Numerical Simulation of Polarization Multiplexing for Suppressing FWM

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Outline

- Introduction
- Longitudinal ZDW Fluctuation
- Numerical Simulation using "1.6T-LR8" system as example
  - 1.6T LR8 is solely used for illustration purposes as it is not part of the adopted objectives of the IEEE P802.3dj
- Summary

Background - Suppression of Four Wave Mixing (FWM)

- Fiber Four Wave Mixing (FWM) is one of a key degradation factor to realize IM/DD 800G-LR4 and 1.6T-LR8 links
  - Polarization arrangement "**XYYX**" is proposed by liu_3df_01b_2207[1] to reduce FWM crosstalk.
  - Combined allocation of dispersion and FWM penalty is proposed in liu_3df_01a_2210[2] and adopted in rodes_3df_2211[3].

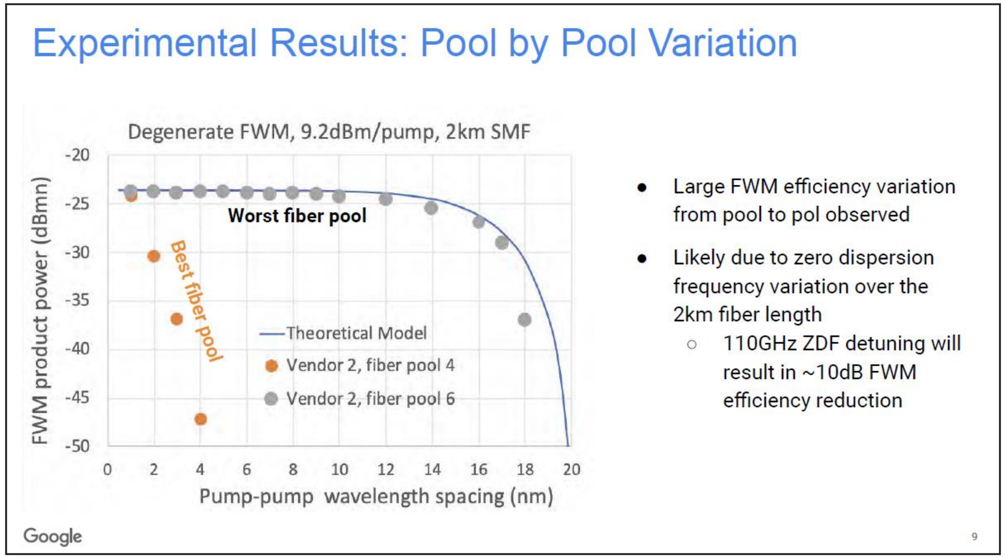
- This presentation is a supplement of lewis_3df_01_2210[4].
  - We explain the effect of the longitudinal fluctuation of ZDW in optical fiber, which narrows FWM gain bandwidth of practical fibers, and propose its numerical modeling.
  - The effectiveness of previously proposed 8-channel polarization arrangement "**XYYXGXYYX**" is confirmed by numerical simulation for 1.6T-LR8 link using practical O-band parameters.

[1] X. Liu, "Effective suppression of inter-channel FWM for 800G-LR4 and 1.6T-LR8 based on 200Gb/s PAM4 channels," IEEE 802.3df Plenary meeting, July 2022.
[2] X. Liu, "Assessment of the combined penalty from FWM and dispersion in 800G-LR4 based on 224Gb/s PAM4," IEEE 802.3dj Electronic Session, Oct. 2022.
[3] R. Rodes, "Refined 800G-LR4 IM/DD Optical Specifications," IEEE 802.3df Plenary Meeting Nov. 21, 2022.
[4] D. Lewis, "Experimental Verification of Polarization Multiplexing for Suppressing FWM," IEEE 802.3df Electronic Session, Oct. 2022

Longitudinal ZDW Fluctuation – Motivation

- Experimental observation shows that FWM bandwidth/efficiency greatly varies from fiber to fiber.
  - lam_3df_01a_220524[5] reports 3-dB FWM bandwidth of 1 to 16 nm from fiber to fiber.
  - lewis_3df_01_2210[4] reports only a single fiber out of 13 showed strong FWM.

- It is mainly due to the longitudinal ZDW fluctuation in fiber. In the calculation of FWM penalty, fiber ZDW is typically assumed to be constant over fiber span (=worst case fiber), which may lead to excessive outage than the practical cases.



[5] X. Zhou, "Four Wave Mixing Penalty for WDM-based Ethernet PMDs in O-band," IEEE 802.3df Electronic Session, May. 2022

Longitudinal ZDW Fluctuation – Measurement

- So far, various measurement of fiber longitudinal ZDW/dispersion mapping have been performed, for example, by using "pulsed FWM technique."

- Longitudinal ZDW/dispersion is actually not constant, as shown below.
  – It is induced by the longitudinal change of fiber structural parameters such as mode diameter.
  – Longer fibers show larger ZDW change (thus, short fibers are used for non-linear experiments).
  – Various measurements show ZDW shift of up to a few nano-meters in 10-km fibers.

