A Low Complexity Pre-Distortion Method for Intra-channel Nonlinearity

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Abstract: We propose a low complexity intra-channel nonlinearity pre-distortion method based on symbol rate operation. The method is experimentally verified under a 43Gb/s DP-QPSK coherent system, and the performance is comparable with back-propagation method.

OCIS codes: (060.2360) Fiber optics links and subsystems; (060.4370) Nonlinear optics, fibers

1. Introduction

Kerr nonlinearity is the major obstacle to realize the high spectral efficiency optical communication systems [1]. In dual-polarization QPSK (DP-QPSK) systems without in-line dispersion compensation, which is the main stream technology for the next generation optical communication, intra-channel nonlinearity can be the primary impairment [2]. Due to its deterministic nature, intra-channel nonlinearity could be compensated either by digital back-propagation (BP) [3]-[6] or adaptive nonlinear equalization [7]. The main idea of BP is to solve a nonlinear Schrödinger equation (NLSE) with polarity inverted link parameters. If there is no in-line dispersion compensation, BP in the receiver side needs at least 1 split-step Fourier stage per span [4], therefore the computational complexity is very high [5]. BP can also be implemented in the transmitter side by employing a look-up table (LUT), but the LUT size increases exponentially with respect to the memory length of the link [6]. The nonlinear equalizer, which takes multi-pulse interactions into consideration, can adaptively mitigate the intra-channel nonlinearity without the knowledge of the transmission link [7]. However, its complexity is even higher than that of BP [7].

In this paper, we propose a low complexity pre-distortion method operating at symbol rate to compensate for intra-channel nonlinearity based on the perturbation analysis. The proposed method was experimentally verified in 43Gb/s DP-QPSK coherent transmission without in-line dispersion compensation. The Q improvement is comparable with BP method, whereas the proposed method needs no multiplication.

2. Principle

The basic idea of the proposed method is to calculate the perturbation terms caused by intra-channel nonlinearity, and then to subtract those perturbations to generate the pre-distorted waveform. The closed-form expression for such perturbation in the single polarization system was firstly revealed by Mecozzi [8]. Assuming that an input pulse sequence passes through one section of lossless fiber with length L and the total accumulated dispersion is fully compensated linearly before the receiver, only those three-pulse patterns with time indices $[(m+k)T,\ (n+k)T,\ (m+n+k)T]$ can generate an additional perturbation pulse at the time index k with the complex amplitude as

$$\Delta_{(m,n)}(k) = j\gamma A_{m+k} A_{n+k} A^{*}_{m+n+k} \frac{\tau^2}{\sqrt{3}|\beta_2|} E_1\left(-j\frac{mnT^2}{\beta_2 L}\right), \tag{1}$$

where $(A_{m+k}, A_{n+k}, A_{m+n+k})$ represents the corresponding symbol complex amplitudes, m and n are arbitrary integers, and T is the symbol period. τ, β_2 and γ, respectively, are the pulse width, dispersion coefficient and nonlinear coefficient. $E_1(\ )$ is the exponential integral function [9]. As a result, the final complex amplitude of the generated perturbation pulse at time index k, short for kT, is the summation of all the possible indices combinations as (2).

$$\Delta(k) = \sum_m \sum_n A_{m+k} A_{n+k} A^{*}_{m+n+k} coef(m,n) = \sum_m \sum_n A_{m+k} A_{n+k} A^{*}_{m+n+k} \left[j\gamma \frac{\tau^2}{\sqrt{3}|\beta_2|} E_1\left(-j\frac{mnT^2}{\beta_2 L}\right)\right] \tag{2}$$

