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

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Supporters

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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 >1,000 PMD realizations with DGD=0.1 ps/sqrt(km).

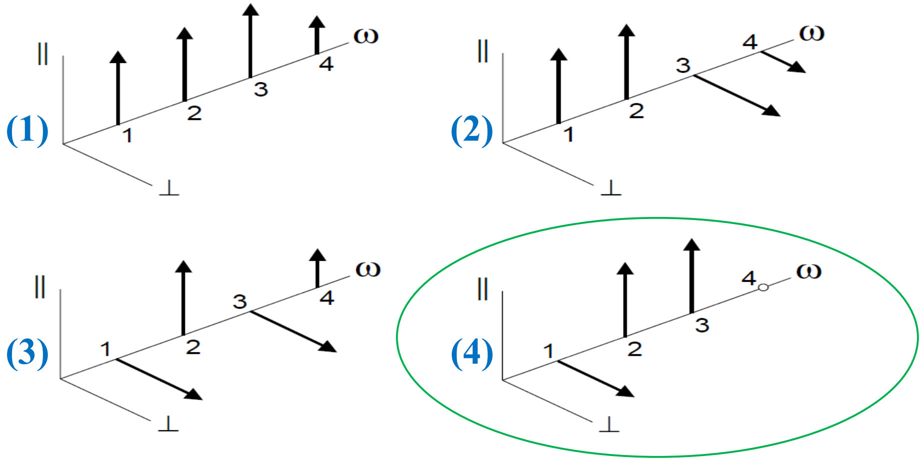
FWM suppression by “XYYX” polarization arrangement

- 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

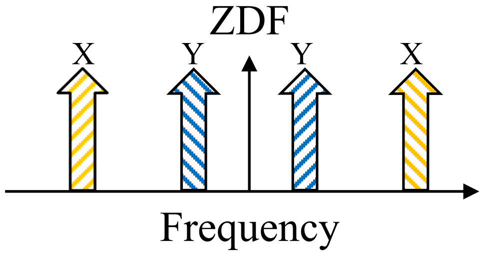
		$\lvert E_4 \rangle$	P_4
(1)	$\lvert E_1 \rangle \parallel \lvert E_2 \rangle \parallel \lvert E_3 \rangle$	$\lvert E_2 \rangle$	1
(2)	$\lvert E_1 \rangle \parallel \lvert E_2 \rangle \perp \lvert E_3 \rangle$	$\lvert E_3 \rangle$	1/4
(3)	$\lvert E_1 \rangle \parallel \lvert E_3 \rangle \perp \lvert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

The wavelength plan

LAN-WDM channels

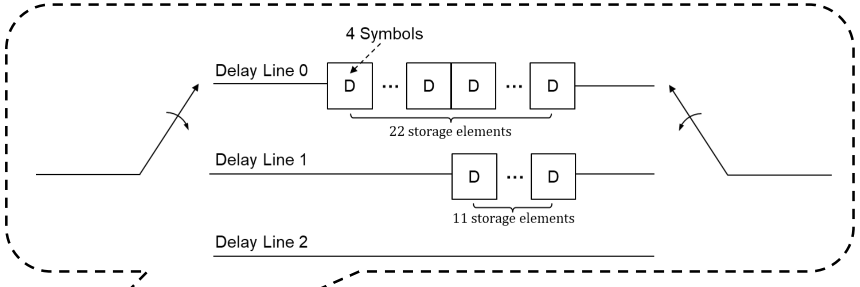
Channel index	Center frequency (THz)	Center wavelength (nm)	Dispersion range after 10km (ps/nm)
ch0	231.4	1295.56	-26.16 ~ -4.08
ch2	230.6	1300.05	-22.03 ~ 0.05
ch4	229.8	1304.58	-17.87 ~ 4.21
ch6	229.0	1309.14	-13.67 ~ 8.41

