Assessment of the combined penalty from FWM and dispersion in 800G-LR4 based on 224Gb/s PAM4

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Supporters

- John Johnson (Broadcom)

More to be added in the future.

Introduction

- The FWM penalty and the dispersion penalty depend on fiber zero-dispersion wavelength (ZDW) differently, so it is necessary to consider the FWM and dispersion penalties collectively for all possible ZDW values.

- This presentation is an extension of the July 2022 presentation liu_3df_01b_2207 with the following new aspects
  1) increasing the bit rate per channel from 200Gb/s to 224Gb/s to reflect the increased dispersion effect when the FEC overhead is included;
  2) considering the wavelength plan suggested by Roberto and Frank, i.e., the longest four LAN-WDM wavelengths with 400GHz red shift;
  3) using a more likely FEC BER threshold of 4.5E-3 instead of 8E-3;
  4) assessing the FWM+dispersion penalty over all possible ZDW values; and
  5) conducting >2,000 PMD realizations with DGD=0.1 ps/sqrt(km).

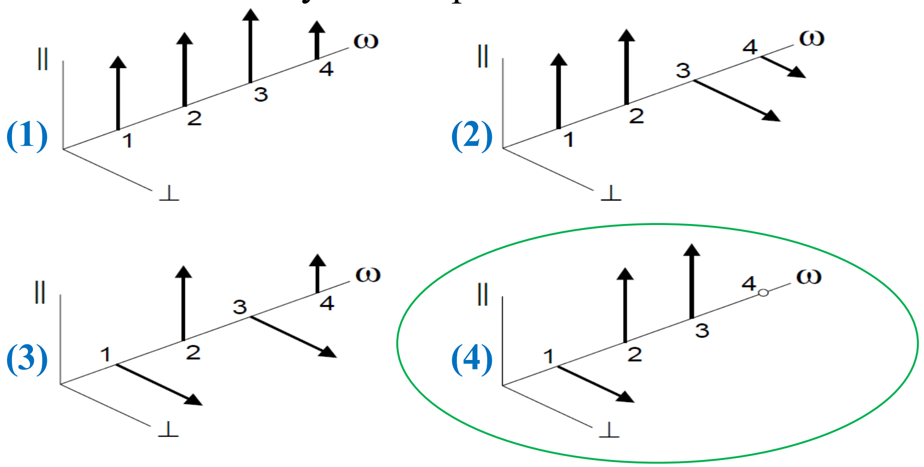
FWM suppression by “XYYX” polarization arrangement

- For typical transmission fibers, the random birefringence model (RBM), where the fiber polarization axes and birefringence strength vary randomly with distance, is commonly used [1,2].
- Under the RBM, the non-degenerate FWM strength on a 4th wavelength depends on the polarization arrangements of the 3 interfering wavelengths as shown in Table 2 and Fig. 3 of Ref.[2]:

Table 2. Properties of nondegenerate FWM driven by three input waves

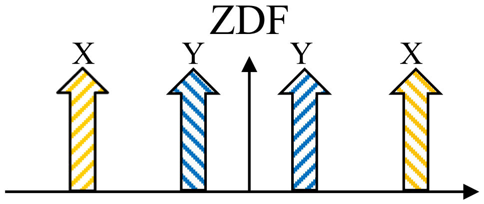
		$\lvert E_4\rangle$	P_4
(1)	$\lvert E_1\rangle \parallel \lvert E_2\rangle \parallel \lvert E_3\rangle$	$\lvert E_2\rangle$	1
(2)	$\lvert E_1\rangle \parallel \lvert E_2\rangle \perp \lvert E_3\rangle$	$\lvert E_3\rangle$	1/4
(3)	$\lvert E_1\rangle \parallel \lvert E_3\rangle \perp \lvert E_2\rangle$	$\lvert E_2\rangle$	1/4
(4)	$\lvert E_1\rangle \perp \lvert E_2\rangle \parallel \lvert E_3\rangle$	—	0
	random	random	3/8

Fig. 3. Polarization diagrams for nondegenerate FWM driven by three input waves.



- To effectively mitigate the FWM penalty, we can use the XYYX (or YXXY) polarization arrangement for the four input signals of 800G LR4 [3]:

(*: Note that the degenerate FWM from the center two co-polarized channels generates side tones that are orthogonal to the two edge channels in polarization, so the degenerate FWM-induced penalty is also negligibly small.)



Physical picture: $\Delta\varphi(z)\sim 2\varphi_y(z)-\varphi_x(z)$ is fast varying (due to the very short fiber beat length of ~10m).

[1] K. Inoue, “Polarization effect on four-wave mixing efficiency in a single-mode fiber,” IEEE J. Quantum Electron. 28, 883–894 (1992).
[2] C. J. McKinstrie, H. Kogelnik, R. M. Jopson, S. Radic and A. V. Kanaev, “Four-wave mixing in fibers with random birefringence,” Opt. Express 12, 2033–2055 (2004).
[3] X. Liu, Q. Fan, T. Gui, K. Huang, and F. Chang, “Effective suppression of inter-channel FWM for 800G-LR4 and 1.6T-LR8 based on 200Gb/s PAM4 channels,” IEEE 802.3df contribution liu_3df_01b_2207, July Plenary, 2022. (Available online at: https://www.ieee802.org/3/df/public/22_07/liu_3df_01b_2207.pdf)

