Demonstration of digital phase-sensitive boosting to extend signal reach for long-haul WDM systems using optical phase-conjugated copy

Yue Tian,1,2,* Yue-Kai Huang,1 Shaoliang Zhang,1 Paul R. Prucnal,2 and Ting Wang1

1NEC Laboratories America, Inc., Princeton, NJ 08540, USA
2Lightwave Communication Research Laboratory, Department of Electrical Engineering, Princeton University, Princeton, NJ 08544 USA
*yuetian@princeton.edu

Abstract: We demonstrate a hybrid optical/digital phase-sensitive boosting (PSB) technique for long-haul wavelength division multiplexing (WDM) transmission systems. The approach uses four-wave mixing (FWM) to generate a phase-conjugated idler alongside the original 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 noise and nonlinear phase distortion. The proposed hybrid PSB scheme is independent of modulation format and does not require an optical phase-locked loop to achieve phase matching required by conventional phase-sensitive amplifiers. Our simulation and experimental results of 112-Gb/s dual-polarization quadrature phase-shift-keying (DP-QPSK) transmission confirmed the principle of the PSB scheme, attaining a Q-factor improvement of 2.4 dB over conventional single-channel transmission after 4,800 km of dispersion-managed fiber (DMF) link at the expense of 50% reduction in spectral efficiency and extending the system reach by 60% to 7,680 km.

©2013 Optical Society of America

OCIS codes: (060.1660) Coherent communications; (060.2360) Fiber optics links and subsystems; (070.4340) Nonlinear optical signal processing.

References and links


1. Introduction

Coherent detection and digital signal processing (DSP) have been the enabling technologies for improving spectral efficiency in long-haul wavelength-division multiplexing (WDM) transmission using polarization multiplexed multi-dimensional modulation formats [1,2]. Since linear impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) can be compensated by DSP [3], accumulation of amplified spontaneous emission (ASE) noise from inline erbium-doped fiber amplifiers (EDFAs) and fiber nonlinear impairment are the limiting factors to system reach. Fiber nonlinear impairments can be categorized into single-channel effect created by self-phase modulation (SPM) and effects due to WDM operation such as four-wave mixing (FWM) and cross-phase modulation (XPM). It has been reported that fiber dispersion in dispersion-unmanaged link can substantially reduce SPM-induced nonlinear penalty [4,5]. In dispersion-managed transmission, however, SPM still imposes a severe limitation on signal launch power and therefore the transmission distance [4–6]. To increase the nonlinearity tolerance of coherent systems, several optical and electronic approaches have been reported. Electronic pre-compensation [7–9], post-compensation [10–13] and the combination of both [14,15] are used to pre-distort and correct the signal phase according to the signal power variation, which are
subjected to the accuracy of the link nonlinearity estimation. Digital back-propagation is attractive for its flexibility and performance [16]. However it requires a priori knowledge of the system’s dispersion map and optical power map with extensive computational resource. Mid-span phase conjugation employs optical [17] or electrical devices [18] to conjugate signal phase at the middle point of the transmission link in order to achieve cancellation of the nonlinear phase shifts from the two halves. To obtain meaningful performance improvement using the scheme, however, not only the whole link needs to be homogeneous, but also the signal power evolution profile before and after mid-span phase conjugation needs to have resemblance as mirrored images. Coherent superposition of several signal copies in a multi-core fiber is also reported to effectively improve the quality of phase-modulated signals [19]. But it requires space-division multiplexing configuration, which cannot be implemented in a standard single-mode fiber.