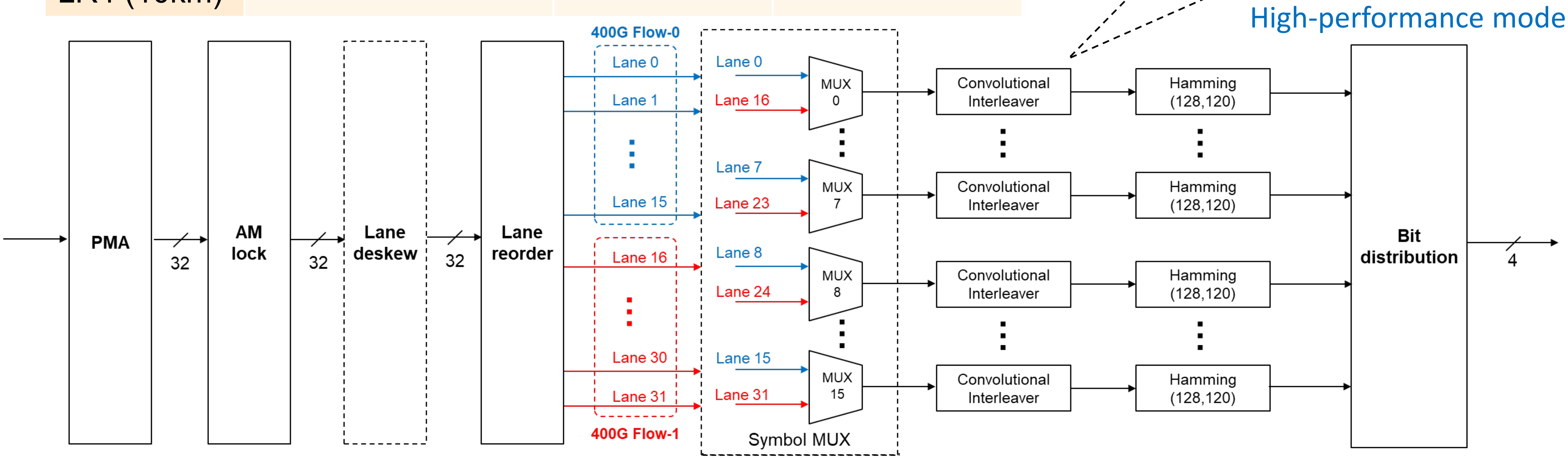
LAN-WDM channels with 400GHz red shift

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

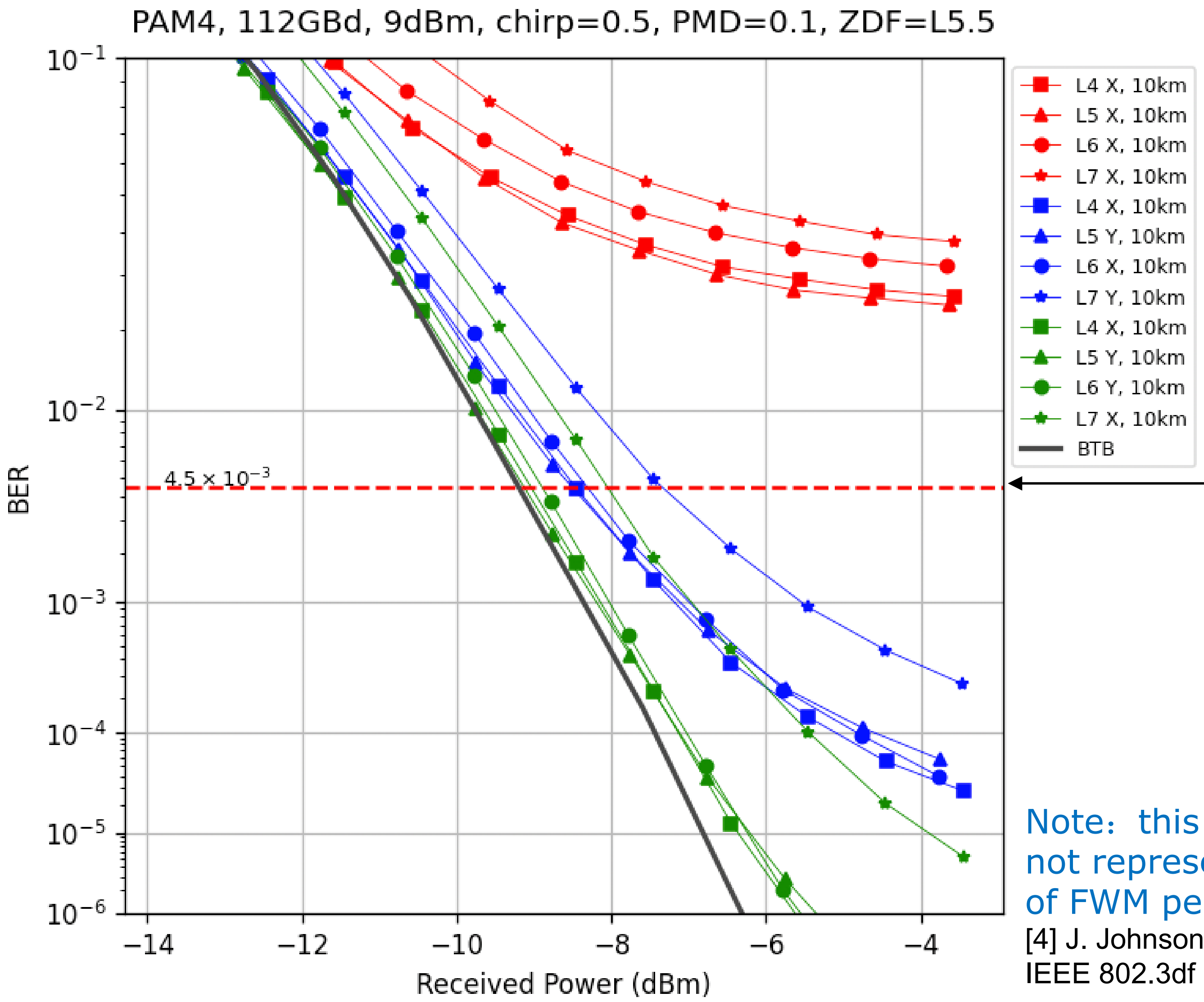
Reach	FEC (113.3GBaud)	FEC Latency	BER threshold
DR4 (500m)	KP4 + Hamming(128,120)	~20 ns	~2.2E-3
FR4 (2km) LR4 (10km)	KP4 + Interleaver Hamming(128,120)	~70 ns	~4.8E-3





