PAM Modulation for 400G SMF

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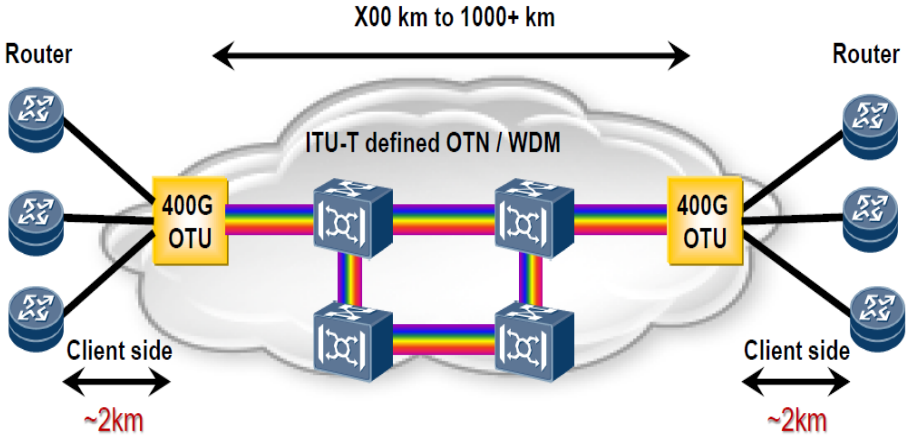
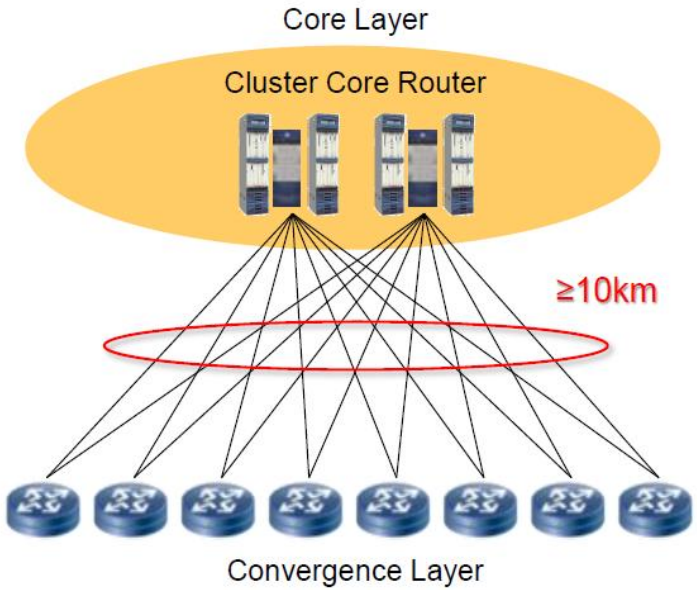
400GE Reach Objectives

- IEEE 400G SMF has 3 reach objectives 500m, 2km, 10km
  - 2km - 10km, Client Optics, 6.3dB link loss budget
  - 500m – 2km, Inside Data Center, 4dB link loss budget
  - 1, 2 or 3 PMDs?