Optical 2R regeneration using frequency-degenerate and non-degenerate phase sensitive amplifiers (PSA) [20–25] has been proposed to increase optical signal-to-noise ratio (OSNR) and mitigate the nonlinear distortion. In degenerate PSAs [20–22], two optical pumps symmetrical (or identical) to the phase-modulated signal in frequency are used to generate an idler with identical frequency as signal via FWM, and through coherent sum of the signal and idler, the signal phase is stabilized with respect to the pumps. Non-degenerate PSAs [23–25], on the other hand, employ FWM of single pump with signal and idler at different frequencies to stabilize the sum of signal and idler phases. However, degenerate PSAs are sensitive to the modulation format and can only be applied on single wavelength for a fixed pump configuration, which limits their application in multi-phase modulation formats and WDM systems. Moreover, due to stringent requirements in aligning the phase of the pump and signal at the PSA, both degenerate and non-degenerate PSAs require high-quality carrier regeneration and optical phase locking, which dramatically increases system complexity. It is worth noting that to maintain a system noise figure (NF) lower than the traditional long-haul systems and improve the performance to the ideal value of 6-dB gain [23], all the in-line amplifiers have to be replaced by PSAs, otherwise the overall NF will be dominated by the phase-insensitive amplifiers in the system.

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, by both simulation and experiment. FWM is adopted 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 symbols are conjugated digitally and summed with the signal symbols with proper phase alignment, thereby suppressing the nonlinear phase shifts contributed from both signal and idler components by phase-sensitive boosting (PSB). Moreover, by combining the signal and idler components, the SNR per symbol can be enhanced digitally by 3 dB at linear regime in principle. The proposed hybrid optical/digital scheme is transparent to modulation format and optical fiber types, and does not require optical phase locking or carrier regeneration thanks to digital frequency offset compensation in DSP. Obviously the phase-conjugate copy consumes additional bandwidth other than the original optical signal, so the PSB scheme trades the spectral efficiency for longer system reach. Therefore it is much more suitable for systems which demand ultra-long system reach and high signal quality but with less requirement on spectral efficiency. It can also be applied at a network node where bandwidth would be available for implementing PSB due to the reduced number of output channels/wavelengths after the traffic divergence (i.e. branching unit in a submarine network).

2. Principles

Figure 1 shows the setup of our proposed optical/digital PSB scheme applied to a dual-polarization quadrature phase-shift-keying (DP-QPSK) system. To generate the phase-conjugated copy, we combine the DP-QPSK signal with a high-power continuous-wave (CW) pump whose polarization is positioned at 45° relative to both orthogonal polarizations of the
polarization-multiplexed signal. A polarization beam splitter (PBS) aligned with the signal polarization axes de-multiplexes the polarization components and projects 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:

\[
\theta_s + \theta_i = 2 \theta_p. \tag{1}
\]

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. A second PBS recombines the two polarization components of the signal and idler. An optical filter then rejects all unwanted 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). Provided the signal and idler are relatively close in wavelength so they experience near-identical CD, the nonlinear phase-shift \( \theta_{NL} \) by both the signal and idler are near-identical. At the receiver, the signal and idler phases can be expressed as \( \theta_s + \theta_{NL} \) and \( \theta_i + \theta_{NL} \) respectively. Two coherent receivers are used to downconvert the signal and idler to electrical baseband. CD, PMD, frequency offset and laser phase noise are compensated in DSP. Assuming that phase error due to carrier recovery is negligible, we can conjugate the phase of the idler symbols digitally and obtain \( -\theta_i - \theta_{NL} \). The signal and conjugated idler component are then digitally summed up with proper timing and phase alignment to obtain:

\[
e^{\theta_s+\theta_{NL}} + e^{-\theta_i-\theta_{NL}} = e^{\theta_s+\theta_{NL}} + e^{\theta_i-\theta_{NL}} = 2 \cos \theta_{NL} \cdot e^{\theta_i}. \tag{2}
\]

It is observed that nonlinear phase-shift results only in amplitude fluctuation of magnitude \( 2\cos \theta_{NL} \). Due to the positions of the nearest neighboring points in the QPSK constellation, the information in \( \theta_s \) is much less affected by the amplitude fluctuation in the radial direction, as shown by the inset in Fig. 1. Note that, by digitally compensating the frequency offset and phase noise between signals and local oscillator (LO) lasers, the use of complicated all-optical carrier recovery techniques used in most PSA demonstrations [20–25], are no longer required.

In addition to single channel application, the proposed PSB scheme can be extended to WDM systems. Similarly to the setup in Fig. 1, multiple wavelength channels can share the same optical pump and locate on one side of the pump. Then after FWM, the idlers will be generated on the other side of the optical pump, in reverse order in spectrum compared with signals. To keep the validity of near-identical CD between each pair of signal and idler, dispersion-managed links are preferred for WDM application.

