Four-Wavelength 400G on Duplex SMF

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IEEE 802.3bs 400 GbE Task Force Meeting
July 14, 2014 San Diego

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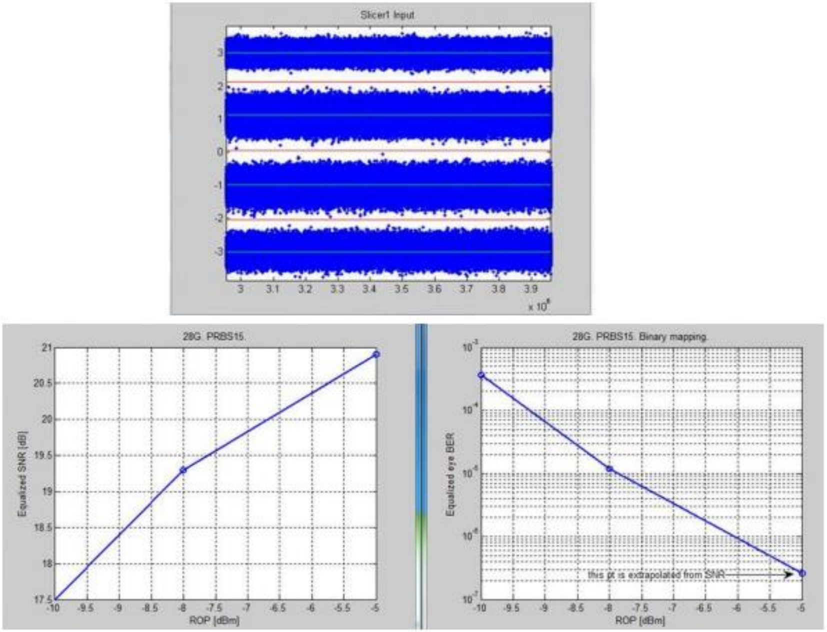
Proposed PMD: Four-wavelength 400G on Duplex SMF

- Meets 2 km Objective on Duplex SMF
- Meets 500 m objective as well
- Four CWDM wavelengths, 100 Gb/s per wavelength
- Each optical lane: PAM4 53.125 GBaud
- Electrical interface: 16x25G or 8x50G
- FEC: 802.3bj KP4, assumed to be inside module, but may reside outside the module

Context

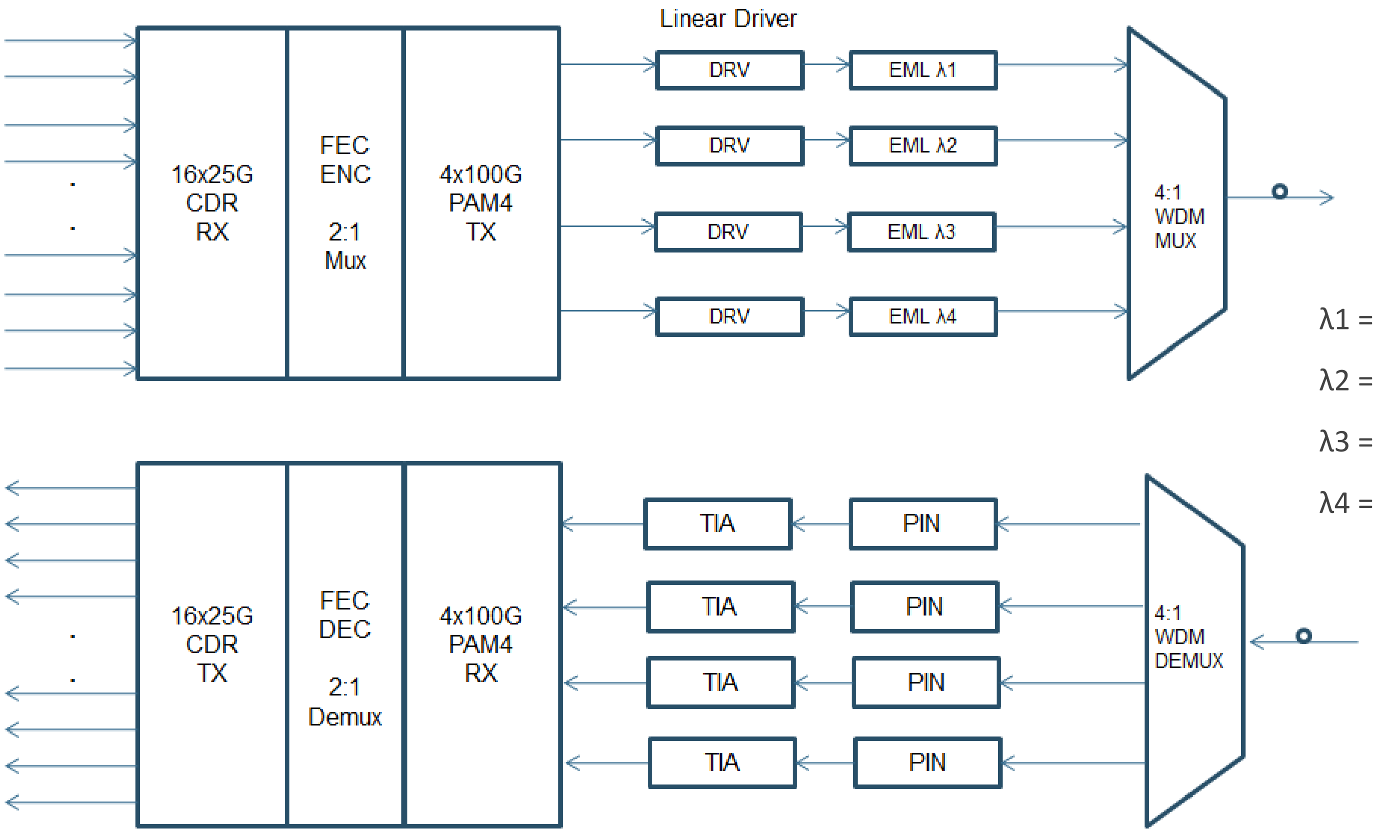
- In Norfolk meeting bhoja_3bs_01_0514 presented experimental feasibility of 50G per wavelength.
- In the same meeting, Task Force straw poll suggested overwhelming desire to see feasibility of 100G per wavelength (74 votes)
- This presentation is in response to that. We (the authors) have worked together to understand technical feasibility of 100G per wavelength. We believe it is feasible.
- It will be up to this Task Force to choose the right PMD based on cost, complexity tradeoffs, and anticipated deployment intercept of 400 GbE in the market.



