Effective suppression of inter-channel FWM for 800G-LR4 and 1.6T-LR8 based on 200Gb/s PAM4 channels

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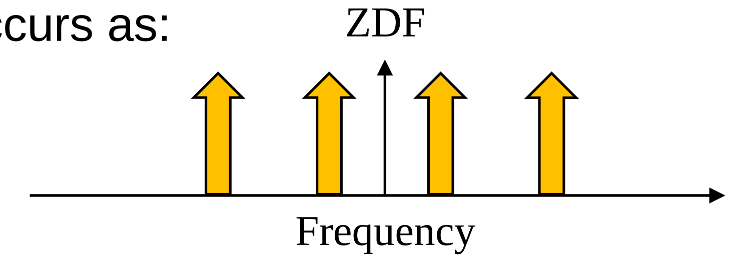
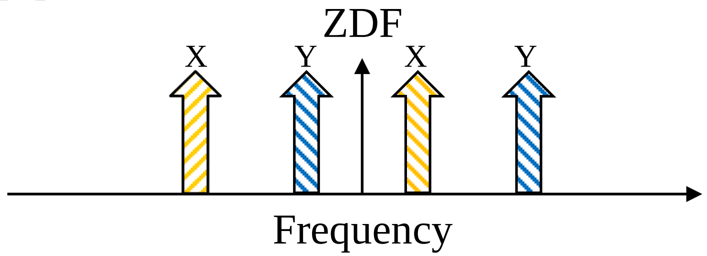
The FWM issue in 800G-LR4

- The strength of the FWM effect depends on signal power, fiber nonlinear coefficient, dispersion, dispersion slope, polarization-mode dispersion (PMD), and channel plan w.r.t. the fiber zero dispersion wavelength (ZDW) or zero-dispersion frequency (ZDF).
- The worst-case non-degenerate FWM occurs as:



- To mitigate the FWM penalty, polarization interleaving had been proposed [1,2], allowing the power tolerance to be increased by ~3dB [2].



[1] X. Liu, C. McKinstrie, N. Cheng and F. Effenberger, “Suppression of Four-Wave-Mixing (FWM) for 100G-EPON,” IEEE 802.3 Meeting, May 2017. https://www.ieee802.org/3/ca/public/meeting_archive/2017/05/liuxiang_3ca_1a_0517.pdf

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

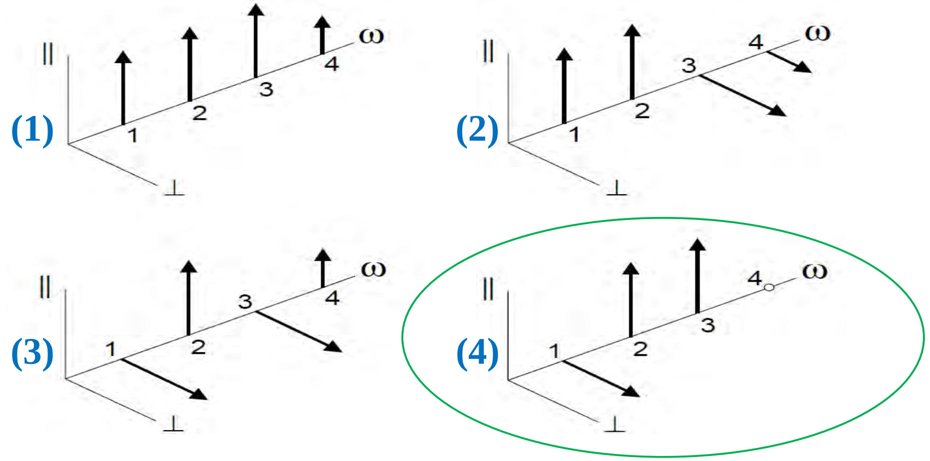
Effective FWM suppression for 800G LR4

- For typical transmission fibers, the random birefringence model (RBM), where the fiber polarization axes and birefringence strength vary randomly with distance, is commonly used [3,4].
- 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.[4]:

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

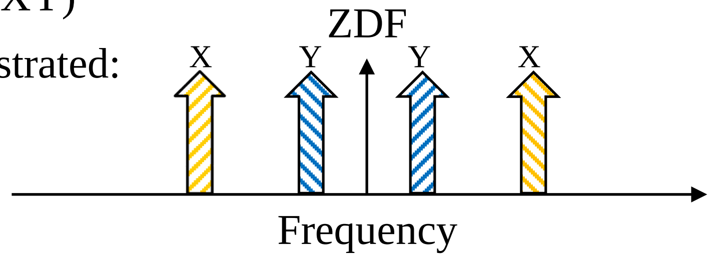
		$\|E_4\rangle$	P_4
(1)	$\|E_1\rangle \parallel \|E_2\rangle \parallel \|E_3\rangle$	$\|E_2\rangle$	1
(2)	$\|E_1\rangle \parallel \|E_2\rangle \perp \|E_3\rangle$	$\|E_3\rangle$	1/4
(3)	$\|E_1\rangle \parallel \|E_3\rangle \perp \|E_2\rangle$	$\|E_2\rangle$	1/4
(4)	$\|E_1\rangle \perp \|E_2\rangle \parallel \|E_3\rangle$	—	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, as illustrated:

(*: 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.)

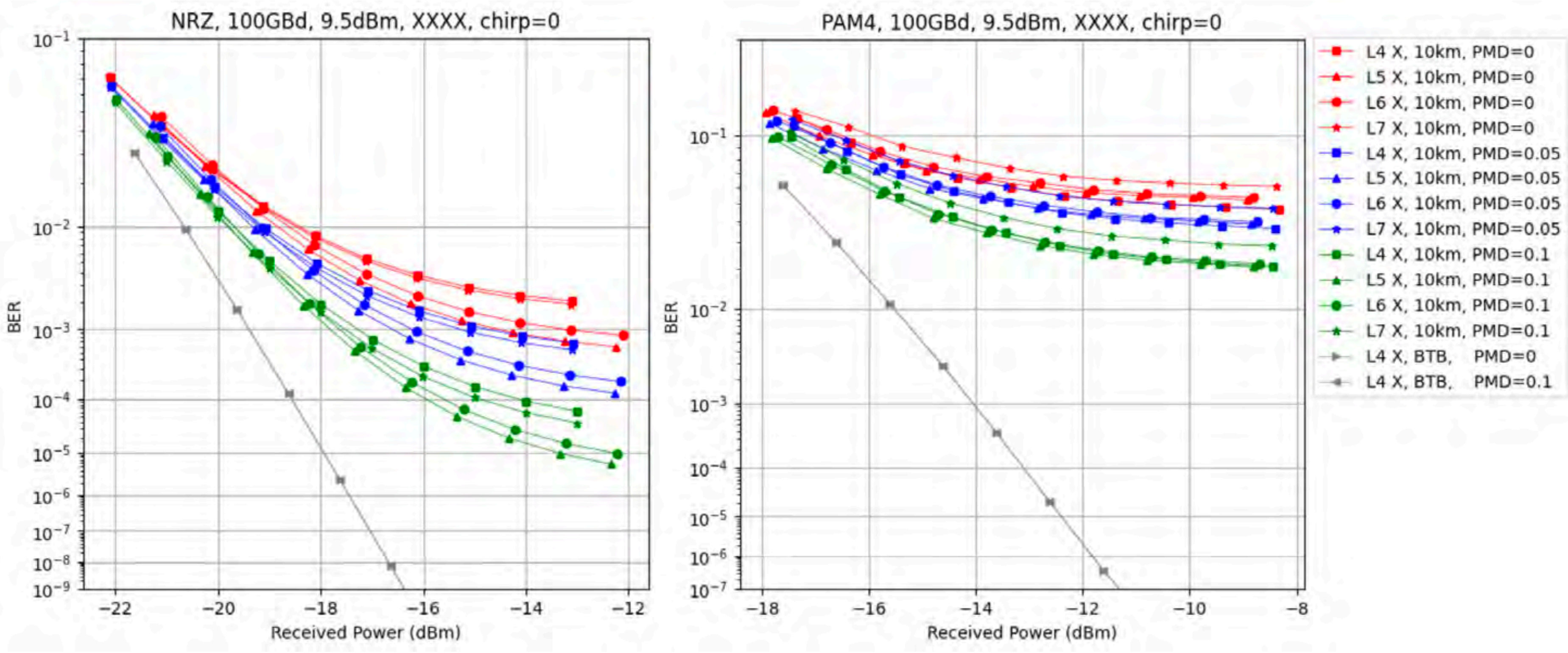


[3] K. Inoue, "Polarization effect on four-wave mixing efficiency in a single-mode fiber," IEEE J. Quantum Electron. 28, 883–894 (1992).

[4] 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).

800G-LR4 Results (1): “XXXX” polarization arrangement

Simulation conditions: VPI-based simulations with four 100Gbaud LAN-WDM channels at L4/L5/L6/L7, ZDF=L5.5, ER=6dB, Chirp=0, L=10km, PMD=0/0.05/0.1 ps/sqrt(km), RBM with a step size of 100m, and PIN-based receiver with a 7-tap FFE.



LAN-WDM channel index	Center frequency (THz)	Center wavelength (nm)
L0	235.4	1273.54
L1	234.6	1277.89
L2	233.8	1282.26
L3	233.0	1286.66
L4	**231.4**	**1295.56**
L5	**230.6**	**1300.05**
L6	**229.8**	**1304.58**
L7	**229.0**	**1309.14**

- In the back-to-back (BTB) case, PAM4 is ~5dB worst than NRZ, as expected.
- After fiber transmission, PAM4 suffers much more than NRZ due to FWM, as also expected.

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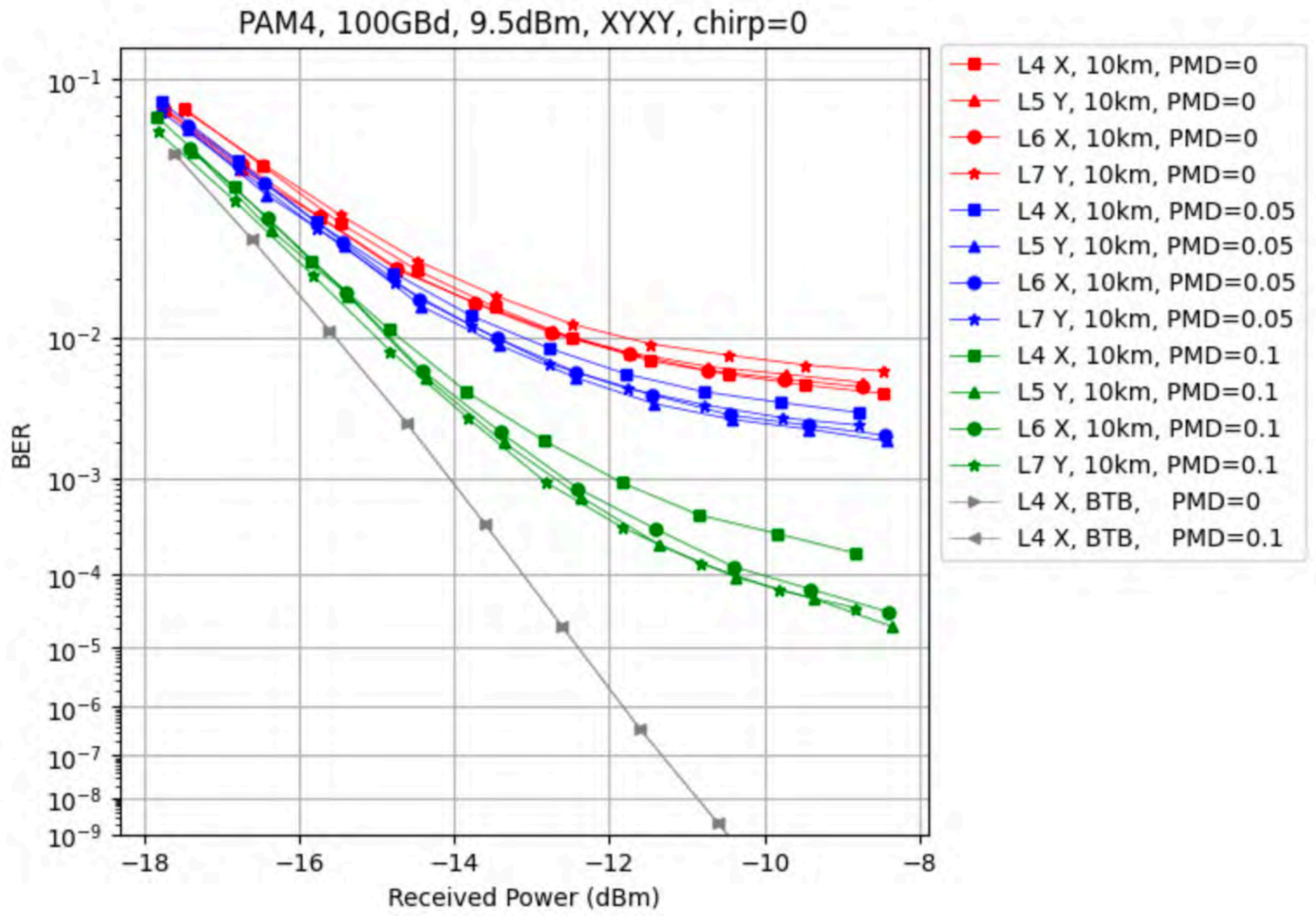
800G-LR4 Results (2): “XYXY” polarization arrangement

