On Technical Feasibility of 800G-LR4 with Direct-Detection

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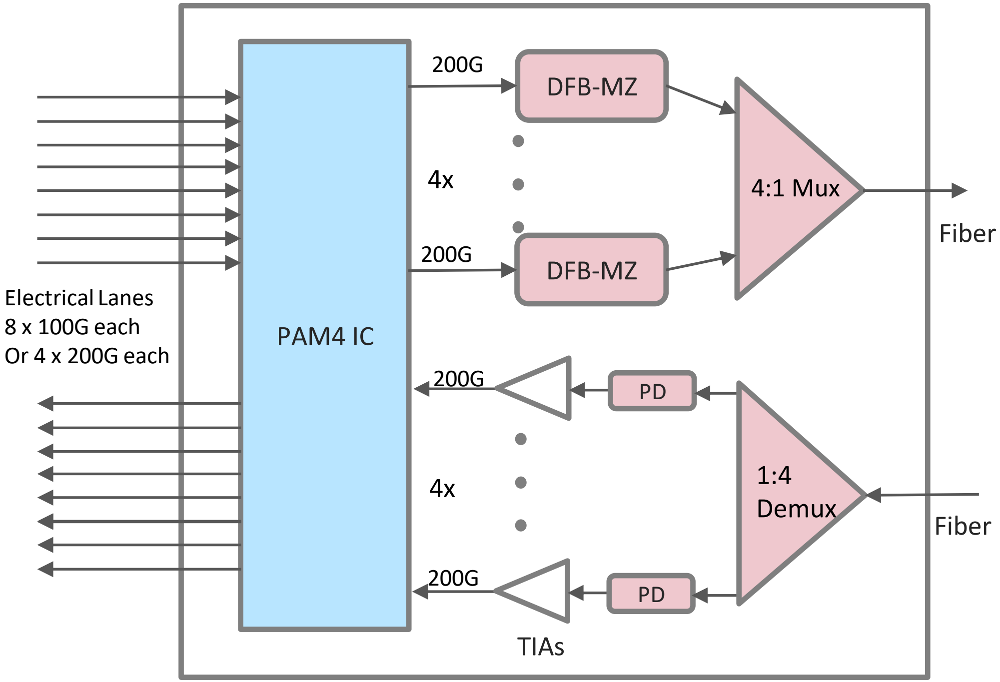
Introduction

- In this presentation, we show that 800G-LR4 with PAM4 direct-detection is technically feasible
- The key enabler is the combined consideration of four-wave mixing (FWM) and chromatic dispersion (CD), leading to an optimized wavelength plan
- This keeps FWM probability small, while supporting a reach of 10 km
- Based on 4x200G direct-detection, the PMDs serving 500 m, 2 km, and 10 km reaches can jointly leverage a huge volume of re-usable base of technologies and components

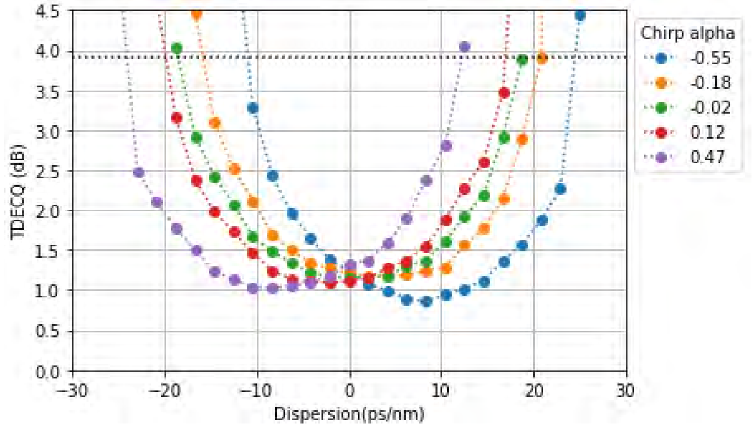
800G-LR4 : Transceiver Implementation Example

- Reach: 0 to 10 km
- Each fiber carries 4x200G PAM4, wavelength-multiplexed
- Uses one fiber pair
- Possible transmitter implementations may use: DFB-MZ laser, EML, silicon photonics, etc.
- Expected power dissipation of a transceiver implementation: 12-14W



Dispersion Compensation by Controlling Tx Chirp

- Electro optical modulators can produce controlled chirp
  - EML: limited tunability with EA bias. Techniques like MLSD will help
  - DFB+MZ , SiP MZ: using asymmetry between branches
- This can partially offset fiber dispersion
- Each channel can be tuned independently