8λ 10km experimental DSP results, bhoja_3bs_01_0514

Proposed PMD for 2 km Objective

Electrical Interface can evolve to 8x50G or 4x100G, while keeping optics the same



λ1 = 1270 nm

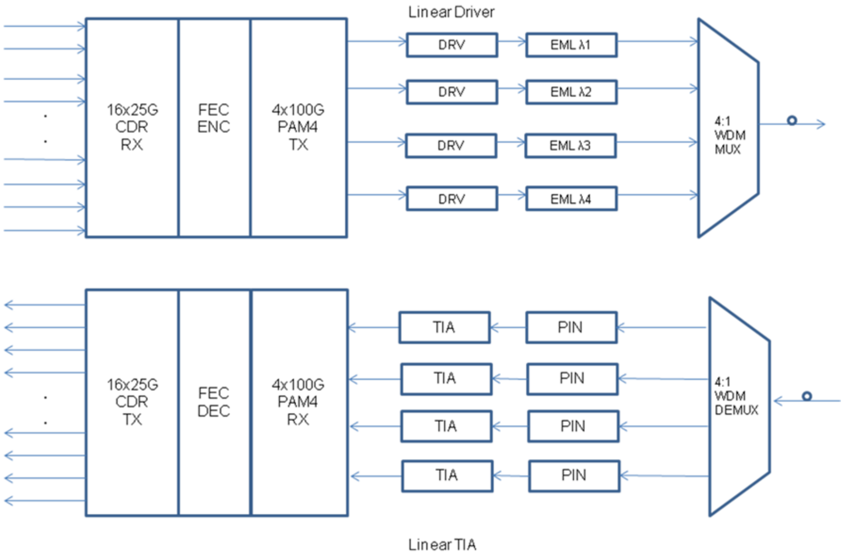
λ2 = 1290 nm

λ3 = 1310 nm

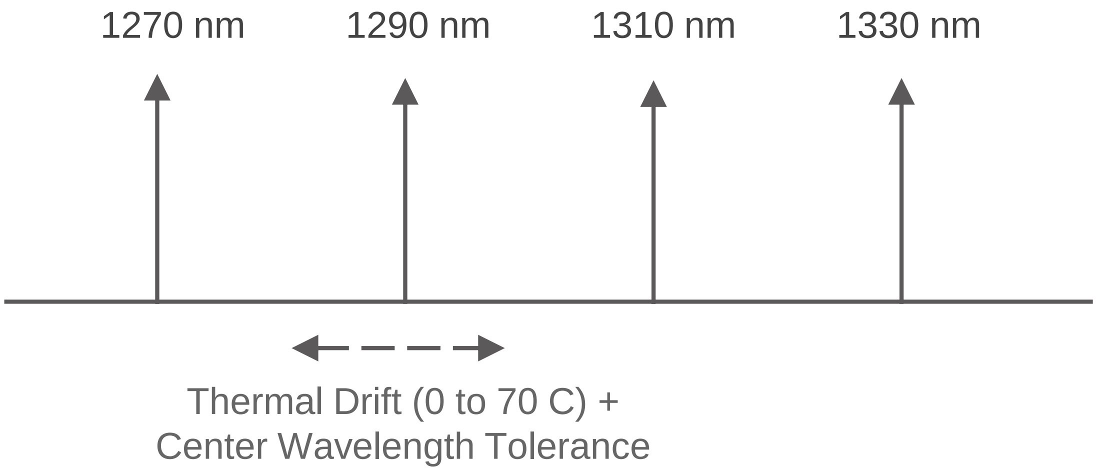
λ4 = 1330 nm

Why 100G per Wavelength?