Simulation conditions: 4x 200Gb/s, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE.

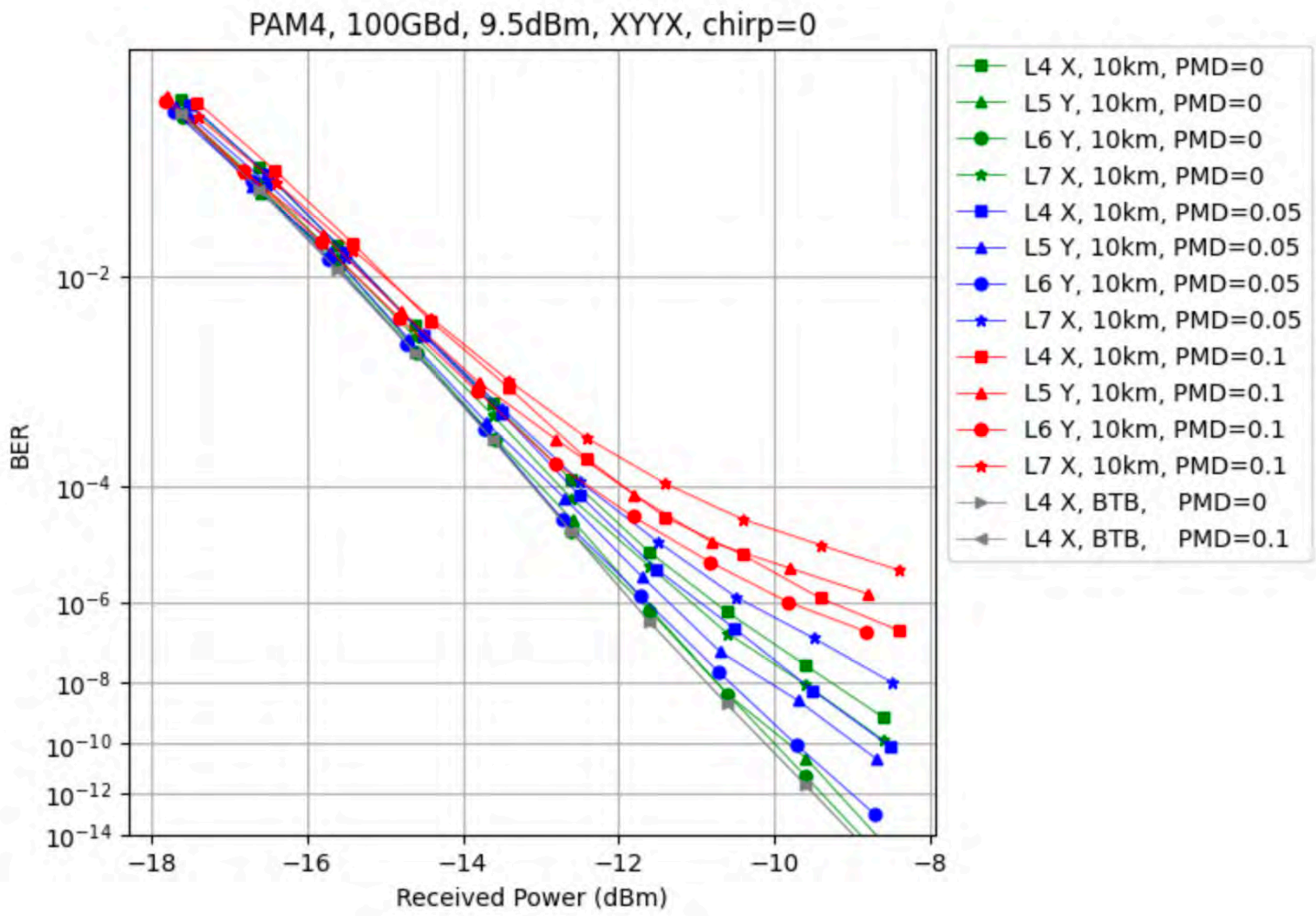
- “XYXY” performs better than “XXXX”, as expected from [1,2]



800G-LR4 Results (3): "XYYX" polarization arrangement

Simulation conditions: 4x 200Gb/s, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE.

- "XYYX" performs much better than both "XXXX" and "XYXY"



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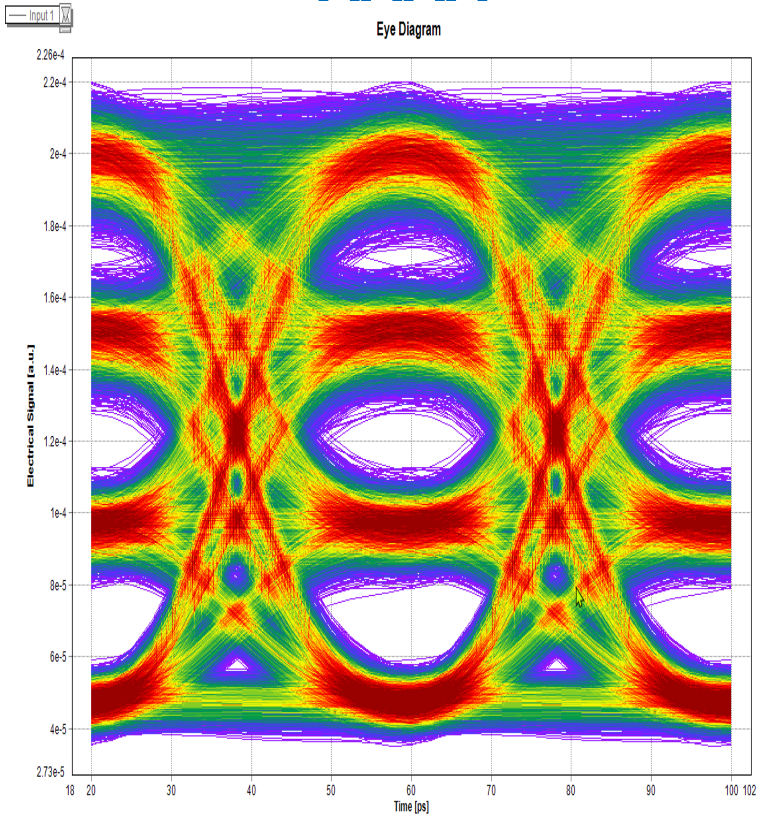
Eye diagrams for the “XXXX” and “XYYX” cases

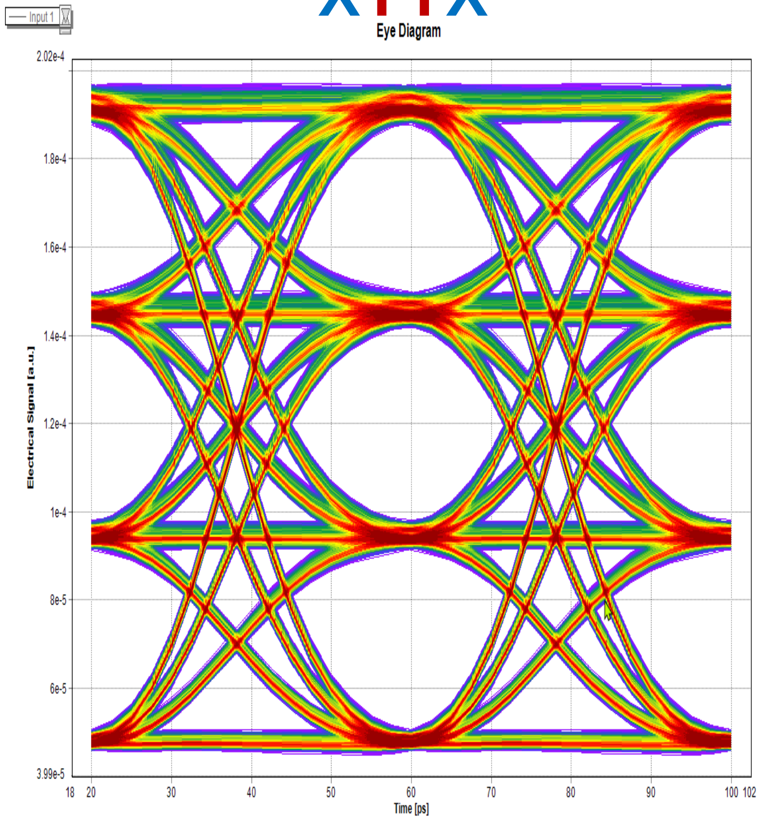
Simulation conditions: 4x 200Gb/s, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE.

- The FWM induced coherent crosstalk causes most degradation to the upper eye after fiber transmission (as shown below, for an exemplary case of L=10km, P=5dBm, without PD noise).

“XXXX”



“XYYX”



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High-performance FEC options for 800G-LR4

The OIF 800G-LR group is considering the following high-coding-gain and low-latency FEC options with BER thresholds of >4E-3 [5] and >8E-3 [6].

[5] Xiang He, Hao Ren, Xinyuan Wang, “Updated Investigation on Low Latency Concatenated FEC for 800LR,” “ oif2022.223.00, May 2022.

Type	Unterminated KP4 + BCH(76,68)
Total/incremental FEC OH	18.3%/11.7%
Threshold	**5.9E-3**
Net Coding Gain	9.6 dB
Latency(FEC+ Interleaver)	**~10ns** (no interleaver)**
Client adaption	Supports all client interfaces
Remark	Lower latency and low power consumption as no interleaver is needed.

