Reconfigurable Optical Inter-Channel Interference Compensation of 20/25-Gbaud QPSK Signals using Nonlinear Wave Mixing

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Abstract *A reconfigurable optical inter-channel interference compensation method without channel spacing estimation and relative time delay calibration is proposed for a high density multi-carrier transmission system. Experiments demonstrate the effectiveness for both 20/25-Gbaud dual-carrier QPSK systems with different channel spacing conditions.*

Introduction

A major advance in optical communications over the past several years has been the use of digital signal processing in coherent receivers to compensate inter-channel interference (ICI)[1-4]. A common approach is to use multiple-input-multiple-output (MIMO) algorithms after photodetection[1-4], which typically requires receiving all data channels that contribute to ICI.

Motivations for implementing optical "MIMO-like" ICI compensation might be: (i) the potential for high-speed operation, (ii) the avoidance of pre-possessing of channel spacing estimation[1] or relative time delay calibration[4], (iii) no need of optoelectronic conversion, (iv) the possibility of optically adding/dropping the individual channel.

Previously, it has been reported of using optical signal processing to compensate intra-channel inter-symbol interference (ISI)[5]. However, there has been little reported in utilizing neighbouring channels to compensate ICI using optical signal processing.

In this paper, a reconfigurable "MIMO-like" optical ICI compensation method using nonlinear wave mixing is proposed. This method is experimentally demonstrated in both 20/25-Gbaud dual-carrier QPSK systems with different channel spacing conditions. The improved signal constellation and Q factor confirm the effectiveness of the proposed method.

Concept

Figure 1 illustrates the concept of the proposed optical ICI compensation. The inputs are two partially overlapping data channels, *i.e.*, S_1 and S_2 with certain channel spacing. The constellations are degraded by ICI as shown in Fig. 1. S_1 and S_2, along with a continuous wave (CW) pump (P), are sent into a periodically poled lithium niobate (PPLN) waveguide to generate the conjugate copies, *i.e.*, S_1^* and S_2^*, via cascaded processes of second-harmonic-generation (SHG) and difference-frequency-generation (DFG). An optical programmable filter is then used to select the desired channels

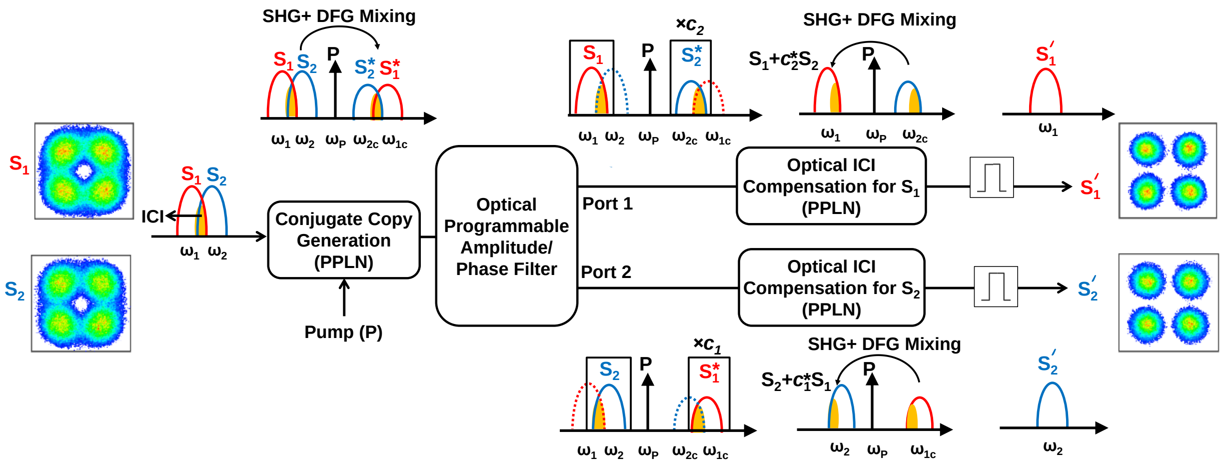

Fig. 1: Conceptual diagram of the proposed optical inter-channel interference (ICI) compensation method