- We can make time available
  - Beyond baseline in Jan 2015, we have comment resolution phase
- We get interoperable optics while 3 generations of electrical interfaces can evolve
  - 16x25G
  - 8x50G
  - 4x100G
- Enables CWDM implementation
  - Significant mindshare at 100G



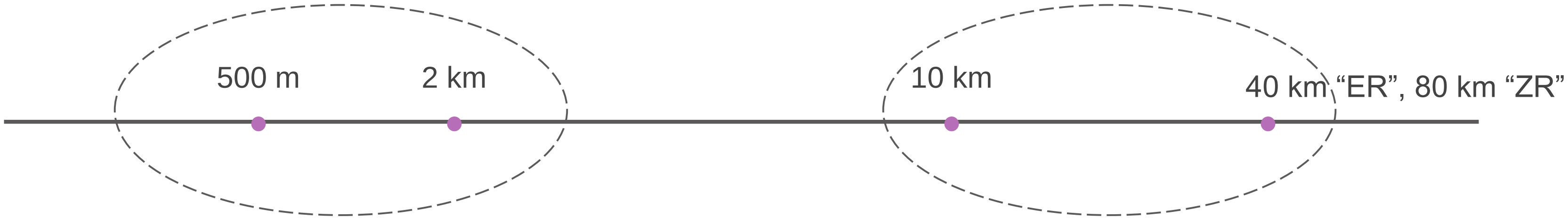
Why CWDM?



- CWDM enables the possibility that future PMD implementations may be uncooled, as technology evolves...
- … while maintaining interoperability.
- Recent interest in 100G CWDM MSA suggests cost-effectiveness as well.

Which PMD Implementations Need to Interoperate?

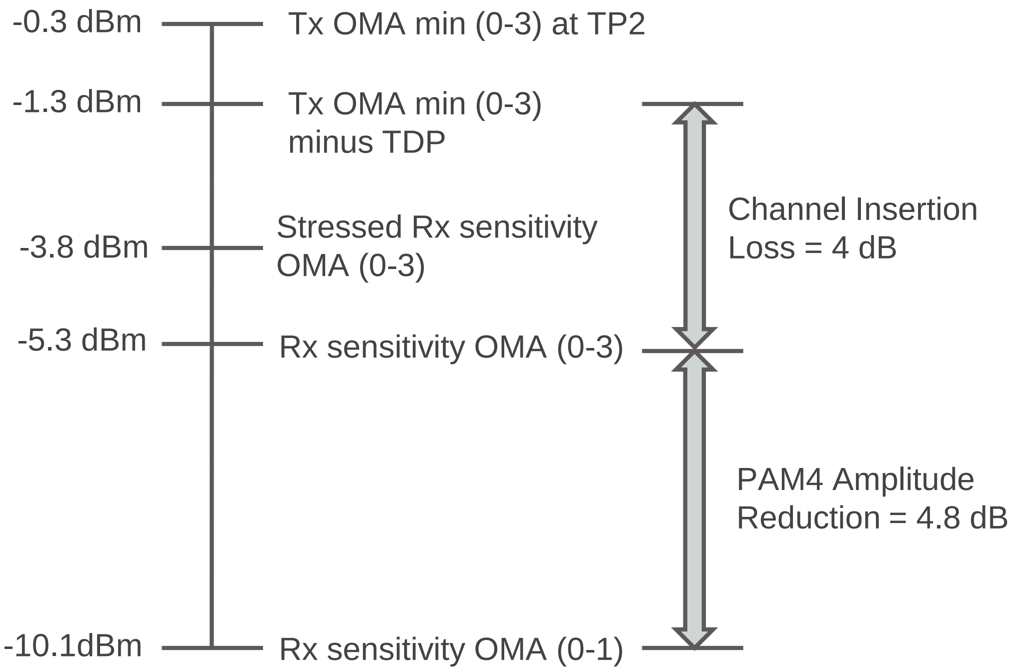
- In principle, we should optimize each PMD for its own reach objective, not for interoperability with PMD for another objective.
- In practice, the market may well favor the following implementations:



- Data Center and short reach Client optics
- High-density form factor
- Uncooled possible in future
- Interoperable, or just one PMD

- Longer reach Client optics
- Larger form factors
- Cooled
- Interoperable

Link Design



Penalties:
About 2.5 dB (1.5 dB residual ISI after equalization, 1 dB other penalties)

Assumptions:
WDM mux + demux loss: 4.6 dB, included in TP2, TP3 specs.
Effective TIA NEP: 21 pA/sqrt(Hz)
Tx bandwidth: 28 GHz
Rx bandwidth: 28 GHz

Methodology:
Use equalization in Rx to reduce ISI penalty.
Make up for PAM4 amplitude reduction with KP4 FEC.
Pre-FEC: Q ~ 4, BER ~ 1e-5
Post-FEC: Q > 7.34, BER < 1e-13
Plan for margin