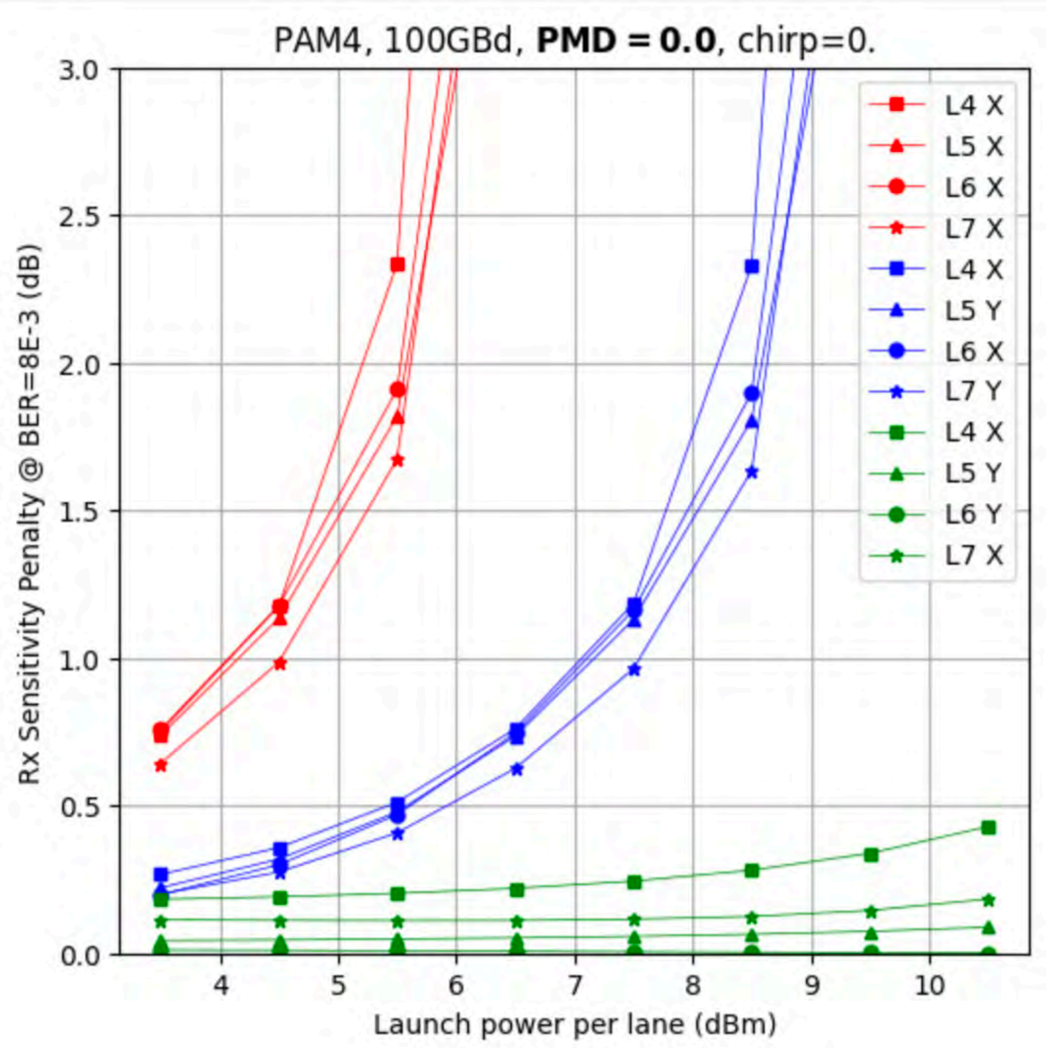
[6] Mehmet Aydinlik, Mike Sluyski and Tom Williams, “800 LR FEC Proposal”, Contribution oif2022.228.02, May 2022.

Ciena/Marvell	Huawei (with Acacia modifications)
Unterminated KP4 + Conv IL-A + BCH (126,110)	Unterminated KP4 + Conv IL-B + BCH(176, 160)
21.2% / 14.6%	16.4% / 10.0%
1.2e-2†	**8.6e-3‡**
9.94 dB	9.8 dB
~75ns*	**~60ns***

†: This is with *a decoder more advanced compared to Chase decoder;* ‡: *Flexibility to support other BCH codes with slightly higher OH and higher FEC threshold*

* Extrapolated from Marvell and Huawei contributions. OIF2022.178.00 estimates the Huawei interleaver/deinterleaver (combined) latency as 40 ns, while OIF2022.192.00 estimates the Ciena/Marvell interleaver latency as 55 ns.

800G-LR4 Results (4): Penalty vs Power @PMD=0 ps/sqrt(km)



<u>Simulation conditions:</u>

4x 200Gb/s PAM4, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE, and PMD=0 ps/sqrt(km).

<u>Simulation results:</u>

- For 1dB receiver sensitivity penalty BER=8E-3, the signal launch powers for the "XXXX", "XYXY", and "XYYX" cases are limited to about 4dBm, 7dBm, and >10dBm, respectively.
- The 3dB advantage of "XYXY" over "XXXX" agrees with Ref. [2].
- As expected, ""XYYX" offers much better power tolerance than "XYXY" and "XXXX", and 10dBm signal launch power is allowed.

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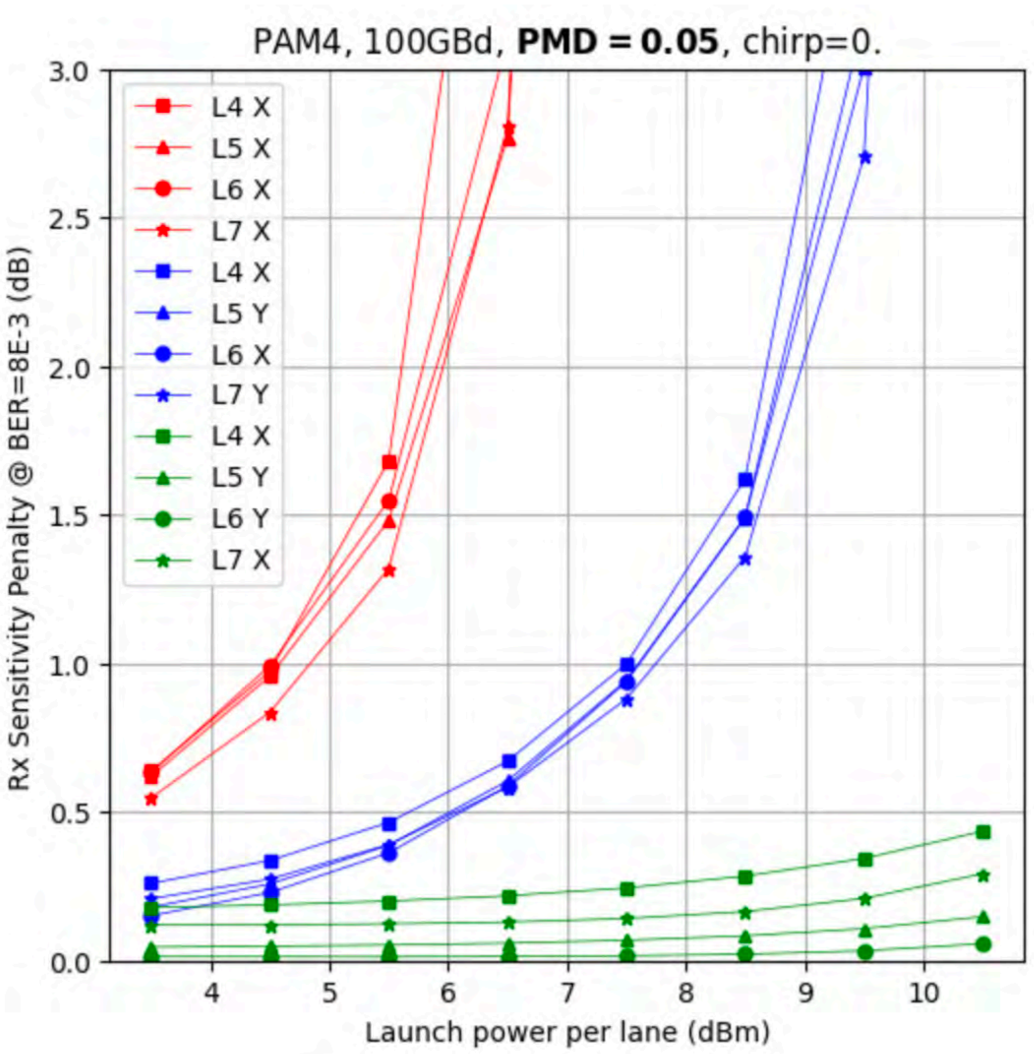
800G-LR4 Results (5): Penalty vs Power @PMD=0.05 ps/sqrt(km)



<u>Simulation conditions:</u>

4x 200Gb/s PAM4, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE, and PMD=0.05 ps/sqrt(km).

<u>Simulation results:</u>

- For 1dB receiver sensitivity penalty BER=8E-3, the signal launch powers for the “XXXX”, “XYXY”, and “XYYX” cases are limited to about 4.5dBm, 7.5dBm, and >10dBm, respectively.
- The 3dB advantage of “XYXY” over “XXXX” agrees with Ref. [2]. Also, non-zero PMD helps increase the power tolerance in the “XXXX” and “XYXY” cases, in agreement with Ref. [2].
- As expected, ““XYYX” offers much better power tolerance than “XYXY” and “XXXX”, and 10dBm signal launch power is allowed.

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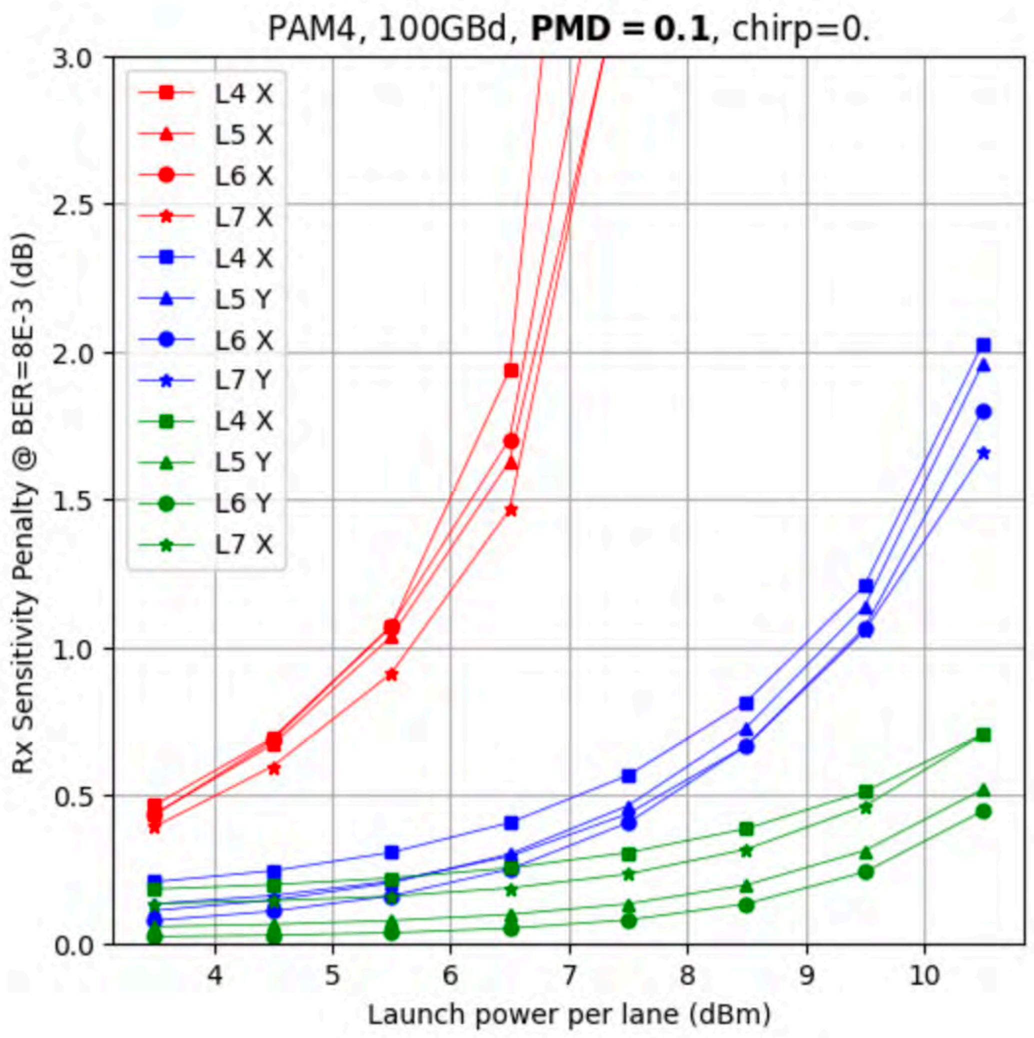
800G-LR4 Results (6): Penalty vs Power @PMD=0.1 ps/sqrt(km)



Simulation conditions:

4x 200Gb/s PAM4, ZDF=L5.5, ER=6dB, Chirp=0, PIN receiver with a 7-tap FFE, and PMD=0.1 ps/sqrt(km).