112GBaud PAM4 with TDECQ reference Rx:
- BW= 56GHz
- EQ= 21-taps FFE
- BER= 2.0e-3

Four-Wave Mixing (FWM) overview

- FWM is the 'new' impairment for LR links with wavelength division multiplexing (WDM)
- FWM can cause crosstalk, therefore it must be mitigated
- FWM is high when:
  - Signal power is high
  - Long fiber transmission
  - Phase mismatch condition $\Delta k \approx 0$
    - Wavelengths around SMF λ_0
- FWM penalty can be mitigated by 1 or more of this options:
  - Limiting the number of channels per fiber
  - Keeping signal power within limit
  - Ensuring sufficient phase mismatch
  - Uneven WMD grid design with FWM components out of bands

Ref: G.P Agrawal. Fiber-Optic Communication Systems

FWM is a nonlinear optical phenomenon. If three optical fields with carrier frequencies ω_1, ω_2, and ω_3, copropagate inside the fiber simultaneously, there is a fourth field generated with a frequency $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$

FWM new frequency:

$$\omega_{fwm} = \omega_i + \omega_j - \omega_k$$

FWM power:

$$P_{fwm} = \eta_F (d_F \gamma L)^2 P_i P_j P_k e^{-\alpha L}$$

FWM efficiency:

$$\eta_F = \left| \frac{1 - exp[-(\alpha + i\Delta k)L]}{(\alpha + i\Delta k)L} \right|^2$$

Phase mismatch:

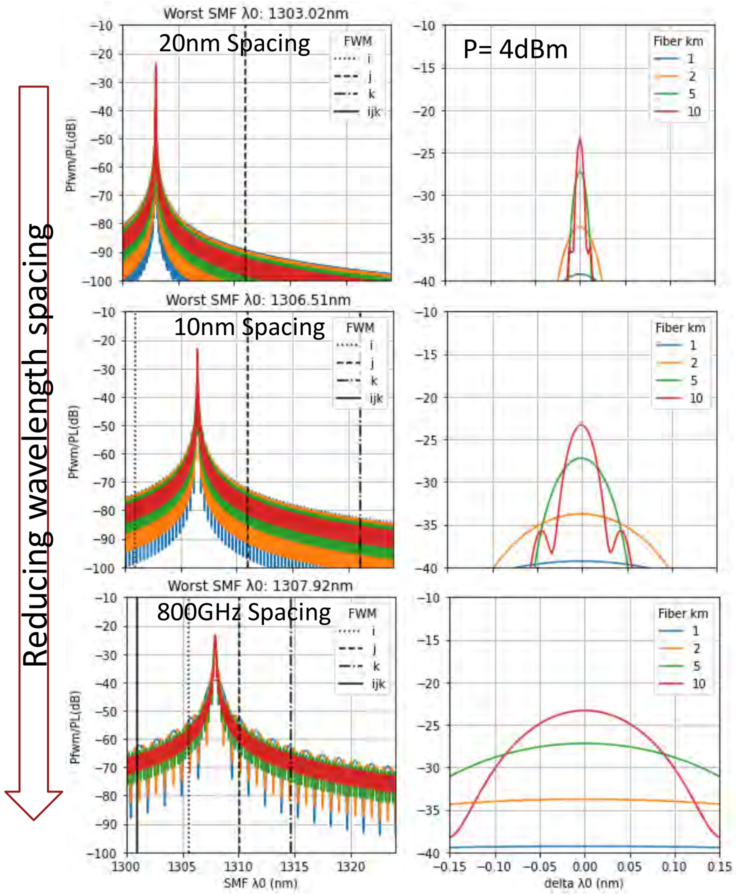
$$\Delta k = \beta_{fwm} + \beta_k - \beta_i - \beta_j$$

What impact has wavelength spacing, transmission length and power on FWM?

It is helpful to rewrite FWM in terms of crosstalk ratio:

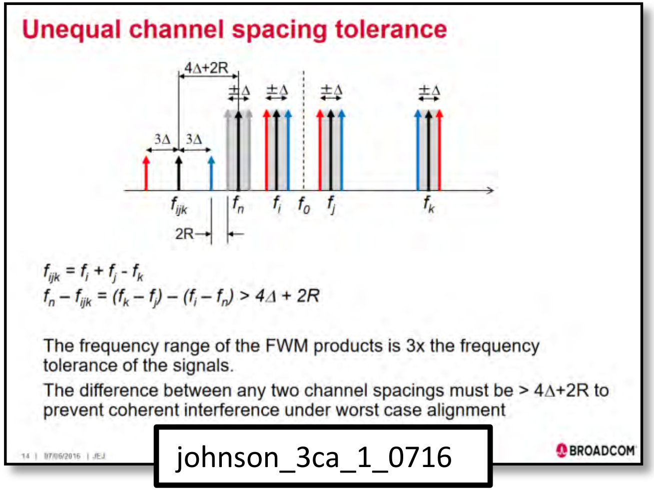
$$\frac{P_{fwl}}{P_L} = \eta_F (d_F \gamma L)^2 P^2$$