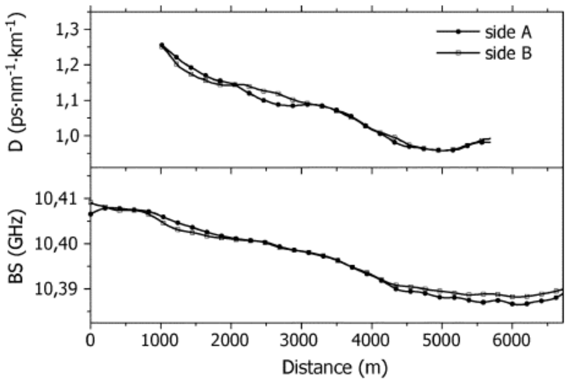


Fig. 4. Calculated chromatic dispersion map and Brillouin shift of the dispersion-shifted fiber from Manufacturer A quoted in Fig. 3. The analysis window is 2 km wide ($\simeq$5 signal periods) to provide a very low uncertainty in the local value of the dispersion.

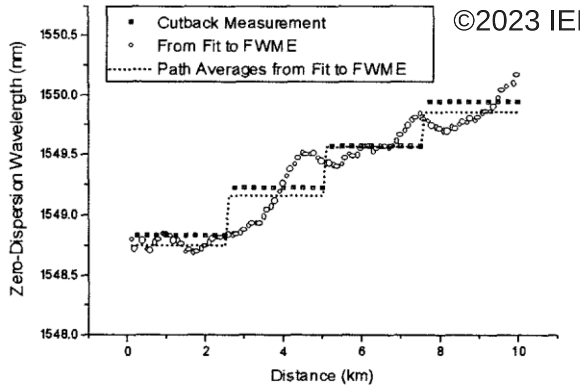


Fig. 2 Length Distribution of λ_0 for the first 10 km fiber determined from calculation and from cutback measurements using the freq.-domain phase shift system

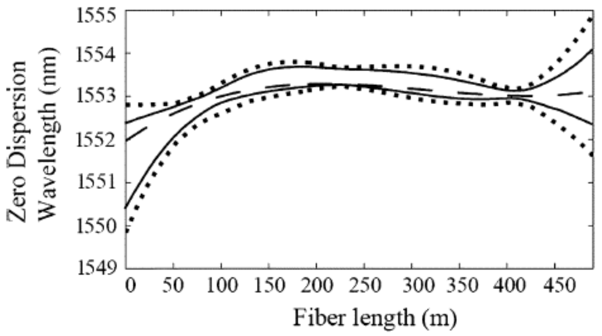


Fig. 3. Estimation of accuracy: retrieved ZDW map (dashed line), minimum and maximum uncertainties (dotted line), with 95% of the events located between the solid lines. At ± 2 standard deviations corresponding to 95% of confidence, uncertainties on D_S and β_4 are $D_S = 0.027 \pm 0.003$ ps/nm^2/km, $\beta_4 = -3.6 \pm 0.6 10^{-56} s^4$ m^{-1}.

[5] M. Gonzalez-Herráez *et al.*, “Simultaneous Position-Resolved Mapping of Chromatic Dispersion and Brillouin Shift Along Single-Mode Optical Fibers,” IEEE PTL Vol.16, No.4, pp. 1128-1130, Apr. 2004.

[6] J.B. Schlager, “Zero-Dispersion Wavelength distribution in Optical Fibers From CW Four-Wave Mixing,” Conference Proceedings. LEOS 1998 Annual Meeting (Cat. No.98CH36243), pp. 308-309, Feb. 1998.

[7] Mussot *et al.*, “Zero-Dispersion Wavelength Mapping in Short Single-Mode Optical Fibers Using Parametric Amplification,” IEEE PTL Vol.18, No.1 pp. 22-24, Jan. 2006.

Longitudinal ZDW Fluctuation - Fiber model

- We introduce a simple fiber model with "linear longitudinal ZDW-shift" to show the relationship of FWM bandwidth and ZDW change
  – Amount of ZDW shift for fiber (length L) is defined as ($\lambda_0(L)-\lambda_0(0)$), it can be positive or negative.

- FWM efficiency is calculated by Split-Step Fourier-based simulator
  – Assuming O-band fiber parameters (Loss: 0.3 dB/km, S_0: 0.093 ps/nm^2/km, A_{eff}: 70 μm^2) .
  – A pump (+10 dBm) is located at the average ZDW of a 10-km test fiber with/without ZDW shift.
  – A signal (0 dBm) is located one side of the pump with detuning D and FWM power generated on the other side is measured, by changing D.

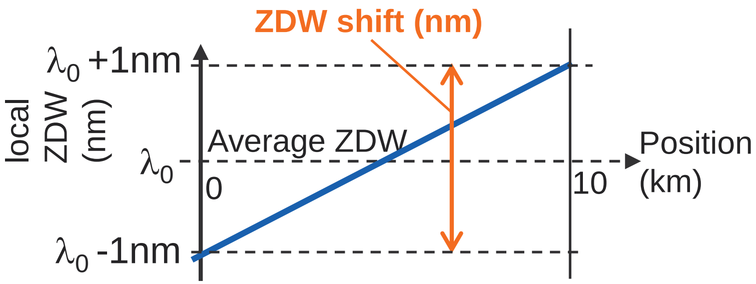


Fig. Longitudinal ZDW variation of fiber with linear ZDW-shift
(This example shows the case of ZDW shift is +2 nm)

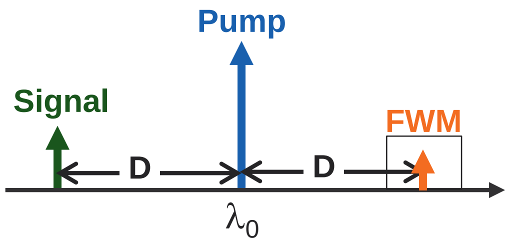


Fig. Wavelength allocation in numerical simulation

Longitudinal ZDW Fluctuation - Simulation results

- FWM gain bandwidth is shown to reduce greatly with longitudinal ZDW shift.
  – Even with 0.5-nm shift of ZDF, 3-dB FWM gain bandwidth drops from 18 to 6.5 nm.