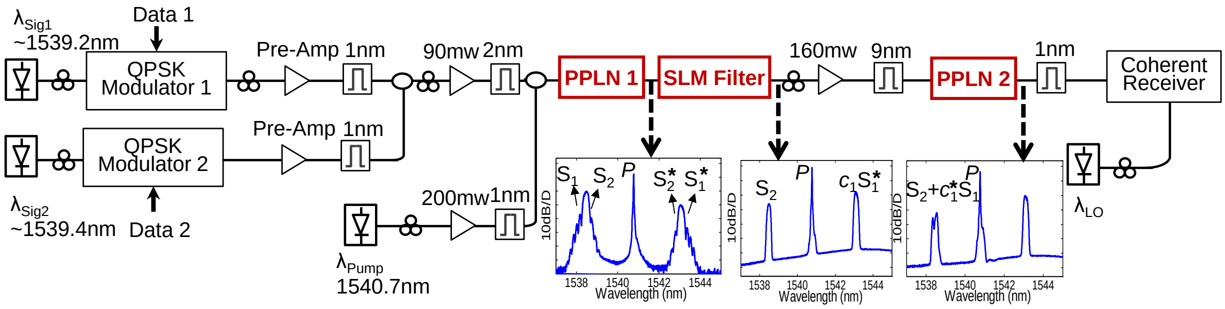

Fig. 2: Experimental setup and optical channel spectra

and adjust their amplitudes and phases by multiplying the complex coefficients c_i(i=1, 2) in Fig. 1. At Port 1, channels S_1 and S_2^* are selected; separately, S_2^* is multiplied by a coefficient c_2. It is notable that the original CW pump is preserved. For ICI compensation on channel S_1, S_2 should be multiplied by a particular coefficient and added on S_1. This operation is realized by sending S_1, $c_2S_2^*$ and the original pump into another PPLN waveguide. Because of the preservation of the original pump and cascaded SHG/DFG processes, the conjugate conversion of $c_2S_2^*$, which is $c_2^*S_2$, is added to channel S_1 with the exact channel spacing. Therefore, channel spacing estimation is not required. Furthermore, because the operation on S_1 and S_2^* is kept to a single path, relative time delay calibration is also not necessary. By adjusting c_2, the ICI compensation can be achieved on channel S_1. At Port 2, a similar operation is carried out for ICI compensation on channel S_2. The improved qualities of the output channels S_1', S_2' are shown in Fig. 1. The entire process is analogous to a 2×2 MIMO processing system with 1-tap length.

Experimental Setup

Figure 2 shows the experimental setup of optical ICI compensation for dual-carrier QPSK systems. At the transmitter, the frequencies of two separate lasers are tuned to have a desired channel spacing Δf. Then, the lasers are modulated by separate NRZ-QPSK modulators with uncorrelated data streams. A polarization controller (PC) is placed right after Modulator 1 in Fig. 1, which aligns the polarizations of two channels to maximize ICI. Pre-amplifiers ensure the same optical power for the two channels, which are then combined by a 50/50 coupler to generate the partially overlapping spectrum.

For optical ICI compensation, the two channels are amplified and sent to a PPLN waveguide (PPLN 1), along with an amplified CW pump (P) at the wavelength of 1540.7nm, to generate conjugate copies of the original channels. The quasi-phase matching (QPM) wavelength of PPLN 1 is temperature-tuned to the CW pump wavelength. The output spectrum is shown in Fig. 2, where due to the high density channel spacing, only a partial spectrum of channels is visible. Then, all the components, including the pump, are sent into a spatial light modulator (SLM) filter, based on liquid crystal on silicon (LCoS) technology, for channel selection and amplitude/phase adjustment. For the ICI compensation on channel S_2, the outputs of the SLM filter are S_2 and $c_1S_1^*$, where c_1 is the result of the amplitude/phase adjustment. The original pump is also preserved at the SLM filter output. The resulting output spectrum is shown in Fig. 2. Then, S_2, $c_1S_1^*$ and pump P are amplified and sent into the second PPLN waveguide (PPLN 2) with the same QPM wavelength of PPLN 1. In PPLN 2, $c_1S_1^*$ is converted back to $c_1^*S_1$ and added on channel S_2 with the exact channel spacing Δf. The spectrum after PPLN 2 is shown

