Analysis of Potential Four-wave Mixing Risk in 5G Front-haul System

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Abstract: FWM is proposed as a new major impairment for 5G front-haul network for the first time. Corresponding theoretical analysis and experiment in FWM penalty have been done for two main commercial plans for comparison. © 2022 The Author(s)

1. Introduction

In recent years, 5G construction is in rapid growth globally. At the same time, ITU-T Q6/15 has also been initiating the process of standardizing 5G front-haul network scheme since 2020, which is coded as G.owdm [1]. Currently, ITU-T Q6/15 has confirmed that 12-channel wavelength division multiplexing (WDM) located between 1260 nm-1380 nm with 25G non-return-to-zero (NRZ) modulation is the basic scheme. However, which 12 wavelengths should be used is still in discussion. Currently, there are two wavelength arrangements proposed for the draft Recommendation G.owdm. The first one is medium WDM (MWDM) with uneven spacings of 7 nm and 13 nm between adjacent channels, whose frequency range per channel is 5 nm and odd/even channels are for different directions [2-3]. The second one is 800-GHz grid 12-λ WDM derived from LAN-WDM defined by IEEE 802.3 with ±400 GHz frequency tolerance, whose shorter 6 channels are for one direction, while the longer 6 channels are for another direction [4-5]. Both wavelength proposals are listed in Table 1 and shown in Fig.1.

Table 1. The Wavelength Proposal for 5G Front-haul Network

Ch.	MWDM	800-GHz grid WDM	Ch.	MWDM	800-GHz grid WDM
	nm	THz		nm	THz
1	1267.5	236.2	7	1327.5	231.4
2	1274.5	235.4	8	1334.5	230.6
3	1287.5	234.6	9	1347.5	229.8
4	1294.5	233.8	10	1354.5	229.0
5	1307.5	233.0	11	1367.5	228.2
6	1314.5	232.2	12	1374.5	227.4

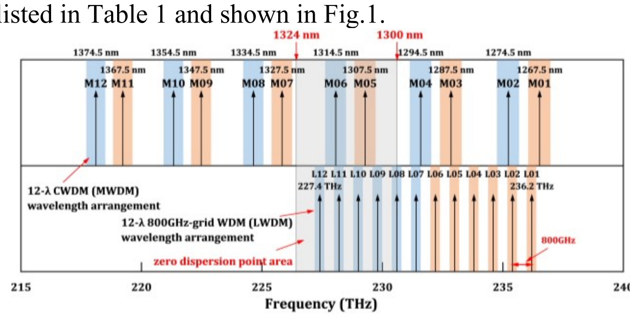

Fig. 1 The two wavelength proposals for 5G front-haul system.

Traditionally, for intensity modulation and direct detection (IM/DD) schemes in O-band, penalty caused by chromatic dispersion (CD) in transmission is the main concern for both ITU-T SG15 and IEEE 802.3. However, as we can see from Fig. 1, the zero dispersion frequency (f_{zd}) of G.652.D ranges from 1300 nm to 1324 nm [6], which overlaps with the wavelength arrangements of the two proposals. Four-wave mixing (FWM) impairments might cause non-negligible penalty and be a risk for network stability. As we know, larger launch power of the transmitter is always welcome for reserving larger margin in the past. However, if FWM is taken into consideration, then larger launch power will inversely introduce FWM penalty and reducing the margin. Though FWM was intensively investigated for C-band applications in dispersion shifted fibers (DSFs) like G.653 with relatively lower rates in 1990s [7-10], there is still no corresponding research for current 5G front-haul systems with 25G NRZ. Therefore, it is necessary to confirm the penalty of different wavelength proposals for the reference of both academic and industry.

In this paper, we investigate the FWM penalties of both MWDM and 800-GHz grid WDM in theory and by experiment. Up to about 4 dB penalty by FWM can be observed when the launch power per channel is 4.03 dBm for 800-GHz grid WDM under the condition of free polarization, while MWDM has no affection. FWM is not a non-negligible effect in 5G front-haul systems and should also be taken into considerations for similar standardizations, e.g. 800GBASE-LR4 and 800GBASE-ER8, in the future.