400G 2km - 10km Client Optics





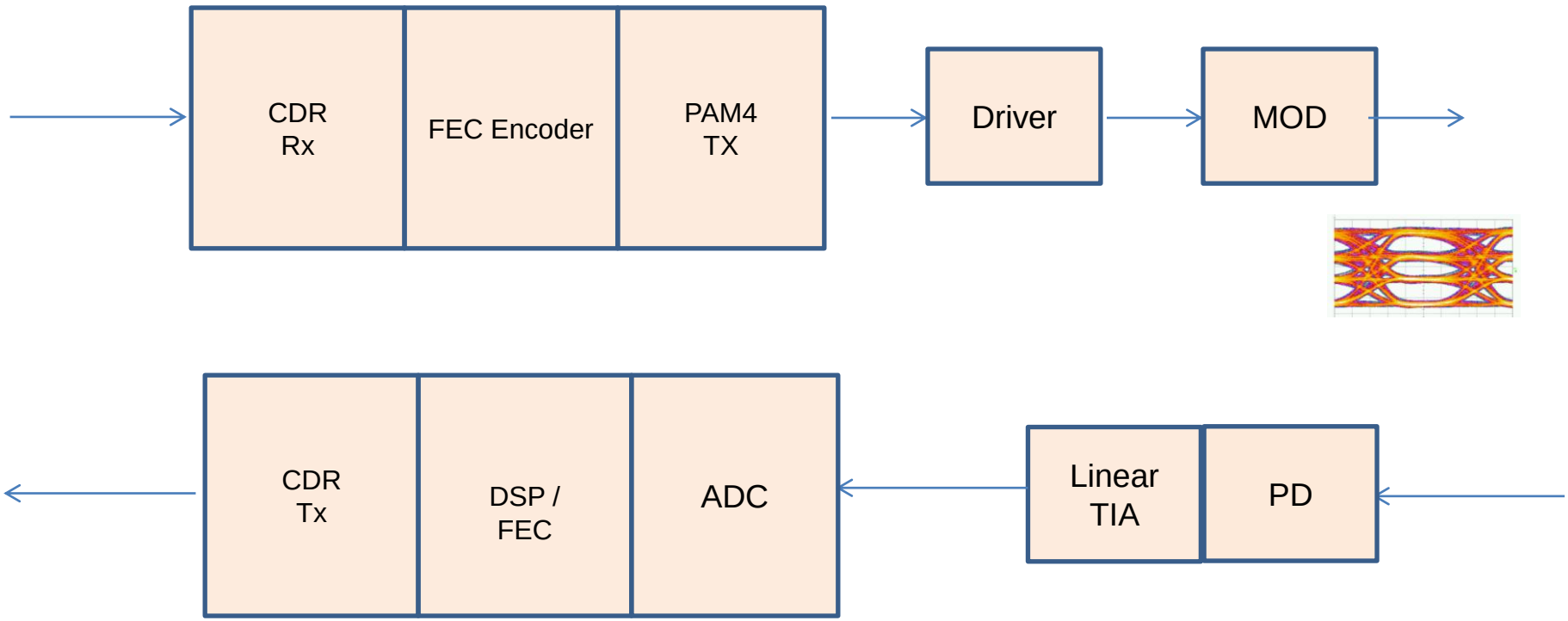
http://www.ieee802.org/3/400GSG/public/13_07/song_400_01a_0713.pdf

- Router to Router interconnect
- Router to OTN Transport interconnect
- CFP LR4 successfully deployed at 100G
- Multi-generational interoperability? Long term PMD?