Wavelength plan options

LAN-WDM channels

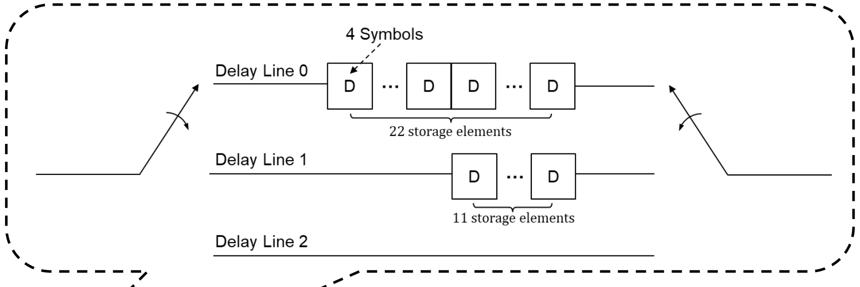
Channel index	Center frequency (THz)	Center wavelength (nm)	Dispersion range after 10km (ps/nm)
ch0	231.4	1295.56	-26.16 ~ -4.08
ch2	230.6	1300.05	-22.03 ~ 0.05
ch4	229.8	1304.58	-17.87 ~ 4.21
ch6	229.0	1309.14	-13.67 ~ 8.41

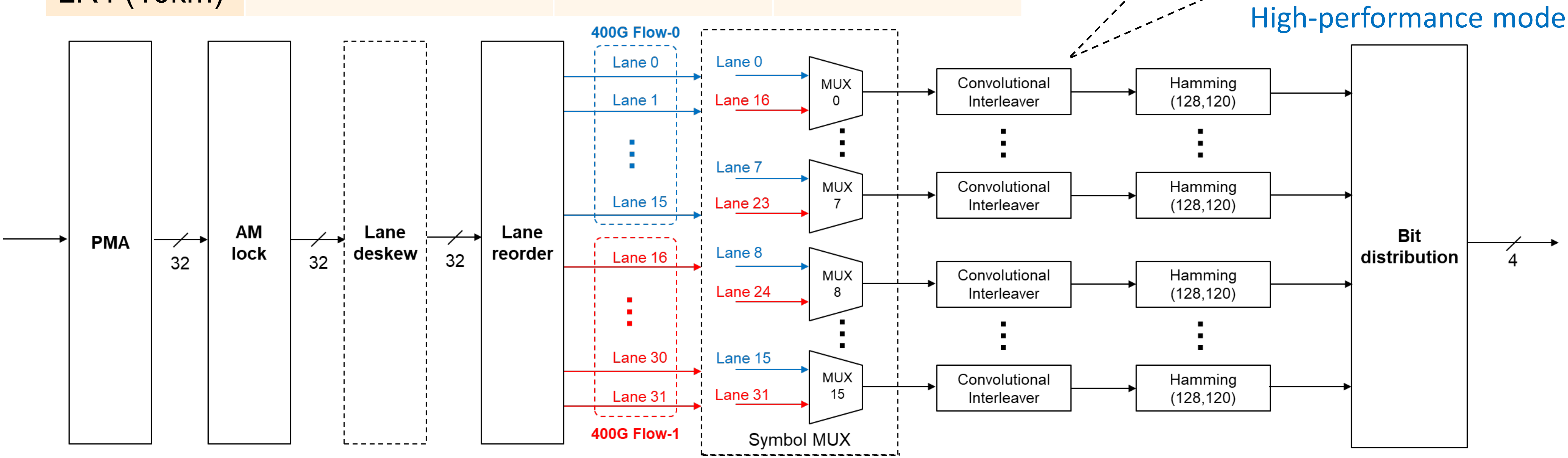
LAN-WDM channels with 400GHz red shift

Channel index	Center frequency (THz)	Center wavelength (nm)	Dispersion range after 10km (ps/nm)
ch1	231.0	1297.80	-24.10 ~ -2.02
ch3	230.2	1302.31	-19.95 ~ 2.13
ch5	229.4	1306.85	-15.78 ~ 6.30
ch7	228.6	1311.43	-11.56 ~ 10.52