2. Risk Analysis and Corresponding Experimental Setup for FWM Verification

The risk of experiencing FWM penalty that can significantly impact front-haul transmission should be considered in two aspects. One is the magnitude of FWM penalty when FWM happens, another one is the probability of FWM occurrence. For the first aspect, we know that the maximum magnitude of FWM penalty can be achieved when phase matching condition is satisfied and the magnitude of FWM tones reach their peaks [11]. For a continuous wave (CW) light, its phase mismatch coefficient $\Delta\beta$ is in positive correlation to channel spacing when the chromatic dispersion slope D_λ is non-negligible [11]. Hence, the maximum magnitude of FWM penalty is negatively correlated with channel spacing. The channel spacing for channels in the same direction of MWDM and 800-GHz grid WDM are about 3.22 THz - 3.67 THz and 800 GHz, respectively. Thus, the maximum magnitude of FWM tone of MWDM will be far lower than that of 800-GHz grid WDM when the same launch power and transmission distance are applied. For the second aspect, Ref. [12] roughly estimated the probabilities of FWM occurrence for both MWDM and 800-GHz grid WDM. The probability of FWM tones falling into the receiver bandwidth, the probability of satisfying phase matching condition and the probability of co-polarization were analysed. The total probabilities of experiencing potential FWM penalty for 800-GHz grid WDM and MWDM are ~150 ppm and ~3.5 ppm, respectively, without considering the difference of maximum FWM penalties. When tens of thousands of 5G front-haul links are being deployed worldwide, the risk is non-negligible for 800-GHz grid WDM. It should also be noted that even though a link may have no significant FWM penalty when it is installed, it is still facing the possibilities of FWM penalty due to changes in environmental conditions or laser aging, and the risk will furtherly increase.

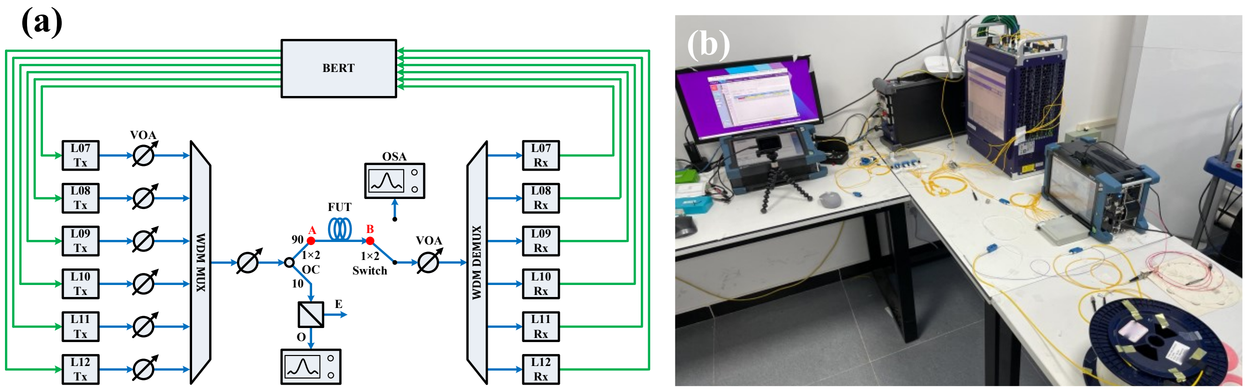

Fig. 2 (a) experimental setup; (b) actual test environment.

An experiment is designed to measure the magnitude of FWM penalty. Fig. 2 (a) shows the experimental setup, and Fig. 2(b) shows the actual test environment. 6 sets of 25-Gb/s optical modules for 10-km scenario are used as transmitters and receivers, of each output power has been adjusted to ~7.2 dBm. Variable optical attenuator (VOA) array is used for power equalization. One 90:10 optical coupler (OC), one polarization beam splitter (PBS) and one optical spectrum analyzer (OSA, EXFO FTB-5) are used for polarization monitoring of each individual channel. The launch power of all channels is adjusted by the VOA after the MUX. All 6 channels are launched into the fiber under test (FUT) without polarization control or external perturbation. The FUT is a spool of 10-km long G.652.D fiber, whose f_{zd} is 229.7107 THz (1305.087 nm). An ethernet analyzer VIAVI ONT-804 is used as a bit error ratio tester (BERT). Moreover, the central frequencies of all channels can also be tuned to target values by changing I^2C sheets of optical modules via ONT-804.

3. Experimental results and Analysis

Based on the experimental setup shown in Fig. 2 (a), we carried out the experiment under the condition of free polarization. Once the connection of the experimental system was done, the patch cords were not touched for a second time. Fig.3 shows the measured spectra at the end of the FUT for both 800 GHz grid WDM and MWDM. Here, L09 and M05 were tuned to align with f_{zd}, the channel spacing of 800 GHz grid WDM and MWDM are 800 GHz and 3430 GHz, respectively. We can see that even without making all channels co-polarized by PCs, under the condition of free polarization, quite large FWM tone can still be observed on the right side of the spectra with the launch power of 5 dBm for 800 GHz grid WDM. While for MWDM, there was no FWM tone observed even under co-polarization. We also measured the BER curves of all 6 channels for both proposals with different launch powers and received powers. For MWDM, no significant FWM penalty can be measured. While for 800 GHz grid WDM, the BER curves are plotted in Fig. 3 (b-g) and significant performance degradation by FWM can be observed. The receiver sensitivity penalties of all 6 channels are shown in Fig. 3(h). The allowed maximum launch power per channel into the FUT and out of the 25G optical module corresponding to different receiver sensitivity penalties for free polarization are summarized in Table 2. Current insertion loss of single WDM MUX is about 0.8~1.8 dB, and we take 0.8 dB to calculate it. If 1 dB budget is considered, then the maximum launch power of the 25G optical module should be 2.23 dBm, which will greatly decrease the yield of 25G optical module production.