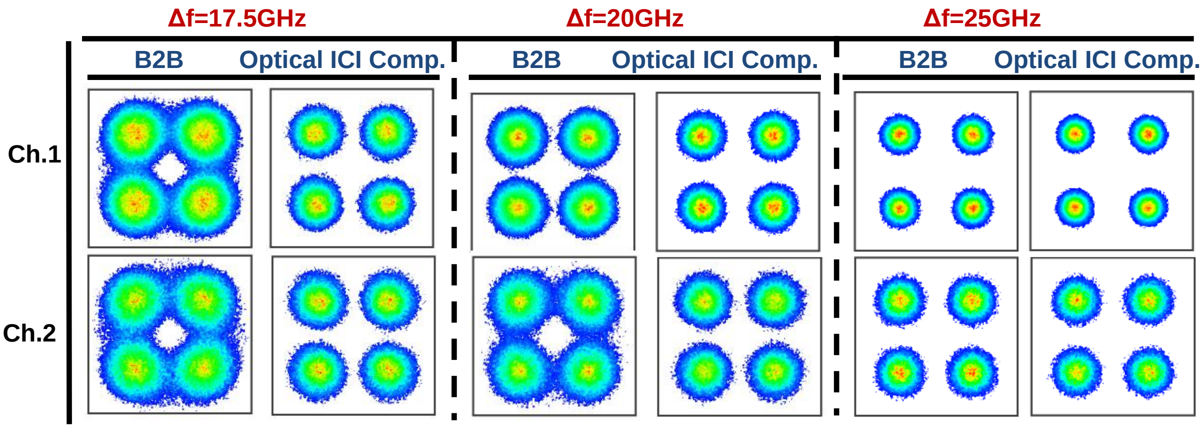

Fig. 3: Experimentally measured signal constellations in a 20-Gbaud dual-carrier QPSK system at different channel spacing Δf

in Fig. 2. Finally, the compensated channel is filtered and sent to one coherent receiver for detection and bit error counting.

Results and Discussions

The system performance is first assessed using two 20-Gbaud QPSK signals. Three channel spacings Δf of 17.5GHz, 20GHz and 25GHz are examined. To highlight ICI, there is no spectrum shaping or filtering at the transmitter. The bandwidth of the optical receiver is 25GHz. Compared to a back-to-back (B2B) configuration, Fig. 3 shows the constellation quality improvement for both channels with the proposed method. The OSNRs are 21.8dB, 19.7dB and 16.5dB for Δf of 17.5GHz, 20GHz and 25GHz respectively. The proposed method has more effect for high density channel allocation (17.5/20GHz), while for larger channel spacing (25GHz), there is negligible benefit from the method due to small ICI. It is notable that since the two data streams are from separate pattern generators and are modulated by different optical modulators, the two channels have different constellation qualities in Fig. 3.

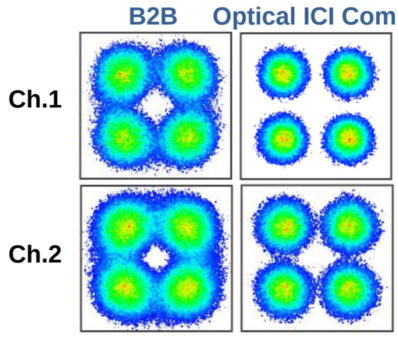

Fig. 4: Experimentally measured signal constellations in a 25-Gbaud dual-carrier QPSK system with Δf of 22.5GHz

To show the baud rate tunability of this method, the system is changed to 25-Gbaud and the channel spacing Δf is tuned to 22.5GHz. The bandwidth of the optical receiver is set to 30GHz and OSNR is 21.8dB. Fig. 4 shows the effectiveness of the method in this scenario.