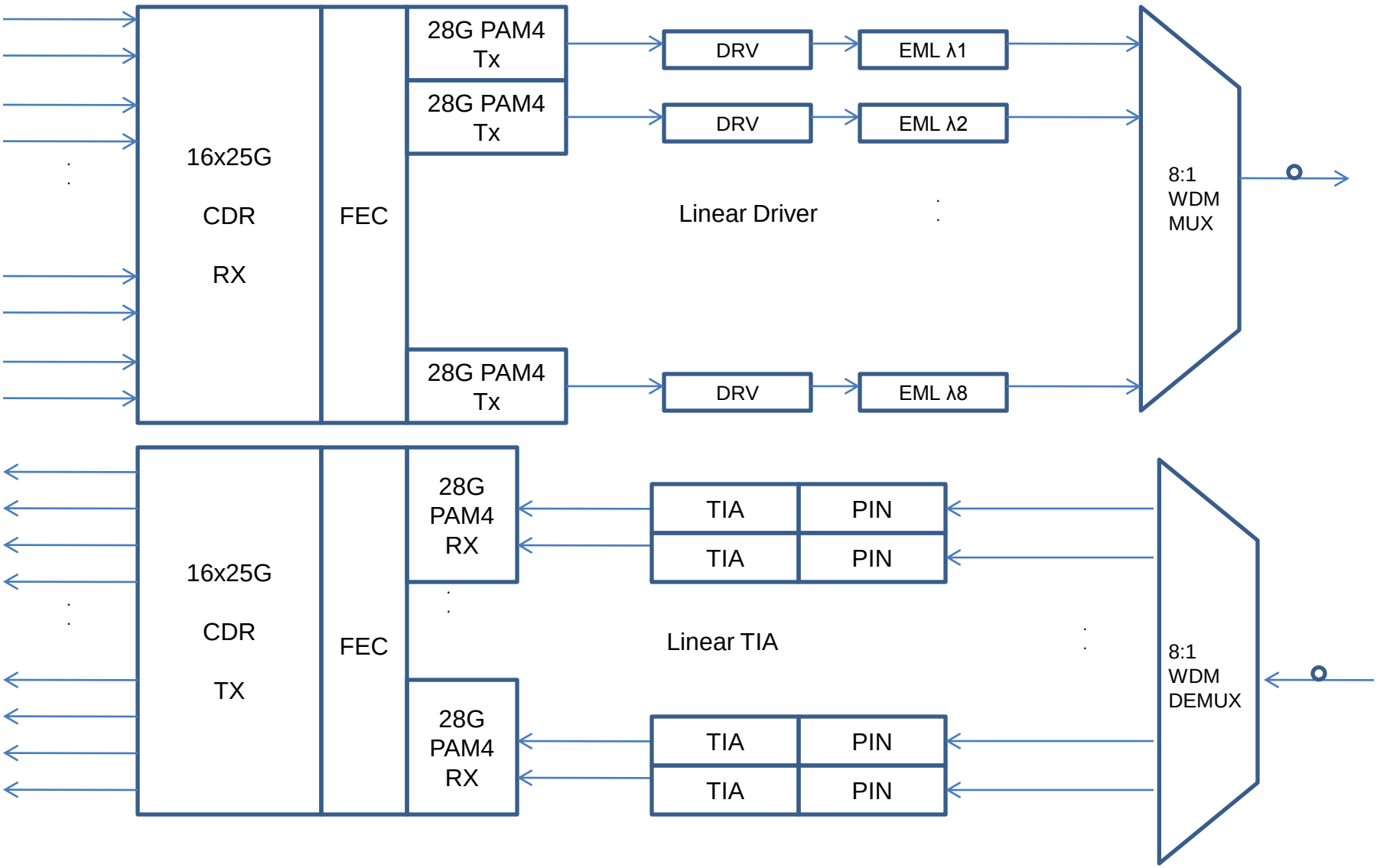
400G 500m - 2km Data Center Optics

- Multiple MSAs, CLR4, PSM4, CWDM to address 100G cost challenges
- Data center requirement: 400G cost < 4x100G cost
- Support 400G uplinks **and** 4x100G leaf and spine breakout?