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

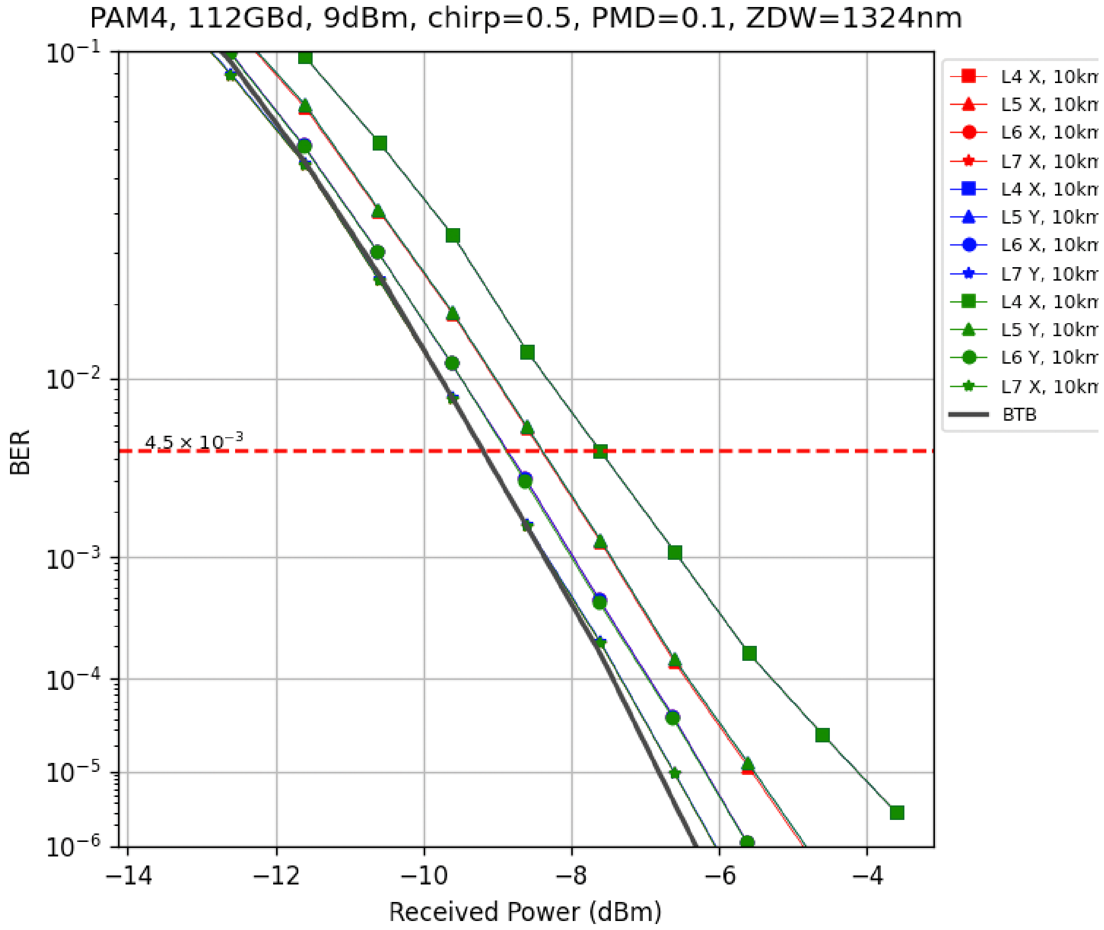
Assuming 4.5E-3 as the FEC BER threshold

