Optical and Digital Phase Conjugation Techniques for Fiber Nonlinearity Compensation

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Abstract **— We discuss recent progress on the use of optical and digital phase conjugation techniques for nonlinearity compensation in optical fiber links. We compare the achievable performance gain of phase conjugated twin wave applied in two polarization states and time segments with mid-link optical phase conjugation and digital back propagation. For multicarrier transmission scheme such as orthogonal frequency division multiplexing, two recently proposed schemes, namely phase-conjugated pilots and phase-conjugated subcarrier coding are reviewed.**

Index Terms **— Nonlinearity mitigation, coherent detection, coherent optical transmission.**

I. INTRODUCTION

The Kerr nonlinearity effect sets an upper bound (nonlinear Shannon limit) on the achievable data rate in optical fiber communications using traditional linear transmission techniques [1]. In recent years, extensive efforts in attempting to surpass the Kerr nonlinearity limit have been made through several nonlinearity compensation techniques and nonlinear transmission schemes [2]. Digital-back-propagation (DBP) [3] is an effective nonlinearity compensation method, which removes the inter signal nonlinear distortion by inverting the distorted signal at the receiver digitally. However, DBP has some serious challenges, limiting its success in practice so far. These include the digital signal processing (DSP) complexity, polarization mode dispersion effect and the carrier frequency uncertainty problem [4]. Mid-link optical phase conjugation (OPC) [5] has also attracted a lot of attention recently as a promising technique for communication above the Shannon limit. The OPC conjugates the signal phase after transmission in one segment of the link in order to achieve a net cancellation of the nonlinear phase shift using the nonlinearity generated in the second segment of the link. However, OPC imposes significant symmetry conditions with respect to the phase conjugator, and, significantly reduces the flexibility in an optical network.

Recently, a breakthrough fibre nonlinearity compensation technique called phase-conjugated twin wave (PCTW) has been proposed by X. Liu et al [6]. PCTW is a transponder-based technique that can be implemented with minimal additional optical hardware or DSP, providing a simple and effective solution in compensating optical fiber nonlinearity. However, PCTW halves the spectral efficiency (SE) because of the 50% overhead associated with the transmission of the signal's phase conjugated copy.

To address this problem, a dual PCTW scheme combined with quadrature pulse shaping was proposed for single carrier systems, yielding an improvement of ~1.2 dB [7] without any overhead. For coherent optical orthogonal frequency division multiplexing (CO-OFDM), a flexible nonlinear compensation scheme with the insertion of phase-conjugated pilots (PCP) was proposed in [8], allowing the overhead to be adjusted (up to 50%) according the required performance gain, up to a limit of ~4 dB. Furthermore, a frequency-domain coding technique called phase-conjugated subcarrier coding (PCSC) was also proposed recently in [9] for BPSK CO-OFDM transmission, yielding an improvement of ~1.5 dB without suffering any overhead.

In this paper, we compare the use of these phase conjugation concepts for fiber nonlinearity compensation. We investigate the achievable performance gain of temporally multiplexed PCTW with polarization multiplexed PCTW, OPC and DB for the first time. We also discuss the advantages and performance of phase conjugation techniques for CO-OFDM transmission.

II. PHASE CONJUGATION CONCEPT FOR FIBER NONLINEARITY MITIGATION

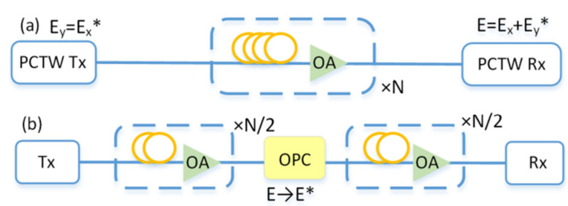

Fig. 1. Illustration of PCTW (a) and mid-link OPC (b) for fiber nonlinearity compensation, OA – optical amplifier, N – number of span.

The original concept of PCTW is illustrated in Fig. 1 (a), where the signal complex waveform and its phase-conjugate copy are simultaneously transmitted in x- and y-polarization states. If the dispersion map of the link is symmetrical, the nonlinear distortions on x-and y-polarizations are essentially anticorrelated, and thus, it can be effectively mitigated at the receiver through coherent superposition (CS) of the two copies. CS enhances the signal to noise ratio of the signal, since the signals add coherently, but random noise adds incoherently. It is also possible to "twin" a signal with its phase conjugated copy in any other orthogonal dimension rather than polarization state [10]. In particular, one may "twin" a signal and its phase conjugated copy in different time segments as:

$$E((2k+2)\cdot T) = E^*((2k+1)\cdot T)$$

Where k is an integer number and T is the symbol period. At the receiver, CS can be performed as:

$$E((2k+1)\cdot T) = \left(E((2k+1)\cdot T) + E^*((2k+2)\cdot T)\right)/2$$

We will show later that this scheme also mitigates effectively the nonlinear impairments. However, the overhead of PCTW scheme always remains 50% due to the phase conjugated copy redundancy.