Concatenated FEC scheme for 800G IMDD

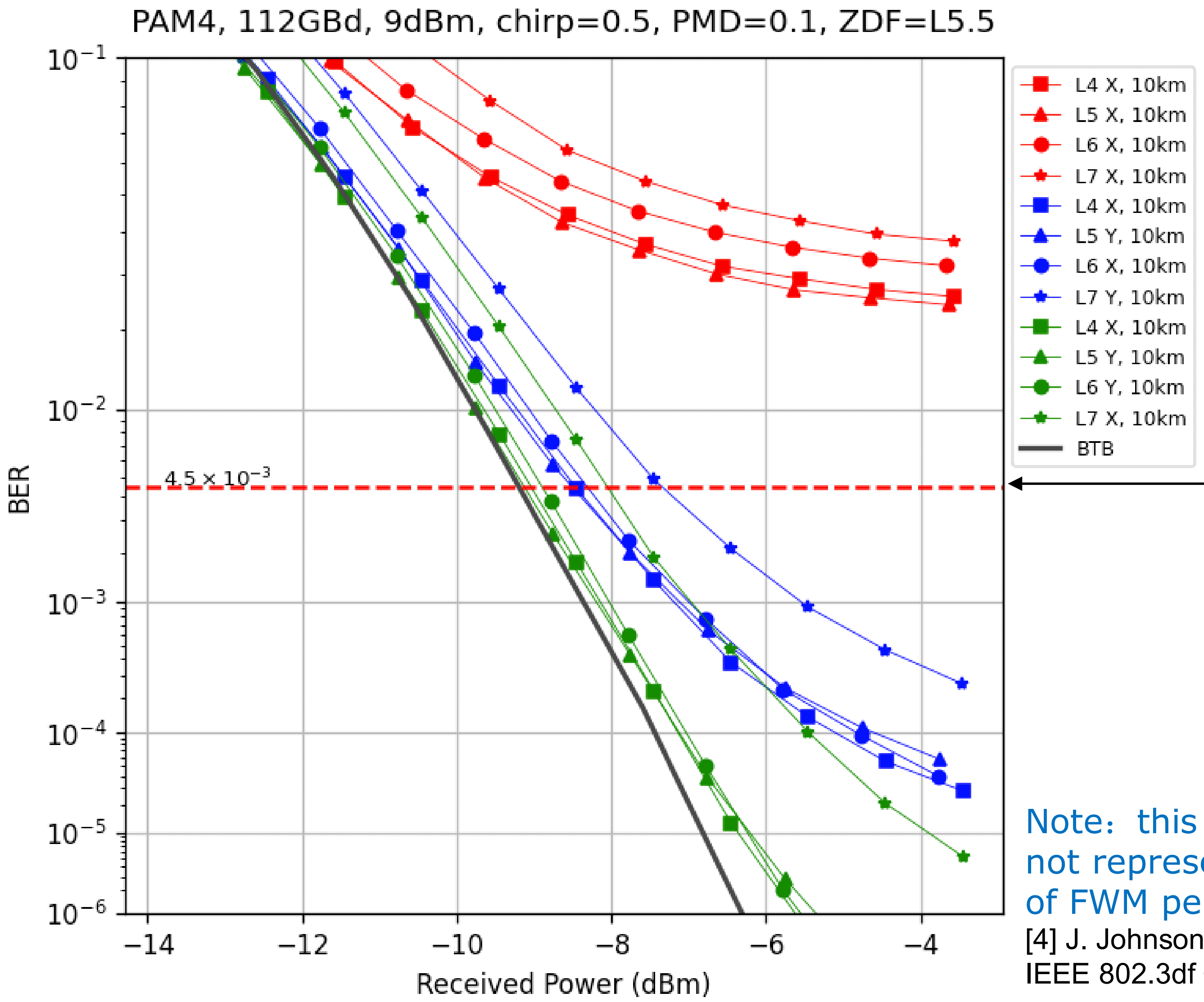
Reach	FEC (113.3GBaud)	FEC Latency	BER threshold
DR4 (500m)	KP4 + Hamming(128,120)	~20 ns	~2.2E-3
FR4 (2km)	KP4 + Interleaver Hamming(128,120)	~70 ns	~4.8E-3
LR4 (10km)			





One ASIC to support High-performance or ultra-low latency mode by configurable interleaver.

Impact of FWM in 800G-LR @224Gbps/λ



Channel index	Center frequency (THz)	Center wavelength (nm)
L4	231.0	1297.80
L5	230.2	1302.31
L6	229.4	1306.85
L7	228.6	1311.43

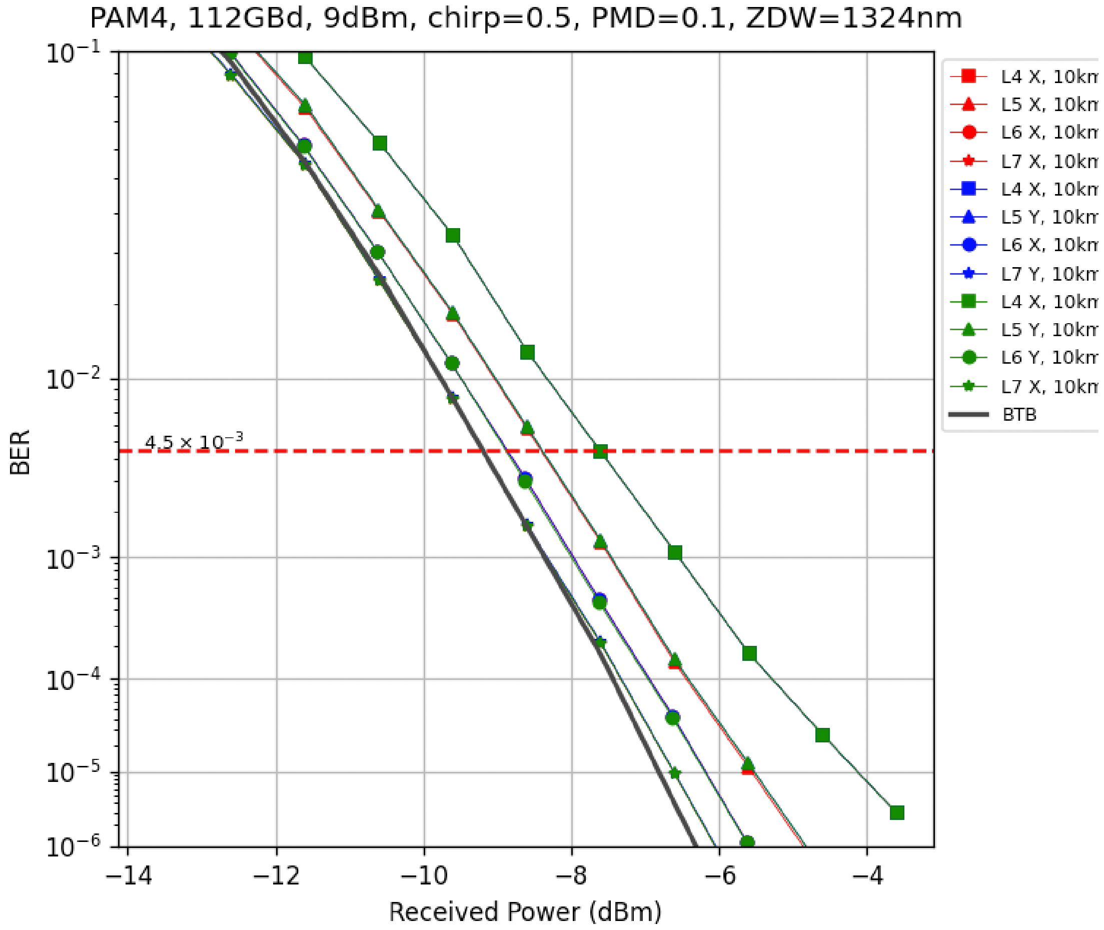
Assuming 4.5E-3 as the FEC BER threshold