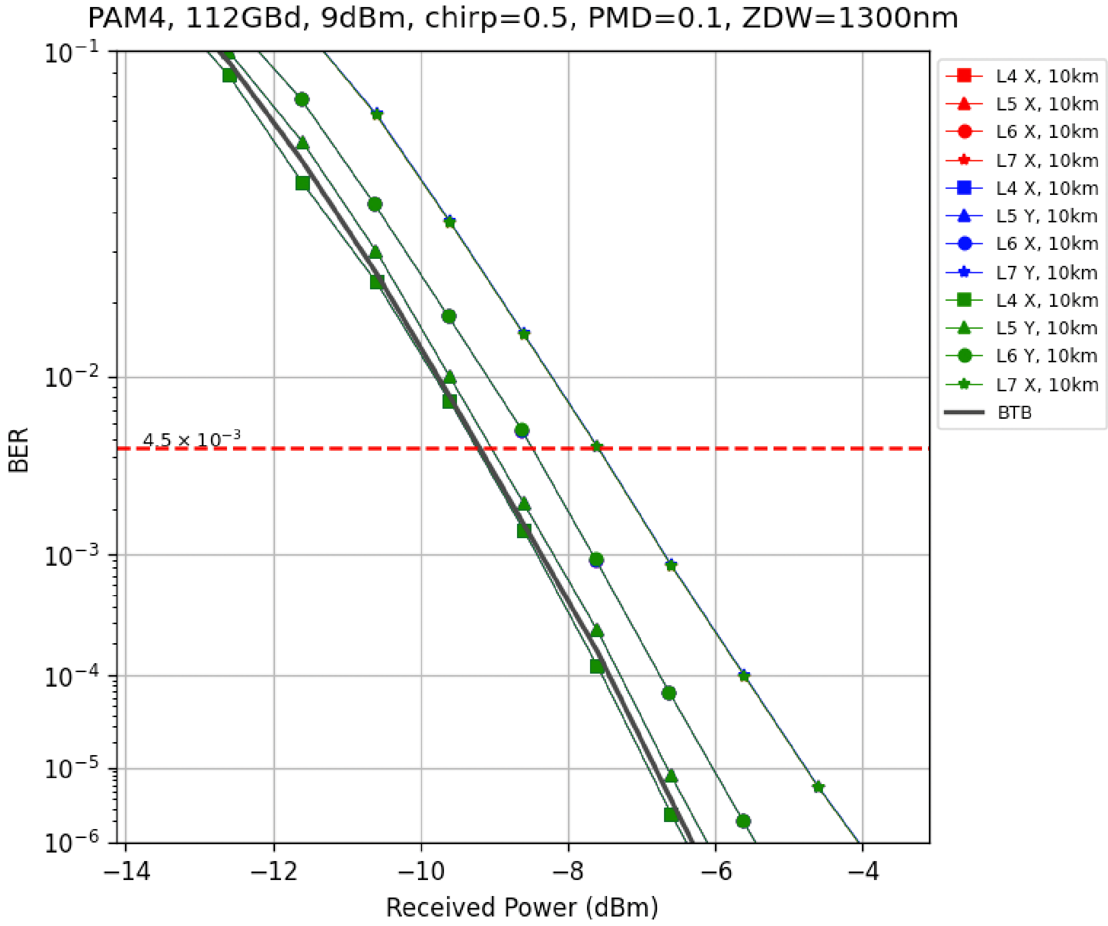
Note：this is a single realization of PMD, not representative of the full distribution of FWM penalties over PMD [4].