Transmitter Characteristics

Parameter		Units
Nominal Signaling Rate (each Lane)*	53.125	GBd
Modulation	PAM4	
Wavelengths, nominal center value	1270, 1290, 1310, 1330	nm
OMA (0-3), each lane, min**	-0.3	dBm
OMA (0-3) minus TDP, each lane, min*	-1.3	dBm
TDP, each lane, max	2.5	dB
Extinction Ratio, min	7	dB
RIN, max	-142	dB/Hz
Transmitter Reflectance, max	-35	dB

* 53.125 = 544/514 * 100 * 257/256/2

** Max values can be consistent with 100G-LR4 values.

Receiver Characteristics

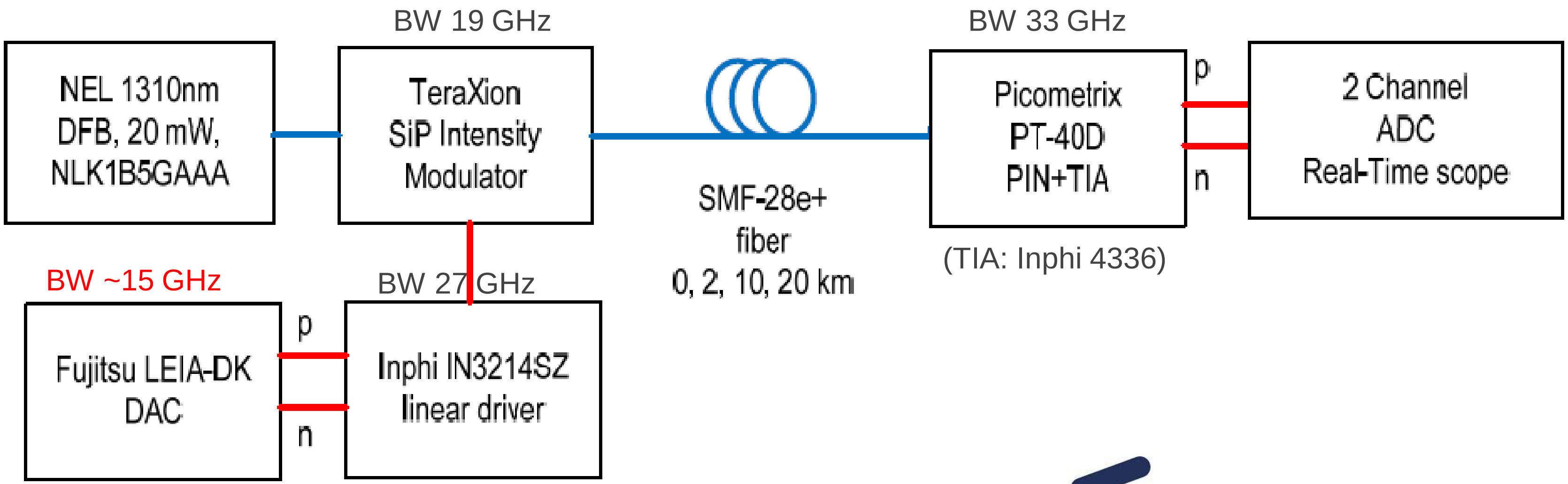
Parameter		Units
Nominal Signaling Rate (each Lane)	53.125	GBd
Lane Wavelengths, nominal center values	1270, 1290, 1310, 1330	nm
Receiver sensitivity, OMA (0-3), each lane, max	-5.3	dBm
Stressed receiver sensitivity, OMA (0-3), each lane, max	-3.8	dBm
Receiver Reflectance, max	-35	dB

Illustrative Link Power Budget

Parameter		Units
Power Budget (for maximum TDP)	6.5	dB
Operating distance	2	km
Channel insertion loss	4	dB
Max discrete reflectance	-35	dB
Allocation for penalties	2.5	dB
Additional insertion loss allowed	0	dB

Experiment

Independently, a team of contributors from Teraxion, Ericsson and McGill University have taken experimental measurements of various PAM links, including 100G per wavelength, PAM4, 2 km. In the next few slides, we present their results. For details, see references [1], [2].