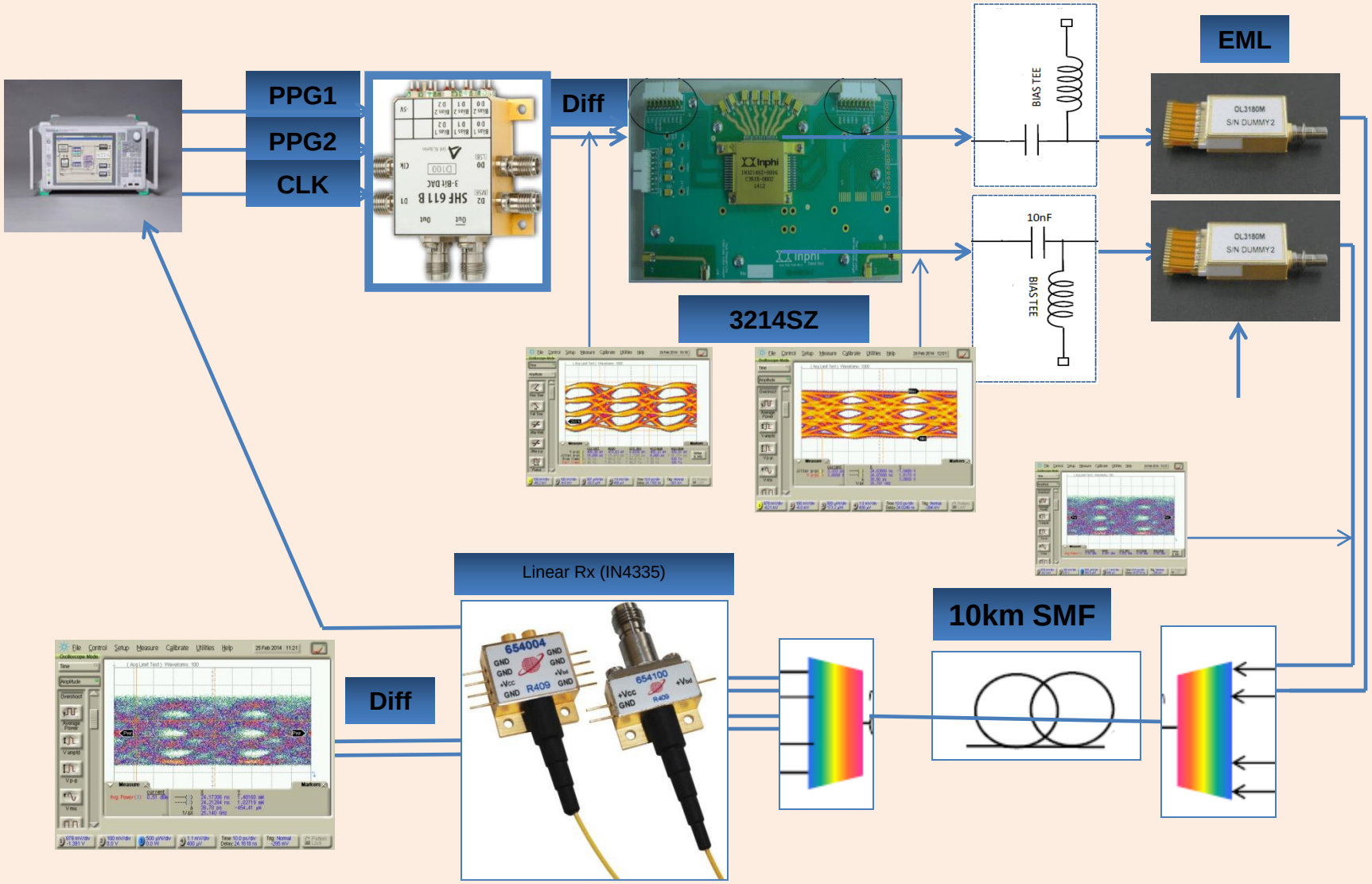
PAM4 TX & RX block diagrams



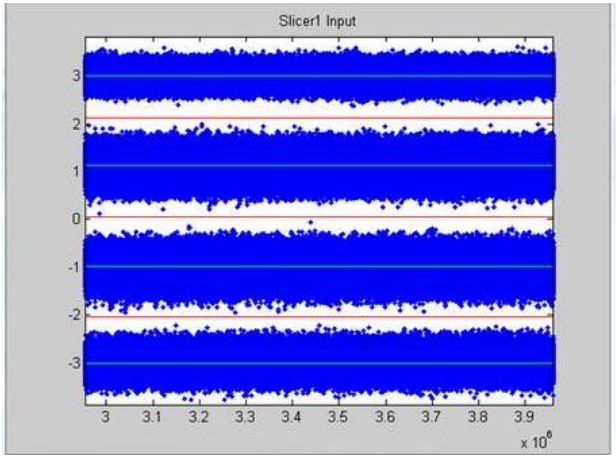
400G Using 8λ 56Gb/s PAM4

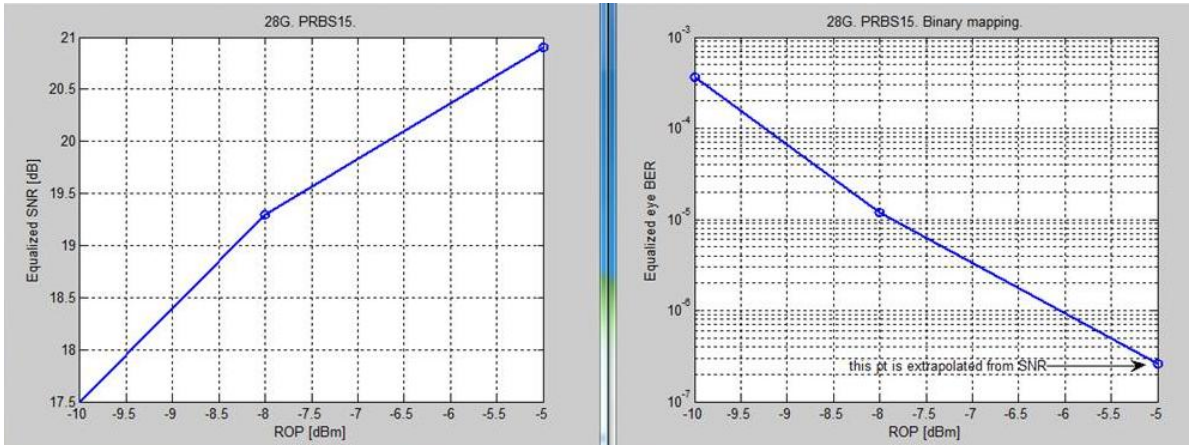


8λ 56Gb/s PAM4 Experimental Setup (10km)



8λ 10km Experimental DSP Results





- Sensitivity better than -10dBm for 3E-4 BER
- 4.2dB loss for 8λ Mux/Demux pair
- 6.3dB link loss budget can be supported

400G using 4λ PAM4 (500m)