Figure 5 shows the curve of Q factor versus OSNR in the 20-GBaud system with channel spacing of 17.5GHz and 20GHz. As depicted, the proposed optical ICI compensation brings improvement over a B2B system. An OSNR gain of more than 6dB is achieved when the Q factor reaches FEC threshold of 8.5dB. Fig. 6 shows a similar result for the 25-GBaud system. Also note that, due to the increased baud rate, the overall Q factor drops. However, the system improvement is maintained.

Finally, Q factor dependency on the phase of the complex tap coefficients c_i (i =1, 2) is investigated. Fig. 7 shows there is an optimal phase giving the highest Q factor.

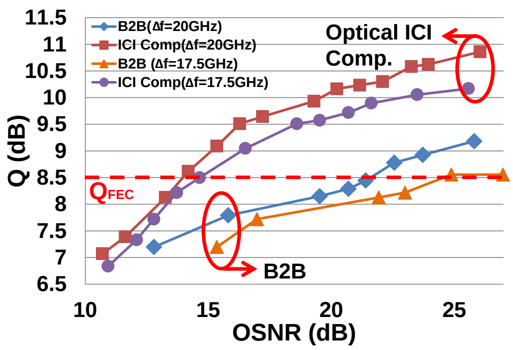

Fig. 5: Q vs OSNR in a 20-Gbaud dual-carrier QPSK system

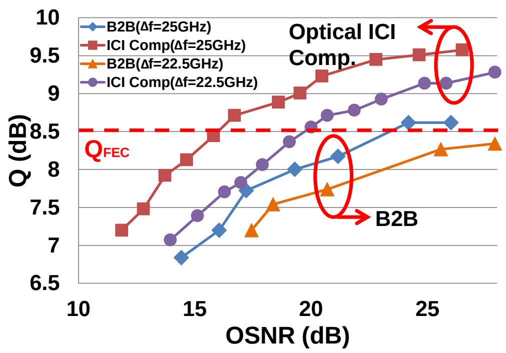

Fig. 6: Q vs OSNR in a 25-Gbaud dual-carrier QPSK system

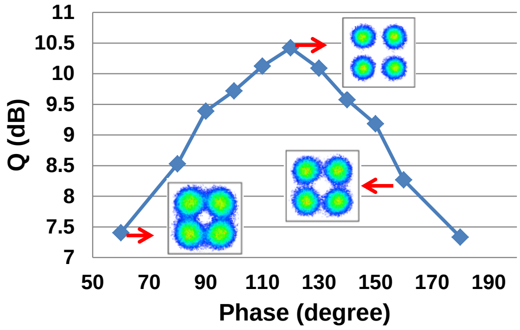

Fig. 7: Q factor with changing phase of the tap coefficient

Acknowledgements

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References

[1] M. Sato et al., “Frequency Diversity MIMO Detection for DP- QAM Transmission,” J. Lightwave Technol., Vol. **33**, no. 7, p. 1388 (2015)

[2] F. Hamaoka et al., “Super High Density Multi-carrier Transmission System by MIMO Processing,” Proc. ECOC, Mo.3.5.4, Cannes (2014).

[3] N. Kaneda et al., “Frequency Diversity MIMO Detection for Coherent Optical Transmission,” Proc. ECOC, Th.2.C.1, London (2013).

[4] J. Pan et al., “Fractionally-Spaced Frequency Domain Linear Crosstalk Cancellation with Spectral Alignment Techniques for Coherent Superchannel Optical Systems,” Proc. OFC, OW4B.6, Anaheim (2013).

[5] P. Winzer et al., “107-gb/s optical signal generation using electronic time-division multiplexing,” J. Lightwave Technol., Vol. **24**, no. 8, p. 3107 (2006).