- For example, introduction of uniform distribution of maximum ZDW shift within 0 to 2 nm reduces the chance of FWM Bw >10 nm to 1/10.
  – Reasonably matches to the experimental observations.

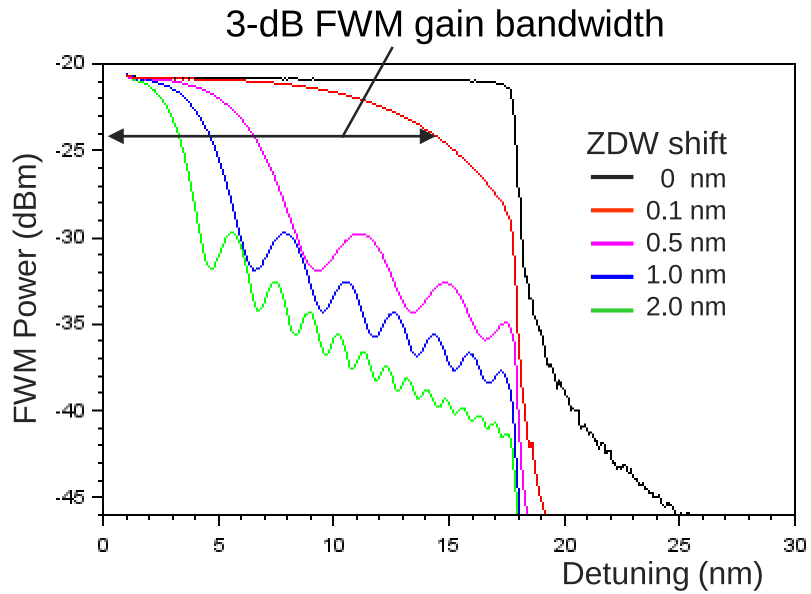


Fig. FWM efficiency vs. Pump-Signal detuning (Pump is located at average ZDW)

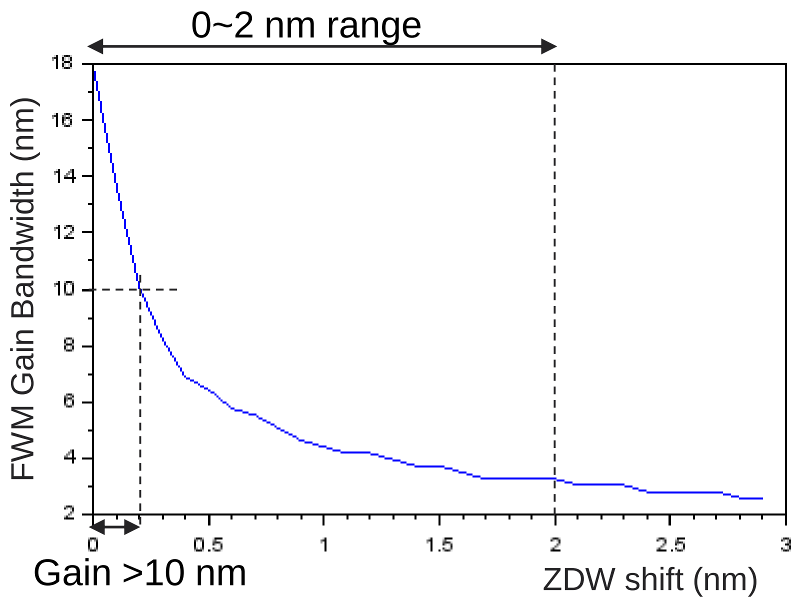


Fig. ZDW shift vs. FWM gain bandwidth

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Longitudinal ZDW Fluctuation – Discussion

- Practical fibers with longitudinal ZDW fluctuation will show lower outage of 1/2~1/4, due to reduced FWM bandwidth.

- The referenced data in slide 6 is nearly 20 years old, and the modern Ethernet fibers are pretty much improved in the uniformity of the average ZDW.
  - But it does not necessarily mean that its longitudinal ZDW fluctuation is completely negligible, or its FWM gain bandwidth can be considered as the theoretical maximum value.
  - To avoid overestimation of FWM outage, it is better to take those of the modern fibers into the consideration.

- Actual 10-km fiber can be multiple segments of shorter fibers with the length of a few kilometers.
  - Its FWM suppression effect in 400G-ER4 is pointed out by Rang-Chen Yu, Frank Chang, Xiang Liu and Qirui Fan (will appear in future contribution). It should also be considered.

Numerical Simulation of 1.6T-LR8 System – Motivation

- In lewis_3df_01_2210[4],
  - Simple rule of thumb for FWM Suppression is introduced and the concept of sub-band for local FWM suppression considering limited FWM gain bandwidth.
  - Polarization arrangement "**XYYXGXYYX"** (G: Guard grid) is suggested, which can suppress FWM for any sub-bands up to five-successive wavelength grids (~11.25 nm in 400-GHz spaced LAN-WDM case), which can reduce FWM outage probability.