To address this problem, a flexible scheme based on the transmission of PCP was proposed for CO-OFDM [2] and illustrated in Fig. 2. In this scheme, a portion of the OFDM subcarriers (up to 50%) are transmitted as PCPs of other subcarriers. At the receiver, the PCPs are used firstly to estimate the nonlinear distortion of their respective original subcarriers. The estimated nonlinear distortion then is used to mitigate the nonlinear impairments in other subcarriers close to the PCP. This mitigation scheme is effective thanks to the narrow OFDM subcarrier spacing (tens of MHz), which enhances the correlation between nonlinear phase shifts of neighbouring subcarriers compared to temporally correlated PCTW (tens of GHz bandwidth).

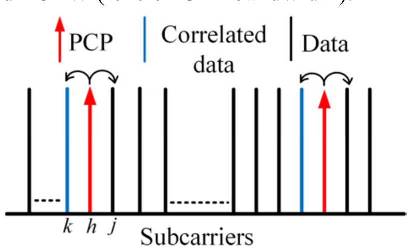

Fig. 2. Insertion of phase-conjugated pilots.

To avoid completely 50% loss in SE of PCTW scheme, a novel approach based on joint processing of two transmitted signal in x- and y-polarizations was proposed in [7]. In this scheme, two generated signals are mapped on two polarizations before PDM transmission as, $E_x=E_1+E_2$, $E_y=E_1^*-E_2^*$. At the receiver, the original signals can be recovered through inverse mapping as, $E_1=E_x+E_y^*$, $E_2=E_x-E_y^*$. As a result of this processing scheme, the nonlinear distortion of each signal is essentially coming from other signal and can be reduced by quadrature pulse shaping. Of course, the additional noise processes associated with this approach eliminate the SNR enhancement of PCTWs.

The concept of dual PCTW can be extended effectively to CO-OFDM in form of a frequency-domain coding scheme [9], termed as PCSC. In the PCSC scheme each pair of enamouring OFDM subcarriers after symbol mapping are encoded before being fed into the IFFT block to generate the time-domain signal as, $S_1(k) = S(k)+S(k+1)$, $S_1(k+1) = S^*(k)-S^*(k+1)$. At the receiver, before symbol demapping, the received information symbols in this subcarrier pair are decoded as, $R_1(k) = R(k)+R^*(k+1)$, $R_1(k+1) = R(k)-R^*(k+1)$.

Mid-link OPC (Fig. 1(b)), on the other hand, is an all optical technique which provides compensation of both intra and inter channel nonlinear effect if the power profile along the link is symmetrical and third order dispersion is ignored. In this case, the system performance is limited by parametric noise amplification [11]. Assuming ideal compensation of inter and intra signal nonlinearities, the compensated SNR in system with ideal OPC/DBP can be estimated as:

$$SNR_C = \frac{P_S}{P_{ASE} + \left(N/N_L + N_L \cdot \sum_{n=1}^{N/N_L-1} n\right)\eta_{WDM} P_{ASE} P_S^2} \quad (1)$$

where P_S, P_{ASE} are the signal and ASE noise power spectral densities, η_{WDM} is the nonlinear efficiency and N_L = 1 for DBP and 2 for mid link OPC, with an optimum for long links of approximately:

$$SNR_{opt} = (3/2)^{3/2} \cdot SNR_0^{3/2} \sqrt{N_L} \quad (2)$$

where SNR_0 is the SNR of the uncompensated system.

III. Performance Comparison

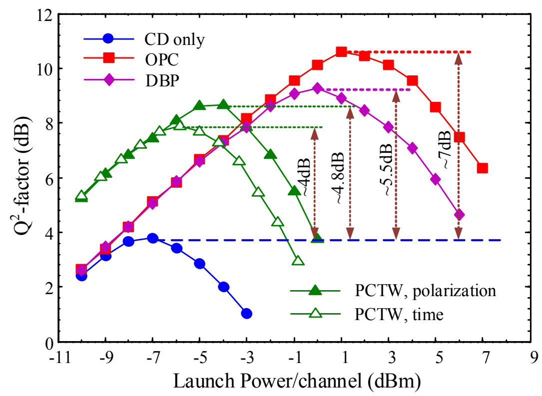

Fig. 3. Performance comparison of PCTW applied in two different polarization states and time segments with mid-link OPC and DBP.