[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

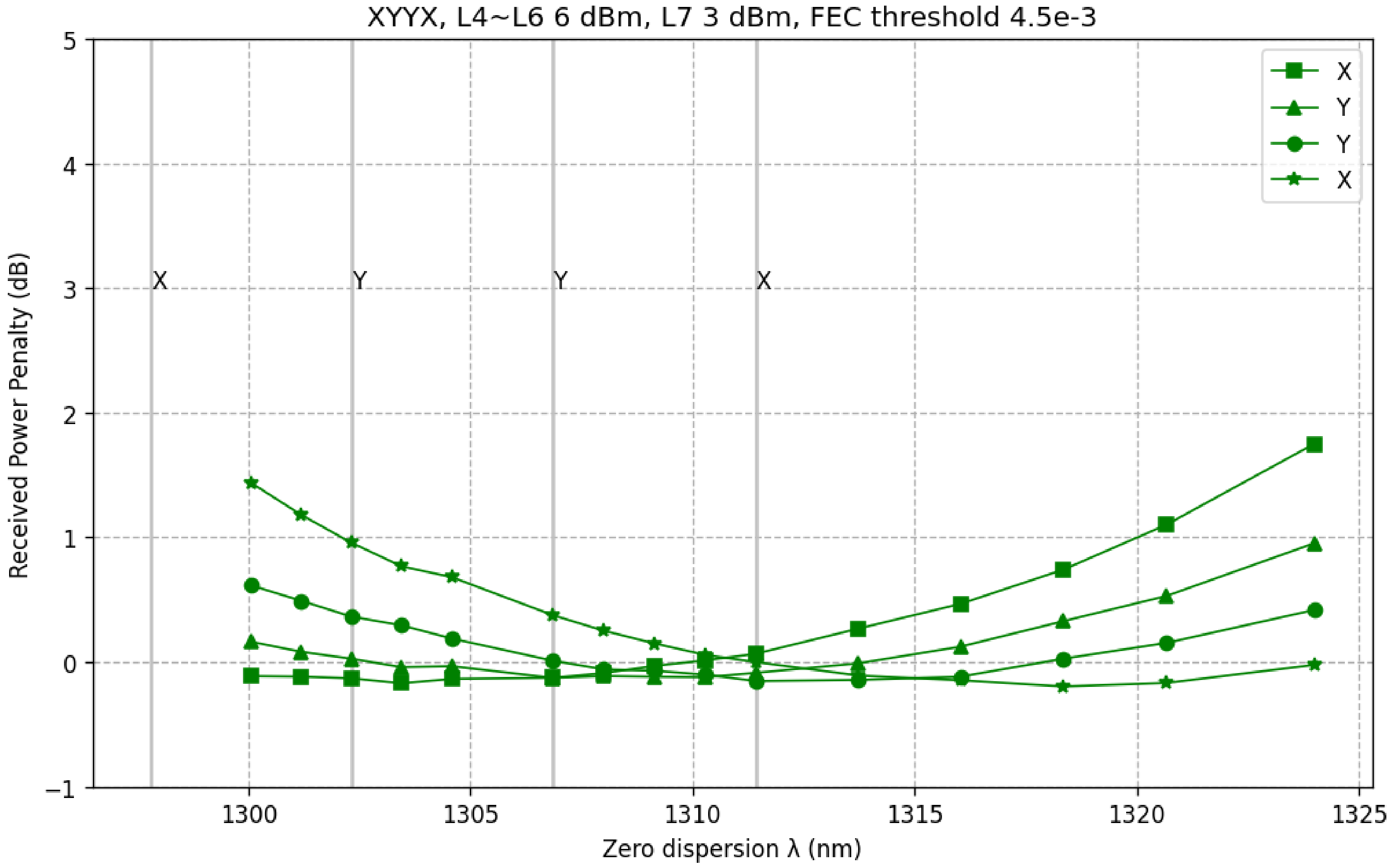




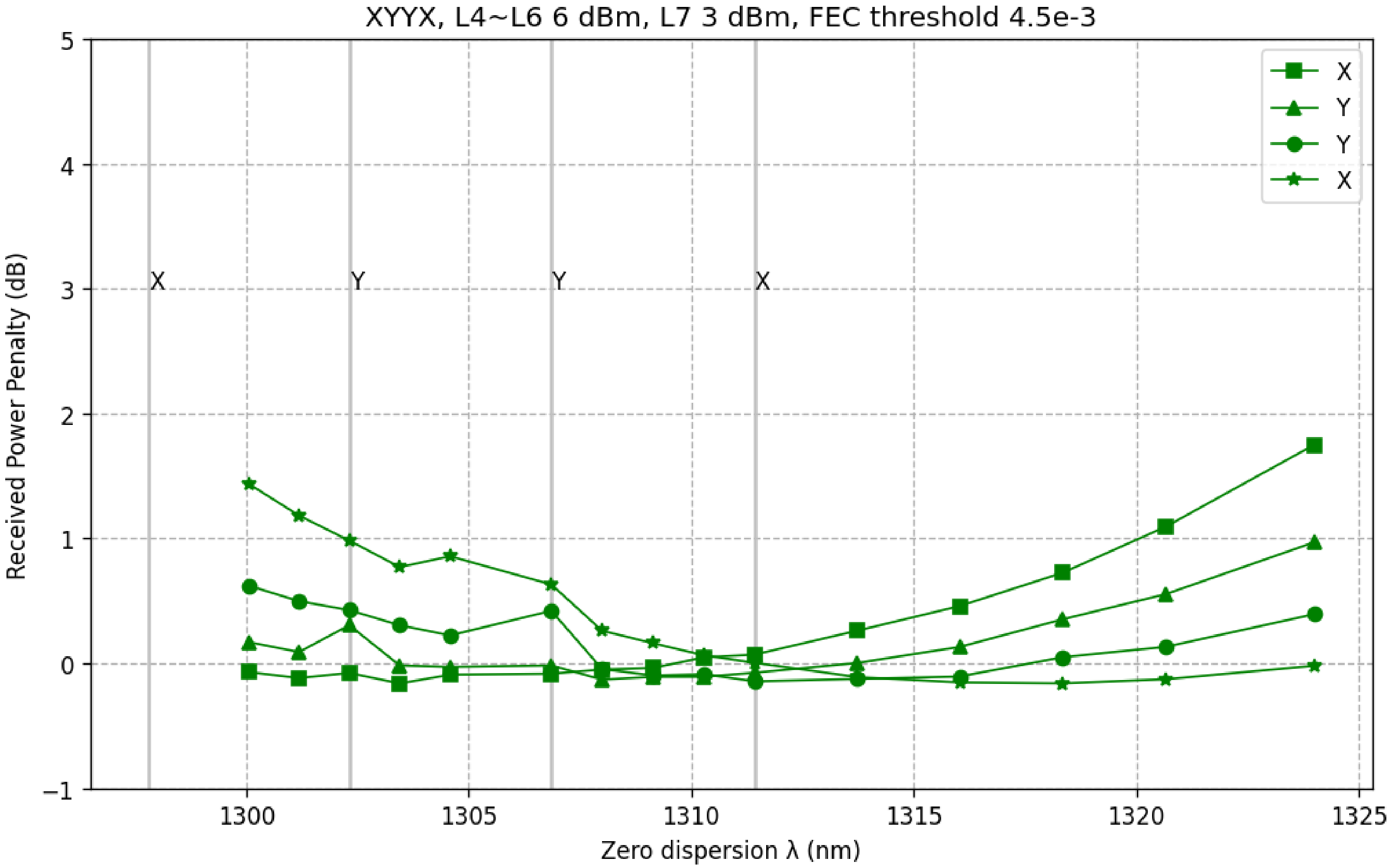
The worst-case dispersion penalty is limited to <2dB.