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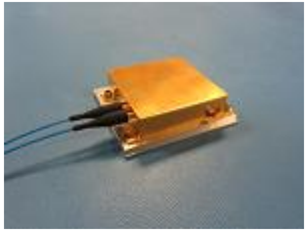
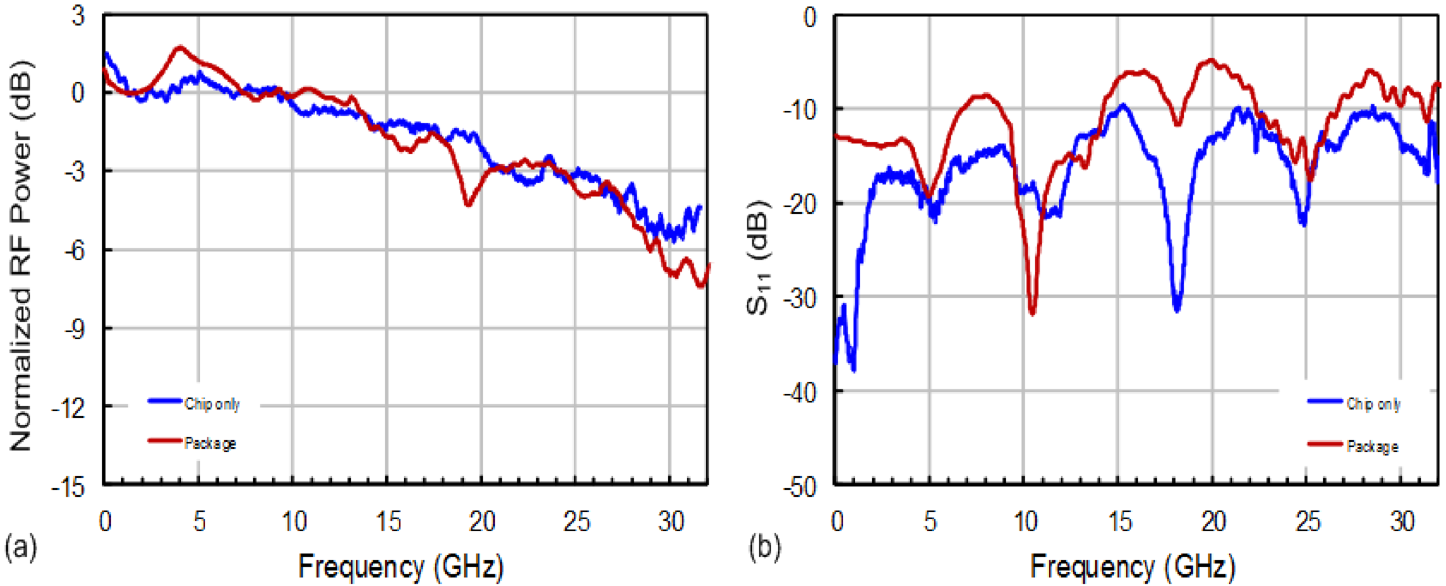
Modulator RF Performance





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(a) EO frequency response of the modulator chip (blue) and of the packaged modulator (red). (b) S_{11} of the modulator chip and of the packaged modulator. References: [1], [2].

Link Performance at Various Bit Rates

SNR, Q-factor [dB, 10LogQ] and BER for PAM orders 4 and 8, after propagation distance of 0, 2, 10 and 20 km, for varying bitrates. Dotted line is BER=3.8×10^{-3} threshold. Black solid curve in represents theoretical BER(Q) relation. References: [1], [2].