- 400G: Direct Detection 56GBaud PAM4

  Modulation Speed: 28G → 56GBaud

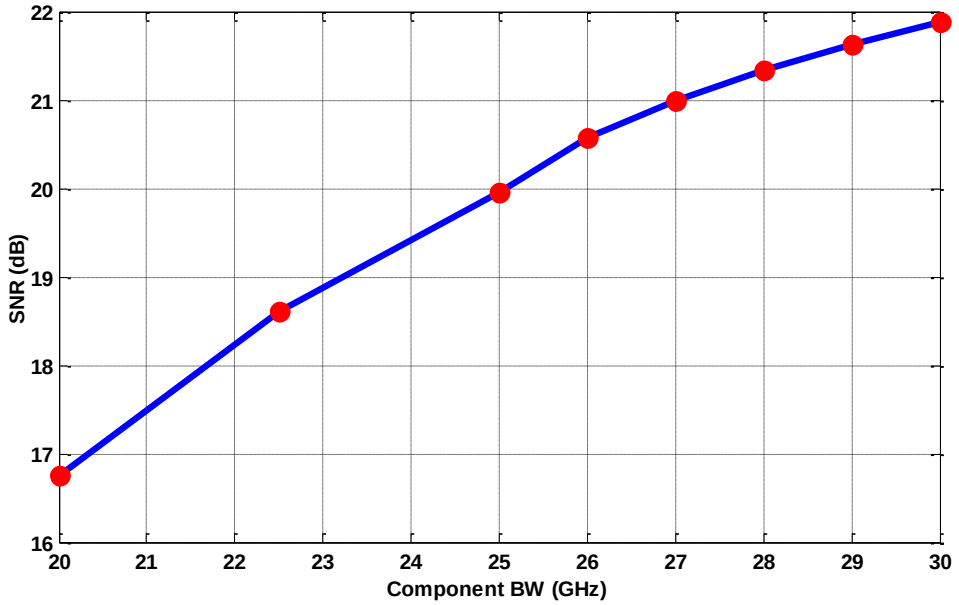
  Higher Order Modulation: NRZ → PAM4

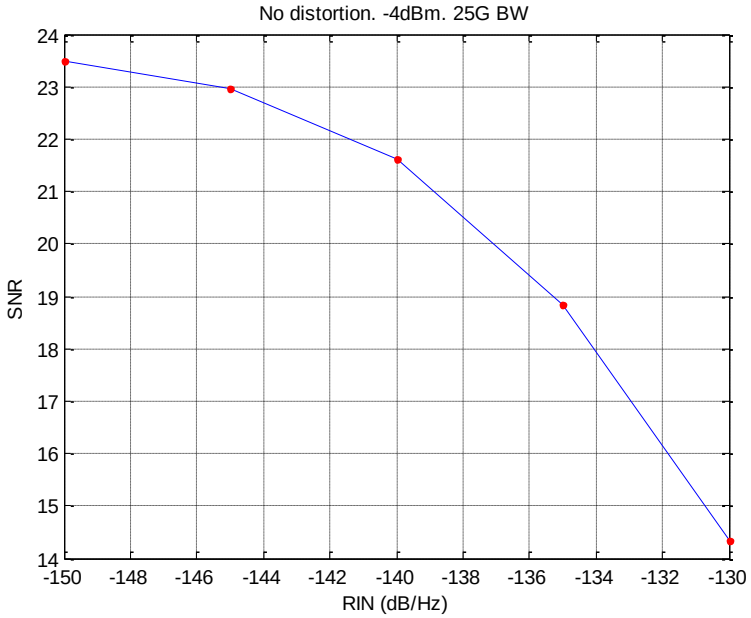
  Single λ Rate: 25G → 100G

  4 λ: 100G → 400G

- 56GBaud PAM4 lowers size, cost, power by shifting complexity to ICs

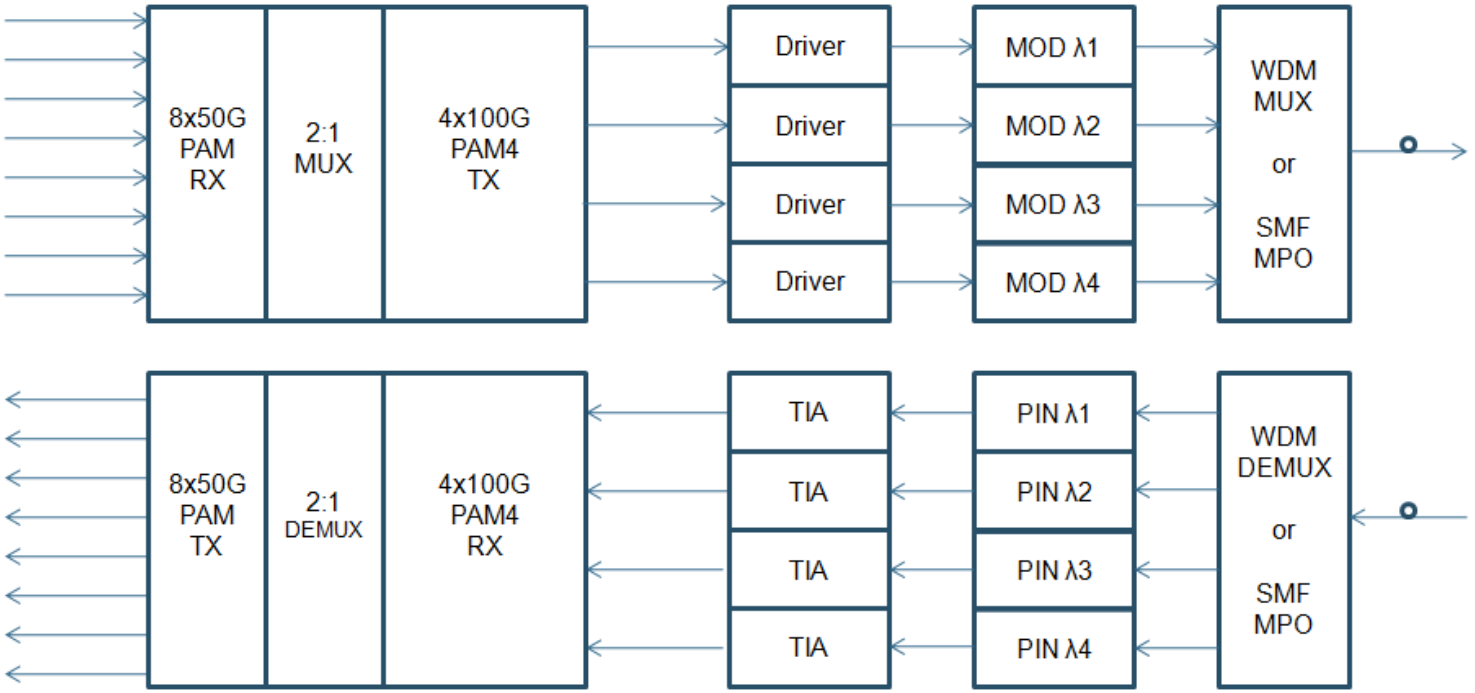
4λ PAM4 Simulation Results





- 4dB optical link budget can be supported
  - 25-30G component bandwidth, 20-22dB SNR