- Power and transmission length impact the maximum FWM crosstalk
- Spacing, however, reduces the fiber zero dispersion range that leads to high FWM
- There is always a fiber zero dispersion value, between the input wavelengths, that minimizes phase mismatch equation (and maximizes FWM). Fortunately, the probability of FWM penalty has been very small in previous standards like 400G-LR8
- For more details, see excellent presentation on this topic by John Johnson: johnson_3ca_1_0716

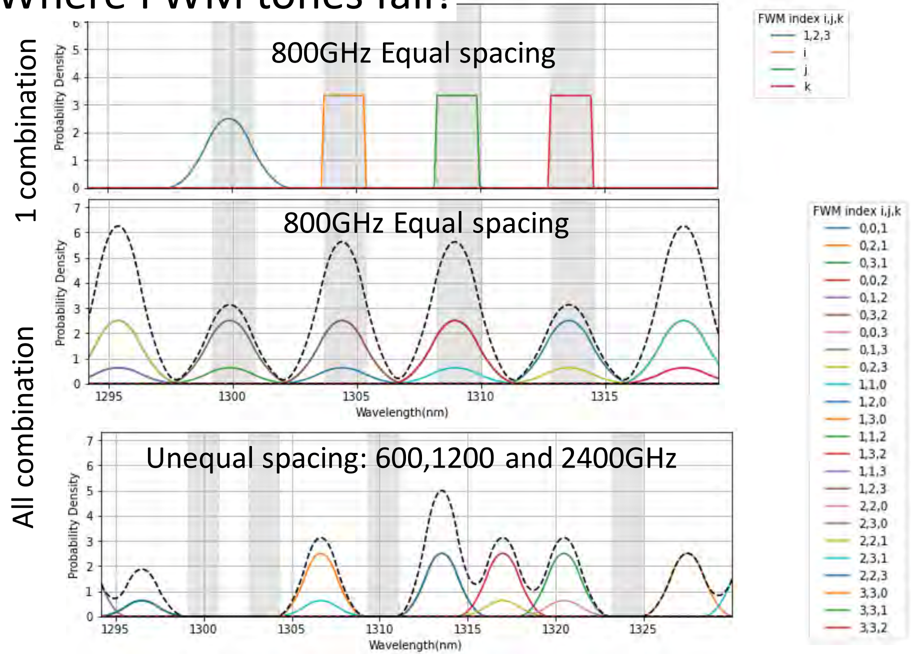


A way to avoid FWM effect: Unequal Wavelength Spacing

- Equal spaced wavelengths are very susceptible to FWM penalty
- The idea of unequal spacing WDM grid was investigated in 802.3ca. John shows the condition to guarantee FWM tones to fall outside the channel passband



Where FWM tones fall?



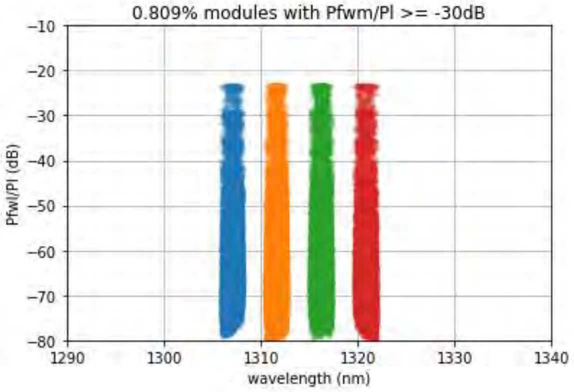
- 300GHz passband is assumed to account for wafer-to-wafer variation and temperature drift
- We propose unequal spacing of 600, 1200 and 2400GHz
- It doesn't completely satisfy the zero FWM condition, but it allows small overlap of the probability density function to limit spectrum range

How likely is FWM penalty?