- Numerical simulation is performed to show its effectiveness
  - In-house optical transmission simulator based on Split-Step Fourier method (like VPI) is used to evaluate FWM outage probability via Monte Carlo Analysis.
  - Time-variant outage events (such as PMD) and invariant ones are mixed in this simulation, and all the transceiver and fiber parameters are randomized once per a single run to estimate total signal outage probability.

Numerical Simulation of 1.6T-LR8 System – Simulation Setup

- Most parameters are based on rodes_3df_2211[3]
- O-band IM-DD 112.5 GBaud PAM4 TRX is assumed
  - Emulates EML or LN-MZ, Alpha is set to 0, ER is fixed to 4.75 dB
  - OMA: Gaussian distrib. centered at 4.4 dBm (truncated at 3.5 and 5.5 dBm)
  - AOP: Calculated from OMA and ER, total AOP is limited at 14.5 (=11.5+3) dBm
  - To evaluate FWM penalty alone, fiber chromatic dispersion is optically compensated channel by channel, before launching into Rx. Wide-band analogue PIN receiver model without FFE is employed, which is sufficient for evaluating FWM crosstalk only.
  - BER threshold is set to 4.0E-3.
  - Channel frequency: Uniform distribution within passband (400-GHz: ±0.5 nm) .

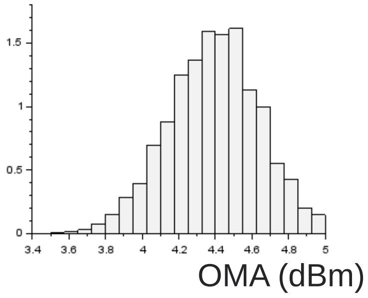

Fig. Distribution of OMA

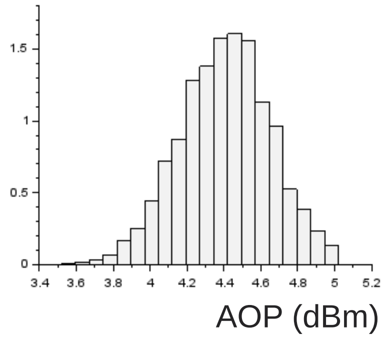

Fig. Distribution of AOP

Numerical Simulation of 1.6T-LR8 System – Simulation Setup (Cont.)

- 10-km standard SMF
  - Average ZDW: Single Gaussian (center: 1313 nm, s: 2.5 nm) truncated within 1300-1324 nm.
  - PMD: Rotating waveplate model (step=100 m) with PMD of 0.05 ps/sqrt(km)
  - Loss: 0.3 dB/km, S_0: 0.093 ps/nm^2/km, A_{eff}: 70 µm^2, Nonlinear coefficient: 2.6E-24

- LR8 wavelength plan with 400-GHz spacing (only for test, not proposals)
  - 400-GHz spacing to keep chromatic dispersion range almost the same as LR4 in rode_3df_2211[3] (1295.56/1300.05/1304.58/1309.14 nm).
  - From the distribution of average ZDW and wavelength plan, FWM outage probability is expected to be low, since it only occurs when average ZDW is <1308 nm, which is the 2σ tail of Gaussian distribution.

Table. Example LR8 wavelength plan

ch0	1291.10±0.5	-	-	-	X
ch1	1293.32±0.5	X	X	X	Y
ch2	1295.56±0.5	X	Y	Y	Y
ch3	1297.80±0.5	X	X	Y	X
ch4	1300.05±0.5	X	Y	X	G
ch5	1302.31±0.5	X	X	X	X
ch6	1304.58±0.5	X	Y	Y	Y
ch7	1306.86±0.5	X	X	Y	Y
ch8	1309.14±0.5	X	Y	X	X

Channels

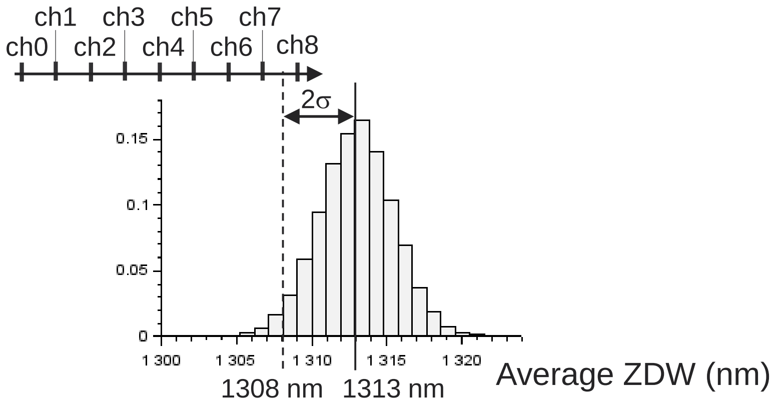

Fig. Distribution of Average ZDW (Center: 1313 nm, σ: 2.5 nm) and wavelength plan

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Example) FWM Penalty in 1.6T-LR8 with 400-GHz spacing