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

Combined FWM+Dispersion Penalties (PMD=0)



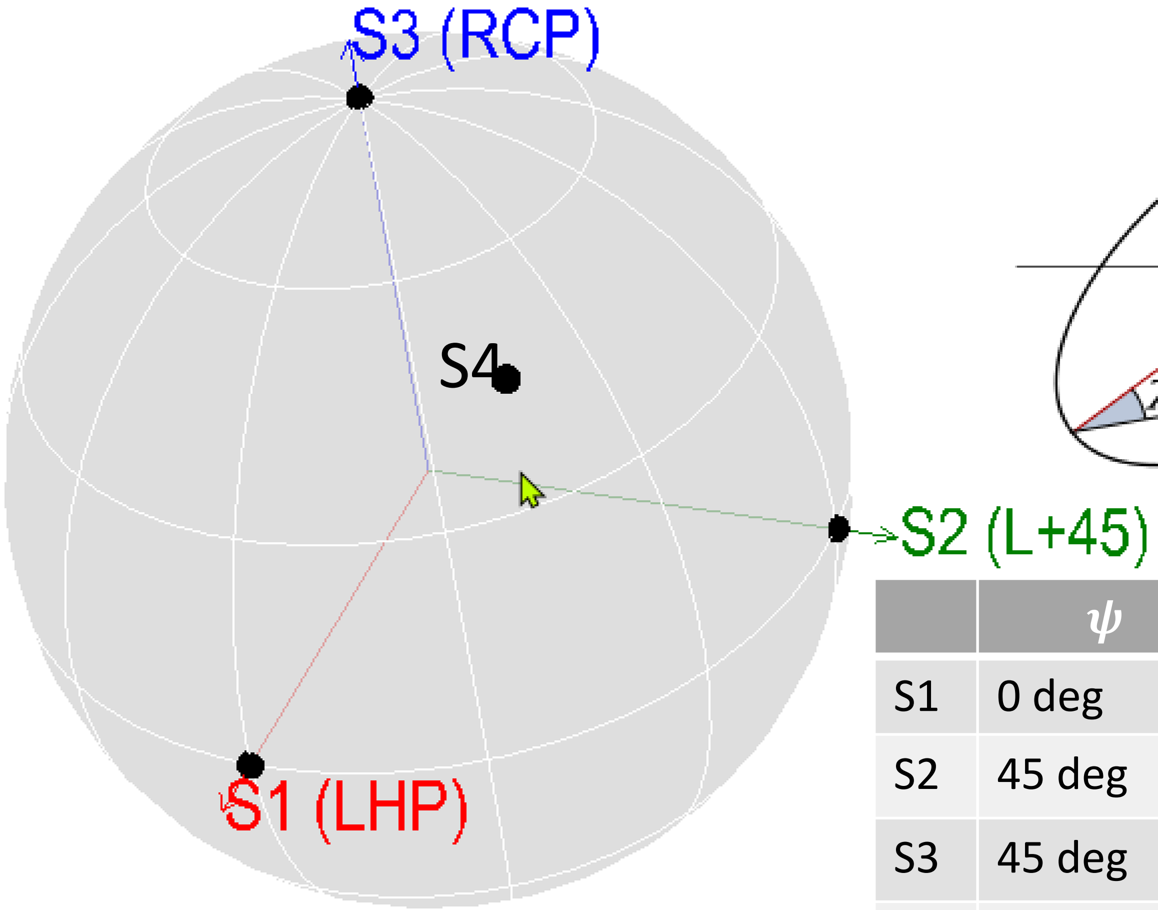
Combined FWM+Dispersion Penalties (A realization with PMD=0.1ps/sqrt(km))