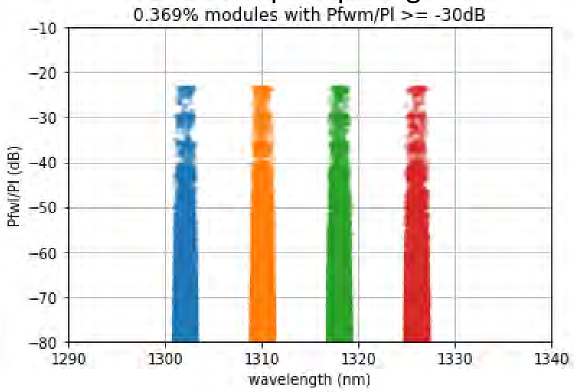
- Monte Carlo analysis to compute FWM crosstalk (ratio) and probability of a transceiver crossing -30 dB value:
  - 100,000 iterations
  - Uniform distribution of wavelength within channel passband (300GHz)
  - Uniform distribution of SMF λ0 from 1300nm - 1324nm
  - All lanes P = 4dBm
  - 10km fiber transmission
  - Worst case polarization

- Equal spaced grids (800GHz or 8nm) could lead to significant probability of FWM
- The proposed wavelength plan: 1300.0, 1303.4, 1310.2, 1324.1 nm, can reduce FWM to a 0.001% probability
- Probability could be 0 if we satisfy unequal spacing condition, e.g., tighter laser λ accuracy, polarization interleaving

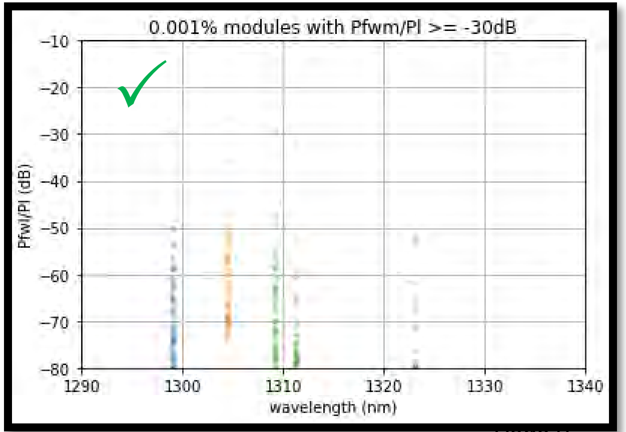
800GHz equal spacing



8nm equal spacing



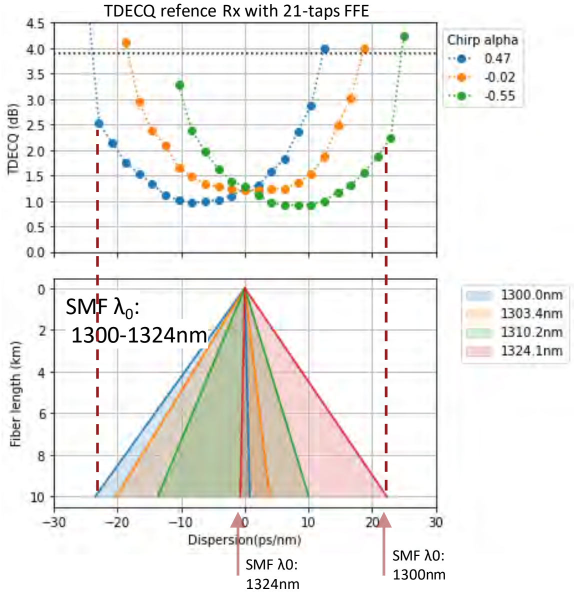
Unequal spacing: 600,1200 and 2400GHz



Dispersion tolerance with FFE and MLSD

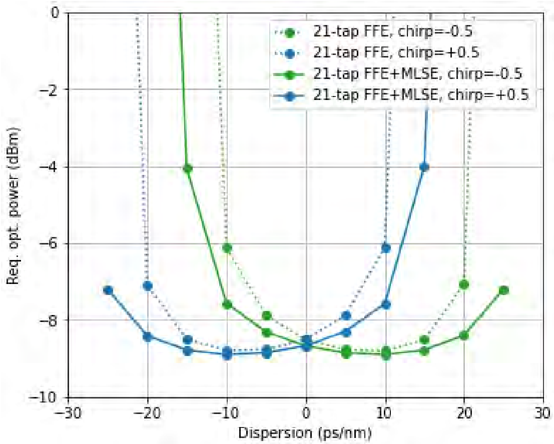
FFE only

- Expected TDECQ using 21-tap FFE Rx equalizer
- Bottom plot show the full dispersion range of each lane of the proposed wavelength plan up to 10km