Simulation results:

- For 1dB receiver sensitivity penalty BER=8E-3, the signal launch powers for the “XXXX”, “XYXY”, and “XYYX” cases are limited to about 5.5dBm, 9dBm, and >10dBm, respectively.
  - The 3dB advantage of “XYXY” over “XXXX” agrees with Ref. [2]. Also, non-zero PMD helps increase the power tolerance in the “XXXX” and “XYXY” cases, in agreement with Ref. [2].
- As expected, ““XYYX” offers much better power tolerance than “XYXY” and “XXXX”, and 10dBm signal launch power is allowed.
  - Note that the performance of “XYYX” is slightly reduced due to large PMD, as reported in [1] and [7].

[7] C. J. McKinstrie and M. Karlsson, "Effects of Polarization-Mode Dispersion on Degenerate Four-Wave Mixing," in Journal of Lightwave Technology, vol. 35, no. 19, pp. 4210-4218, Oct.1, 2017.

Discussion on Power budget for 800G-LR4

- With the effective FWM suppression by using the "XYYX" (or "YXXY") polarization arrangement, the signal launch power per channel can be as high as 10dBm in **800G-LR4** for a typical FWM-induced receiver sensitivity penalty of <1dB at the BER threshold of 8E-3.
  - Assuming a channel power non-uniformity of 3dB, the operating range of the signal launch power for each channel can be 4dBm~7dBm .

- With an ER of 6dB, the achievable receiver sensitivity at 8E-3 can be about -9dBm.
  - Assuming 1dB penalty for FWM and 1dB penalty for dispersion, the achievable receiver sensitivity after transmission is about -7dBm.

- Thus, the power budget for fiber and DMUX losses is 11 dB (=4dBm-(-7dBm)), which may be sufficient for 800G LR4 [8,9], even when weaker FEC and more margin for PMD are considered.

[8] R. Rodes, V. Bhatt, and C. Cole, "On Technical Feasibility of 800G-LR4 with Direct Direct-Detection," IEEE 802.3df Meeting, March 29, 2022.
[9] X. Zhou and C. Lam, "Four-Wave Mixing Penalty for WDM-based Ethernet PMDs in O-band," IEEE 802.3df Meeting, May 24, 2022.

1.6T-LR8 design options

- **Wavelength plan**: eight 400GHz-spaced 200-Gb/s PAM4 channels as shown below:

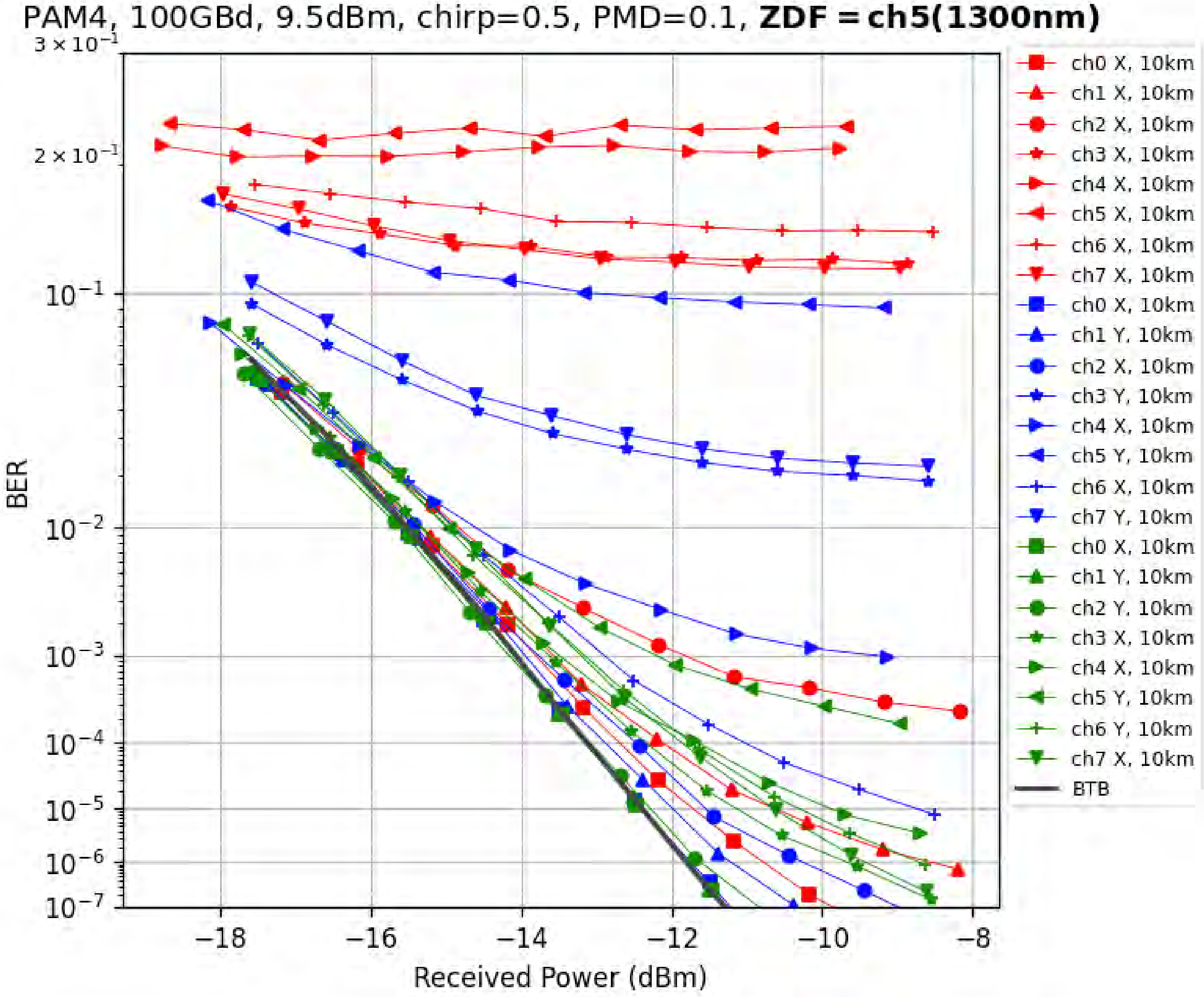
WDM channel index	Center frequency (THz)	Center wavelength (nm)
Ch0	232.6	1288.88
Ch1	232.2	1291.10
Ch2	231.8	1293.32
Ch3	231.4	1295.56
Ch4	231.0	1297.80
Ch5	230.6	1300.05
Ch6	230.2	1302.31
Ch7	229.8	1304.58

  - The worst-case FWM would occur with ZDF at Ch5, Ch5.5, and Ch6.

- **Transmitter chirp:** ~0.5 to accommodate both EML and MZM.

- Three **polarization arrangements** are studied:
  1) Polarization-aligned: XXXXXXXX
  2) Polarization-interleaved: XYXYXYXY
  3) "XYYX" based: XYYXXYYX

1.6T-LR8 Results (1): ZDF=CH5



- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 8E-3.

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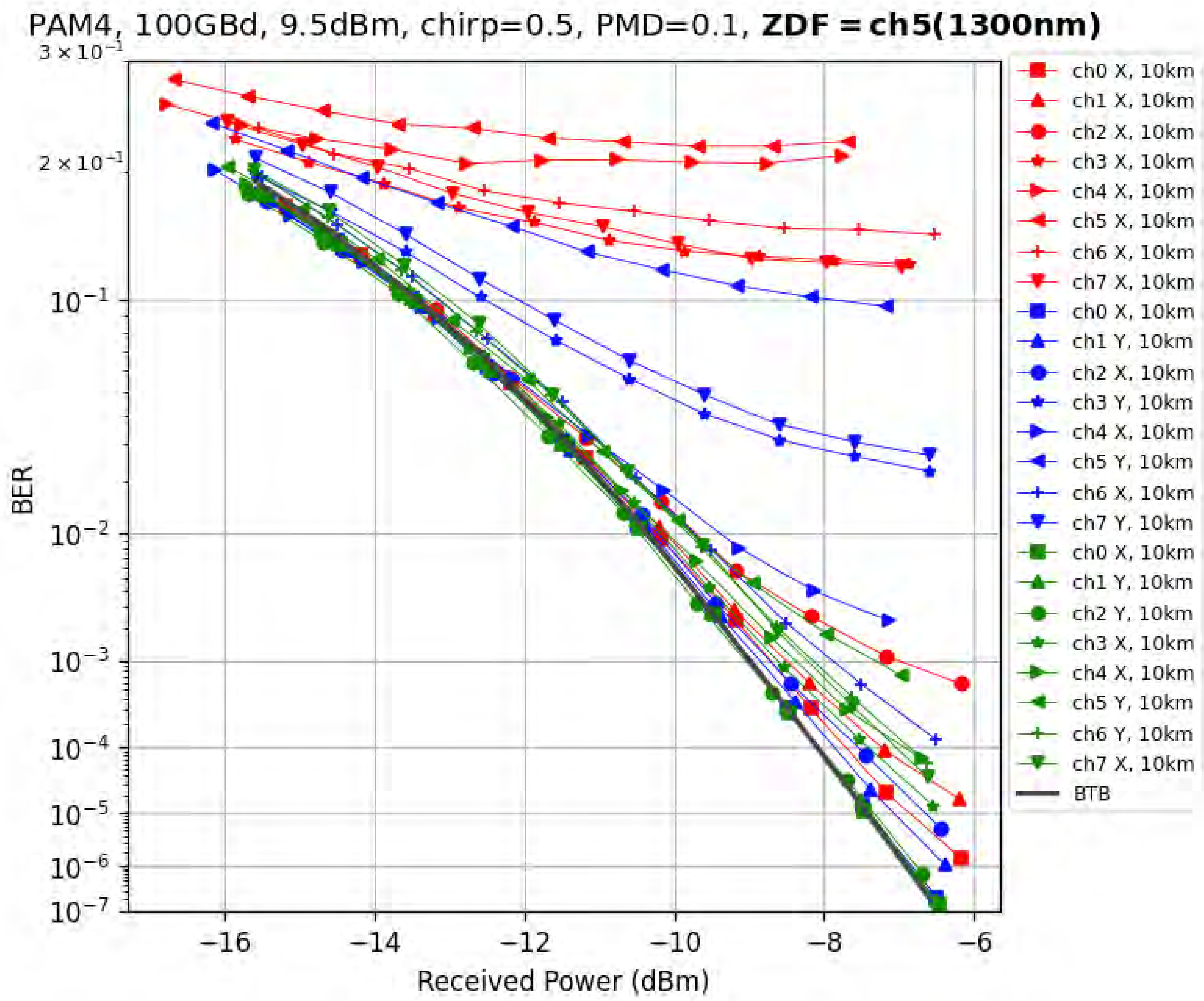
1.6T-LR8 Results (1b): ZDF=CH5 (with more realistic PIN noise)



PIN parameters:

- Shot Noise = ON
- **ThermalNoise = 27.5e-12 A/Hz^(1/2)**

- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 8E-3.

