Spectral Overlap of Two Bandwidth Variable Nyquist-WDM Signals to Resolve Wavelength Conflict in Elastic Optical Networks

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Abstract: *We investigate a simple spectral overlap method to resolve the wavelength conflict for two independent bandwidth variable Nyquist-WDM signals by relative power control. Individual signals can be separated and recovered by digital signal processing.*
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I. Introduction

Nyquist signal based wavelength division multiplexing (Nyquist-WDM) is a promising solution to enable the future elastic optical networks (EON), since it occupies minimal bandwidth, which is close to the signal's baud rate, and requires relatively small inter-channel guard band. Hence, it achieves much higher spectral efficiency, compared with traditional modulation format without pulse shaping applied in optical system. In EON, the usable spectrum in fiber is quantized into a finite number of contiguous frequency slot units (FSUs) [1]. With the increasing demands for network capacity, wavelength contention may occur due to the limited spectrum resource for network routing.

To resolve the possible wavelength conflict issue, wavelength conversion technologies are proposed [2]. One conventional approach adopts the optical-electrical-optical (O-E-O) conversion, in which the optical signal needs de-multiplexing and regeneration onto other available FSUs with tunable laser. The nonlinear optical effect is another method for wavelength conversion, in which wavelength select switch (WSS) and pump lasers are required. The pump lasers demands precise polarization to achieve the optimal conversion efficiency, especially for polarization-multiplexed signals [3].

In this paper, a simple and cost-effective spectral overlap method of two independent optical Nyquist polarization-multiplexed quaternary phase-shift keying (Nyquist-PM-QPSK) channels is investigated, as a feasible solution to resolve wavelength conflict. The spectral overlap method is realized by combining two optical channels with relative power control as in [4]. Herein, we mainly analyze the impacts of time offset and relative polarization state on the overlapped system performance, via numerical simulations. Furthermore, since one optical channel can occupy more than more FSUs in EON, the system performance of the case of combining two optical channels with different bandwidths, is also characterized.

II. Operation Principle

Fig.1 (a) illustrates an example of wavelength conflict in network routing. Two channels, denoted by S_d and S_w, transmit from their respective source nodes A and B and contend for the same output fiber link CD. At node C, their respective signal powers, P_d and P_w, are carefully adjusted such that the dominant channel S_d is set to have relatively higher power than the weak channel S_w, before being optically combined, via an optical coupler, to form the output overlapped composite signal S_o. Then, S_o is transmitted over the fiber link CD, before being power-split for further

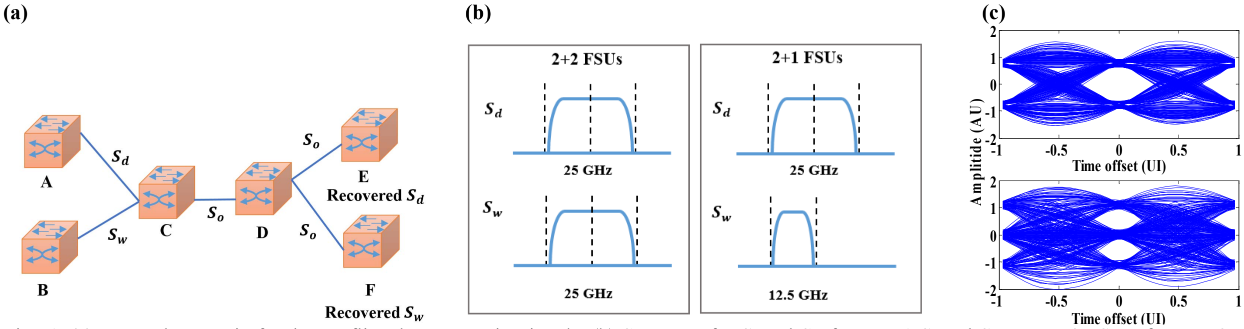

Fig. 1. (a) Network scenario for the conflicted two Nyquist signals; (b) Spectrum for S_d and S_w, for case 1 S_d and S_w occupy 2 FSUs, for case 2, S_d and S_w occupy 2 FSUs and 1 FSU, respectively; (c) eye diagrams for Nyquist-QPSK signal (up) and after 45-degree relative polarization rotation (down).

transmissions to their respective destination nodes E and F. As shown in Fig.1 (b), we consider two independent Nyquist-PM-QPSK signals with variable bandwidth. Both S_d and S_w occupy two FSUs as case "2+2 FSUs". In "2+1 FSUs" case, S_d and S_w occupy two FSUs and one FSU, respectively.

At node E, S_d is going to be recovered and demodulated, while the component of S_w contained inside S_o is treated as the interference. The recovery of S_d involves several steps. First, the acquired signal S_o is filtered by a digital fifth-order Bessel filter and is re-sampled to 2 samples per symbol, with respect to S_d. Timing phase recovery based on Gardner timing error detector (TED) is employed. Then, the signal is polarization de-multiplexed and equalized based on the constant modulus algorithm (CMA). The carrier is synchronized by Viterbi-Viterbi (VV) frequency estimation and blind phase search (BPS) method. Hence, S_d can be retrieved and forward error corrected. At node F, in order to recover S_w, the 2-samples-per-symbol version of the recovered S_d is reconstructed by Nyquist filtering, and is subtracted from the carrier synchronized signal S_o. At last, S_w can be recovered via the CMA, VV and BPS algorithms in sequence. For the "2+1 FSUs" case, additional frequency shift is applied before the second round of signal processing.