- To accelerate the simulation, we skip calculation when randomly generated average ZDW>1308 nm, by assuming FWM penalties are zero.
- The FWM outage probabilities of XYYXGXYYX and XYYXXYYX is low, and that of the latter is around 1E-5 with 0.3 dB penalty. Both are further lowered by the introduction of random ZDW shift, which suggest the acceptably low FWM outage probability in practical situation.
- Some worst case outage probabilities with the combination of ZDW and channel frequencies are shown in appendix.

w/o ZDW shift,
PMD=0.05 ps/km$^{1/2}$
100,000 runs each

w ZDW shift
(linear model random +/-2 nm),
PMD=0.05 ps/km$^{1/2}$,
100,000 runs each

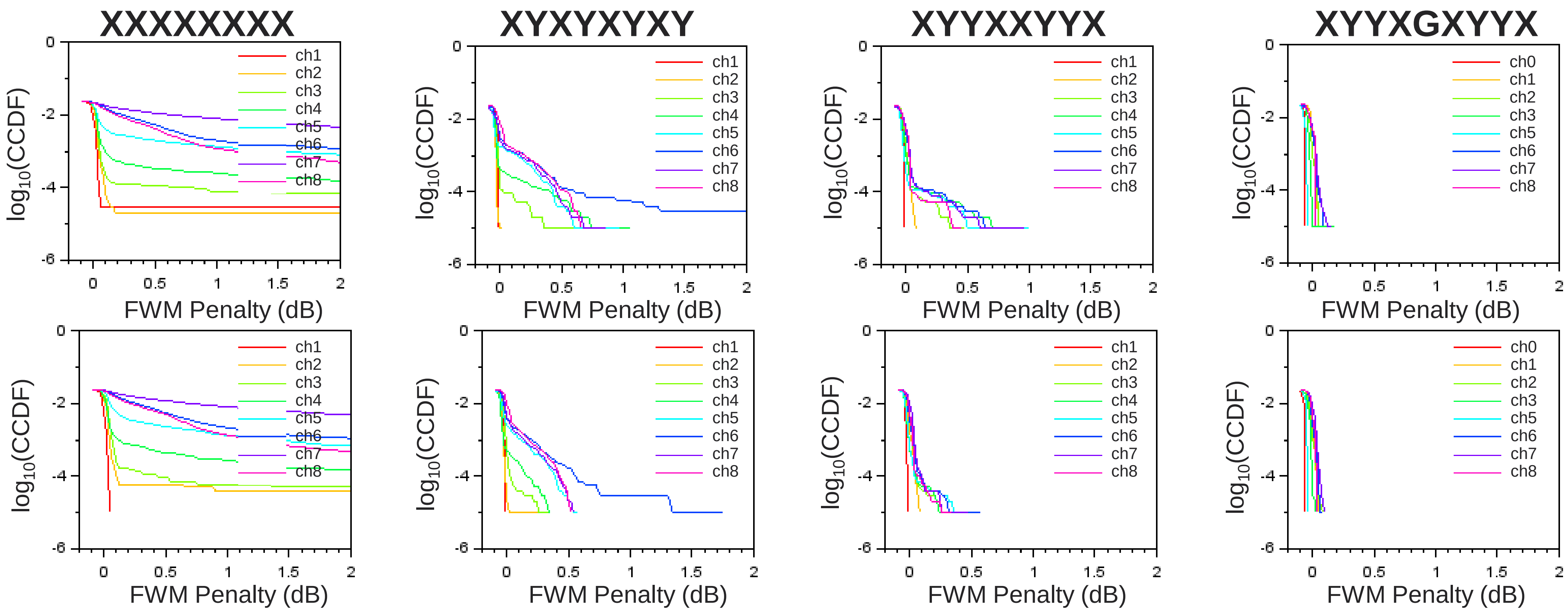

Fig. FWM outage probability vs. channel polarization arrangement

Summary

- Effect of longitudinal ZDW fluctuation is explained.
  - Previous measurements show longitudinal ZDW-shift of a few nano-meter in ~10 km fiber, which leads to narrower FWM bandwidth of real optical fiber than theoretical model.
  - Its consideration seems to be important to avoid overestimation of FWM penalty.
  - However, its statistical data for modern Ethernet fibers does not seem to be reported yet.

- The effectiveness of "**XYYXGXYYX**" polarization arrangement for 8-wavelength IM/DD PAM system (G: Guard grid) is verified by numerical simulations.
  - Simulation results suggest the possibility of 1.6T-LR8 with low FWM outage probability (<0.3 dB penalty at 10^{-5}).

Thank you

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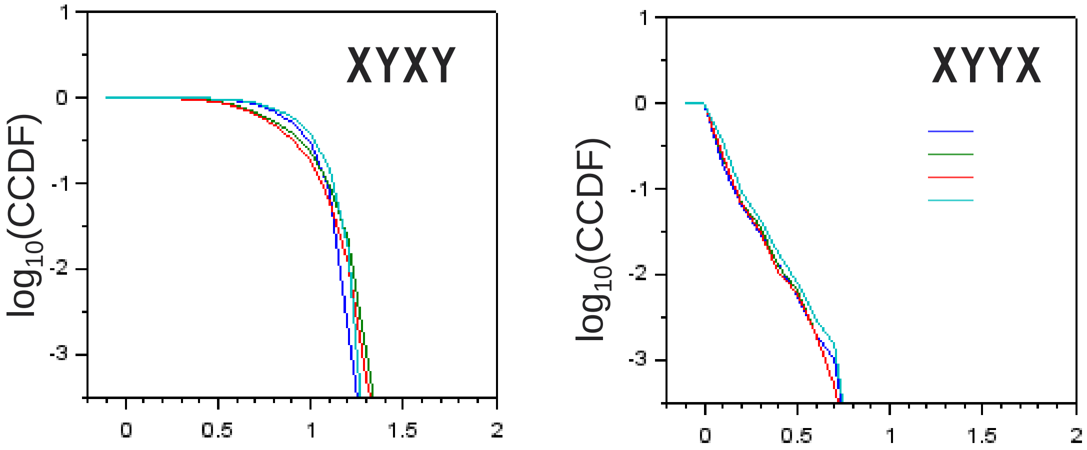
Appendix; Comparison of FWM Outage Probability