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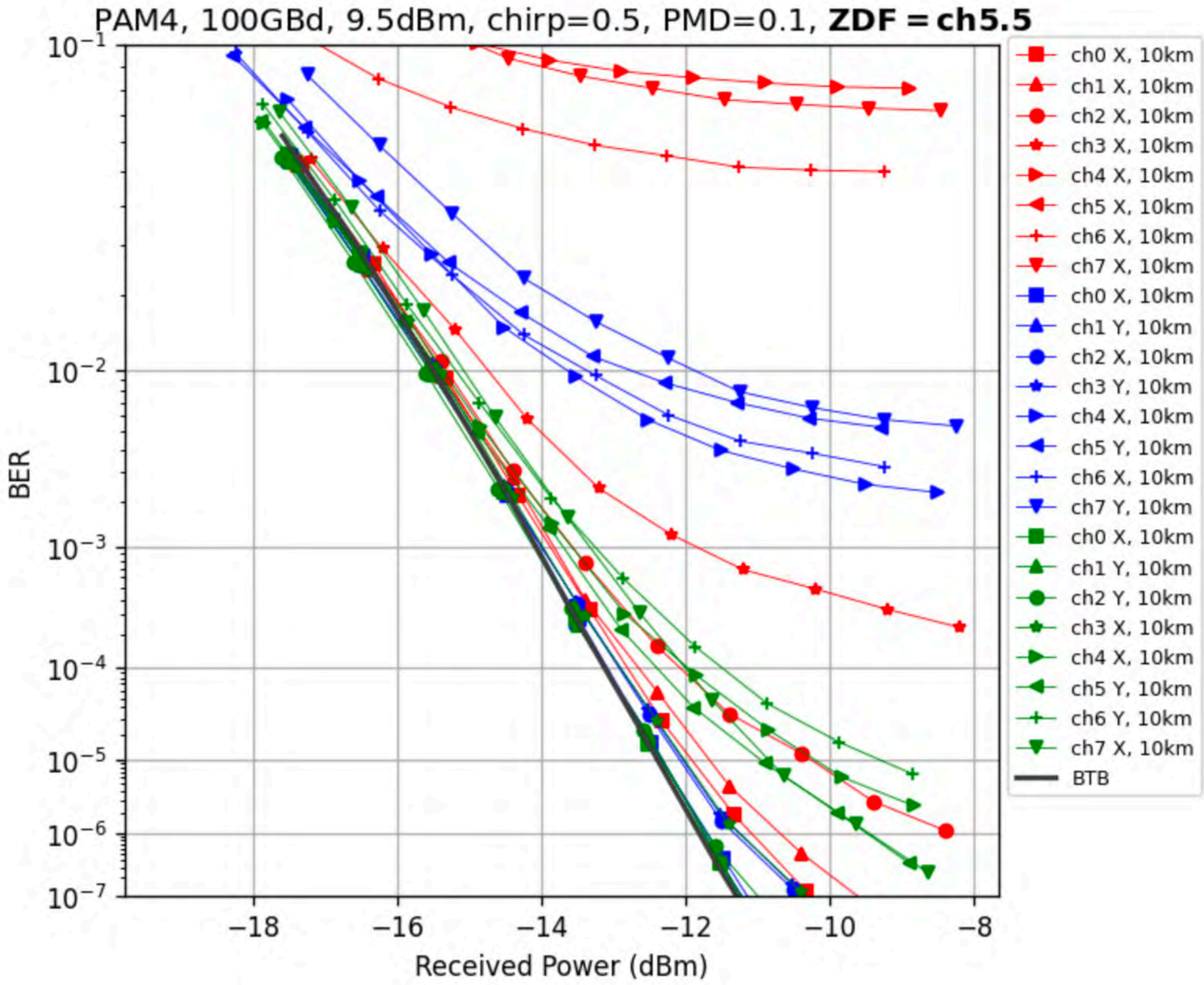
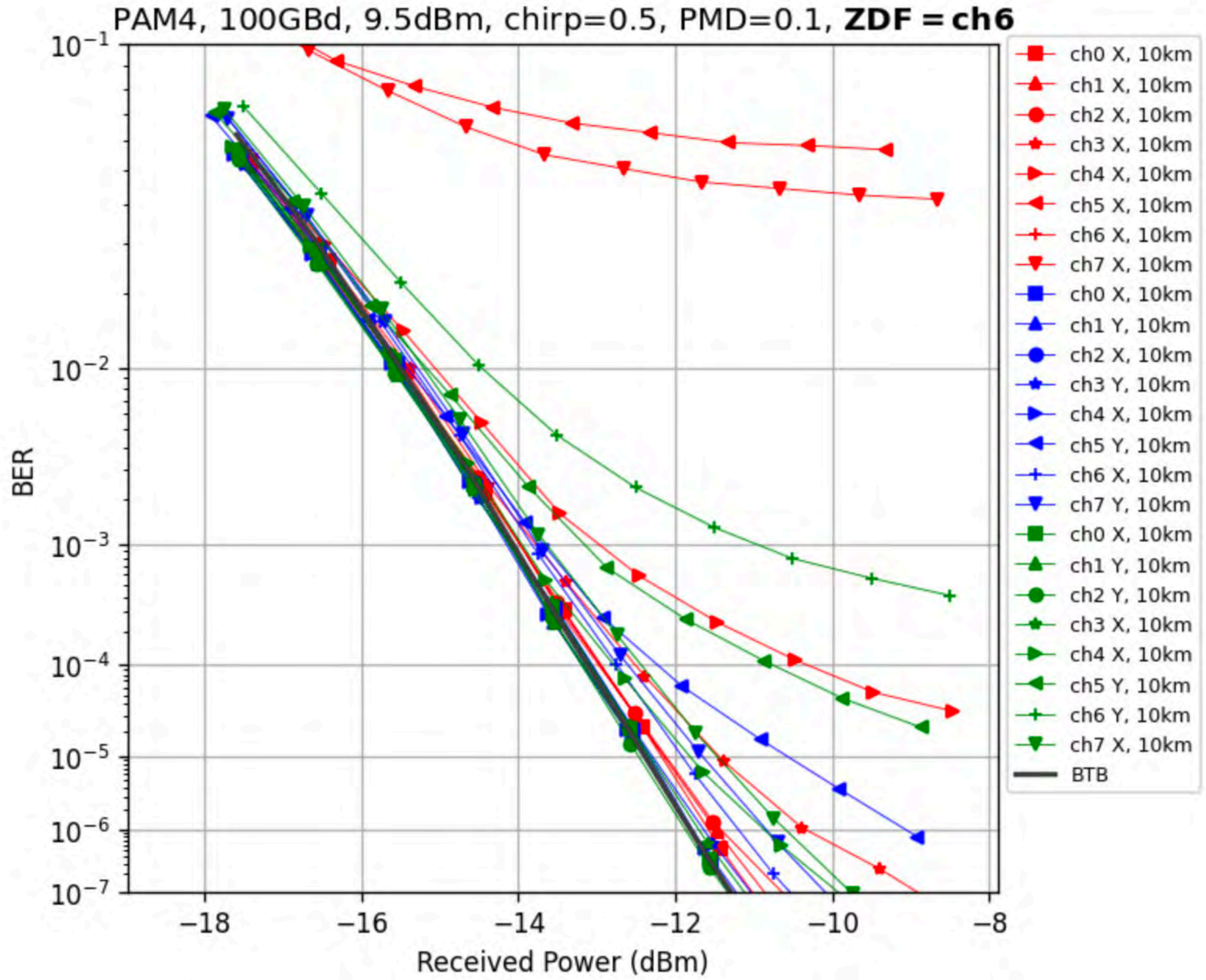
1.6T-LR8 Results (2): ZDF=CH5.5



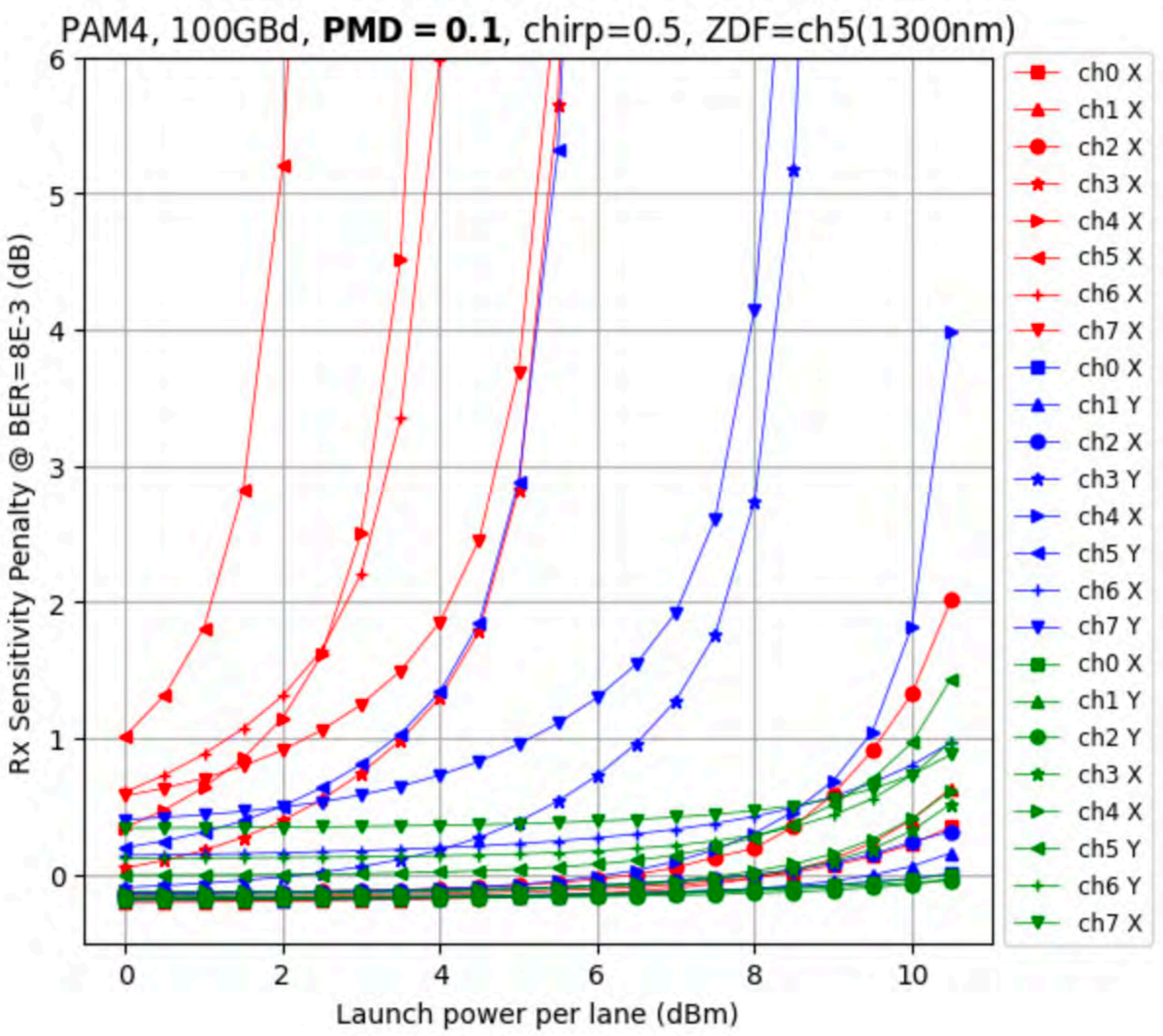
- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 8E-3.

