Rigorous 800G-LR4 FWM Suppression Analysis using Actual Fiber Cable Segmentation

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Introduction

- **The four-wave mixing (FWM) induced transmission impairment in 800G-LR4 has been well studied by multiple teams within IEEE 802.3df/dj [1-5].**
- **The FWM penalty can be avoided by:**
  - Using statistically significant zero-dispersion wavelength (ZDW) lower limit of 1306nm [6], or
  - Shifting the laser wavelengths by ~0.2nm via slight temperature tuning [7]
- **The FWM penalty is lower when using real fiber ZDW distribution [6], achieving a low static outage probability of 4E-5 at a fixed PMD of 0.1 ps/sqrt(km) [8].**
- **In this presentation, we show that the FWM-induced static outage probability (OP) is below 1E-7 when actual fiber cable segmentation [9,10] is used in rigorous analysis.**

[1] johnson_3df_optx_01_220414; [2] lam_3df_01a_220524; [3] liu_3df_01b_2207; [4] lewis_3df_01_221012;
[5] rodes_3df_01a_2211; [6] cole_3df_01a_2211; [7] kuschnerov_3dj_01a_230206; [8] johnson_3dj_01a_230206;
[9] kuschnerov_3df_01a_2211; [10] kikuchi_3dj_01b_230206.

Background on Fiber Cable Segmentation

- Fiber cables are deployed on a segment-by-segment basis, where each segment is typically 1~3 km in length (due to deployment considerations on transportation and installation etc., as illustrated in https://www.istockphoto.com/de/search/2/image?phrase=laying+fiber+optic+cable)

- Each fiber cable contains many fibers (e.g., 144 fibers).

- All the fibers in the adjacent segments are sliced together.

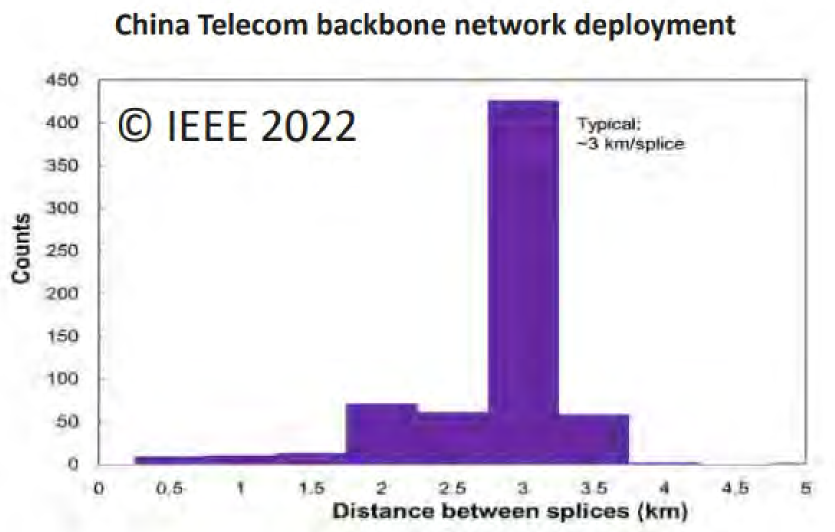
- Two exemplary fiber cable specifications are show below:

Cable Type	Fiber Count	Loose tube count	Cable Diameter (mm)	Cable Weight (Kg/km)
GYTY53-2～6	2～6	1	12.5	160
GYTY53-130～144	134～144	12	18.0	290

Source: https://mefiberoptic.com/product/144-core-gyty53-fiber-optic-cable/

Actual Fiber Cable Segmentation

- According to kikuchi_3dj_01b_230206, it is important to consider the “effect of longitudinal ZDW fluctuation” in order “to avoid overestimation of FWM penalty”.
- As each deployed fiber cable generally consists of multiple cable segments that are sliced together, and the each segment is usually less than 3km (even for ultra-long-haul systems), as shown on the below (after kuschnerov_3df_01a_2211), we need to consider the realistic randomization of ZDW from segment to segment.