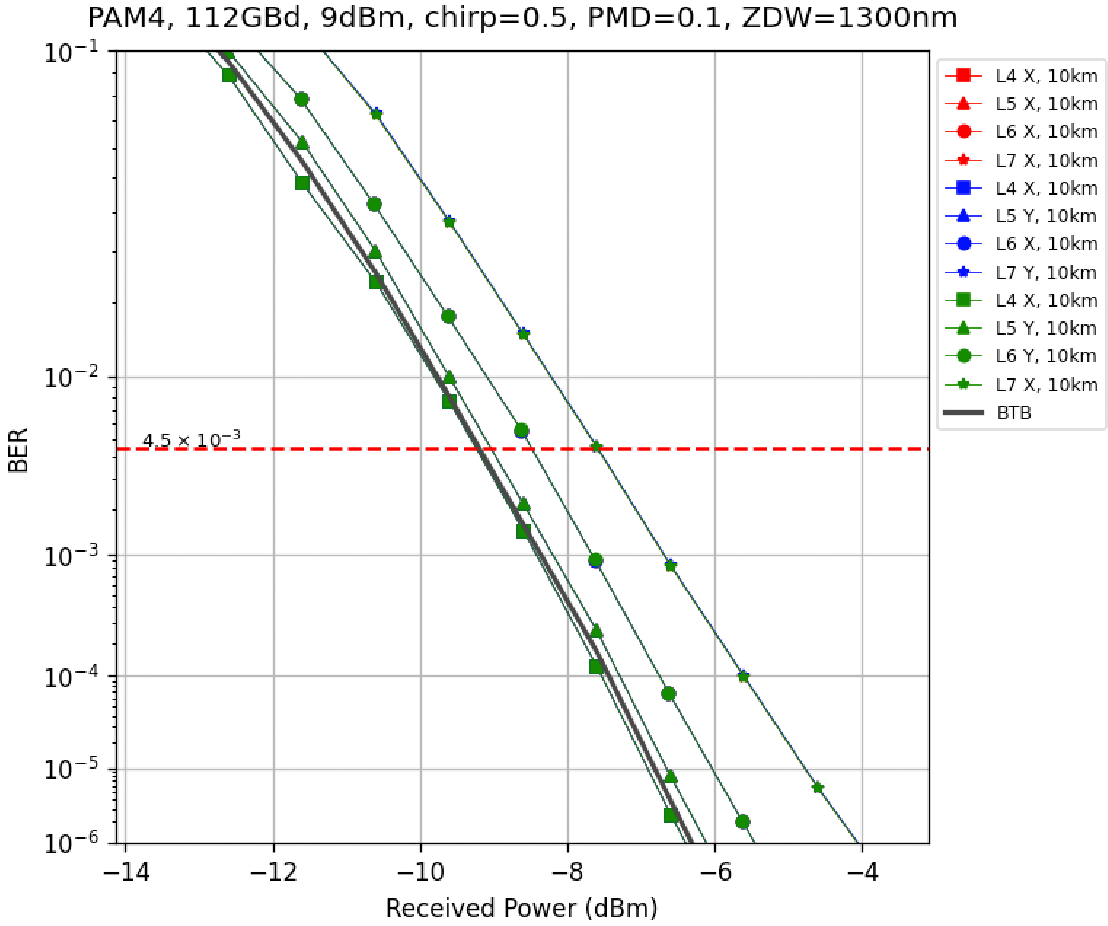
Note：this is a single realization of PMD, not representative of the full distribution of FWM penalties over PMD [4].

[4] J. Johnson, “FWM Analysis of PAM4 LR/ER PMDs,” IEEE 802.3df Optics Ad Hoc Meeting, April 11, 2022.

Impact of dispersion in 800G-LR4 @224Gbps/λ

Channel index	Center frequency (THz)	Center wavelength (nm)
L4	231.0	1297.80
L5	230.2	1302.31
L6	229.4	1306.85
L7	228.6	1311.43