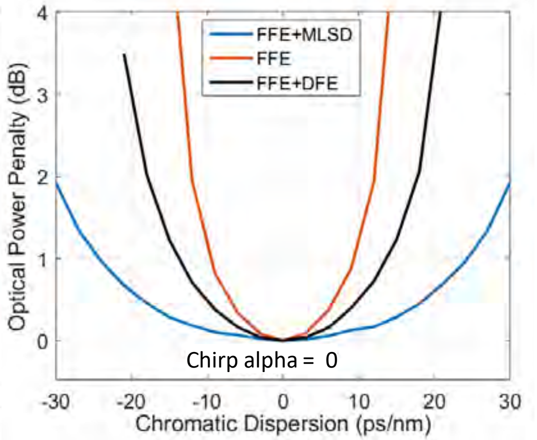


FFE + MLSD

- MLSD can provide additional margin on dispersion tolerance up to ±25 ps/nm

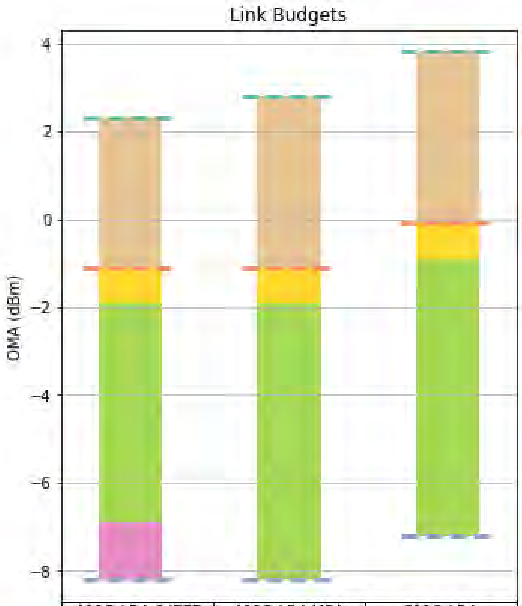


Courtesy of Maxim Kuschnerov, Huawei



Courtesy of Jamal Riani, Marvell

Power Budget Example

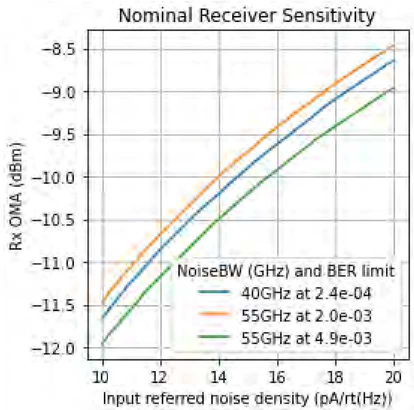


	400G-LR4-6 IEEE	400G-LR4 MSA	800G-LR4
OMA@TDECQmax(dBm)	2.3	2.8	3.8
OMA-TDECQ(dBm)	-1.1	-1.1	-0.1
RSnominal(dBm)	-8.2	-8.2	-7.2
PowerBudget	10.5	11.0	11.0
TDECQmax	3.4	3.9	3.9
AdditionalPenalties	0.8	0.8	0.8
FiberLoss+connectors	5.0	6.3	6.3
AdditionalLossMargin	1.3	0.0	0.0

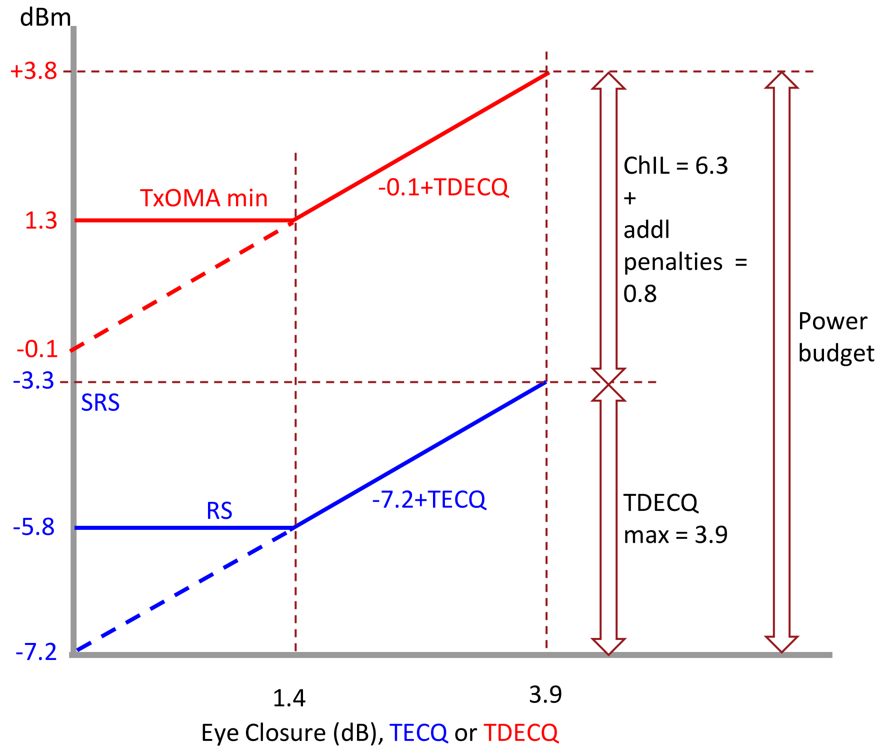
One possible power budget proposal:

- Relax Rx sensitivity by 1dB compared to 400G-LR4
- Increase Tx min OMA requirement by 1dB
- Assume pre-FEC BER 2e-3

This shares the pain of moving to 200G/lane between Tx and Rx fairly, while maintaining max Tx power manageable for FWM



800G-LR4: Example Link Budget



Transmitter

OMA outer, each lane, min For TDECQ < 1.4 dB For 1.4 dB ≤ TDECQ ≤ 3.9	 1.3 -0.1 + TDECQ
TDECQ, each lane (max)	3.9

Receiver

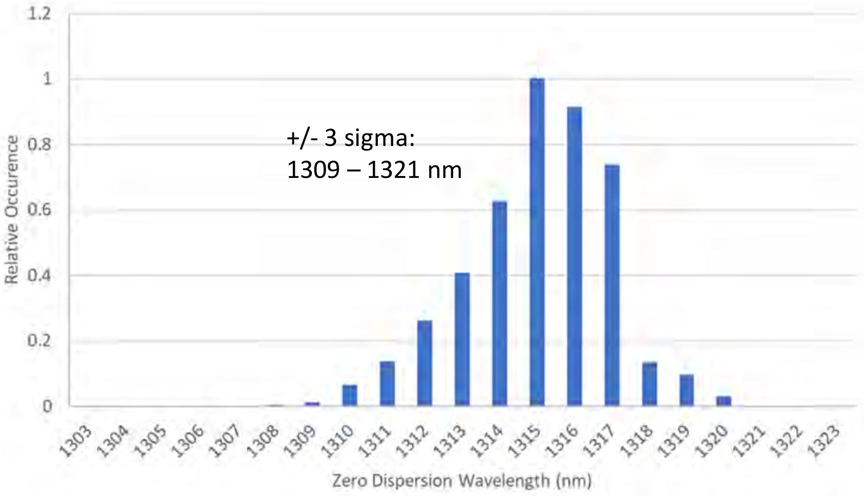
RS, each lane (max) For TECQ < 1.4 dB For 1.4 dB ≤ TECQ ≤ 3.9	 -5.8 -7.2 + TECQ
SRS, each lane (max)	-3.3

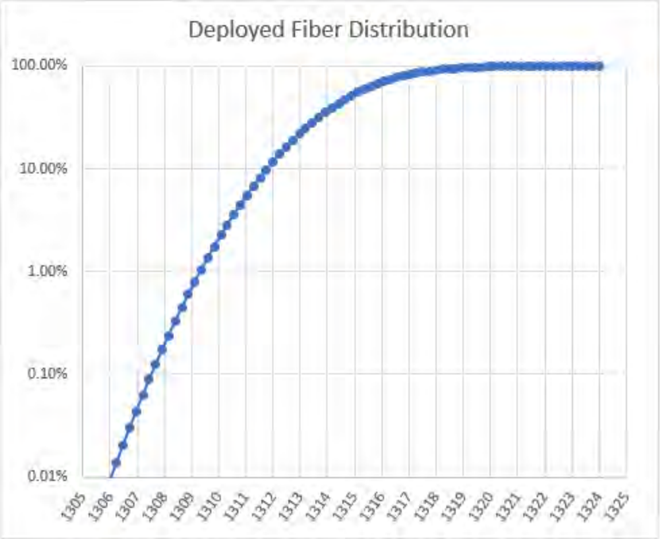
Budget

Power Budget (for max TDECQ)	11.0
Channel Insertion Loss	6.3
Allocation for penalties (for max TDECQ)	4.7
Additional insertion loss allowed	0

Bonus: For Additional Margin, Choose a More Realistic Range of Zero-Dispersion Wavelengths

- Data from 2 sources: The installed fiber has a narrower range of zero-dispersion wavelengths
- Choosing a realistic range will enable realistic penalty allocations for FWM and chromatic dispersion