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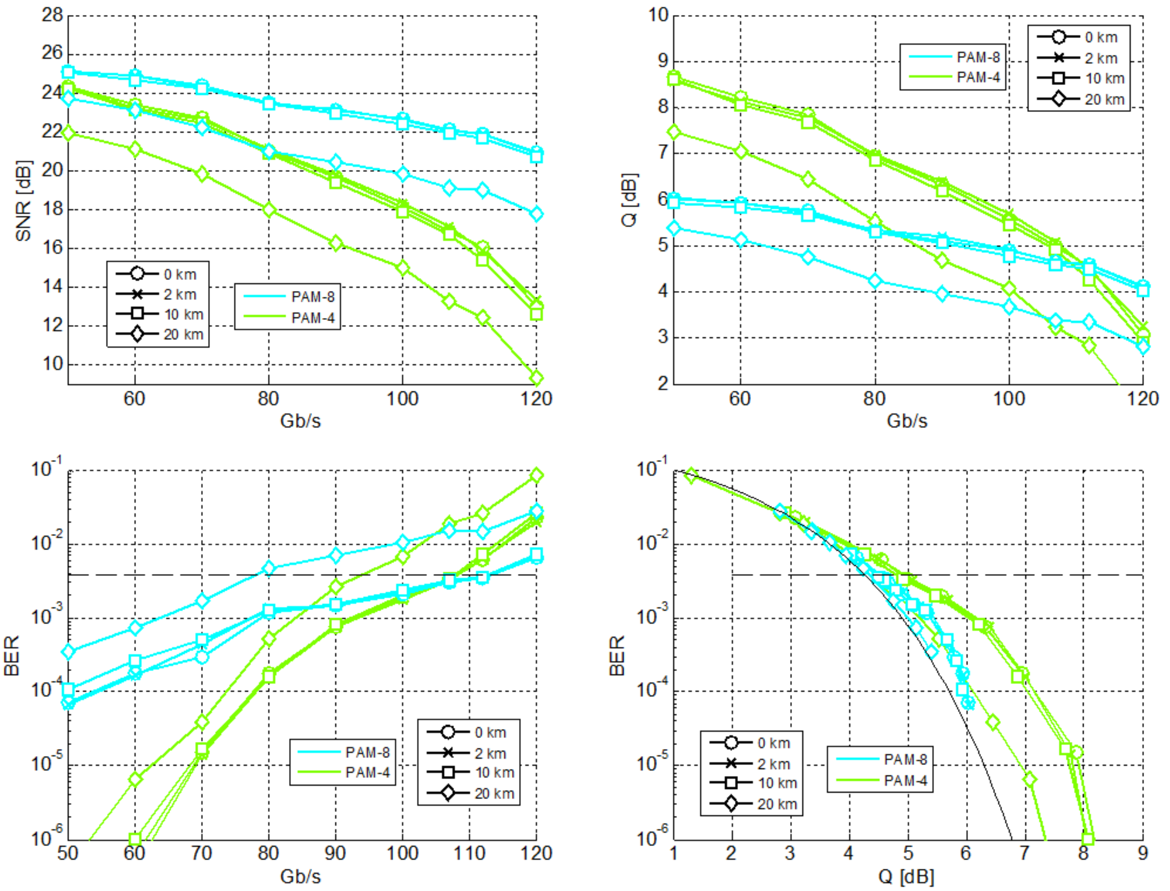
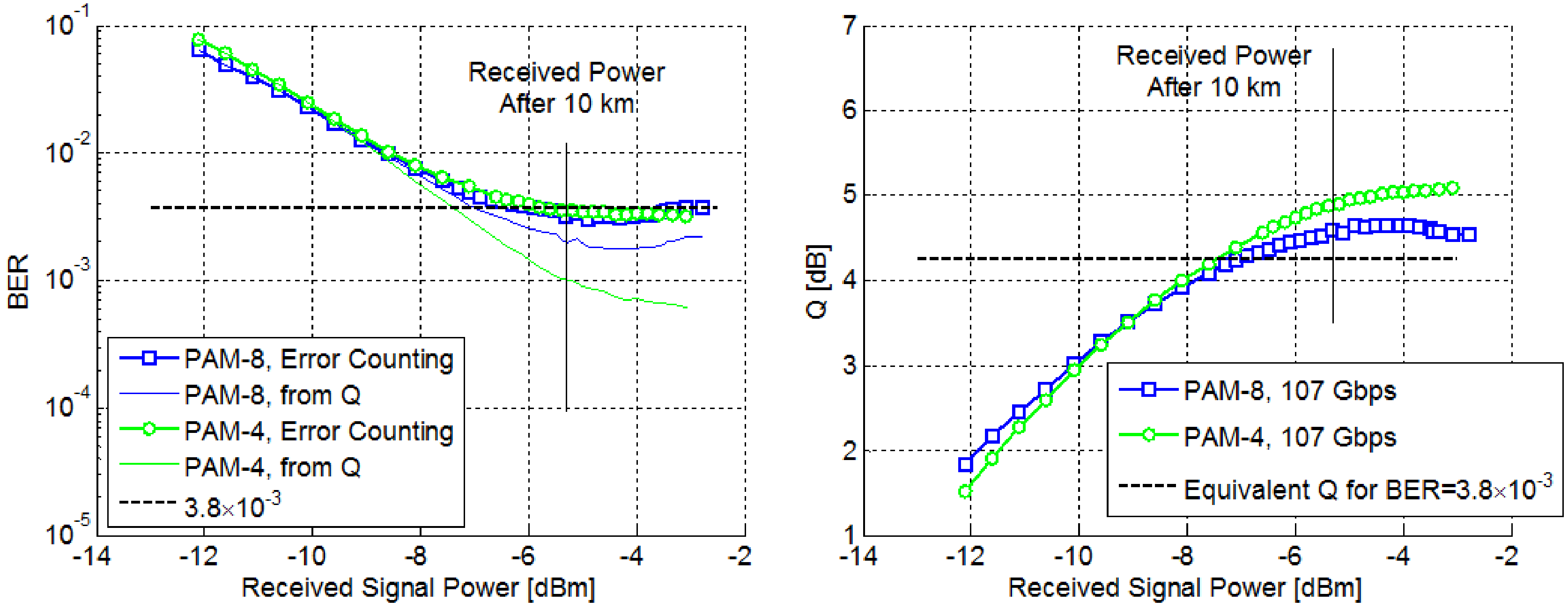


BER and Q vs. Received Power



(a) BER and (b) *Q*-factor for PAM-4 and -8, for varying received signal power. References: [1], [2].