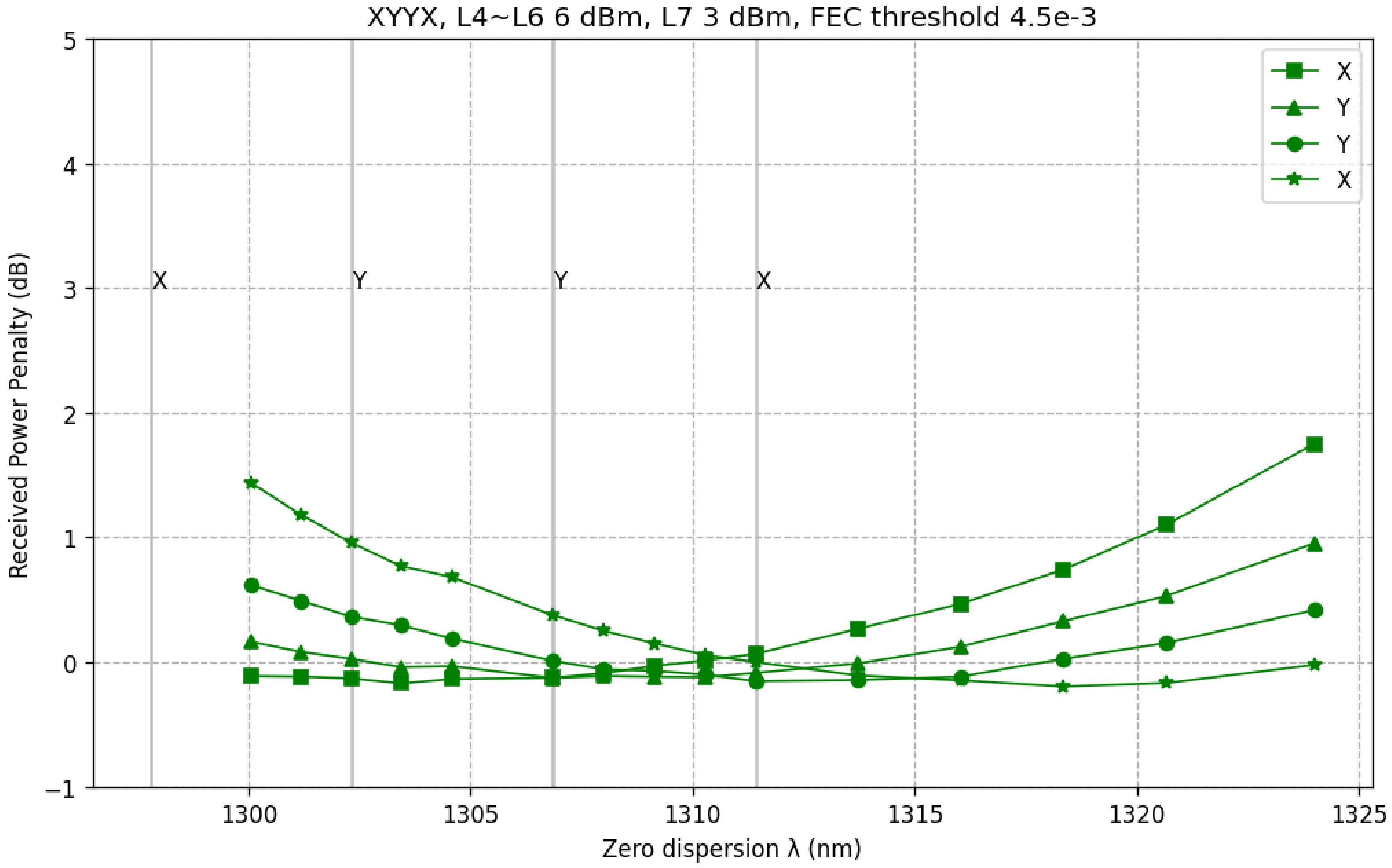




The worst-case chromatic dispersion (CD) penalty is limited to <2dB.

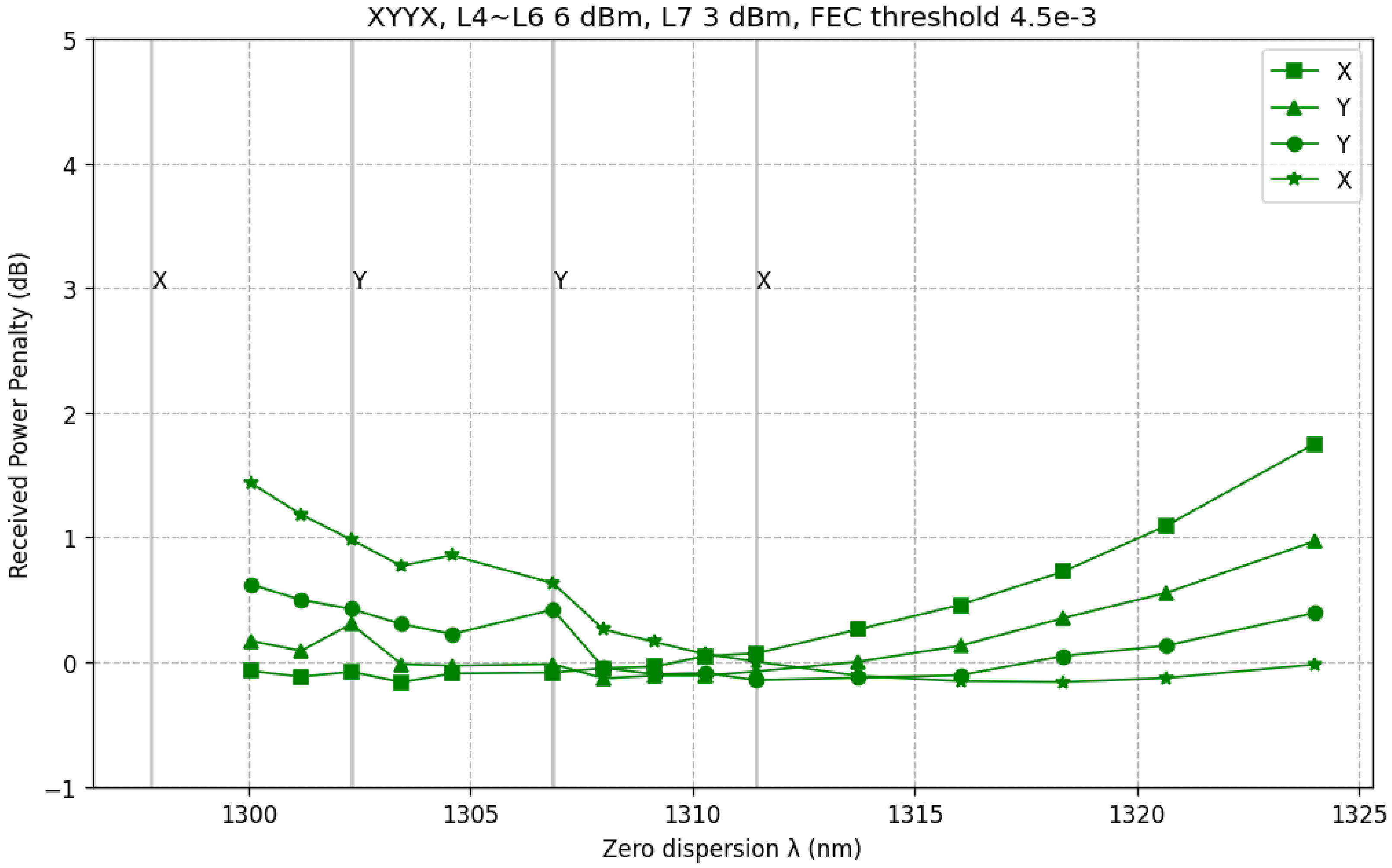
(Note：this is a single realization of PMD with fiber nonlinearity turned off)