We introduce the influence of external perturbation to see the variation of BER as well by twisting the patch cords to certain postures and fixed by tape to maintain the polarizations temporarily. The launch power into FUT is about 5 dBm for each channel. 50 times of perturbations had been done, and we can observe that the BER measured at received power of -11 dBm on each channel behave quite different. For L10,L09 and L10, their BER kept very high, while for L07 and L11, their BER changed hugely with couple of orders of magnitude. Therefore, we can see that, even with intensive external perturbation to change the polarizations, 800-GHz grid WDM still experience very large FWM penalty.

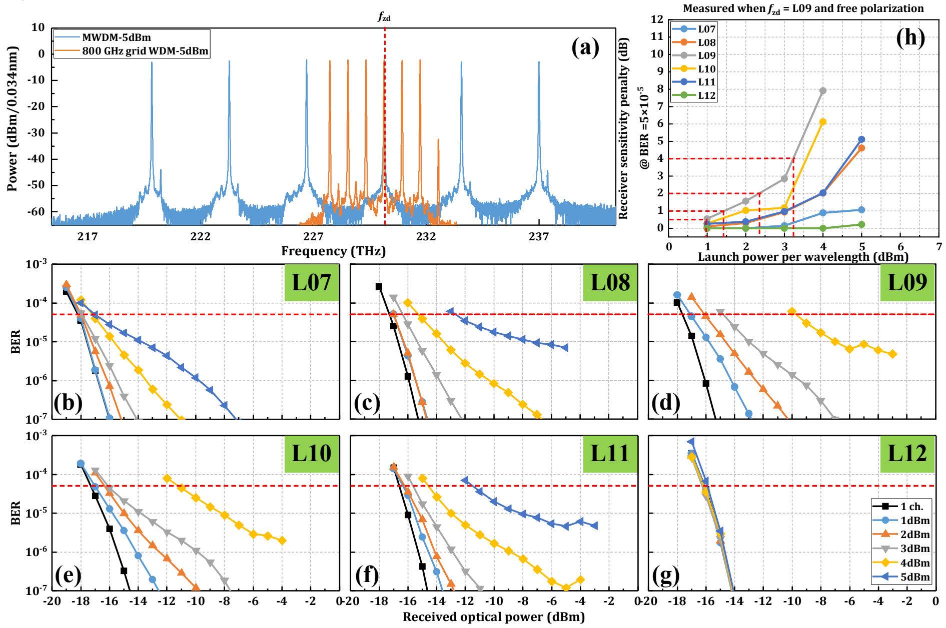

Fig. 3 (a) The measured spectra for both MWDM and 800 GHz grid WDM when launch power per channel into FUT is 5 dBm; (b-g)Curves of BER versus received optical power and (h)sensitivity penalties of all 6 channels under the condition of free polarization.

Table 2. The Allowed Maximum Launch Power Per Channel Into the FUT of 25G Optical Module Corresponding to Different Receiver Sensitivity Penalties Under Free Polarization.

Receiver sensitivity penalty caused by FWM (dB)	Allowed maximum launch power per channel into the FUT (dBm)	Allowed maximum output of 25G optical module (dBm)
4	3.23	4.03
3	3.05	3.85
2	2.36	3.16
1	1.43	2.23

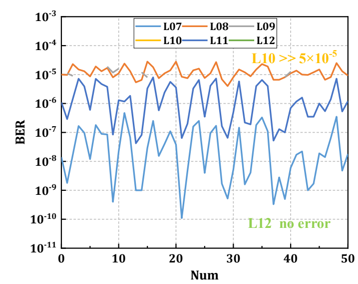

Fig.4 BER of all 6 channels under different external perturbations.

4. Conclusions

In conclusion, for the first time, FWM penalty is proposed as a major possible penalty for 5G front-haul network. For both MWDM and 800 GHz grid WDM, their probabilities of FWM occurrence is analyzed and the FWM penalties is measured by experiment. Higher risk of FWM occurrence and up to 4-dB FWM penalty can be observed for 800 GHz grid WDM while MWDM experiences almost no penalty when launch power per channel into the FUT is merely 4.03 dBm. FWM should also be taken into considerations for similar standardizations, e.g. 800GBASE-LR4 and 800GBASE-ER8, in the future. *This work is supported by National Key Research and Development Program of China (No. 2019YFB1803605).*

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