![Experimental setup of digital phase-sensitive boosting. EDFA: erbium-doped fiber amplifier, HNLF: highly nonlinear fiber, PBS: polarization beam splitter.](image)

### 3. Simulations

As a proof of concept, we conducted simulation of the proposed digital PSB scheme using VPItransmissionMaker™ based on the system setup in Fig. 1. A 112-Gb/s DP-QPSK signal, modulated by pseudo-random binary sequence (PRBS) length of \( 2^{15} - 1 \) at four parallel lanes, is launched into the optical conjugate copier. The signal wavelength and pump wavelength...
are 1550.1 nm and 1549.3 nm respectively, at 100-GHz spacing. Pump power is set to 1 W to generate an idler at 1548.5 nm with the same power level as the original signal. To study the performance of the proposed PSB scheme on ultra-low-loss fiber transmission for future link installation, ultra-low-loss fiber link and parameters are used in the simulation. The transmission link consists of multiple spans of 60-km ultra-low-loss fiber with EDFAs at 5-dB NF to compensate span loss. The fiber attenuation and nonlinear coefficient ($\gamma$) are 0.161 dB/km and 0.731 $W^{-1}/km$. The channel launch power is maintained at $-1$ dBm for both signal and idler. After transmission, the signal and idler components are separately detected by two coherent receivers with LO set at 1550.1 nm and 1548.5 nm. Then the digitized signal and idler are processed with 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 recombined with the signal symbols. The resulting symbol is then analyzed to obtain the signal Q-factor. We test the proposed PSB scheme in both dispersion-managed and dispersion-unmanaged links. In dispersion-managed link, dispersion compensation fiber (DCF) is deployed at the end of each span to completely compensate the span dispersion, while in dispersion-unmanaged link the accumulated dispersion in the whole link is compensated by DSP at the receiver end. The simulation results are plotted in Fig. 2.

Fig. 2. Q-factor improvement by digital PSB in dispersion-managed link (a) and dispersion-unmanaged link (b); Q-factor versus channel power comparison of PSB scheme, DSC scheme and original signal in CD compensated link (c) and CD uncompensated link (d).

As shown in Fig. 2(a) and Fig. 2(b), for both dispersion-managed and dispersion-unmanaged links with $-1$-dBm channel power for both signal and idler, the proposed digital PSB based transmission scheme can improve Q-factor by 2.5 dB after 6300-km transmission, due to its enhanced noise and nonlinearity tolerance. At shorter transmission distance, the nonlinear effect is relatively weak, so the dominant distortions are due to the noises from transmitters and receivers, which cannot be corrected by PSB. Therefore the Q-improvement over the original signal increases with the transmission distance because of less received OSNR and more nonlinear distortion. To verify that the digital PSB scheme does suppress nonlinear distortion on top of improving sensitivity by doubling signal amplitude, we...
compare the performance of PSB with a direct signal-copying (DSC) scheme, which is similar to the coherent superposition scheme in [19]. To create the DSC signals, we remove the phase-conjugate copier in Fig. 1, and then couple and modulate two laser outputs at 1550.1 nm and 1548.5 nm together using the same DP-QPSK transmitter. As a result, both signals will carry the same data for transmission through the link. At the receiver side, after digital equalization in DSP, the two signals are directly summed up without phase conjugation. Therefore, the DSC scheme takes advantage of doubled signal amplitude as same as the PSB scheme, but without the suppression of phase noise distortion. By monitoring the Q-factor while sweeping the channel power, the nonlinear power tolerance has been enhanced by about 1-dB in PSB over DSC in both dispersion-managed and dispersion-unmanaged links, as illustrated in Fig. 2(c) and Fig. 2(d). The maximum Q-factor is enhanced by 0.7 dB in dispersion-managed link (Fig. 2(c)) and by 0.5 dB in dispersion-unmanaged link (Fig. 2(d)). The performance difference between two types of links is likely due to the fact that dispersion-unmanaged links are intrinsically more tolerant to nonlinear distortion than dispersion-managed links [4,5].