- 2022 CommScope data of ~32,000 fibers
- *"While our advertised spec is 1300-1324 nm, the vast majority of the fibers are in a narrower range at longer wavelengths."* – Earl Parsons, CommScope

- G.652 ZD wavelength distribution
- *"The distribution is narrower than the 1300-1324 nm in use today."* – from a large fiber manufacturer based in Asia

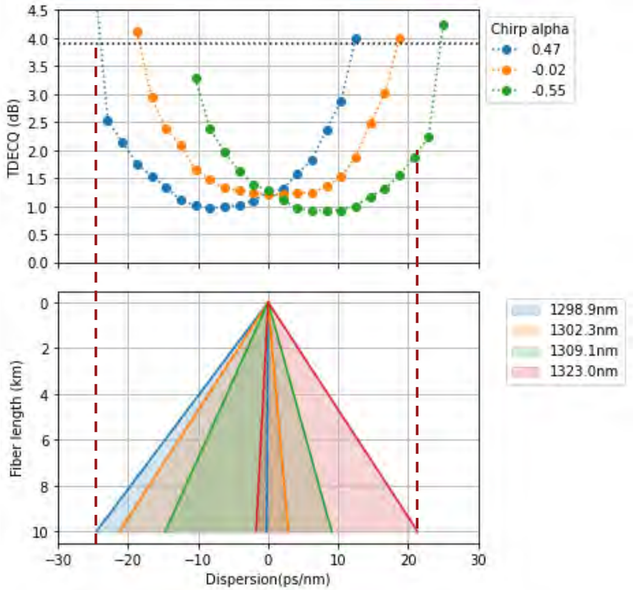
Conclusion

- We presented technical feasibility of 800G-LR4 with PAM4 direct-detection
- Combined consideration of FWM and CD leads to an optimized wavelength plan: 1300.0, 1303.4, 1310.2, 1324.1 nm
  - Variations of this wavelength plan could be investigated (see appendix)
- Additional link margin can be gained
  - By deploying additional techniques like MLSD in the receiver, and they may well be required
  - By choosing a more realistic range of zero-dispersion wavelengths of fiber
- Use of direct-detect for 10 km reach will re-use and leverage a huge base of technologies and components deployed for 500 m and 2 km reach solutions
- Further work
  - Polarization interleaving can further reduce FWM

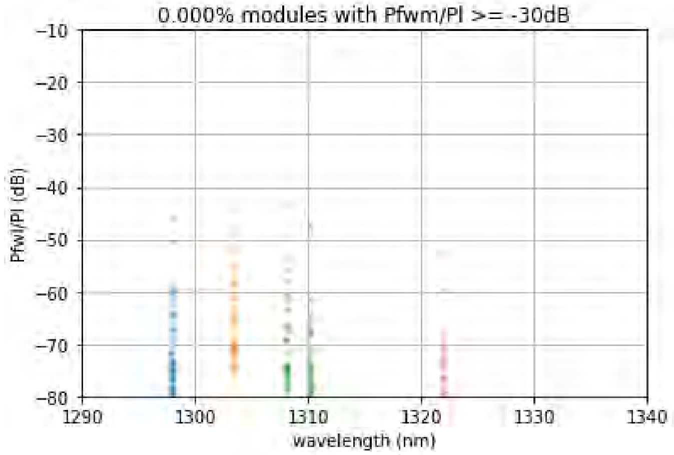
Appendix

Alternate wavelength grid #1

Dispersion Penalty



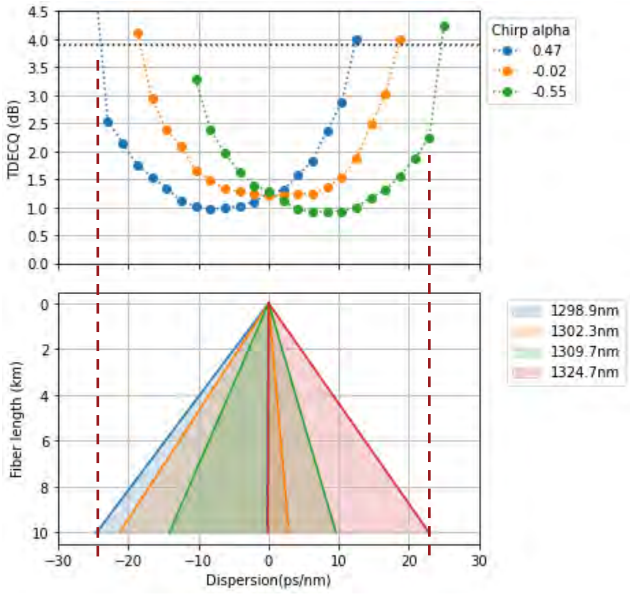
FWM crosstalk (ratio) and probability of a transceiver crossing -30 dB value