C. Zhang *et al*., "Optical Layer Impairments and Their Mitigation in C+L+S+E+O Multi-Band Optical Networks With G.652 and Loss-Minimized G.654 Fibers," in *Journal of Lightwave Technology*, vol. 40, no. 11, pp. 3415-3424, 1 June, 2022. https://ieeexplore.ieee.org/document/9756341

- In this contribution, we evaluate the FWM powers for a 10-km G.652 fiber consisting of (i) 2x 5km (ii) 3x 3.33km (iii) 4x 2.5km and (iv) 5x 2km cable segments where the ZDW is randomized between segments, in comparison with a hypothetic 10km link without cable segmentation.

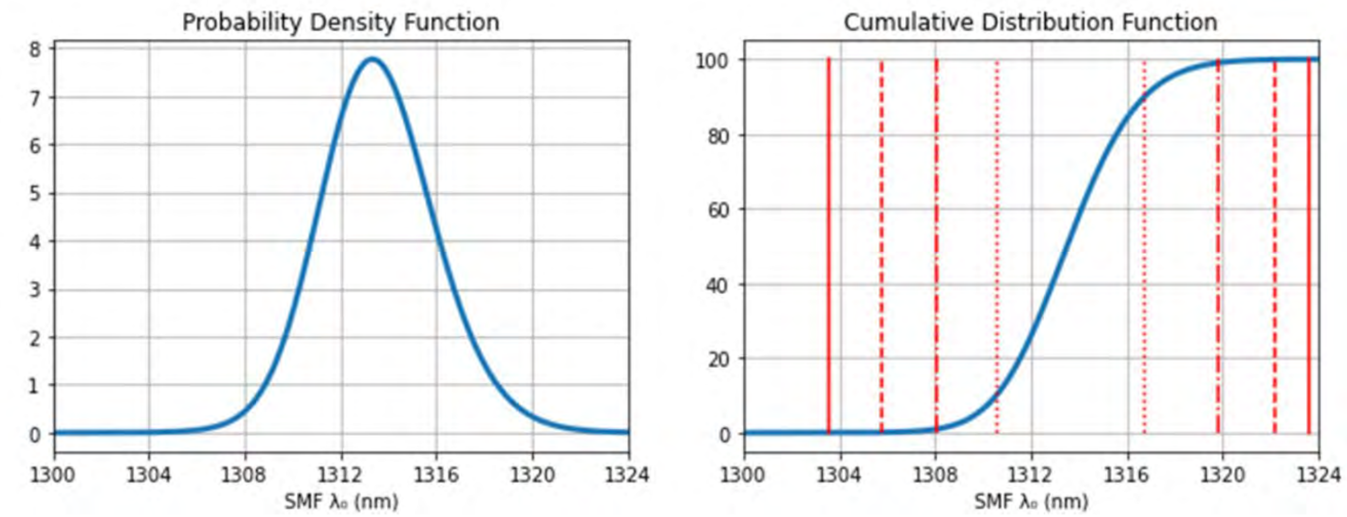
Simulation Parameters

- Average optical power (AOP) per channel: 5.65 dBm (~ highest power considered in rodes_3dj_01_2303)
- Wavelength plan is the same as that in rodes_3dj_01_2303:

The wavelength plan reuses the LAN-WDM channels

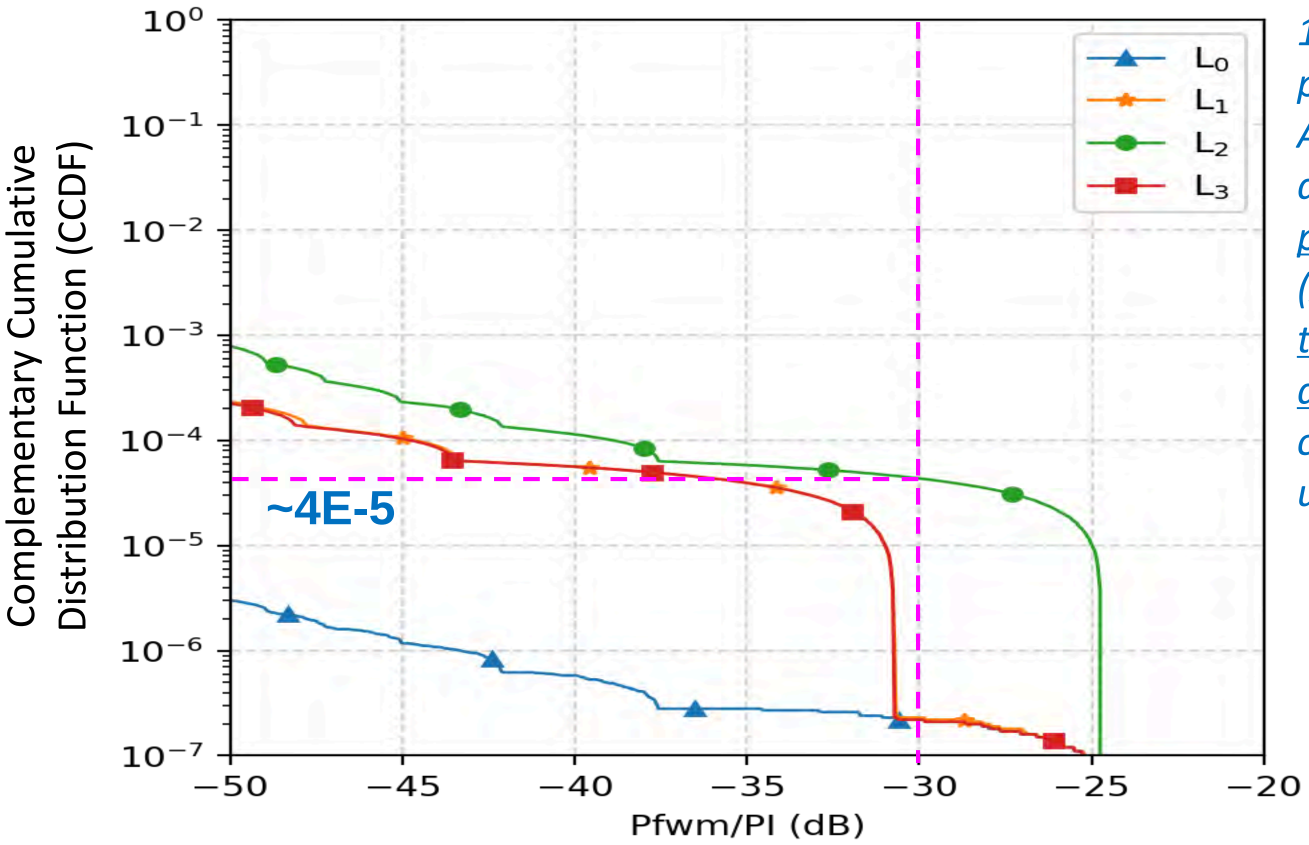
Channel index	Center frequency (THz)	Center wavelength (nm)	Dispersion after 10km (ps/nm)
L_0	231.4	1295.56	-26.16 ~ -4.08
L_1	230.6	1300.05	-22.03 ~ 0.05
L_2	229.8	1304.58	-17.87 ~ 4.21
L_3	229.0	1309.14	-13.67 ~ 8.41

- The fiber ZDW distribution is following the real distribution presented in cole_3df_01a_2211:



Simulation Result (1): 10km=1×(10km segment)

- Using Monte-Carlo simulations as done in rodes_3df_01a_2211, we have assessed the P_{fwm}/P_{launch} distributions under the assumption that the 10km LR link consists of 1x 10km cable segment.