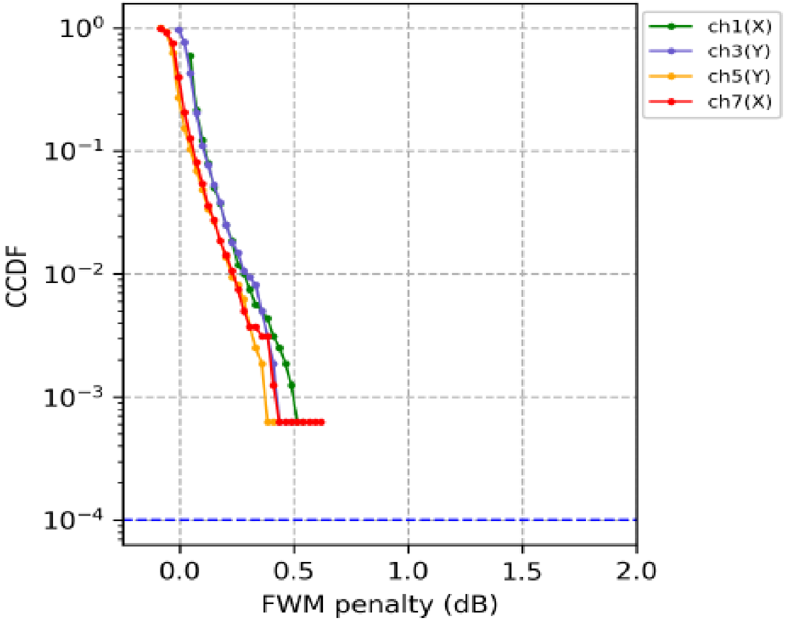
- The validity of our numerical simulation is confirmed by comparing FWM penalty distribution of **XYYX** case with wosrt combination of ZDW at the center of four chnnels (800-GHz spacing) to that of rodes_3df_2211[3].
  - Both results show good agreement with 0.2dB error in FWM penalty



FWM Outage Probability (this contribution)

Simulation conditions

1600 runs with PMD = 0.05 ps/sqrt(km), ER=4dB, OMA=5dBm, AOP=5.65dBm/channel



FWM Outage Probability[3]

Most parameters are based on [3]:
- OMA=5 dBm, AOP=5.6 dBm, ER =4.0 dB
- Channle wavelength: 1295.56 nm ,1300.05 nm, 1304.58 nm, 1309.14 nm
- 10 km fiber, ZDW is fixed at 1302.35 nm, no ZDW shift
- PMD = 0.05 ps/sqrt(km) with rotating wave plate model (step 100m)
- 2000 runs each

Appendix; Worst-case FWM Outage Probability in 1.6T-LR8

- The worst case FWM outage probabilities in the combinations of ZDW and channel frequency are evaluated based on the example LR8 wavelength plan.
  - Signals are exactly aligned on the center of their passband.
  - ZDW matches one of channels or midpoints of two adjacent channels, as shown in the table below.

Table. Example LR8 wavelength plan and the worst case ZDW locations

ZDW

Ch5→ Ch55→ Ch6→ Ch65→ Ch7→ Ch75→

ch0	1291.10	-	-	-	X
ch1	1293.32	X	X	X	Y
ch2	1295.56	X	Y	Y	Y
ch3	1297.80	X	X	Y	X
ch4	1300.05	X	Y	X	G
ch5	1302.31	X	X	X	X
ch6	1304.58	X	Y	Y	Y
ch7	1306.86	X	X	Y	Y
ch8	1309.14	X	Y	X	X