1.6T-LR8 Results (3): ZDF=CH6



- "XYYXXYYX" effectively suppresses the FWM effect, achieving ~1dB transmission penalty at 8E-3.

1.6T-LR8 Results (4a): Penalty @BER=8E-3 vs launch power



- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 8E-3 for a signal launch power of up to ~10dBm per channel.

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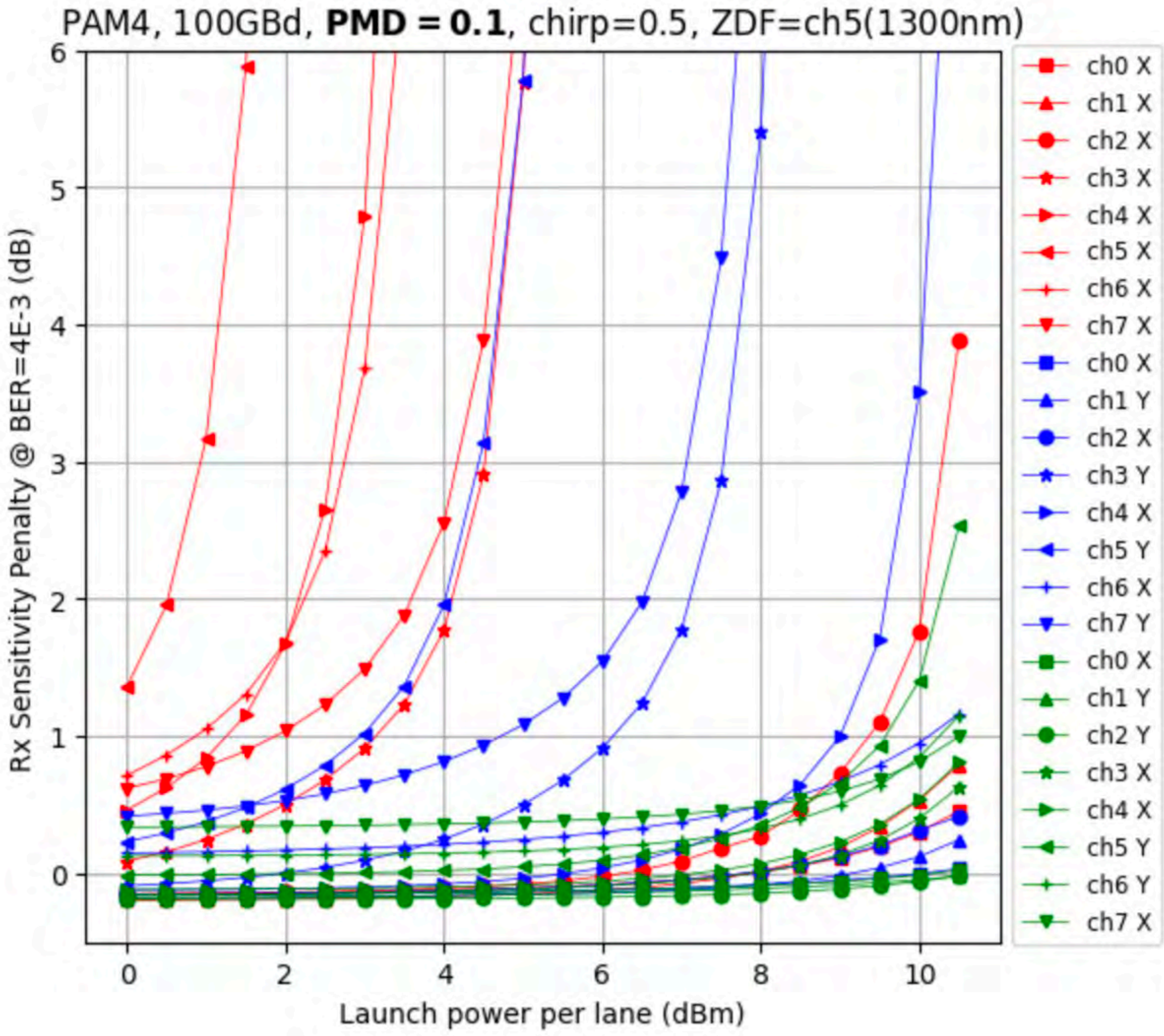
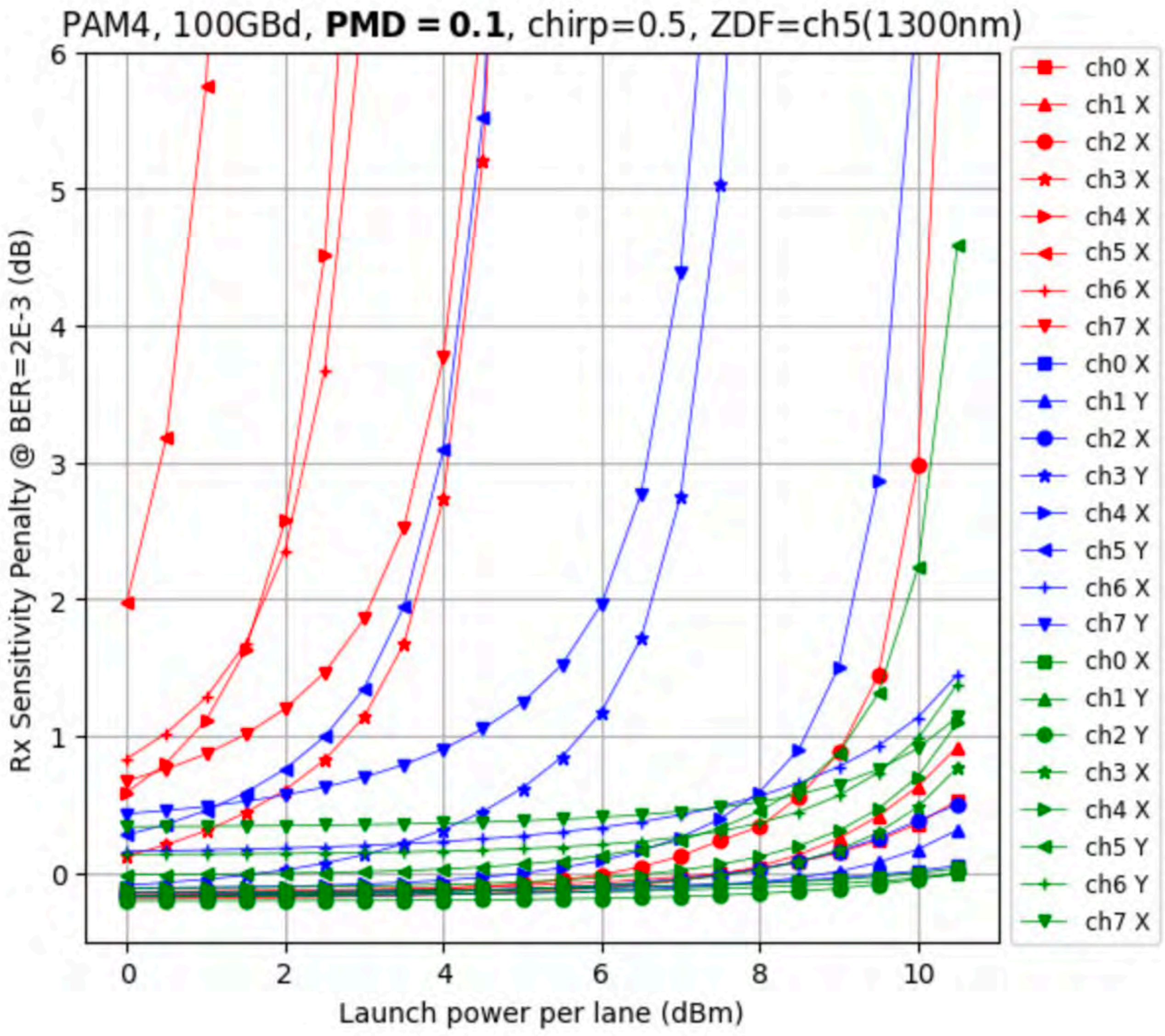
1.6T-LR8 Results (4b): Penalty @BER=4E-3 vs launch power



- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 4E-3 for a signal launch power of up to ~9.5dBm per channel.

1.6T-LR8 Results (4c): Penalty @BER=2E-3 vs launch power



- "XYYXXYYX" effectively suppresses the FWM effect, achieving <1dB transmission penalty at 2E-3 for a signal launch power of up to ~9dBm per channel.