Combined CD+FWM penalties (PMD=0)



The worst-case CD+FWM penalty is limited to <2dB at PMD=0.

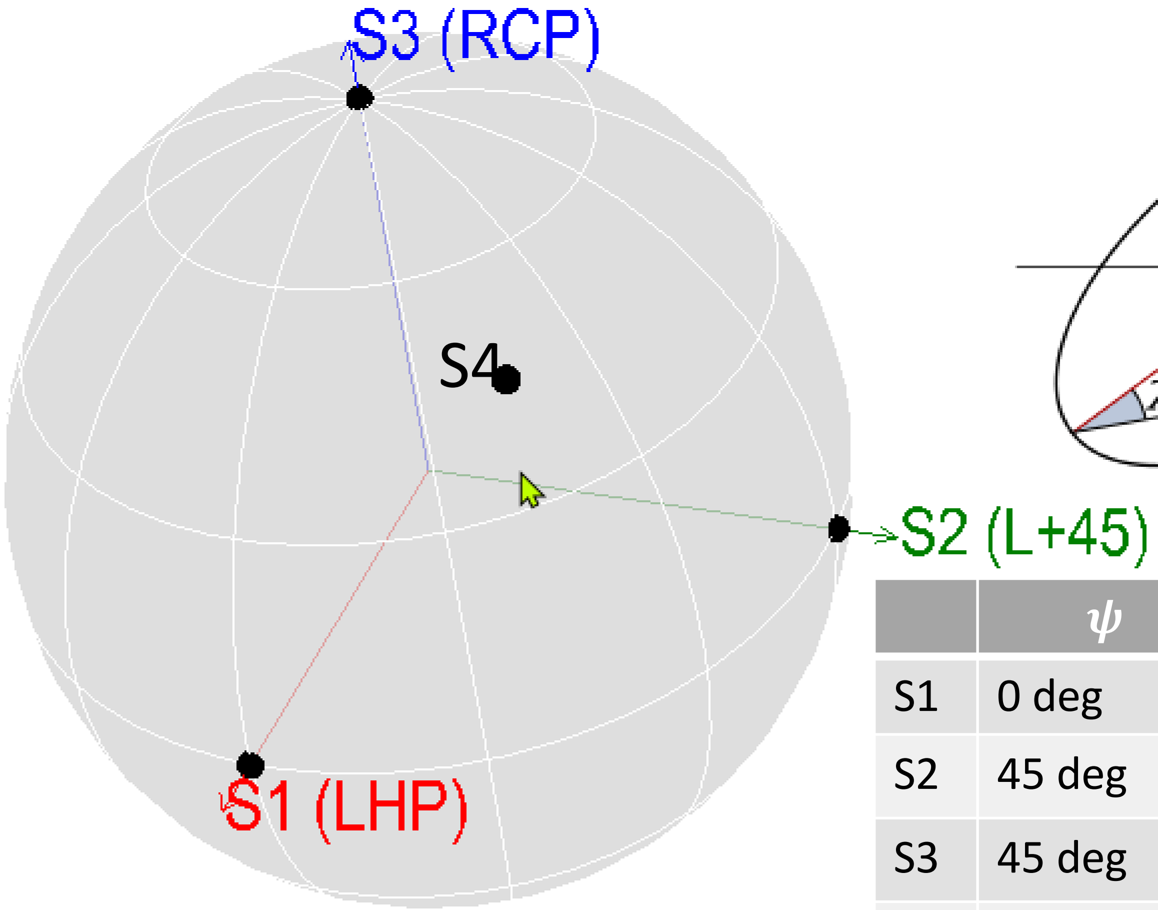
Combined CD+FWM penalties (A realization with PMD=0.1ps/sqrt(km))