  - Improving RIN from -140 to -145 results in 1.35dB SNR gain
  - FEC gain can tradeoff optical specs
- Moore's law is alive and well
  - IC technology exists: 56GS/s ADC, DSP's, Linear TiA, Drivers etc.
  - 56G Optics, packaging and interconnect technology challenging

(100Gx4) 400G 4λ Solution



- 4x100G Optical: 4x (56GBaud PAM4)
- 4x100G Electrical: 8x (28GBaud PAM4)
- Supports 400G uplinks **and** 4x100G leaf and spine breakout

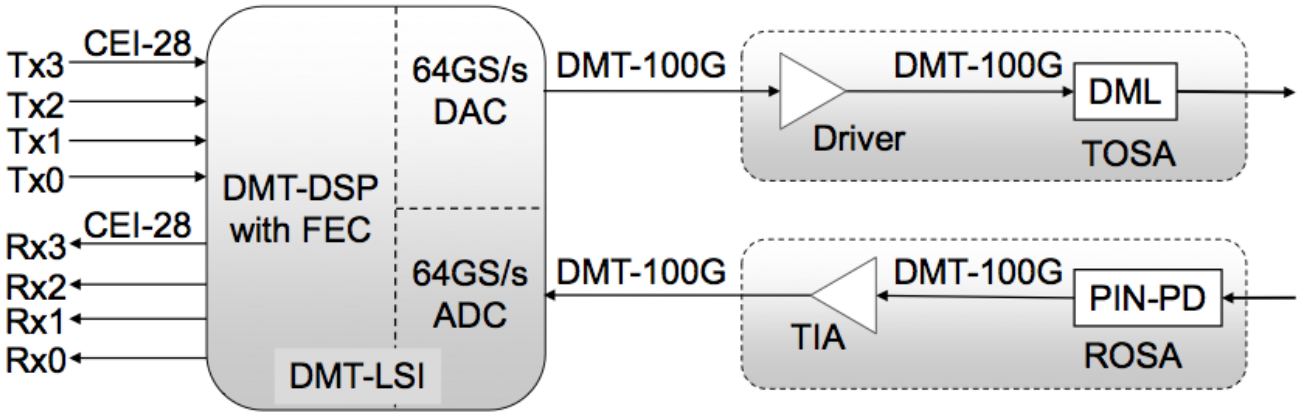
56GBaud PAM4 100Gb/s PAM-4 4λ 400G (4x100G)

