112-Gb/s DP-QPSK Transmission over 7,860-km DMF using Phase-Conjugated Copy and Digital Phase-Sensitive Boosting with Enhanced Noise and Nonlinearity Tolerance

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Abstract: We demonstrate a phase-sensitive boosting technique for extending the reach of 112-Gb/s DP-QPSK. We transmit the signal alongside a phase-conjugated idler. Nonlinearity is partially mitigated by detecting them jointly and summing them with phase conjugation.

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1. Introduction

Coherent detection and digital signal processing (DSP) have been the enabling technologies for high spectral efficiency long-haul transmission using advanced modulation formats [1]. Since linear impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) can be compensated by DSP [2], optical noise accumulation and nonlinear impairment are the limiting factors to system reach. To increase optical signal-to-noise ratio (OSNR) and to mitigate nonlinear phase noise, optical 2R regeneration using degenerate and non-degenerate phase sensitive amplifiers (PSA) have been proposed [3-5]. However, due to stringent requirements in aligning the phase of the pump and signal at the PSA, both approaches require high-quality carrier regeneration and optical phase locking, which dramatically increases system complexity.

In this paper, we propose and demonstrate a hybrid optical/digital scheme based on optical phase conjugation and DSP to improve OSNR and nonlinear tolerance in long-haul transmission systems. We use four-wave mixing (FWM) to generate an idler which is a phase-conjugate copy of the original optical signal. The signal and phase-conjugated idler are transmitted together and detected separately using two coherent receivers. In the DSP module, the idler is conjugated digitally and summed with the signal with proper phase alignment. This enables suppression of nonlinear phase shifts in both signal and idler components by phase-sensitive boosting (PSB) for a dispersion-managed link. Moreover, by combining the signal and idler components, the SNR per symbol is enhanced by 3 dB in principle. Since coherent receivers can digitally compensate frequency offset and phase noise between signals and local oscillator (LO) lasers, it relaxes the requirement of complicated all-optical carrier recovery techniques used in most PSA demonstrations. The proposed hybrid optical/digital scheme is transparent to modulation format and optical fiber types.

2. Principles

Fig. 1 shows the setup of our proposed optical/digital PSB scheme applied to a dual-polarization quadrature phase-shift-keying (DP-QPSK) system. The output of the transmitter is a 28-Gbaud DP-QPSK signal. In the phase-conjugated copier, we combine the DP-QPSK signal with a high-power continuous-wave (CW) pump whose polarization is at 45° relative to the modulated polarizations of the signal. A polarization beam splitter (PBS) aligned with the axes of the signal is used to de-multiplex the polarization components and project the pump equally onto the two axes. In each branch, a highly nonlinear fiber (HNLF) is used to generate a phase-conjugated idler via FWM. Assuming the signal and pump phases are $\theta_s$ and $\theta_p$, respectively, the idler phase $\theta_i$ satisfies the phase relation $\theta_s + \theta_i = 2\theta_p$. Given that we can define $\theta_p = 0$ for the pump phase, the idler phase $\theta_i = -\theta_s$ is a phase-conjugate copy of the signal. We use a PBS to recombine the two polarization components of the signal and idler. A bandpass filter is used to suppress all wanted frequencies except for the signal and idler, which are then amplified and transmitted together.

During transmission, both the signal and idler experience self-phase modulation (SPM) and cross-phase modulation (XPM) proportional to the total power in the fiber. Provided the signal and idler are relatively close in wavelength so they experience near-identical CD, the nonlinear phase-shift $\theta_{NL}$ experienced by both the signal and idler are the same. At the receiver, we can write the signal and idler phases as $\theta_s + \theta_{NSL}$ and $\theta_i + \theta_{NL}$, respectively. We use two coherent receivers to downconvert the signal and idler to electrical baseband. CD, PMD, frequency offset and laser phase noise are compensated in DSP. Assuming phase error due to carrier recovery is negligible, we can conjugate the phase of the idler symbols to obtain $-\theta_i - \theta_{NL}$. The signal and conjugated idler component are then
digitally summed with proper timing and phase alignment to obtain \( e^{i\theta_\text{NL} - i\theta_\text{NL}} = 2\cos\theta_\text{NL} \cdot e^{i\theta} \). It is observed that nonlinear phase-shift results only in amplitude fluctuation of magnitude \( 2\cos\theta_\text{NL} \). As the symbols are encoded in phase, the information in \( \theta \) is much less affected by the amplitude fluctuation, as shown by the inset in Fig. 1.