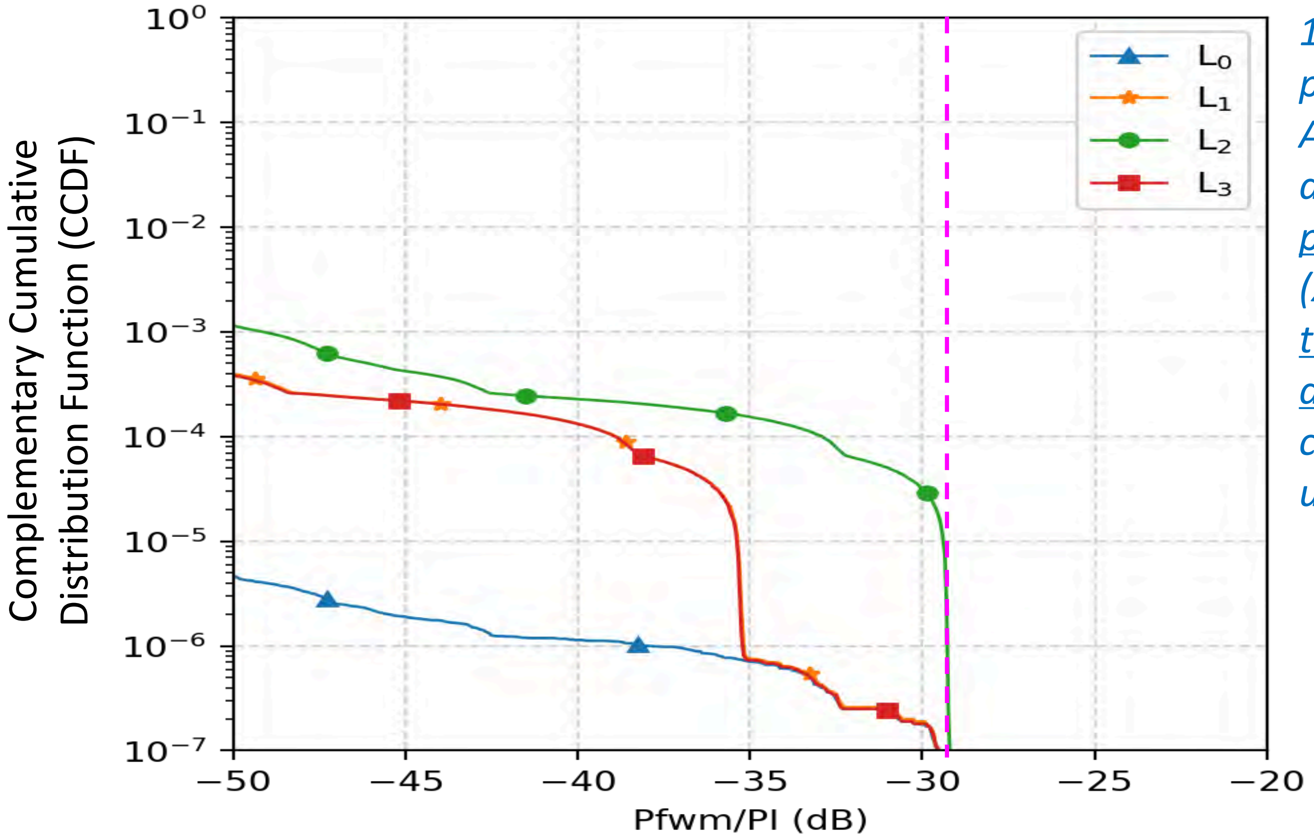


100 million simulations performed with: AOP=5.65 dBm/channel, and the worst-case polarization alignment (XXXX with PMD=0) and the worst-case channel alignment where the four channels are exactly uniformly spaced.

- The probability of having P_{fwm}/P_{launch} of **>-30dB** is **~4E-5**.

Simulation Result (2): 10km=2×(5km segment)

- Using Monte-Carlo simulations as done in rodes_3df_01a_2211, we have assessed the P_{fwm}/P_{launch} distributions under the assumption that the 10km LR link consists of 2x 5km cable segments.