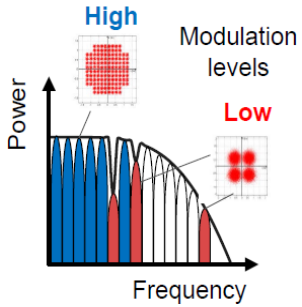
400G PAM4 Options

	8λ	4λ
Time To Market	☑☑	
Electrical Interface	25Gb/s or 50Gb/s	25Gb/s or 50Gb/s
Optical Baud Rate (PAM4)	**28Gbaud**	**56Gbaud**
Optics Cost, Laser, Lenses, etc.	2x Optics BOM	☑☑
Optics Design, MUX/DMUX	8 channels	4 channels ☑
FEC Coding gain	8dB	9dB
High Speed Integrity and Package Design	☑☑	
ASIC Design	☑☑	☑
High Speed Modulator Design	☑☑	
Test Infrastructure	☑	Need high speed test gear

Higher Order Modulation using DMT

Optical DMT (Discrete Multi-Tone)





Note: Based on tanaka_01a_1112 and tanaka_01_0113, IEEE P802.3bm

DMT Experimental Results - 1

- Neophotonics, http://www.ieee802.org/3/400GSG/public/14_01/way_400_01a_0114.pdf

  10km SMF, 4lambda 1294, 1299, 1304.5, 1308nm

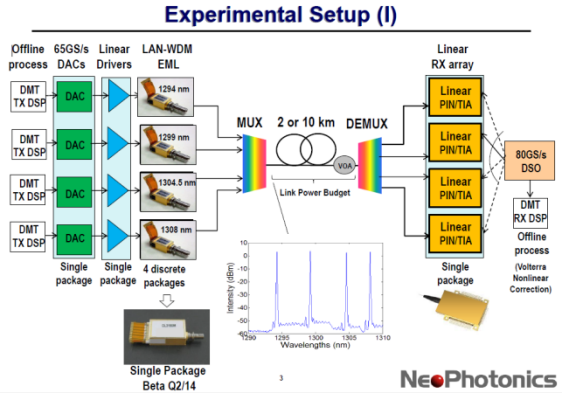
  64Gs/s DAC, 80GS/s ADC,

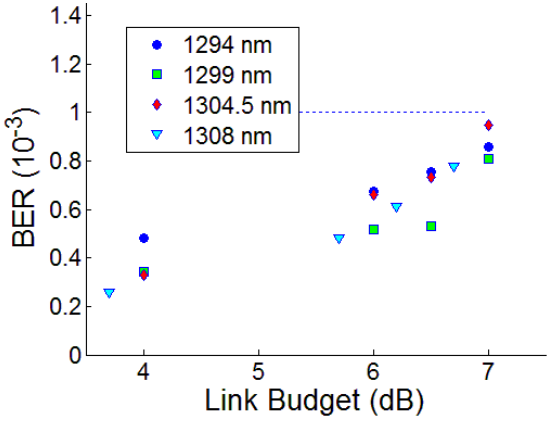
  176 subcarriers, 512 point IFFT

  Volterra kernels: order = 3, memory depth = 4

  1E-3 BER demonstrated at 400G

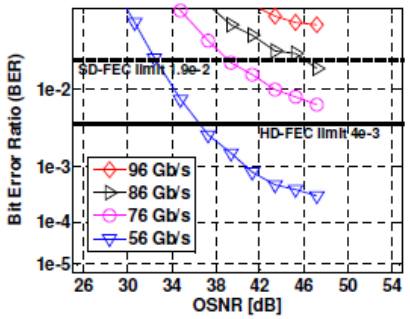
  Addition of SOA presents significant SNR penalty