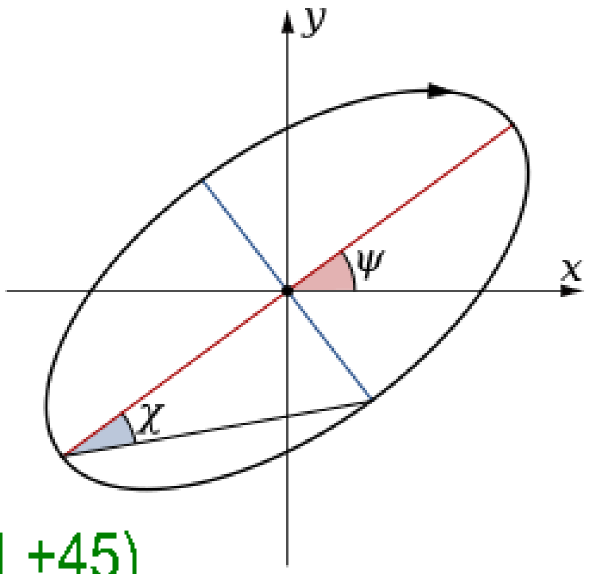


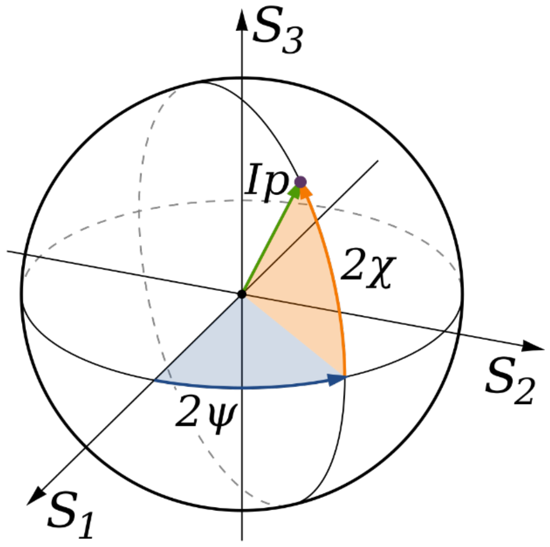
Note：this is a single realization of PMD, not representative of the full distribution of FWM penalties over PMD.