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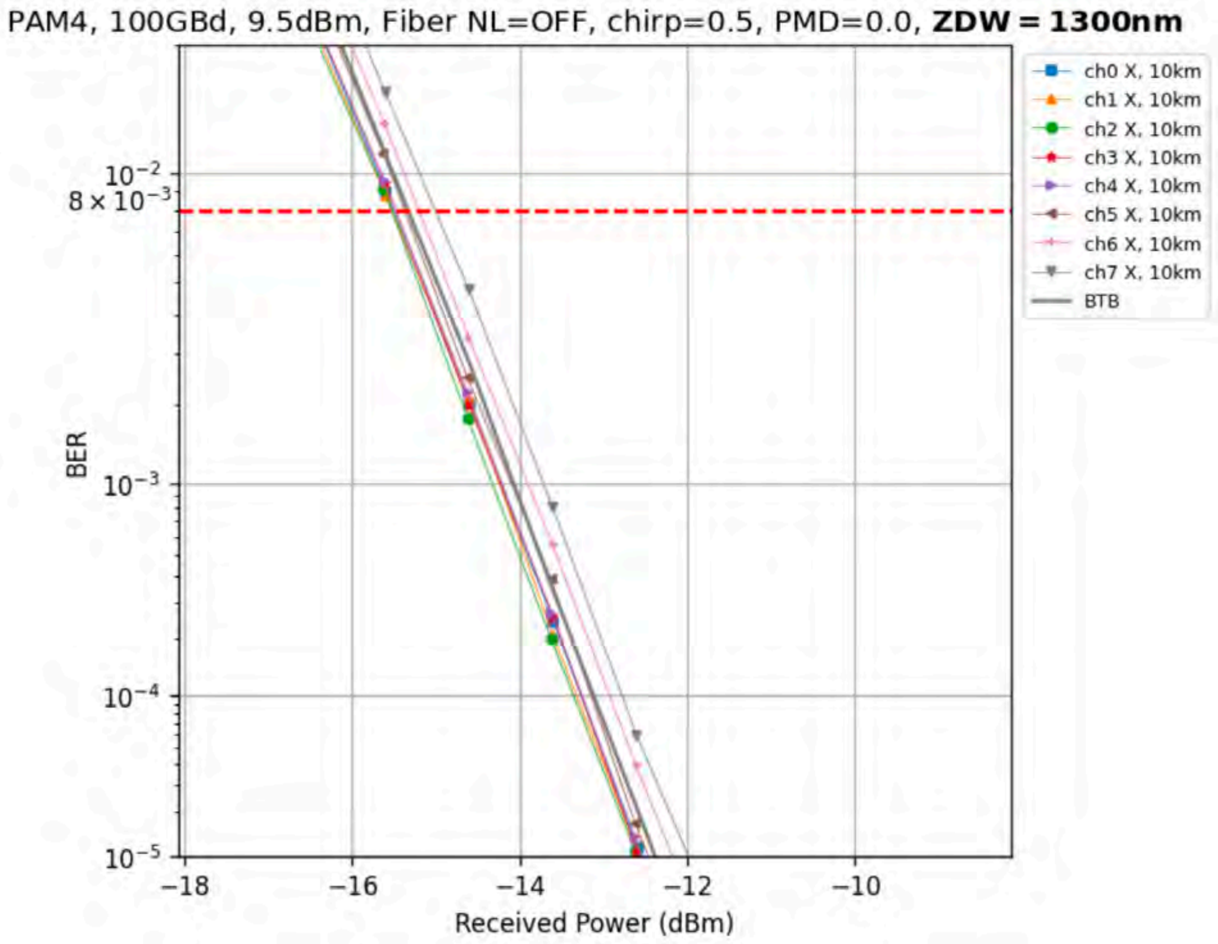
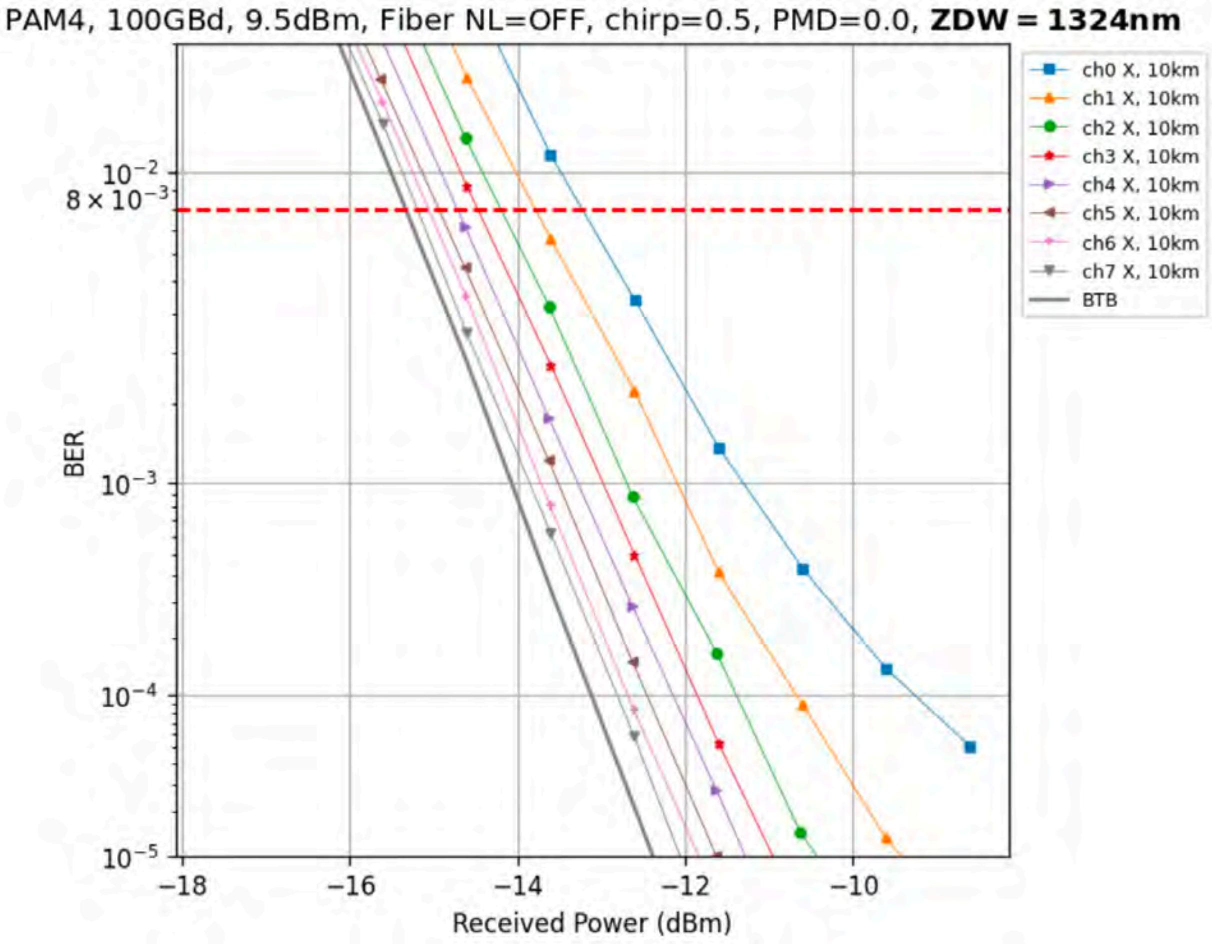
1.6T-LR8 Results (5): Worst-case dispersion penalty

- For the 400GHz-spaced wavelength plan, the worst-case dispersion penalty is 2dB, which occurs when the ZDW is close to the upper limit of 1324nm, where the FWM penalty is negligible .
- The total transmission penalty due to dispersion and FWM can thus be limited to ~2dB.





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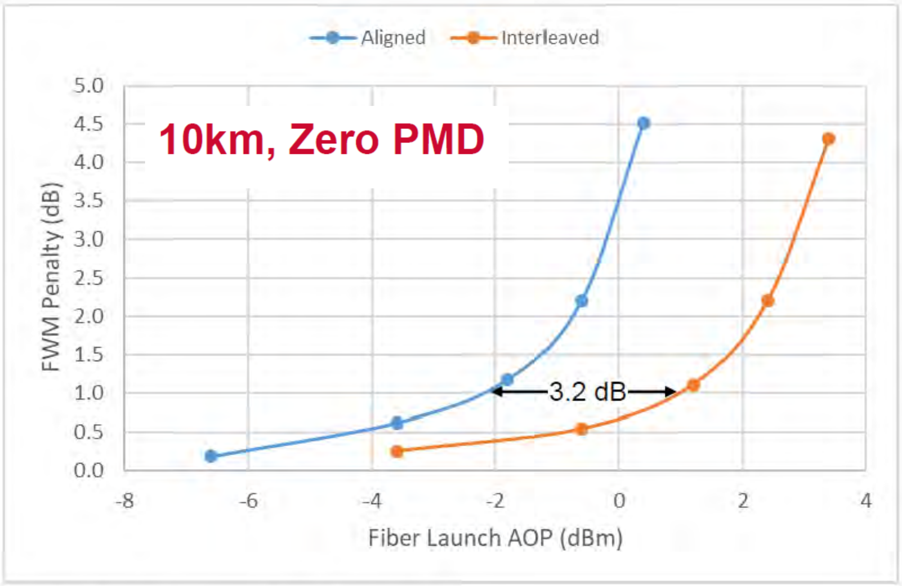
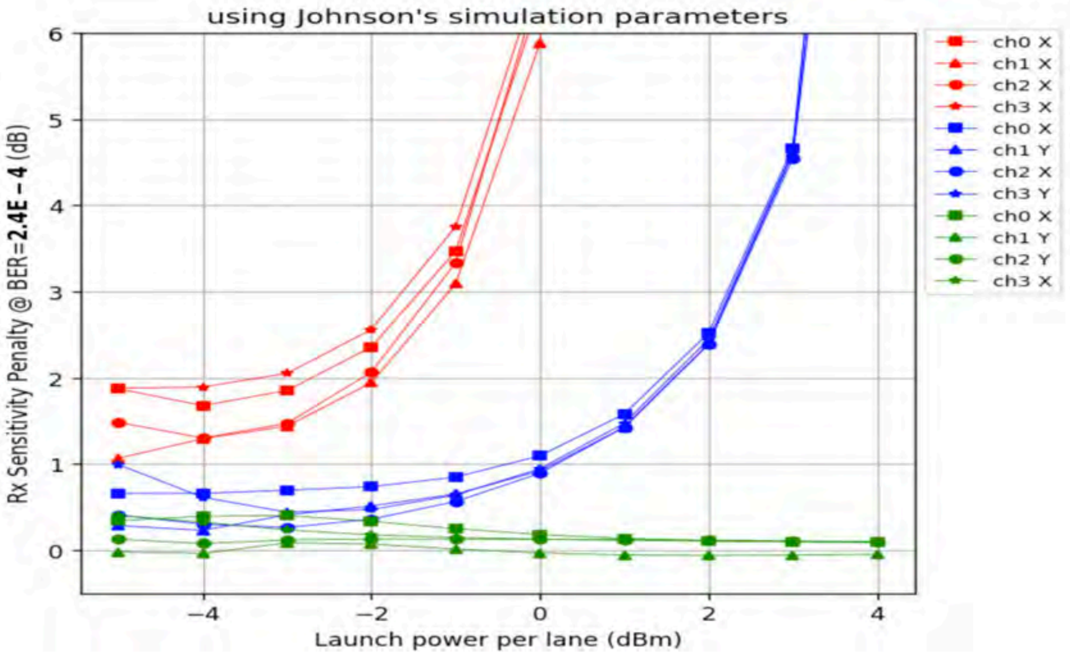
Comparison with “Johnson_3df_optx_1_220411” [2]

Although this contribution appears to show a much higher tolerance to FWM than that reported in Ref. [2], it is actually reasonable after considering the following different assumptions used:

Assumption	BERth	Symbol Rate	Fiber Core Area	Receiver noise	Polarization
Ref. [2]	2.4E-4	53 Gbaud	55 μm^2	20 pA/sqrt(Hz)	XXXX, XYXY
This contribution	4~8E-3	100 Gbaud	70 μm^2	Variable	XYYX, XYYXXYYX



At ER=7.1dB, OMA = AOP + 1.3dB



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

Reasonable agreement reached when the same simulation conditions are used.

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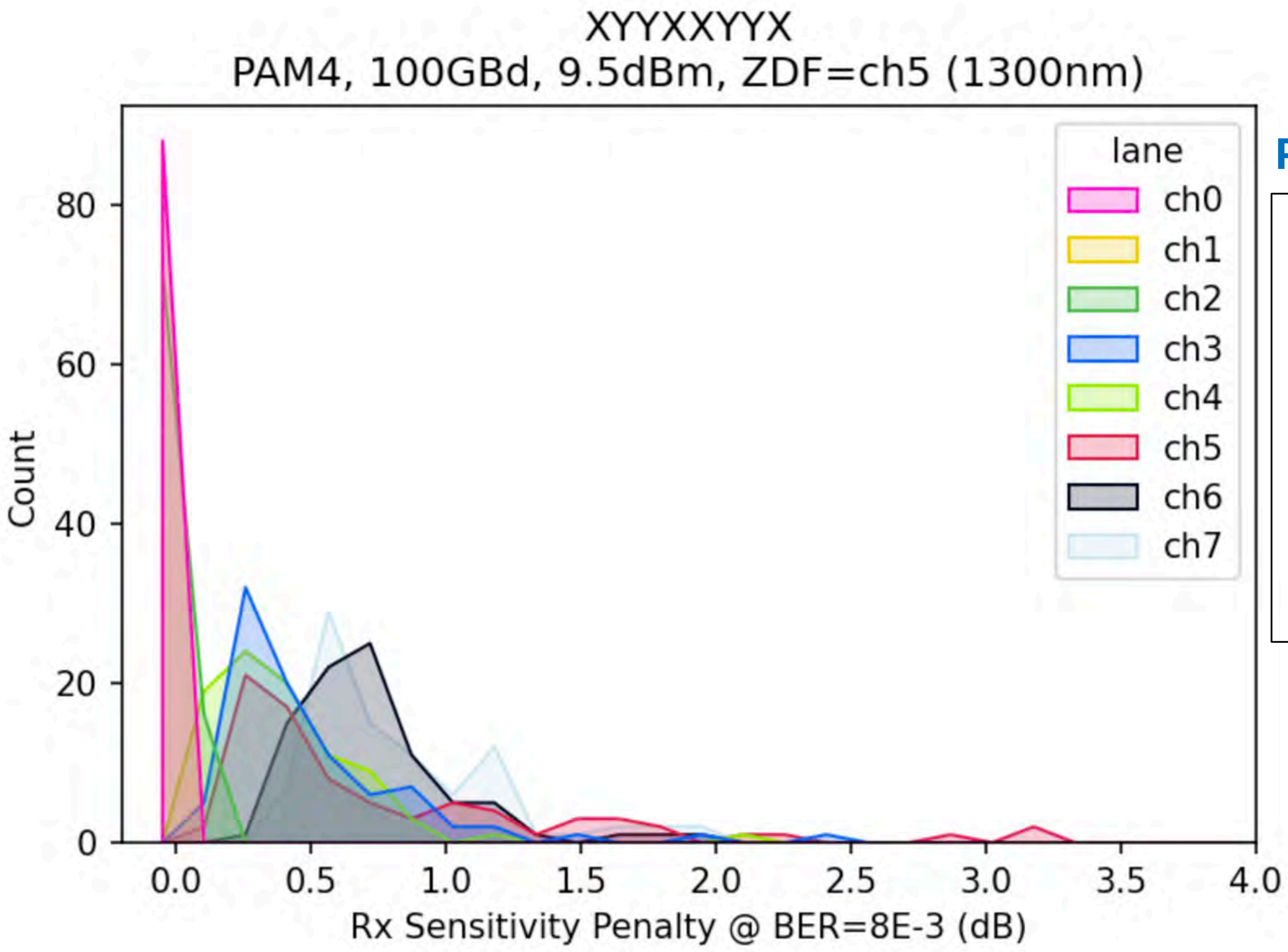
1.6T-LR8 Results: The stochastic effect due to PMD @9.5dBm/ch & 8E-3