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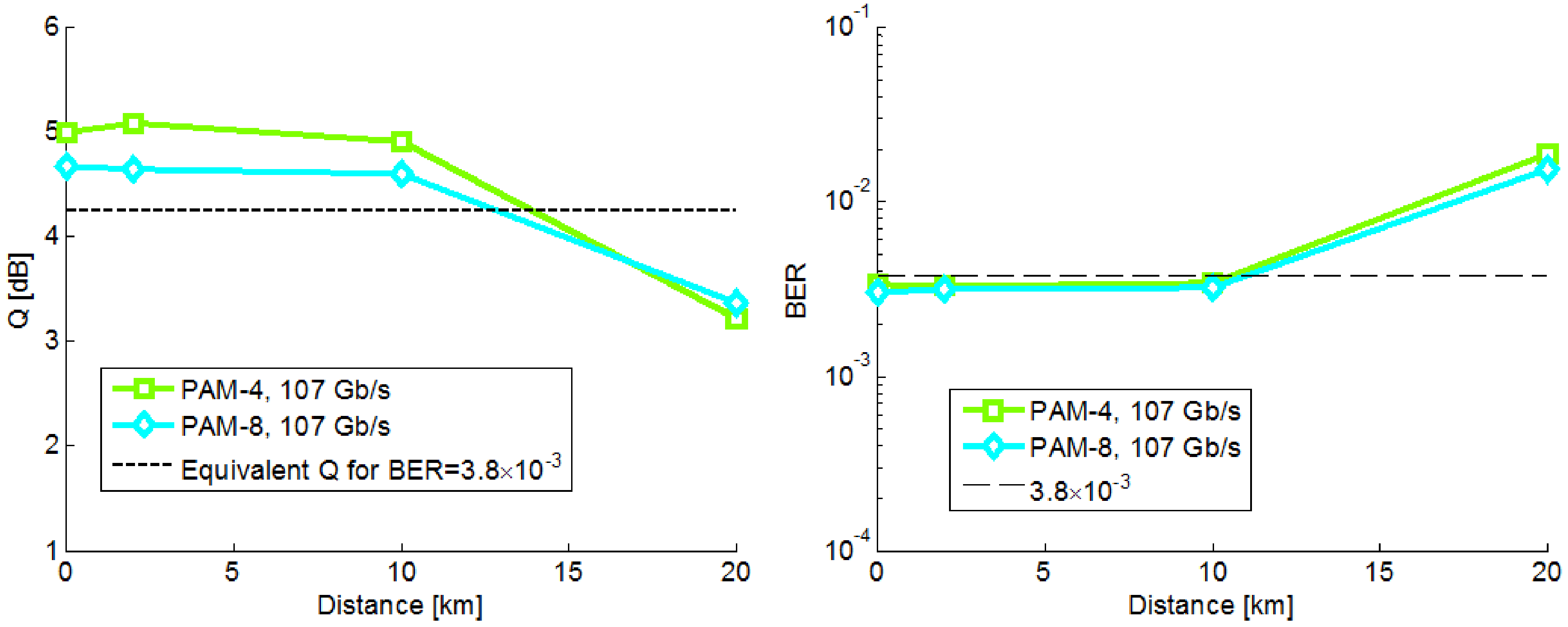
BER and Q vs. Distance



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Comparing Measurements with Link Model

- Took the case of PAM4 100G, 2 km experimental results
- We adjusted link model parameters to match the values used in the experiment
  - Adjusted wavelength to 1310 nm (instead of 1270 nm)
  - Removed WDM demux loss
  - Set Tx bandwidth to 15 GHz (instead of 28 GHz)
  - Adjusted to a Q factor used in experiment, and so on
- Result: Measured and predicted values are within 1.6 dB of each other.
  - The exercise of reconciling measurements with link model also provides recipe-level insight into the selection of component bandwidth. For example, the results suggest the choice of ~28 GHz as the right choice for PAM-4, since 20 GHz may be too low.

Summary

- Proposed PMD: four-wavelength, 400G on Duplex SMF for 2 km objective
- Meets 500 m objective as well
- Experimental results suggest feasibility, even in the presence of current-generation components with limited bandwidth
- 802.3bj KP4 FEC may be sufficient; using a stronger FEC for extra margin is also an option

References

[1] M. Poulin, C. Latrasse, J.-F. Gagné, Y. Painchaud, M. Cyr, C. Paquet, M. Morsy-Osman, M. Chagnon, S. Lessard, D.V. Plant, "100 Gb/s PAM-4 Transmission over 1.5 km Using a SiP Series Push-Pull Modulator at 1310 nm", Accepted, ECOC, 2014.

[2] Mathieu Chagnon, Mohamed Osman, Michel Poulin, Christine Latrasse, Jean-Frédéric Gagné, Yves Painchaud, Carl Paquet, Stéphane Lessard, and David Plant, "Experimental study of 112 Gb/s short reach transmission employing PAM formats and SiP intensity modulator at 1.3 μm," Submitted, Optics Express, 2014.

[3] "Harmonizing Singlemode Connection Return Loss Specification", by V. Bhatt, 400 Gb/s Ethernet Study Group, July 2013, Geneva

[4] "Improved MPI Upper Bound Analysis", by A. Farhood, IEEE P802.3bm Task Force, November 2012, San Antonio

[5] "Experimental measurements of the impact of multi-path interference on PAM signals", by Chris R. Fludger, Marco Mazzini, Theo Kupfer, and Matt Traverso, OFC 2014, San Francisco

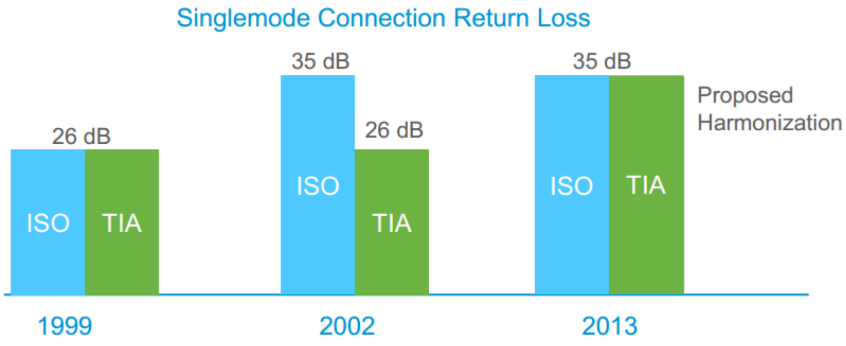
Backup

Link Impairment Penalties Are Manageable

- Key impairments are ISI, RIN, and MPI.
- ISI
  - With FFE/DFE, we have to only deal with residual penalty.
- RIN
  - Externally modulated lasers (large DC bias) have lower RIN
  - With FEC, we are in low-Q region. Low Q => Low RIN Penalty
  - RIN Penalty ~ 10*log(1/sqrt(1 - Q^2 * rin_sigma^2))
- MPI
  - With 35 dB discrete reflectance, PAM4 exhibits moderate MPI penalty
  - See Reference [4], [5]