The two channels S_d and S_w suffer from strong interference after optical combination because of the spectral overlap. The signal-to-interference ratio (SIR) is defined as the optical signal power ratio of S_d to S_w ($SIR= P_d / P_w$). To ensure successful demodulation of S_d, the parameter SIR should be large enough. However, proper signal recovery for S_w requires small value of the SIR in S_o. Therefore, the SIR has to be optimally adjusted such that both tributary signals can be properly recovered, simultaneously.

III. Numerical Simulation

In the numerical simulation, the FSU width was set to 12.5 GHz [1]. Two independent Nyquist-PM-QPSK signals, namely S_d and S_w, were generated, with the roll off factor of 0.2 and Nyquist filter length of 128 symbols. Then, the two channels were optically combined to form the composite signal S_o with relative power control. The OSNR of S_o was varied by adding white Gaussian amplified spontaneous emission (ASE) noise P_{ASE} (in 0.1-nm bandwidth), where $OSNR_o= (P_d+P_w)/P_{ASE}$, for performance characterization. At the receiver, S_o was acquired by coherent detection. The transmitter and local oscillator lasers were independent with 100-kHz linewidth.

As shown in Fig. 1(c), it could be noted that the relative time offset and polarization rotation between the two optical channels would influence the signal temporal characteristics, varying the interference amplitude between S_d and S_w. Thus, two set of conditions have been considered The first case, denoted as Case 1, had zero time offset and matched polarization state between S_d and S_w; while, in the second case, denoted as Case 2, time offset was half of the symbol period and the relative polarization rotation was 45-degree since the interference amplitude between S_d and S_w reached the maximum.

A. Spectral Overlap for 2+2 FSUs

For "2+2 FSUs", the baud rates of both S_d and S_w were 20 GBd with 0.2 roll off factor. Fig. 2(a) shows the bit-error-rate (BER) curves for S_o, S_d and S_w, as a function of $OSNR_o$. The BER of S_o is defined as the average BER of the recovered S_d and S_w, before applying forward error correction. It could be optimized by properly adjusting the SIR, at a given $OSNR_o$ value. As shown, under the optimal SIR, the required OSNR for S_o was 18.8 and 20.5 dB, at a BER of 3.8×10^{-3}, for both Case 1 and Case 2, respectively. Besides, the BER performance of the 20-GBd Nyquist PM-16QAM, as a function of OSNR was also depicted, for comparison. With respect to the case of PM-16QAM, the OSNR penalties for S_o were 0.3 dB and 2 dB, respectively. As shown in the insets of Fig. 2(a), the constellation diagrams for S_d and S_w in Case 1 were more clear than those in Case 2. The constellation of S_d in Case 1 was close to four "rings", since the two optical channels were timing and polarization aligned.

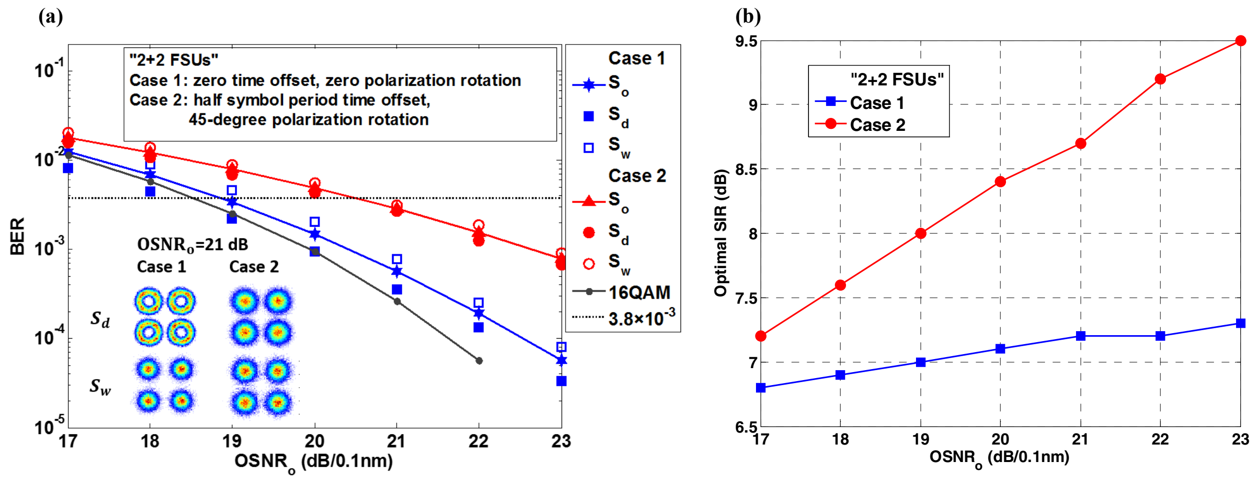

Fig. 2. Simulation results for "2+2 FSUs": (a) the calculated BERs for S_o, S_d and S_w as a function of $OSNR_o$ for Case 1 and Case 2, calculated BER for 20GBd Nyquist PM-16QAM case for reference, the constellations diagrams for two cases under the $OSNR_o$ 21 dB; (b) the optimal SIR as a function of $OSNR_o$ for Case 1 and Case 2.