3. Experiment

We experimentally demonstrate the proposed scheme using a fiber recirculating loop comprising 8x60-km spans of dispersion-managed fiber (DMF), as shown in Fig. 2. At the transmitter, an external cavity laser at 1550.12 nm (\( \lambda_2 \)) is modulated with 28-Gbaud QPSK symbols using an I/Q modulator. The I and Q signals are generated from a 4:1 electrical multiplexing of a 7-Gb/s 2**15−1** PRBS pattern. The 56-Gb/s QPSK signal is coupled with a 26 dBm CW pump at 1550.52 nm and launched into a two-meter Bi-doped HNLF, which generates a phase-conjugated idler at 1550.92 nm (\( \lambda_4 \)). An optical interleaver and a wavelength selective switch (WSS) are used to remove residual pump and to equalize the signal and idler powers. The signal (\( \lambda_2 \)) and idler (\( \lambda_4 \)) form the even channels in this experiment. For the odd channels, we passively combine three lasers and modulate them with 28-Gbaud QPSK by the same technique using a separate 4:1 electrical multiplexer with decorrelated 2**15−1** PRBS inputs resulting in different patterns compared to the even channels. Polarization multiplexing is performed separately on even and odd channels by splitting their signals, delaying one copy by 224 symbols, and rotating them to the orthogonal polarization followed by polarization combining. The odd- and even-channels are then combined with a 50/100-GHz optical interleaver and launched into the fiber re-circulating loop together with eighty-five CW lasers. The transmitted spectrum is shown in Fig. 2. The loop has 8x60-km spans of dispersion managed fiber (DMF) with an inline EDFA after each span. A mechanical transmitter switch and loop switch control signal loading and circulation.

At the receiver, the five modulated channels (\( \lambda_1 - \lambda_5 \)) are extracted by a WSS and amplified by an EDFA, followed by a splitter and two synchronized coherent receivers. In each coherent receiver, the signal (and idler) are downconverted to electrical baseband by combining them with LO lasers centered at the appropriate frequencies using polarization-diversity 90° optical hybrids followed by balanced photodetectors. The electrical signals are then sampled by two synchronized quad-channel digitizing oscilloscope at 40-GSa/s and 16-GHz bandwidth. The digitized signal and idler are processed with offline DSP, where we use a frequency-domain equalizer (FDE) to compensate CD, and an adaptive time-domain equalizer (TDE) to compensate other linear impairments. After frequency offset compensation and carrier recovery, the equalized symbols in the idler channel are phase-conjugated...
and summed with the signal symbols. The resulting symbol is then detected. The inset in Fig. 2 shows the constellations of the signal symbols before and after phase-sensitive boosting.

We firstly measured the back-to-back (B2B) performance without nonlinear impairment. Odd channels are turned off with only the signal and idler channels remaining. The signal Q-factor, derived from BER measurement, is monitored when amplified spontaneous emission (ASE) noise is added at the receiver. Fig. 3(a) shows the Q vs. OSNR results. It is observed that phase-sensitive boosting improves the Q-factor by 2 to 2.4 dB, due to doubling in signal amplitude. At very high OSNR, the Q-factor improvement is somewhat less due to signal distortion by the transmitter which cannot be removed by digital phase-sensitive boosting.

At 4,800 km (10 loops), we swept the launch power per channel (signal, idler and three odd-channels) from −9 dBm to +1 dBm. To show that the digital phase-sensitive boosting (PSB) scheme does not only improve sensitivity by doubling signal amplitude, but also suppresses nonlinearity, we compare the performance of PSB with direct signal copying (DSC) where we replace the idler at 1550.92 nm with a duplicate of the original signal (remove the HNLF and the pump laser in Fig. 2 and insert a laser at λ4 before the I/Q modulator). For DSC, the equalized symbols in λ2 and λ4 are summed without phase conjugation. The experimental results for PSB and DSC are shown in Fig. 3(b). It is observed that using PSB increases the optimum launch power from −5.2 dBm to −4.2 dBm, and the maximum Q-factor is increased by ~0.7 dB. Our results confirmed that the phase conjugation property of the idler contributes to mitigation of nonlinear phase noise in addition to amplitude doubling. Compared with conventional transmission without DSC/PSB, the PSB scheme achieves an improvement of 2.4 dB at maximum Q.

![Fig. 3](OTu2B.5.pdf)

Fig. 3 (a) Comparison of B2B performance with and without digital PSB; (b) Measured Q-factors for digital PSB scheme, DSC scheme and original signal at different launch power; (c) Measured Q-factors versus transmission distance for digital PSB scheme, DSC scheme and original signal at different launch power. PSB: phase-sensitive boosting, DSC: direct signal copy.

Finally, with the launch power set to the optimal values (~4.2 dBm for PSB and ~5.2 dBm for DSC), the number of loops is swept from 2 to 16 to determine system reach at a hard-decision forward error-correction (HD-FEC) limit of 8.5 dB. The results in Fig. 3(c) show that DSC increases system reach from 10 loops (4,800 km) to 14 loops (6,720 km); while PSB increases further to 16 loops (7,680 km) assisted, representing a 60% improvement over conventional transmission.

4. Conclusion

We demonstrated a novel phase-sensitive boosting approach to improve noise and nonlinearity tolerance in long-haul transmission. The approach uses FWM to generate a phase-conjugated idler, which is transmitted together with the signal. At the receiver, the signal and idler are jointly detected, and the phases of the idler symbols are conjugated and summed with the signal symbols to suppress nonlinear phase distortion. The proposed digital phase-sensitive boosting scheme is independent on modulation format and does not require an optical phase-lock loop to achieving phase matching required by conventional phase-sensitive amplifiers. Our experimental result shows that the PSB scheme achieves a 2.4-dB Q-improvement over conventional transmission after 4,800 km of DMF, while system reach using HD-FEC can be increased by 60% from 4,800 km to 7,680 km.

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References