Why choose 35 dB discrete reflectance?

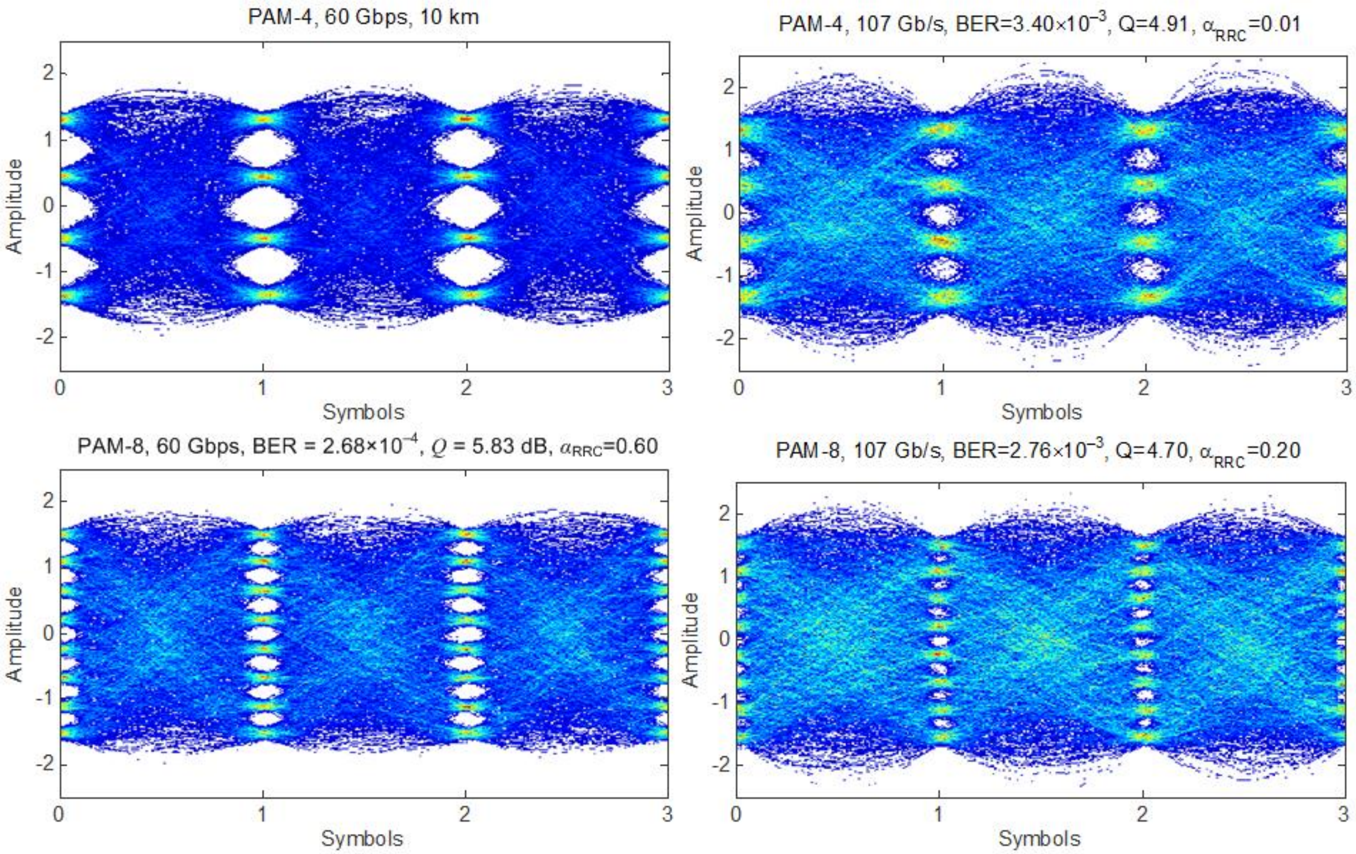
- 35 dB has been an ISO/IEC standard since 2002, and TIA is in the process of ratifying it (currently in ballot stage)
- All commercially available connectors easily achieve it
- Cost of reducing Tx and Rx reflectance is well within the cost budget of 400G PMD
- 400 GbE should be a forward-looking standard
- See Reference [3]



Eye Diagrams

PAM-4 and PAM-8 eyes, each at 60 Gbps and 107 Gbps

These are experimental, measured eyes, processed by DSP after receiver capture.
References: [1], [2].



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