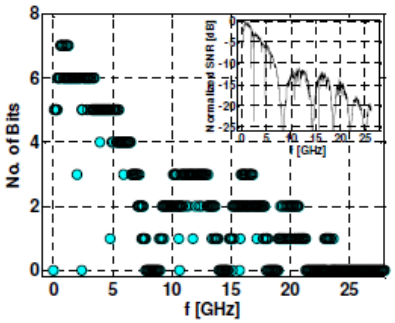


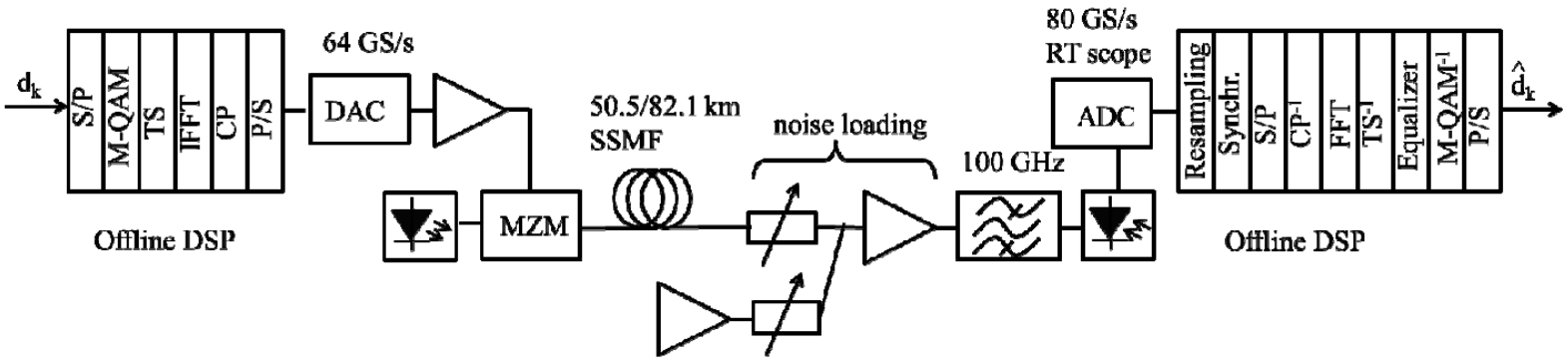


DMT Experimental Results - 2

- Adva, OFC 2014, Tu2G.7, Annika Dochann, et al
- 1550nm, EDFA
- 64GS/s 8 bit DAC with BW of 13GHz
- Driver 30G BW
- MZM 40G BW
- 30G Real time Scope
- 2048 point IFFT







Source: OFC 2014, Tu2G.7, Annika Dochann, et al

DMT Experimental Results - 3

- Source: Fujitsu, OFC 2014 M2I.4
- 1310nm 40km, 80km with SOA, 0.33dB/km
- DML, 18GHz BW, 10dBm
- NLE 31 taps compensates for non-linearity
- Achieves 80km, 1E-3 BER

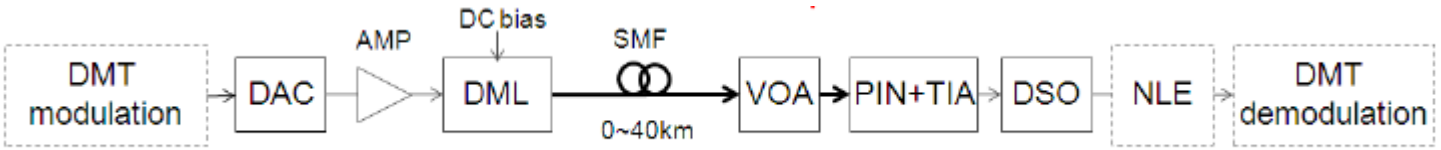


Fig. 1. Experimental setup for 0~40km transmission

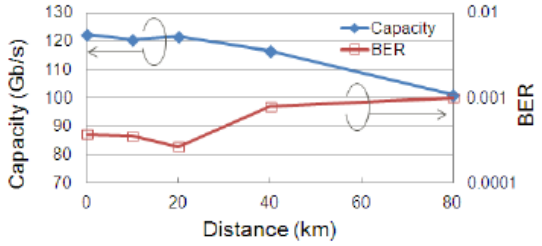


Fig. 12. Capacity and BER for 0~80km transmission

PAM4 vs. DMT IC Comparison

	PAM4	DMT	Complexity
Equalizer	FFE, DFE	IFFT,FFT	
Complexity (Multiply-Acc)	x	10x	Dominated by FFT/IFFT complex multiplications
DAC resolution	2 bits	8 bits	DMT Clipping issues
ADC Power	x	1.5 - 2x	ENOB, Peak to avg. ratio
FEC	x	x	DMT higher coding gain?
Non Linear Canceller	n/a	Volterra	DMT is more sensitive to non-linearity
Bandwidth	32G	20G	PAM requires higher BW
Serdes	x	x	
Total IC Power	**Y**	**2.5Y**	

- CMOS Power consumption estimates
  - 1.5W for PAM4, 3.5W for DMT per 100G

Summary

- 10km telecom Client Optics and 500m cost optimized data center are different
- Experimentally demonstrated 56Gb/s PAM4
- Simulated 112Gb/s PAM4, good progress towards experimental demonstration
- Investigated tradeoffs between 8λ 56Gb/s PAM4 and 4λ 112Gb/s PAM4
- Investigated tradeoffs between PAM4 and DMT
- DMT IC power is >2x PAM4 IC power