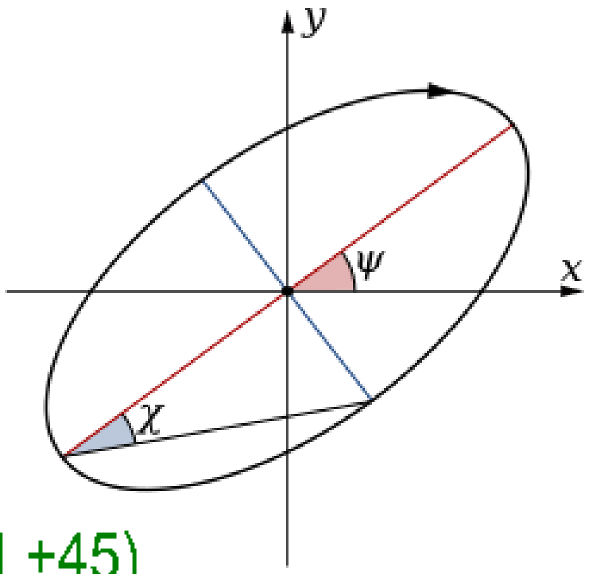


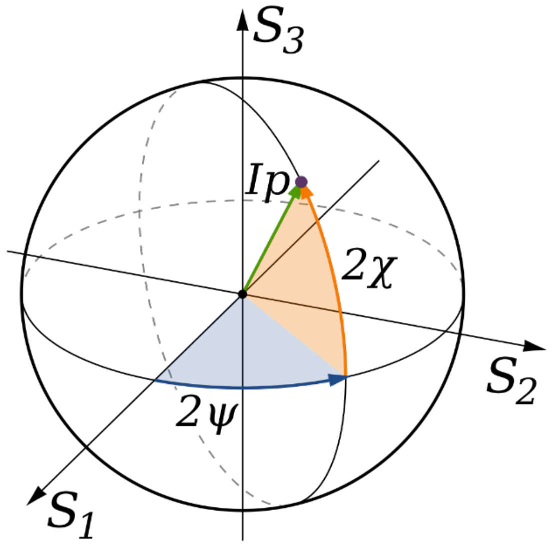
The worst-case FWM+dispersion penalty is limited to <2dB at PMD=0.1 ps/sqrt(km).
(Note：this is a single realization of PMD, not representative of the full distribution of FWM penalties over PMD.)

More PMD realizations - with different incident polarization states & link PMD realizations