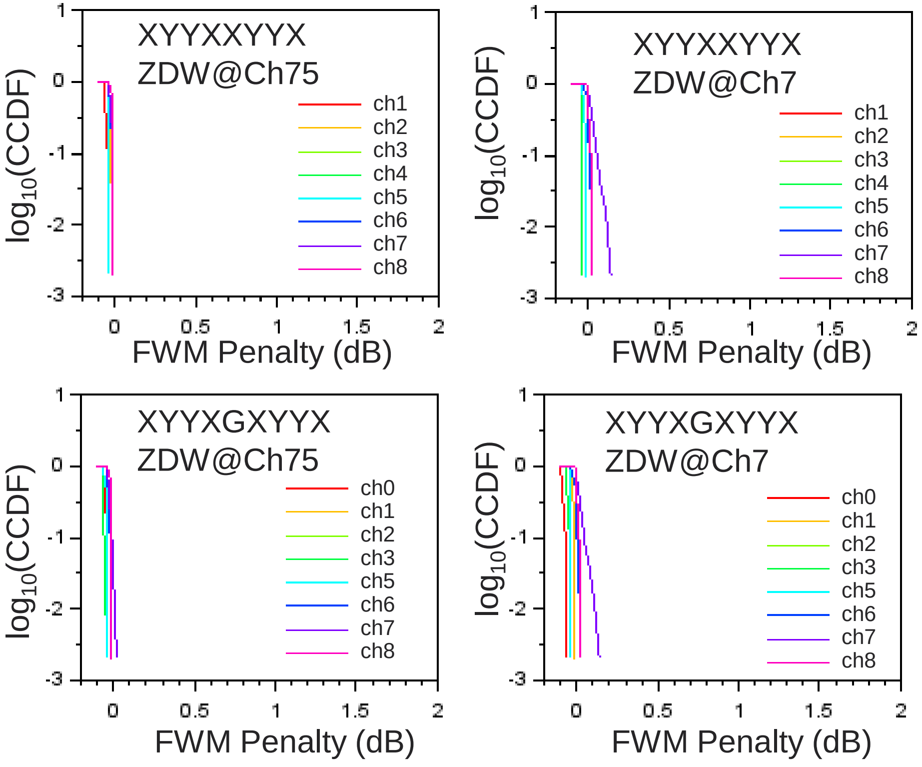


Fig. Worst case FWM outage probabilities

- OMA = 5 dBm, AOP = 5.6 dBm
- ER = 4.0 dB
- 10 km fiber, no ZDW shift
- PMD = 0.05 ps/sqrt(km), PMD alone is the source of randomness.
- 500 runs each.
- Fiber chromatic dispersion is optically compensated and FWM penalties alone are evaluated.

Appendix; Worst-case FWM Outage Probability

- Both XYYXXYYX and XYYXGXYYX shows low FWM outage when ZDW overlaps on long wavelength region (Ch8-Ch6).
- Somewhat large FWM penalty appear when ZDW exactly matches Ch55 (1303.44 nm) and/or Ch5 (1302.31 nm), but such probability is very low considering the ZDW distribution of modern Ethernet fibers.

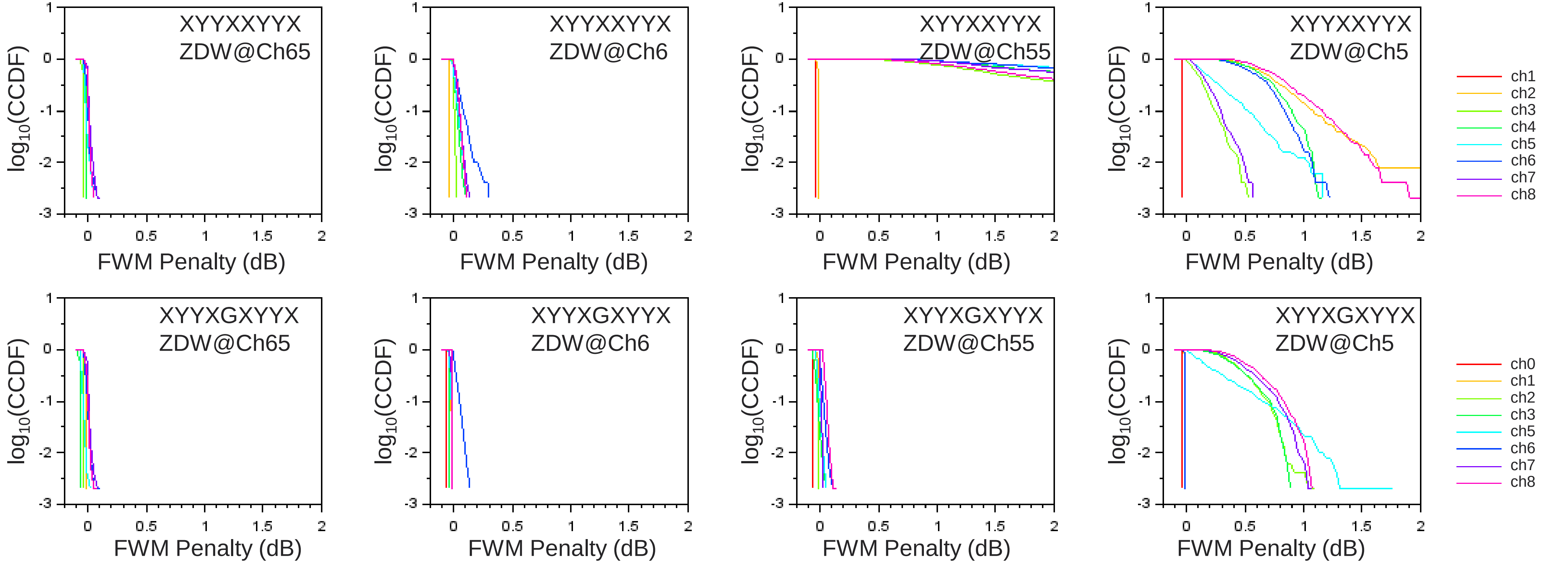


Fig. Worst case FWM outage probabilities (cont.)