The simulated performances of PCTW, mid-link OPC and full-band DBP are compared in the Fig. 3 for a 7×15Gbaud 16QAM Nyquist-spaced PDM WDM transmission over 40×80km standard single mode fiber (SSMF) link with ideal Raman amplification, providing the best link condition. For PCTW techniques, optimized pre- and post-dispersion was applied digitally to create a symmetrical dispersion map along the link. In Fig. 3, PCTW applied in two different time segments provides a performance improvement of 4 dB, meaning that 1 dB net gain is achieved due to the nonlinearity suppression. This result clearly indicates that nonlinear impairments can also be mitigated by applying PCTW in two different time segments. However, PCTW applied in two polarization states is a more effective compensation scheme giving a performance gain of 4.8 dB. In comparison to PCTW, DBP outperforms by 0.7 dB, providing a performance gain of 5.5 dB in line with the expected improvement in SNR [12]. This slight difference may be explained by the fact that ideal DBP compensates all the inter signal nonlinearity while PCTW only compensates the nonlinear distortions to the first-order [6]. As far as performance is concerned, ideal mid-link OPC shows the best performance, which is 1.5 dB better than those achieved with DBP. This is due to the fact that the signal × noise impairment in a system with OPC is half of that in system with DBP (see Eqn. 1).

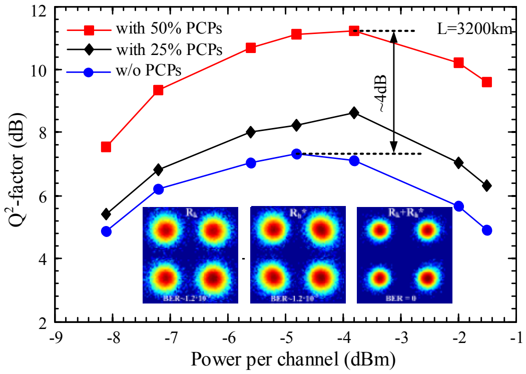

Fig. 4. Experimental comparison of performances of QPSK WDM CO-OFDM systems with and without PCPs for nonlinearity compensation; Inset – Cancellation of the nonlinear distortions by coherent superposition of subcarriers with its counterpart PCPs in WDM CO-OFDM transmission

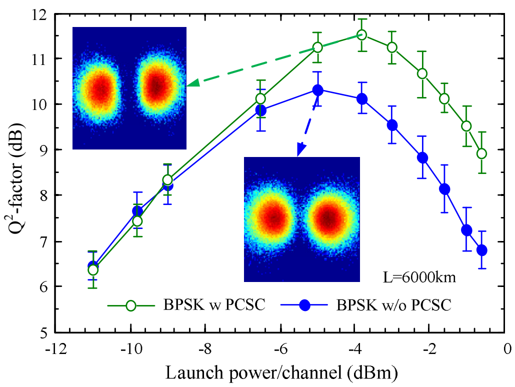

Fig. 5. Experimental comparison of performances of BPSK WDM CO-OFDM systems with and without PCSC for nonlinearity compensation

Figure 4 compares experimentally performances of 25×10Gbaud WDM CO-OFDM systems over 3200km of SSMF with and without PCP, while the inset shows the effectiveness of CS in compensating nonlinear impairments in CO-OFDM transmissions. A high performance gain of 4 dB was achieved, which is comparable with results achieved with the conventional PCTW technique. The overhead can be reduced by using one PCP for 2, 3, 4 or more data subcarriers at the cost of 33 %, 25 %, 20 % or smaller overhead respectively. When the PCP overhead was reduced to 25%, a performance improvement of around 1.5 dB was still achieved. This confirms the flexibility of PCP scheme, where performance gain can be traded with the SE.

Figure 5 shows the experimental results on the performances of 25×10Gbaud BPSK WDM CO-OFDM system with and without PCSC, over 6000km of SSMF. By processing neighbouring OFDM subcarriers simultaneously using the PCSC scheme, a performance gain of 1.5 dB was achieved without any SE reduction. This is due to the fact that the OFDM frequency spacing is small (~ 50 MHz), and thus, neighbouring subcarriers tend to experience correlated nonlinear distortions after propagation over a fiber link. Beside the flexibility and overhead reduction advantage, both PCP and PCSC schemes are very simple and easily to be implemented.

IV. Conclusion

Phase conjugation has been studied recently in both digitally and optically for nonlinearity compensation. Digital techniques such as PCTW and PCP can offer a performance gain comparable to DBP while avoiding the enormous complexity. Mid-link OPC can process multiple wavelengths simultaneously. Mid-link OPC also disrupts growth of nonlinear noise, and so gives 1.5dB advantage over currently proposed electronic techniques.

Acknowledgment

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