Four incident "X" Polarizations



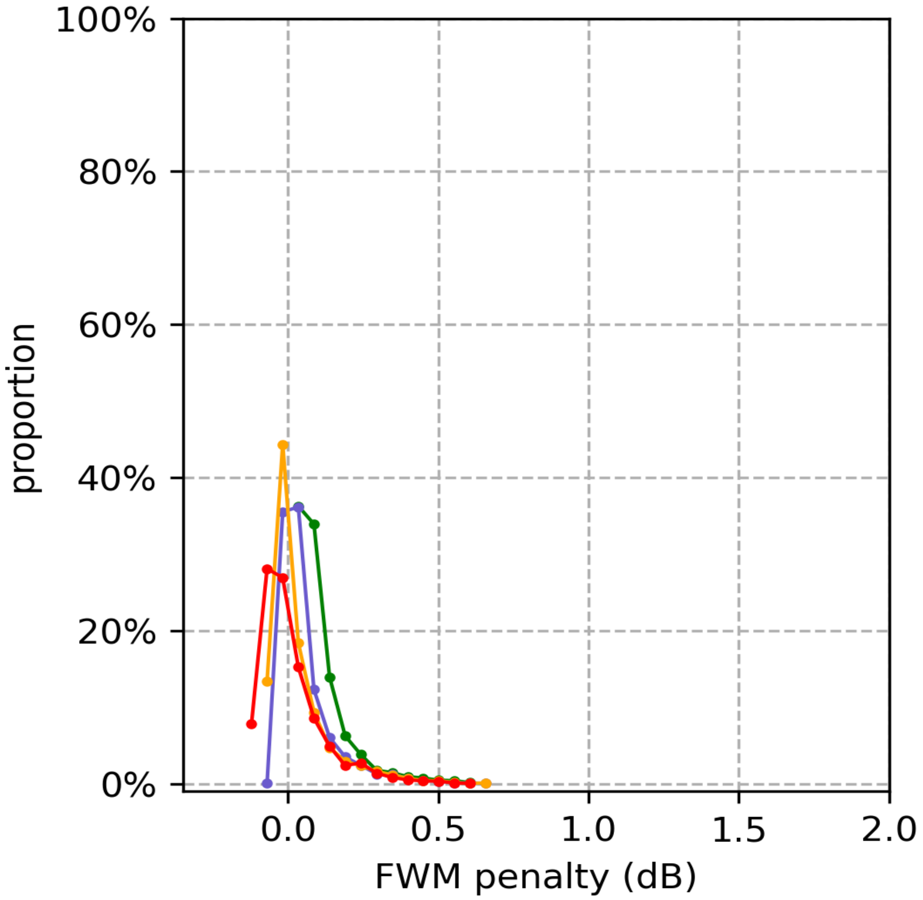


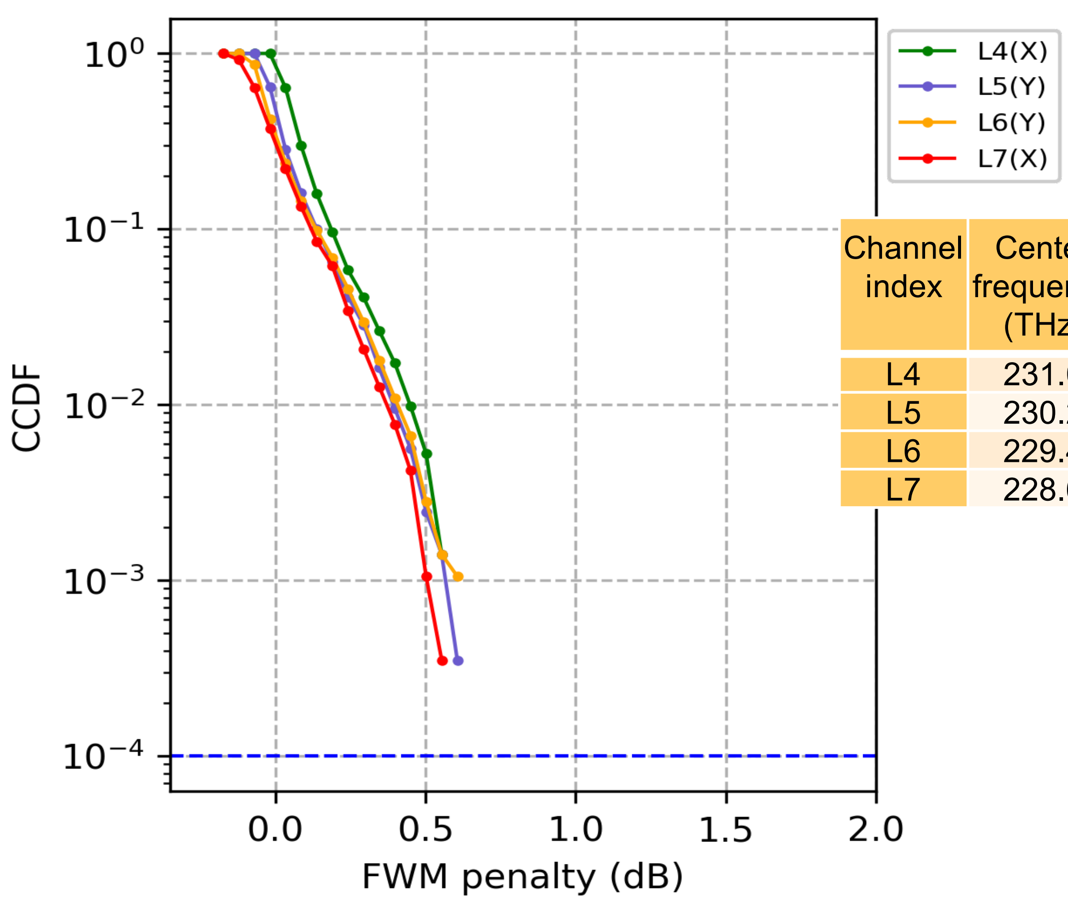


	ψ	χ	x	y
S1	0 deg	0 deg	1	0
S2	45 deg	0 deg	$1/\sqrt{2}$	$1/\sqrt{2}$
S3	45 deg	45 deg	$1/\sqrt{2}$	$-j/\sqrt{2}$
S4	22.5 deg	22.5 deg	$\sqrt{(1+1/\sqrt{3})/2}$	$(1-j)\sqrt{(1-1/\sqrt{3})/4}$

Worst-case FWM penalties with >2,000 PMD realizations

- Under a worst-case scenario with AOP=5dBm per channel, assuming that the ZDW is exactly at L5.5, PMD=0.1 ps/sqrt(km), and BER_{th}=4.5E-3.





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L6	229.4	1306.85
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❑ Even under the worst-case alignment of ZDW and laser frequencies, the FWM-induced “outage” is $<10^{-3}$ for a 1dB penalty and a signal launch power of 5dBm per channel.

Discussion on FWM-induced “overall outage probability”

- Even assuming that the fiber ZDW distribution is uniform over 1300nm~1324nm, the chance of “FWM wavelength matching” is 0.563% (according to rodes_3df_01_221012);
- Due to the laser frequency tolerance of df=100GHz, the probability of the FWM being within the RX bandwidth is ~B/2df=112G/200G=0.56 (according to johnson_3df_optx_01_220414);
- Based on the results from the last slide, under the alignment of ZDW and laser frequencies, the FWM-induced “outage” is ~10^{-3} for a 1dB penalty and a signal launch power of 5dBm per channel;
- Thus, the FWM-induced overall outage probability becomes ~0.563%*0.56*10^{-3} or **3.2×10^{-6}**, which is reasonably low, given that the PMD-induced outage probability specified in OIF 400ZR is 4.1×10^{-6} (https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0_reduced2.pdf).

Summary

- This presentation is an extension of the July 2022 presentation liu_3df_01b_2207 with the following new aspects
  1) increasing the bit rate per channel from 200Gb/s to 224Gb/s to reflect the increased dispersion effect when the FEC overhead is included;
  2) considering the wavelength plan suggested by Roberto and Frank, i.e., the longest four LAN-WDM wavelengths with 400GHz red shift;
  3) using a more likely FEC BER threshold of 4.5E-3 instead of 8E-3;
  4) assessing the CD+FWM penalty over all possible ZDW values; and
  5) conducting >2,000 PMD realizations with PMD=0.1 ps/sqrt(km).

- With a suitable selection of the wavelength plan and the FEC threshold, the combined penalty from FWM and dispersion can be under 2.5dB when the signal launch power is 5dBm per channel for a low overall outage probability of $<10^{-5}$.

Thank you!