4. Experimental demonstration

We experimentally demonstrate the proposed scheme using a fiber recirculating loop comprising 8 × 60-km spans of dispersion-managed fiber (DMF), as shown in Fig. 2. At the transmitter, an external cavity laser at 1550.12 nm (λ2) 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 215−1 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 Bismuth oxide-based nonlinear fiber (Bi-NLF), which generates a phase-conjugated idler at 1550.92 nm (λ4). The two-meter Bi-NLF has an attenuation of 5.2 dB, a nonlinear coefficient of 1050 W−1/km, a dispersion of −250 ps/nm/km at 1550 nm and a dispersion slope less than 0.5 ps/nm2/km across C-band [26]. Thanks to the high stimulated-Brillouin-scattering (SBS) threshold (higher than 30 dBm) [27], a FWM efficiency of −11 dB is achieved without a phase modulation on the CW pump for SBS suppression. An optical interleaver and a wavelength selective switch (WSS) are used to remove residual pump and to equalize the signal and idler powers. After equalization the OSNR of signal and idler is higher than 40 dB. The signal (λ2) and idler (λ4) form the even channels in this experiment, as shown in Fig. 3. For the odd channels, we passively combine three lasers and modulate them with 28-Gbaud QPSK by the same technique using another separate 4:1 electrical multiplexer with decorrelated 215−1 PRBS.
inputs resulting in different patterns from 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, as illustrated by the spectrum in Fig. 4(a). The loop has $8 \times 60$-km spans of dispersion-managed fiber (DMF) with an inline EDFA after each span. Each span is composed of a 40-km positive dispersion (19 ps/nm/km) fiber with 0.2 dB/km loss and effective area of 93 $\mu m^2$, and another 20-km negative dispersion ($-38$ ps/nm/km) fiber with 0.245 dB/km loss and effective area of 24.5 $\mu m^2$. The EDFA output power is fixed at 16 dBm.

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. Then the same offline DSP as in the simulation is used to process the signal and idler. The bottom left inset in Fig. 3 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. Figure 4(b) 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 PSB.

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 PSB scheme does not only improve sensitivity by doubling signal amplitude, but also suppresses nonlinearity, we compare the performance of PSB with DSC scheme 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. 3 and insert a laser at λ4 before the I/Q modulator). For DSC, the equalized symbols in λ2 and λ4 are added up without phase conjugation. The experimental results for PSB and DSC are shown in Fig. 4(c). As can be seen, the PSB scheme is able to increase the optimum launch power from −5.2 dBm to −4.2 dBm, and the maximum Q-factor is improved 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 the optimum Q-factor.

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 for investigating the system reach at a hard-decision forward error-correction (HD-FEC) limit of 8.5 dB. The results in Fig. 4(d) 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. For multi-channel PSB, the optical pump should be placed at a proper wavelength, for instance one side of all signal channels, so that the newly generated idlers do not overlap with original signals. Since the signal channel power is relatively low, the nonlinear effect between signal channels is negligible during optical phase conjugation. Considering the different spectral spaces between signal channels and the optical pump, FWM efficiency may vary for each signal channel. Thus channel power equalization for idler channels might be needed after optical phase conjugation.

5. Conclusion

We demonstrated a novel phase-sensitive boosting scheme to improve noise and nonlinearity tolerance in long-haul WDM transmission. The scheme utilizes copropagation of a phase-conjugated idler signal, which is generated by FWM and transmitted together with the original signal. After transmission, the signal and idler are jointly detected by two coherent receivers, and the received idler symbols after adaptive TDE 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-locked loop to achieving phase matching required by conventional PSAs. The numerical simulations verify the principle of the proposed PSB scheme, and shows 2.5-dB Q-improvement after 6,300-km transmission for both dispersion-managed and dispersion-unmanaged links. Our experimental result shows that the PSB scheme achieves a 2.4-dB Q-improvement over conventional transmission after 4,800 km of DMF at the expense of 50% reduction in spectral efficiency, while system reach using HD-FEC can be increased by 60% to 7,680 km.

Acknowledgments

The authors gratefully acknowledge Dr. Fatih Yaman and Dr. Ezra Ip for inspiring and helpful discussions.