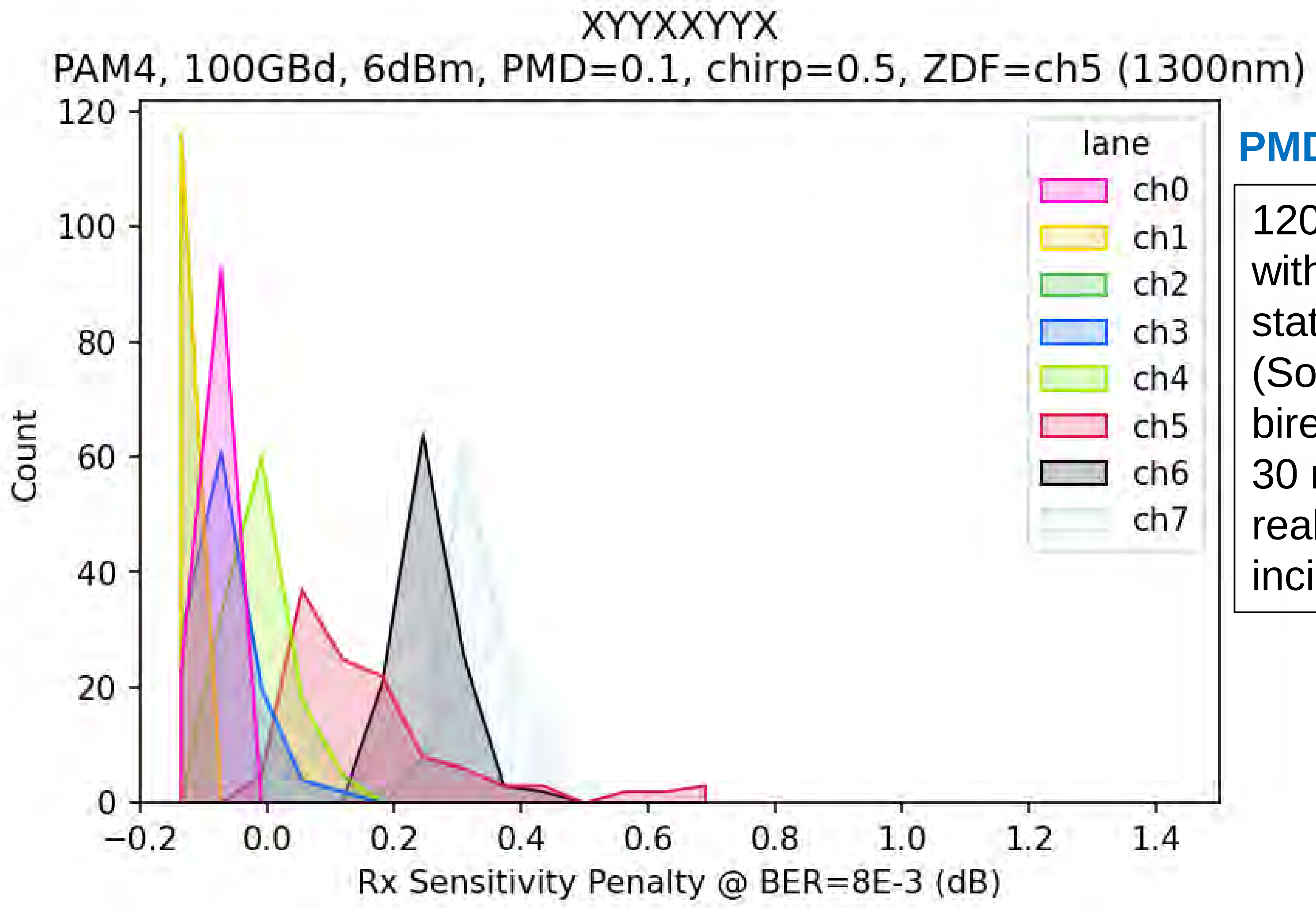


PMD=0.1 ps/sqrt(km)

120 different realizations with 4 kinds of incident states of polarizations (SoPs) w.r.t. fiber birefringence axes, and 30 random PMD realizations for each incident SoP.

Although most of the penalties are within 1dB, there are some outage events with >1dB penalties.

1.6T-LR8 Results: The stochastic effect due to PMD @6dBm/ch & 8E-3

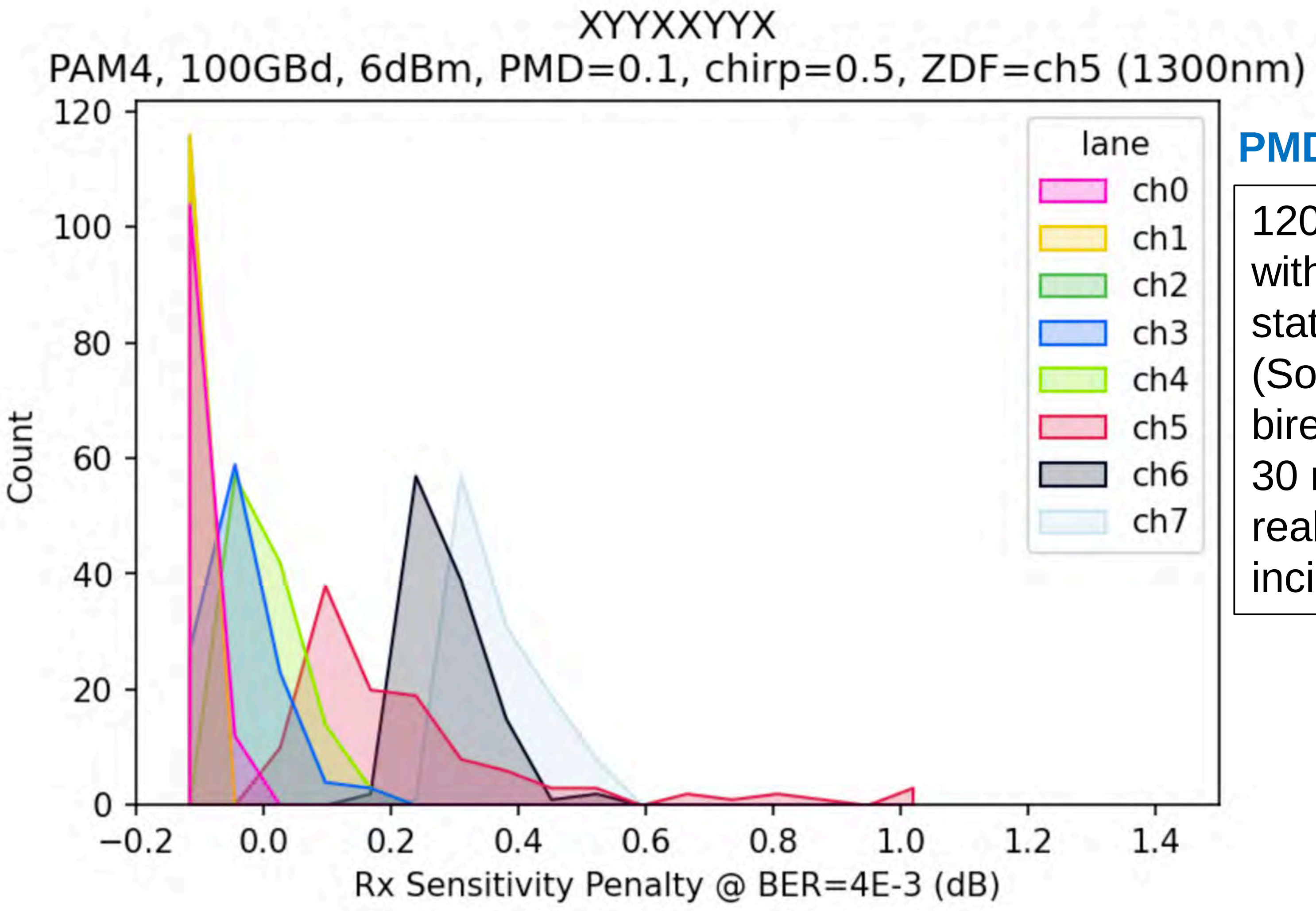


PMD=0.1 ps/sqrt(km)

120 different realizations with 4 kinds of incident states of polarizations (SoPs) w.r.t. fiber birefringence axes, and 30 random PMD realizations for each incident SoP.

All the penalties of the 120 realizations are within 0.7 dB.

1.6T-LR8 Results: The stochastic effect due to PMD @6dBm/ch & 4E-3



PMD=0.1 ps/sqrt(km)

120 different realizations with 4 kinds of incident states of polarizations (SoPs) w.r.t. fiber birefringence axes, and 30 random PMD realizations for each incident SoP.

All the penalties of the 120 realizations are within ~1 dB.

Discussion on Power budget for 1.6T-LR8

- With the effective FWM suppression by using the “XYYXXYYX” polarization arrangement, the signal launch power per channel can be as high as 9dBm in **1.6T-LR8** for a typical FWM-induced receiver sensitivity penalty of <1dB at the BER threshold of 8E-3.
  - Assuming a channel power non-uniformity of 3dB, the operating range of the signal launch power for each channel can be 3dBm~6dBm .
- With an ER of 6dB, the achievable receiver sensitivity at 8E-3 can be about -9dBm.
  - Assuming 2.5dB combined penalty for dispersion and FWM, the achievable receiver sensitivity after transmission is about -6.5dBm.
- Thus, the power budget for fiber and DMUX losses is 9.5 dB (=3dBm-(-6.5dBm)), which may be sufficient, even when weaker FEC and more margin for PMD are considered.

Conclusion

- Sufficient power budget may be practically achieved for both **800G-LR4** based on 800GHz-spaced LAN-WDM channels and **1.6T-LR8** based on 400GHz-spaced WDM channels, each modulated with **200Gb/s PAM4**, by using
  (1) effective FWM suppression via "XYYX" and "XYYXXYYX" polarization arrangements for 800G-LR4 and 1.6T-LR8, respectively
  (2) suitable wavelength plan with the consideration of a moderate transmitter chirp of ~0.5, and
  (3) high-performance FEC with a BER threshold of 4~8E-3.

- Further verifications by simulations and experiments are needed to more accurately quantify the power budget allocations.

Thank you!