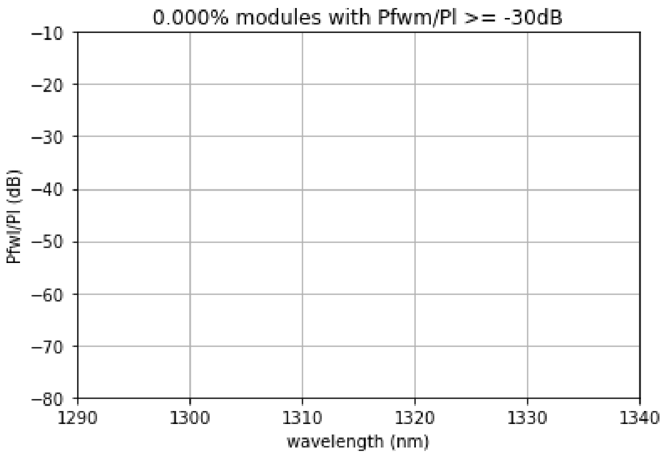
- Shortens the wavelength values slightly, reduces positive dispersion slightly
- Increases negative dispersion slightly
- The spacing is still 600, 1200, and 2400 GHz

Alternate wavelength grid #2

Dispersion Penalty



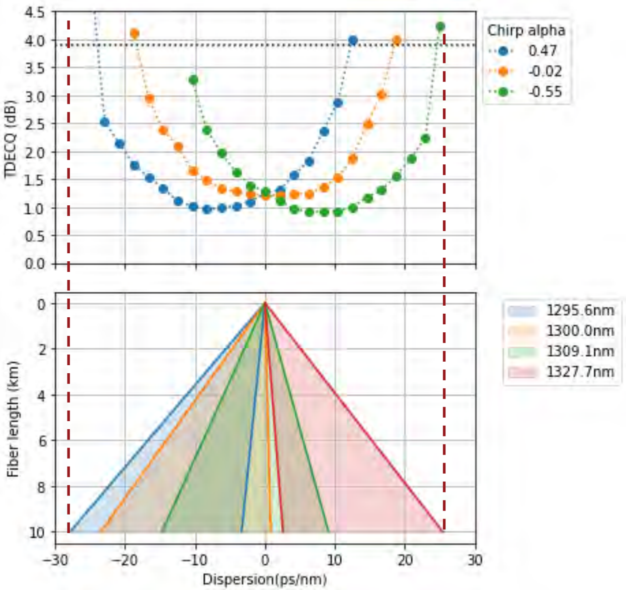
FWM crosstalk (ratio) and probability of a transceiver crossing -30 dB value



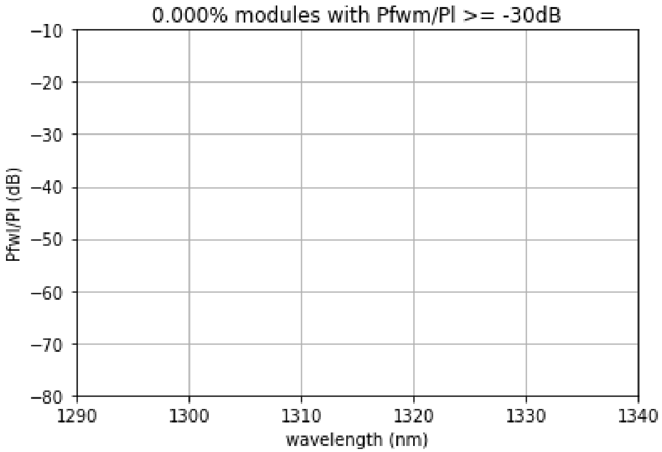
- Same starting wavelength as alternate#1 but satisfies 0 FWM unequal wavelength spacing
- Increases negative and positive dispersion slightly
- The spacing is 600, 1300, and 2600 GHz

Alternate wavelength grid #3

Dispersion Penalty



FWM crosstalk (ratio) and probability of a transceiver crossing -30 dB value



- FWM is 0, satisfies 4D+2R unequal wavelength spacing condition
- Leverages LWDM 800GHz spacing
- Increases both positive and negative dispersion
- The spacing is 800, 1600, and 3200 GHz

Thank You