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

Four incident “X” Polarizations



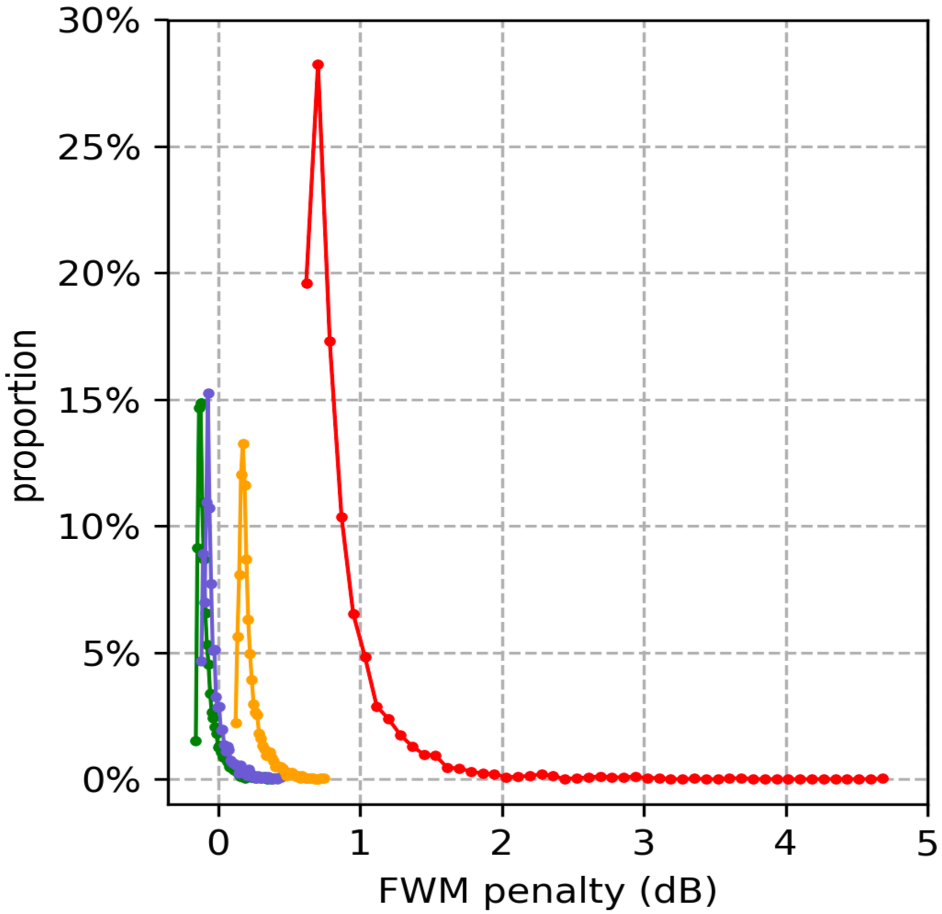


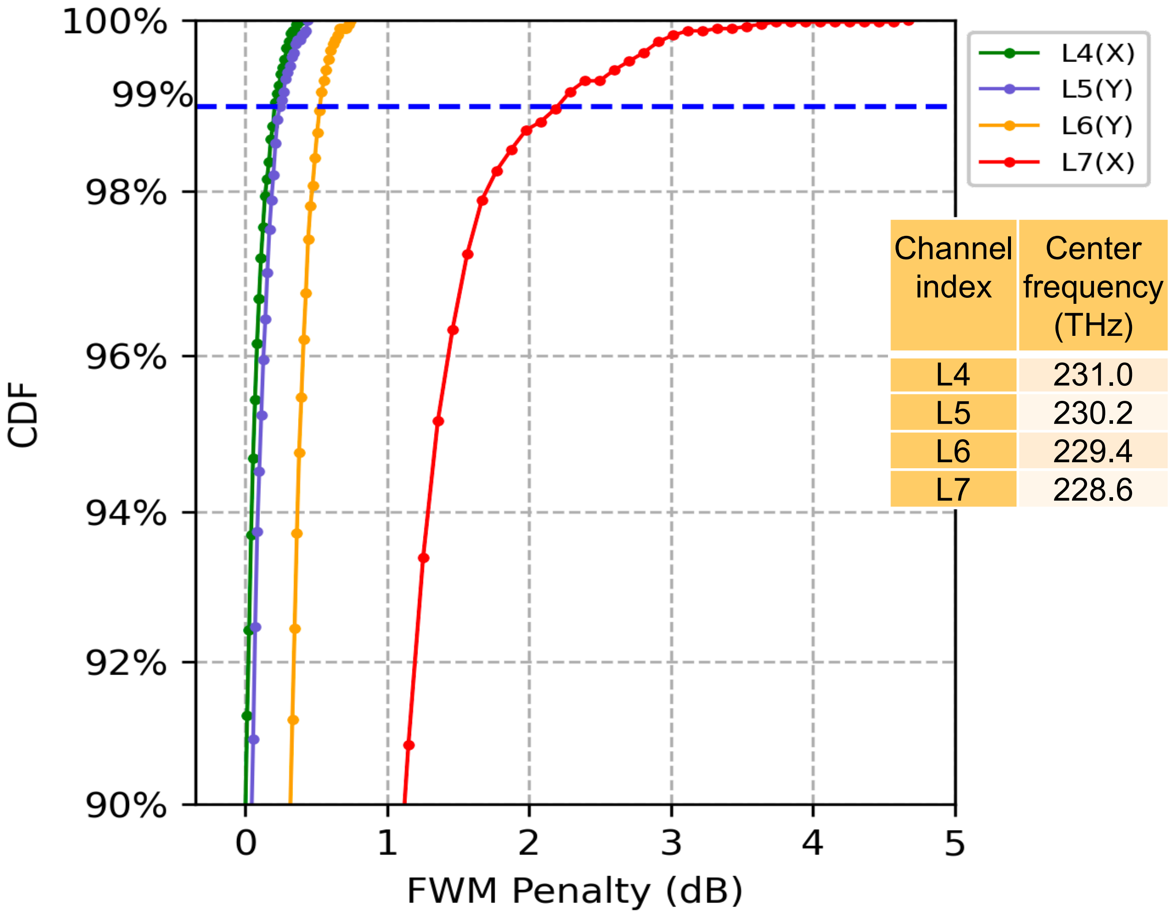


	ψ	χ	x	y
S1	0 deg	0 deg	1	0
S2	45 deg	0 deg	$1/\sqrt{2}$	$1/\sqrt{2}$
S3	45 deg	45 deg	$1/\sqrt{2}$	$-j/\sqrt{2}$
S4	22.5 deg	22.5 deg	$\sqrt{(1+1/\sqrt{3})/2}$	$(1-j)\sqrt{(1-1/\sqrt{3})/4}$

Worst-case CD+FWM penalties with 4,000 PMD realizations

- A worst-case scenario with L4/L5/L6 at +6dBm while L7 at +3dBm, assuming ZDF exactly at L5.5





Channel index	Center frequency (THz)	Center wavelengt h (nm)
L4	231.0	1297.80
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L6	229.4	1306.85
L7	228.6	1311.43

- ❑ Even under the worst-case alignment of ZDF and channel center frequencies, the FWM penalty can be limited to ~2dB for a relatively low outage probability of ~1%.
- ❑ Note that when the highest signal launch power is limited to +4dBm per channel, the FWM penalty can be limited to 1dB for a relatively low outage probability of <1% (even under the worst-case alignment of ZDF and channel center frequencies).

Discussion on FWM-Induced “Overall Outage Probability”

- The FWM-induced “outage” with a 1dB penalty is <1%, assuming the worst-case alignment of the ZDF and the four channel center frequencies for a signal launch power of up to 4dBm.
- The typical SSMF ZDF distribution has ~1% chance of causing the worst-case penalties
- Modules deployed in the field will be operating with significant margin, due to
  - Non-worst-case fiber loss
  - Non-worst-case connector/MUX/DMUX losses
  - Non-worst-case dispersion due to shorter fiber span than 10km
  - Non-worst-case transmitter power (and non-worst-case power non-uniformity)
  - Non-worst-case receiver sensitivity

  We may get another “outage” probability reduction factor of <10%
- Considering all the above, the FWM-induced overall outage probability can be <1E-5, which is reasonably low, given that the PMD-induced outage probability specified in OIF 400G-ZR is 4.1E-6.

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 FWM+dispersion penalty over all possible ZDW values; and
  5) conducting >1,000 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 <2.5dB when the per-channel signal launch power is limited to 4dBm for a reasonably low overall outage probability of <1E-5.