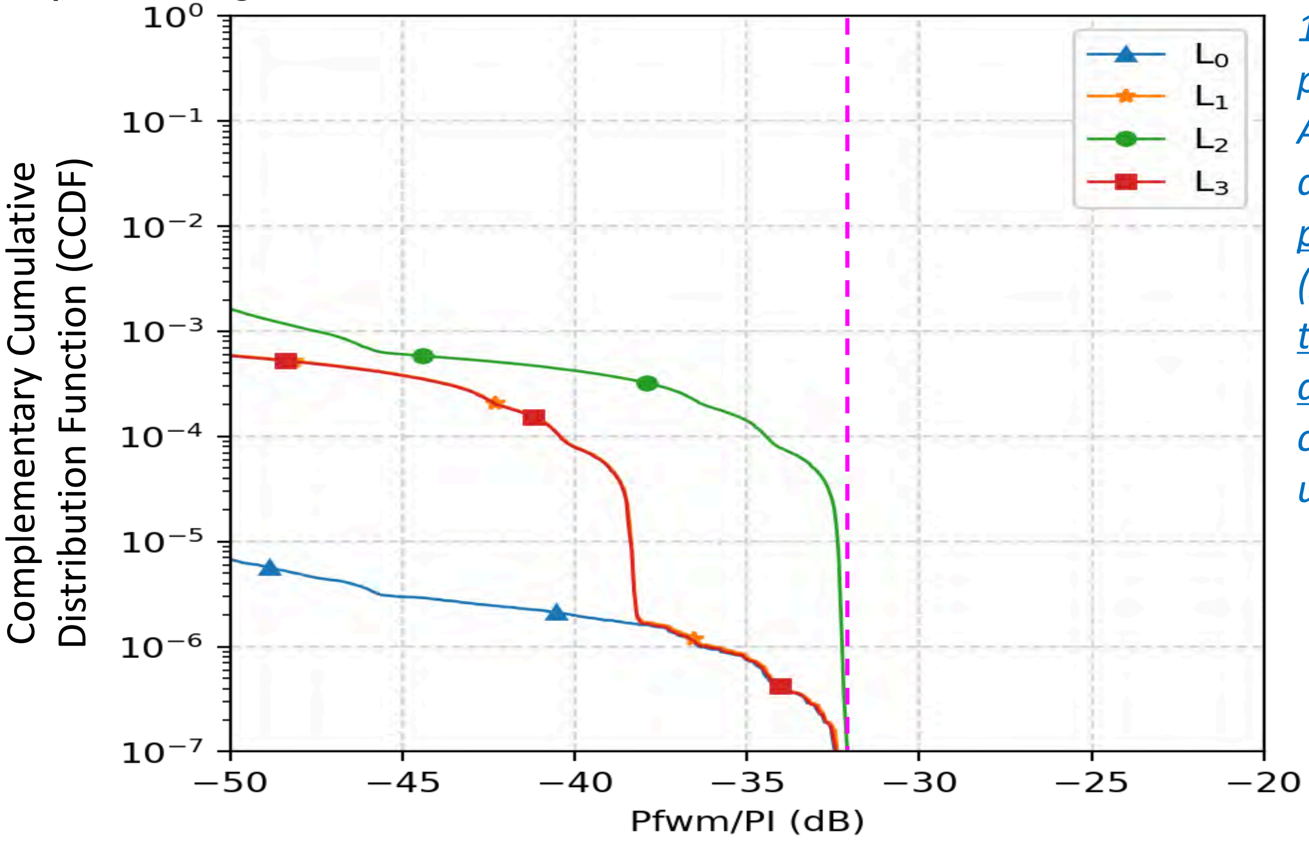


100 million simulations performed with: AOP=5.65 dBm/channel, and the worst-case polarization alignment (XXXX with PMD=0) and the worst-case channel alignment where the four channels are exactly uniformly spaced.

- The probability of having P_{fwm}/P_{launch} of >**-29dB** is **1E-7**. Considering realistic channel alignments and raw BER averaging over 4 channels, the effective P_{fwm}/P_{launch} at 1E-7 static OP is **<-30dB**.

Simulation Result (3): 10km=3×(3.33km segment)

- Using Monte-Carlo simulations as done in rodes_3df_01a_2211, we have assessed the realistic P_{fwm}/P_{launch} distributions under the assumption that the 10km LR link consists of 3x 3.33km cable segments that are spliced together.