As shown in Fig. 2(b), the optimal SIR for Case 1 was around 7 dB with less than 0.3 dB deviation. However, for Case 2, the optimal SIR increased significantly with respect to $OSNR_o$. From the results, it could be noticed that the two channels S_d and S_w could be separated and recovered from the overlapped composite signal S_o. Since the two channels had the same baud rate, we could see that the time offset and the relative polarization rotation would obviously influence the interference characteristics. With the increased interference amplitude in Case 2, a larger SIR was required at the same $OSNR_o$. Such optimal SIR in Case 2 was applied as the power control strategy, to assure successful recovery of S_d and S_w since the relative time offset and polarization state were unknown in most practical applications.

B. Spectral Overlap for 2+1 FSUs

For "2+1 FSUs", the baud rate of S_d was set to 20 GBd, while that of S_w was 10 GBd. Two set of conditions have been analyzed. That is, Case 1 referred to aligned polarization states for S_d and S_w; while Case 2 referred to 45-degree relative polarization rotation. The time offset between S_d and S_w had little impact on the BER performance since the two optical channels had different baud rates, and thus was not considered herein.

Fig. 3(a) shows the BER performance for S_o, S_d and S_w as a function of $OSNR_o$. Under the optimal SIR, the required OSNR for S_o was 18.8 and 19.3 dB at BER of 3.8×10^{-3}, for both Case 1 and Case 2, respectively. It could be observed that the effect of the relative polarization rotation was not significant. Since the two channels had different baud rates, misaligned timing resulted in high interference amplitude. The fact of having two optical channels, S_d and S_w centering at different wavelengths, is another reason leading to the relatively high OSNR requirement. As shown in Fig. 3(b), the optimal SIR increased with respect to $OSNR_o$ in both two cases. In Case 2, about 0.4 to 0.7 dB larger optimal SIR than that of Case 1 was required.

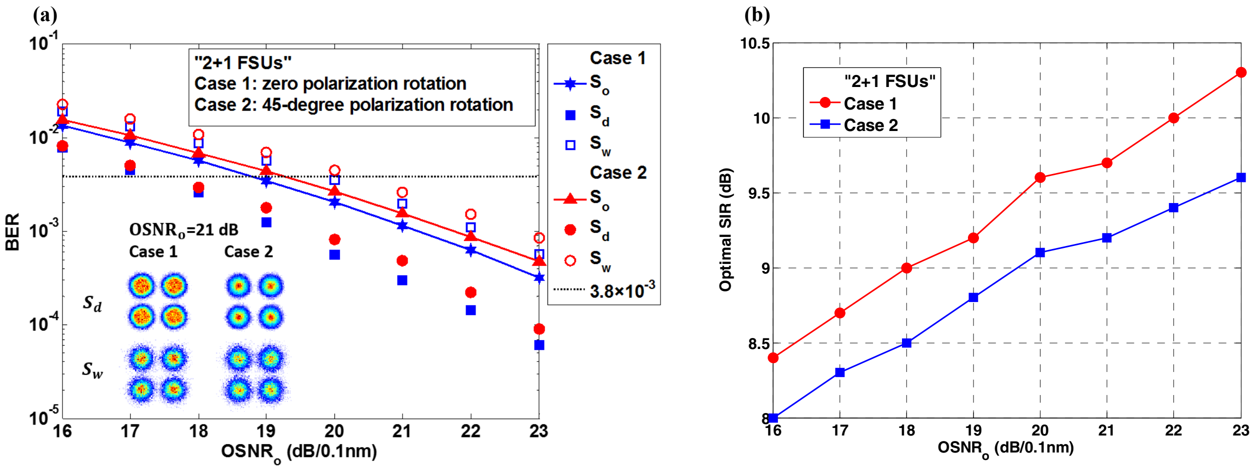

Fig. 3. Simulation results for "2+1 FSUs": (a) the calculated BERs for S_o, S_d and S_w as a function of $OSNR_o$ for Case 1 and Case 2, calculated BER for Nyquist PM-16QAM case for reference, the constellations diagrams for two cases under the $OSNR_o$ 21 dB; (b) the optimal SIR as a function of $OSNR_o$ for Case 1 and Case 2.

IV. SUMMARY

We investigate a cost-effective and simple complete spectral overlap method so as to resolve the possible wavelength contention issue during wavelength routing of two independent bandwidth variable Nyquist-PM-QPSK channels. The two channels can be recovered individually, via proper digital signal processing techniques. The performance of the overlapped system has been characterized, via numerical simulations, under the influence of time offset and relative polarization rotation between the two channels. The power control strategy for two optical channels has also been proposed. This work was partially supported by a research grant from Hong Kong Research Grants Council (Project No. 14200614).

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