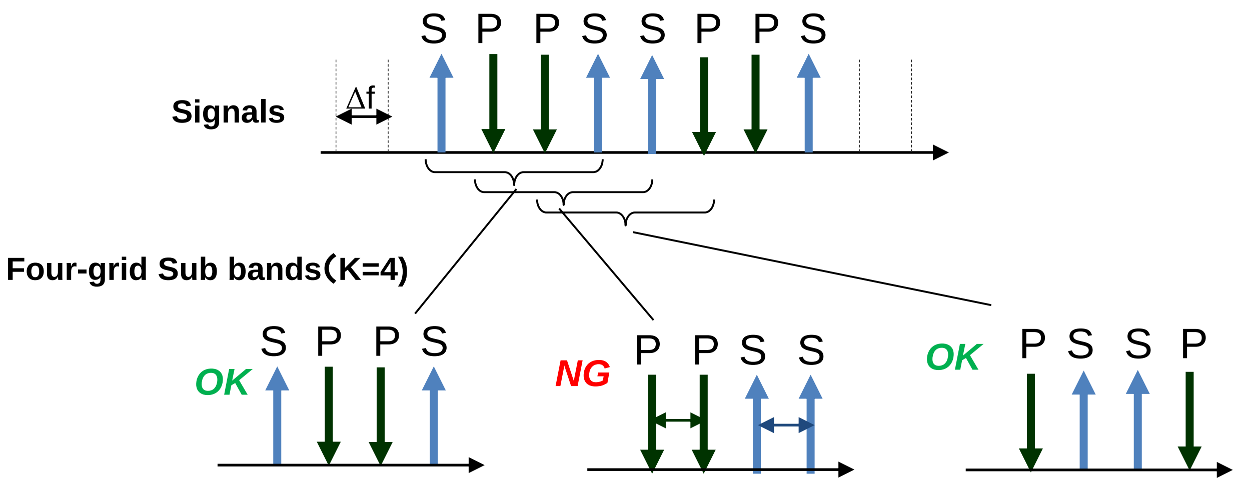
Appendix - Extension to Eight Waves (M=8)

lewis_3df_01_2210[4]

- Without guard grid (N=M), maximum N(or M) satisfies the FWM suppression rule is 4.
- Fully satisfying the FWM rule for M=8 with guard band requires quite wide wavelength range.

- Introduction of "sub-band (K-successive grid, K<N)" seems to be reasonable.
  - FWM is locally-suppressed at any sub-bands over the wavelength band.
  - "Sub-band width KΔf" > "FWM bandwidth" seems to assure FWM suppression

(Ex.3) **SPPSSPPS** (N=M=8) ... **NG**, some sub-bands are weak to FWM, even K=4.



Appendix - Proposal for Extension to Eight Waves (M=8)

lewis_3df_01_2210[4]

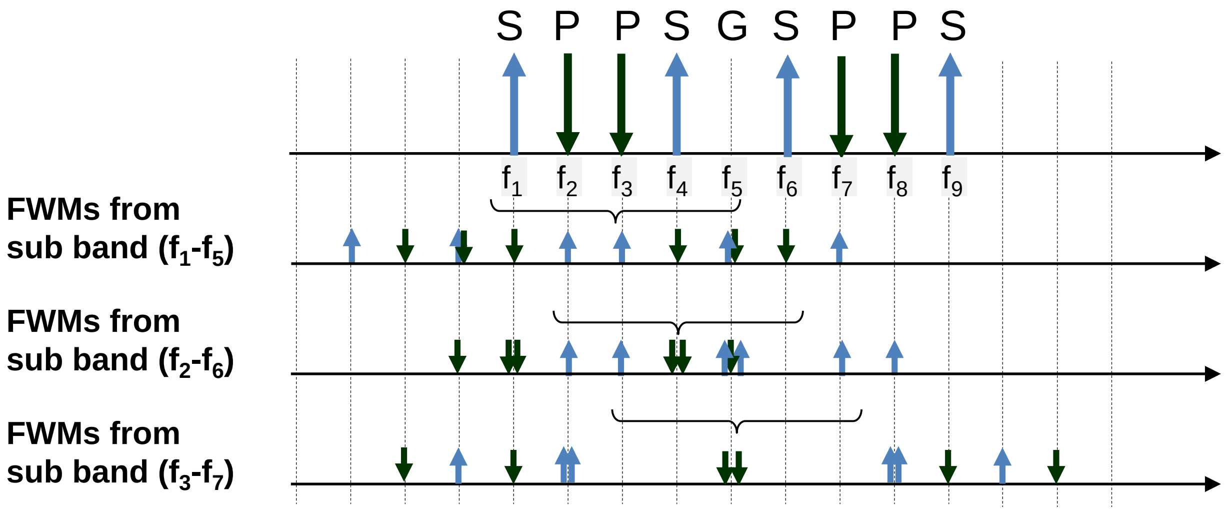
- "**SPPSGSPPS**" (N=9, M=8) is a very special case for FWM suppression

1. Up to any K=5 sub-bands, the FWM suppression rule is satisfied.

   SPPSG: OK, **PPSGS**: OK, **PSGSP**: OK

   ... If Δf=800 GHz, K=5 sub-band width is 4 THz(~22 nm), which may be wider than the FWM bandwidth of the worst case fiber (16 nm).

2. All the FWM components of any K=5 sub-bands overlapping to any signals has orthogonal polarization to it even outside of the sub-bands.



3. It can be further extended limitlessly, like "**SPPSGSPPSGSPPSG....**"

Thank you

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