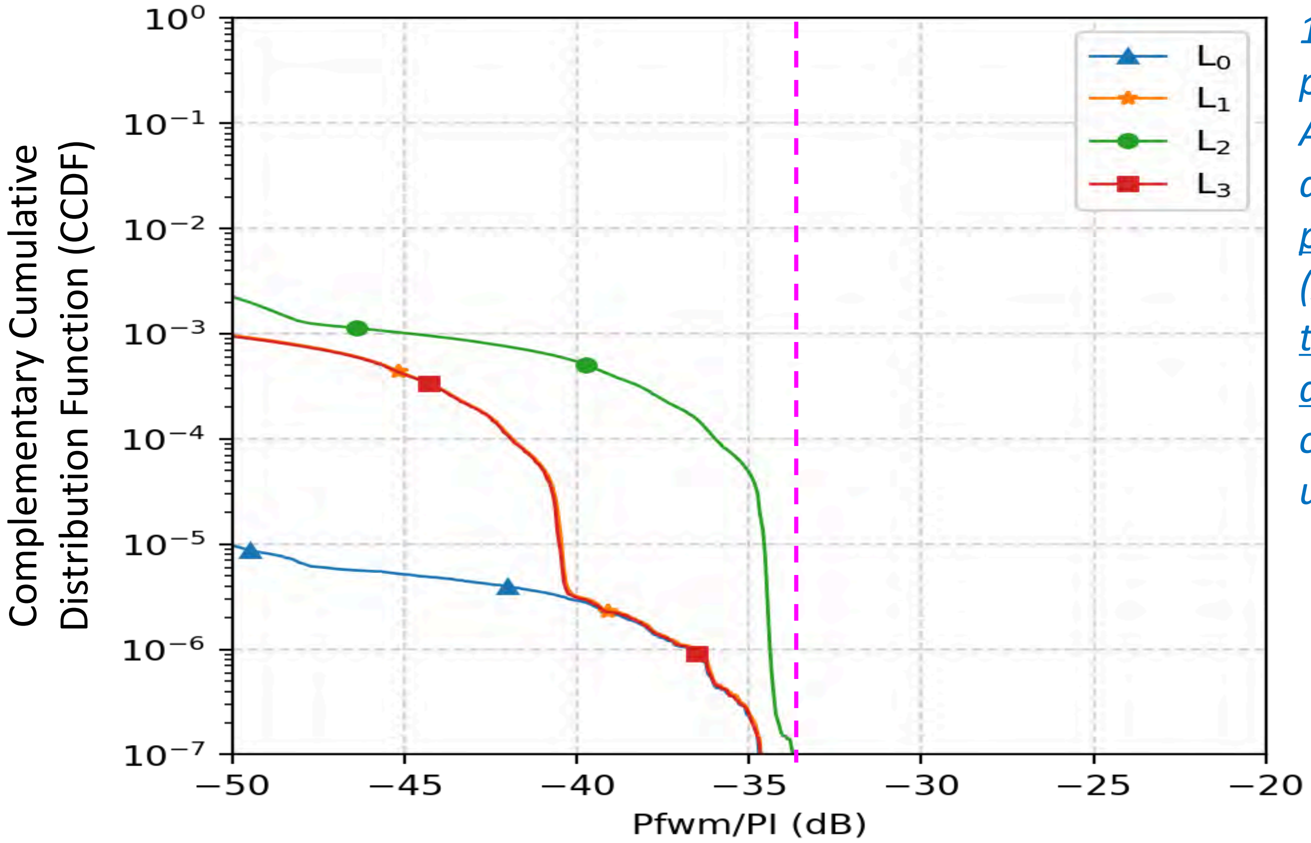


100 million simulations performed with: AOP=5.65 dBm/channel, and the worst-case polarization alignment (XXXX with PMD=0) and the worst-case channel alignment where the four channels are exactly uniformly spaced.

- The probability of having P_{fwm}/P_{launch} of >**-31.5dB** is **<1E-7**. Considering realistic channel alignments and raw BER averaging over 4 channels, the effective P_{fwm}/P_{launch} at 1E-7 static OP is **<-32.5dB**.

Simulation Result (4): 10km=4×(2.5km segment)

- Using Monte-Carlo simulations as done in rodes_3df_01a_2211, we have assessed the realistic P_{fwm}/P_{launch} distributions under the assumption that the 10km LR link consists of 4x 2.5km cable segments that are spliced together.

