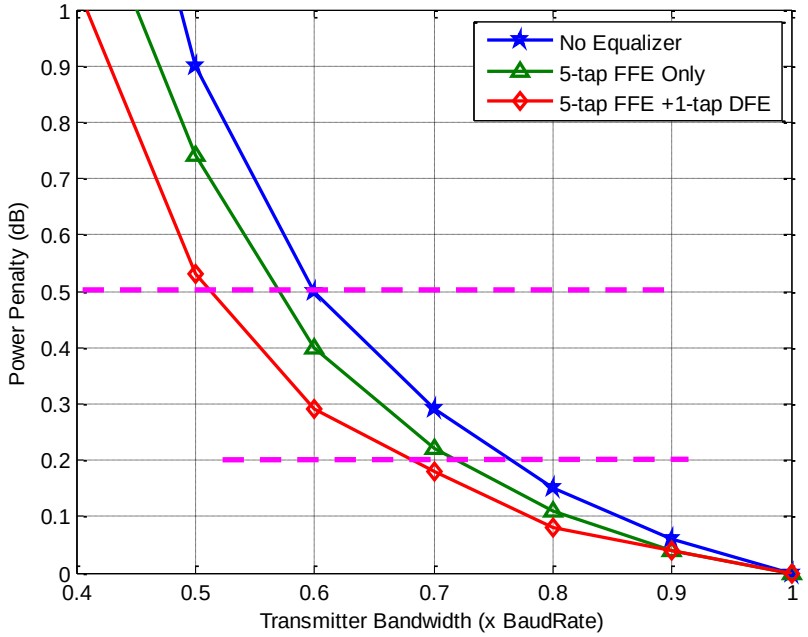
Power Penalty assumed	Nx 56Gbaud 400GbE alternatives	Total Tx 3dB BW (5th order Bessel)	Decomposed component 3dB BW (each component assumed 3rd order Bessel filter, at equal contribution)	
			Driver	Modulator
0.2 dB	448 Gbps PM-16QAM	32 GHz	45 GHz	45 GHz
	112 Gbps PAM4	39 GHz	54 GHz	54 GHz
	56 Gbps NRZ (no EQ)	43 GHz	59 GHz	59 GHz
0.5 dB	448 Gbps PM-16QAM	26 GHz	36 GHz	36 GHz
	112 Gbps PAM4	31 GHz	43 GHz	43 GHz
	56 Gbps NRZ (no EQ)	34 GHz	46 GHz	46 GHz

- **The above assumes no Tx analog or digital BW pre-emphasis, so it is a baseline of the fundamental property of modulation formats;**
- **It is possible to reduce component BW requirement with digital or analog pre-emphasis. However, pre-emphasis could boost noise, and increase linearity requirement, *in particular,* for PAM4 and 16QAM;**

Pre-emphasis can be quite useful. But proper noise & distortion model need to be established for proper assessment.

8x 56Gbaud NRZ: Role of Rx EQ





Notes:

1) At optimal Rx BW of 0.5x Symbol rate (*i.e.*, 28GHz);
2) Rx sensitivity is defined @ BER 1e-3;
3) Power Penalty (PP) is referenced to Tx 3dB BW of 1x Baudrate;
4) No Tx pre-emphasis is applied.

8x 56Gbaud NRZ	**Required Tx BW** (@ Rx 3dB BW = 0.5x)		Tx 3dB BW Decomposed (0.5dBpp, @ Rx 3dB BW=0.5x)	
	@ 0.2dB PP	@ 0.5dB PP	driver	modulator
No Rx EQ	0.76x (*or* 43 GHz)	0.60x (*or* 34 GHz)	46 GHz	46 GHz
5-tap FFE only	0.72x (*or* 40 GHz)	0.57x (*or* 32 GHz)	44 GHz	44 GHz
5-tap FFE + 1-tap DFE*	0.68x (*or* 38 GHz)	0.51x (*or* 29 GHz)	40 GHz	40 GHz

Simulation Parameters

	448Gbps PM-16QAM	**112Gbps PAM4**	**56Gbps NRZ**	*Lyubomirsky_400_01_1113*
Tx:				
RIN	-145 dB/Hz			- 140 dB/Hz
ER	25 dB (IQ)	6 dB (IM)		4 dB
Laser LW	0.1 MHz	0.7 MHz		Not available (not important)
3dB BW	*Variable* to find minimum required @ 0.2 / 0.5dB PP			16 GHz
Filter shape	5^{th} order Bessel			4^{th} order Bessel
Rx:				
3dB BW	0.75x & 0.5x Baudrate			0.75x Baudrate
Filter shape	5^{th} order Bessel (PIN + TIA)			4^{th} order Bessel
Responsibility	0.05 A/W (Cohdet)	0.85 A/W (DD)		0.4 A/W
Rx noise	30 pA/sqrt (Hz)			18 pA/sqrt (Hz)
LO LW/Power	0.1 MHz / 13dBm	N/A		N/A
Rx EQ	9-tap MIMO FIR	9-tap SISO FIR	None/5-tap FFE/ 5-tap FFE+1-tap DFE	None/5-tap FFE /5-tap FFE+1-tap DFE

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 PIN w/linear TIA)	1 ICR (CohDet: Optical Hybrid, 4 balanced PIN w/ linear TIA)
MUX & DeMUX optics	Yes (8:1 & 1:8) extra loss	Yes (4:1 & 1:4) extra loss	N/A
Rx EQ*	May be needed (to reduce Tx BW requirement)	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)

* Essentially the same table from *Zhu_3bs_0X_0514, slightly updated (in red)*

Summary

- **Tx 3dB BW required (likely) of Nx 56Gbaud candidates are analyzed via simulation.**

Modulation Generation/Detection	**400GbE Options**	**Max Rx Sensitivity/λ** (-30dB MPI, @ BER 1X10^{-3})	**Required Tx 3d BW** (@ Rx 3dB BW=0.5x)	**Tx 3dB BW decomposed**	
				driver	modulator
NRZ, IM-DD (*ER=6dB*)	8 x 56 Gbps	-12.3 dBm/Lane	32GHz (5-tap FFE)	44 GHz	44 GHz
PAM4, IM-DD (*ER=6dB*)	4 x 112 Gbps	-6.6 dBm/Lane	31GHz (9-tap SISO)	43 GHz	43 GHz
PM-16QAM, IQ –CohRx *(1x Vpi drive, ER 25dB)*	1x 448 Gbps	-17.8 dBm	26GHz (9-tap MIMO)	36 GHz	36 GHz

This is not to define the specs for Tx or Rx BW, rather to clarify some “myth” about component BW requirement for Nx 56Gbaud 400GbE alternatives, and some “myth” around power consumption.

- **More investigations are needed to understand how much pre-emphasis or Rx EQ would help to reduce component BW requirement before specification can be reached;**
- **The role of EQ in Tx /Rx would have direct impact on power, and would have direct impact on component cost too.**

THANK YOU