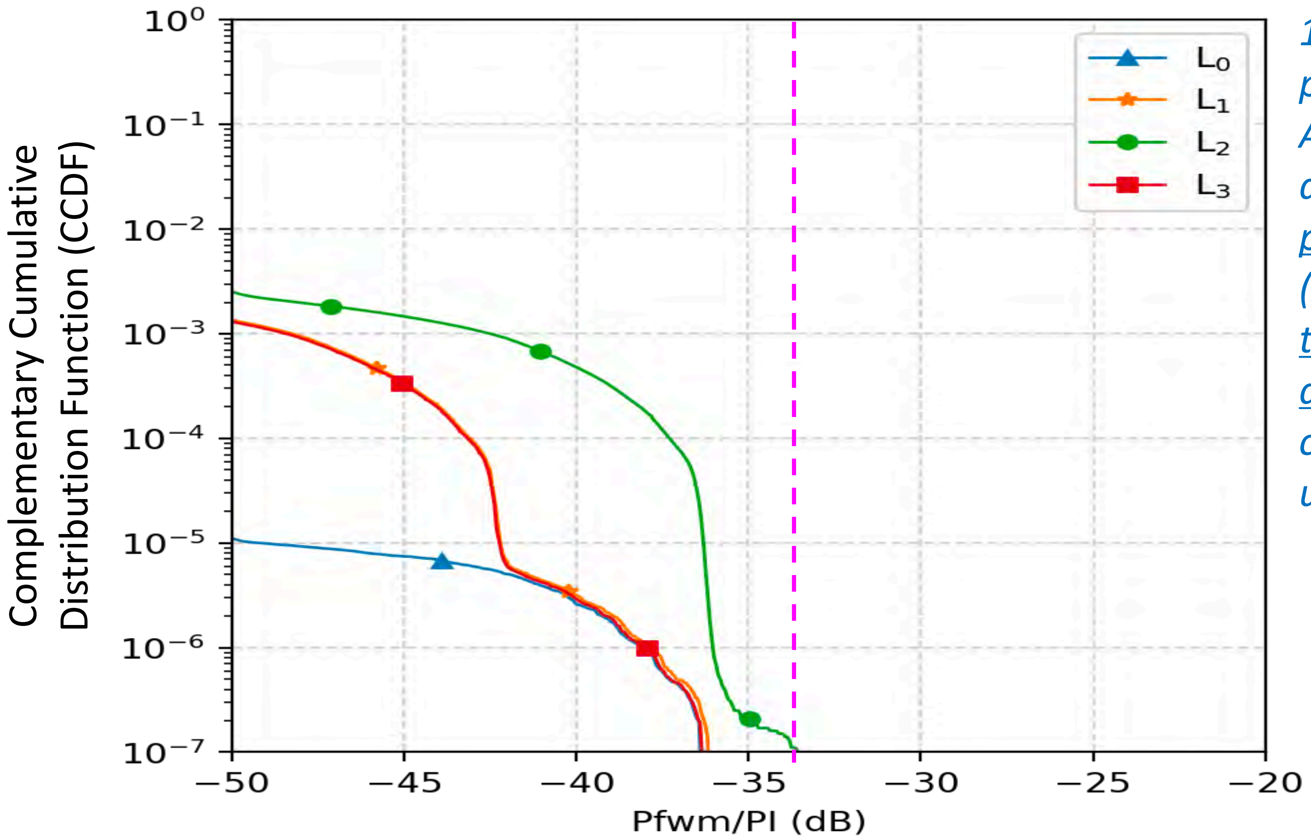


100 million simulations performed with: AOP=5.65 dBm/channel, and the worst-case polarization alignment (XXXX with PMD=0) and the worst-case channel alignment where the four channels are exactly uniformly spaced.

- The probability of having P_{fwm}/P_{launch} of >**-33.5dB** is **<1E-7**. Considering realistic channel alignments and raw BER averaging over 4 channels, the effective P_{fwm}/P_{launch} at 1E-7 static OP is **<-34.5dB**.

Simulation Result (5): 10km=5×(2km segment)

- Using Monte-Carlo simulations as done in rodes_3df_01a_2211, we have assessed the realistic P_{fwm}/P_{launch} distributions under the assumption that the 10km LR link consists of 5x 2km cable segments that are spliced together.



100 million simulations performed with: AOP=5.65 dBm/channel, and the worst-case polarization alignment (XXXX with PMD=0) and the worst-case channel alignment where the four channels are exactly uniformly spaced.

- The probability of having P_{fwm}/P_{launch} of >**-33.5dB** is **<1E-7**. Considering realistic channel alignments and raw BER averaging over 4 channels, the effective P_{fwm}/P_{launch} at 1E-7 static OP is **<-34.5dB**.

Discussion & Conclusion

1) With the consideration of real fiber ZDW distribution, the FWM-induced static outage probability (under the worst-case polarization alignment of XXXX with PMD=0 and the worst-case channel alignment) for the baseline spec proposed in rodes_3dj_01_2303 is **~4E-5**.

2) With the additional consideration of actual fiber cable segmentation with 2~5km segments, the FWM-induced static outage probability can be reduced to **<1E-7**.

3) With the further consideration of the "effect of longitudinal ZDW fluctuation" within each cable segment (as reported in kikuchi_3dj_01b_230206), the static outage probability is expected to further reduced.

4) Field-deployed systems are operating with extra margin, because of statistical distribution of component and fiber losses and impairments, therefore the actual static outage probability is even lower.

Given the above, the 800G-LR4 baseline spec proposed in rodes_3dj_01_2303 is expected to be well supported in real-world deployments.

Thank you!