We extended the above theory to DP system that is modeled by the Manakov equation [10]

$$\frac{\partial}{\partial z} u_{h/v} + j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2} u_{h/v} = j\gamma\left(|u_h|^2 + |u_v|^2\right) u_{h/v}, \tag{3}$$

where $u_{h/v}$ is the electric field on h/v polarization. According to the nonlinear term in the right hand side of (3), perturbation term of h polarization is expressed by

$$\Delta_h(k) = \sum_m \sum_n H_{m+k} H_{n+k} H^{*}_{m+n+k} Coef(m,n) + \sum_m \sum_n H_{m+k} V_{n+k} V^{*}_{m+n+k} Coef(m,n), \tag{4}$$

where H and V represent the original symbol amplitudes of h and v polarization tributaries. Compared with (2), the intra-channel nonlinearity distortions in DP system come from not only the parallel polarization tributary but also the orthogonal one. The coefficients in (4) are the same as those in the single polarization case shown in (2). It is worthy of noticing that the coefficients depend on the link parameters and time intervals between interacting pulses and the current pulse. Finally, the pre-distorted waveform is achieved by subtracting the perturbation term in (4) from the original complex amplitude sequence.

For phase-shift keying (PSK) systems, the calculation of (4) can be simplified further. The first three terms in the right hand side of (5), which is expanded from (4), are independent of bit pattern and only lead to constant phase rotation, so they can be fully compensated at the receiver side. As a result, only the last two terms that represent intra-channel four-wave-mixing from the same polarization (IFWM-SP) and intra-channel four-wave-mixing from the orthogonal polarization (IFWM-OP) are regarded as the perturbation terms in PSK systems as in (6) and should be subtracted from the original sequence during the pre-distorted waveform generation.

$$\begin{aligned}\Delta_h(k) = {} & H_k|H_k|^2 Coef(0,0) + H_k\left(\sum_{n\neq 0}|H_{n+k}|^2 Coef(0,n) + \sum_{m\neq 0}|H_{m+k}|^2 Coef(m,0)\right) + H_k\sum_{n}|V_{n+k}|^2 Coef(0,n) \\ & + \sum_{m\neq 0}\sum_{n\neq 0} H_{m+k}H_{n+k}H^*_{m+n+k} Coef(m,n) + \sum_{m\neq 0}\sum_{n} H_{m+k}V_{n+k}V^*_{m+n+k} Coef(m,n)\end{aligned} \qquad (5)$$

$$\Delta_h^{PSK}(k) = \sum_{m\neq 0}\sum_{n\neq 0} H_{m+k}H_{n+k}H^*_{m+n+k} Coef(m,n) + \sum_{m\neq 0}\sum_{n} H_{m+k}V_{n+k}V^*_{m+n+k} Coef(m,n) \qquad (6)$$

The complexity of the proposed pre-distortion method is mainly dependent on the number of terms included in the perturbation calculation. In general, complex multiplications are required between the product of three information symbols and the coefficients. In transmitter side pre-distortion, the information symbols are always one of the finite modulation alphabets, so the multiplications among information symbols can be realized by logical operation. This significantly reduces the complexity. Luckily for DP-QPSK systems, the product of QPSK symbols are always QPSK symbol and the product with coefficients $Coef(m,n)$, can be replaced by simple logical operations, e.g. exchange of real and imaginary parts or polarity inversion of the real or imaginary part. As a result, the process of perturbation terms calculation is multiplier-free for DP-QPSK system. In addition, the perturbation is calculated every symbol according to (6), so the pre-distortion operates on symbol rate.

3. Experiment and discussion

The proposed pre-distortion method was evaluated in 43Gb/s DP-QPSK RZ symbol-aligned experiments as shown in Fig. 1. Data sequence of PRBS13 was used to calculate the pre-distorted waveform according to (2) and (6). In order to generate the pre-distorted waveform in DP scenario with only one arbitrary waveform generator (AWG), the data sequence was copied and delayed by half the PRBS period for the other polarization. In this way, the perturbations in each polarization are the same except the half PRBS period delay which is realized by the optical delay line with the corresponding length. The optical power of the DP signal was fixed and then it was sent to the transmission loop which consisted of five 60-km single mode fiber (SMF) followed by an erbium-doped fiber amplifier (EDFA) to compensate for the attenuation in SMF. After 1500km transmission, the amplified spontaneous noise (ASE) noise was loaded to set the designated optical signal-to-noise ratio (OSNR). Using coherent detection, the electrical field of the optical signal was captured by digital storage oscilloscope with sampling rate of 50GSa/s. Finally, those signals were processed offline with algorithms used in [11].

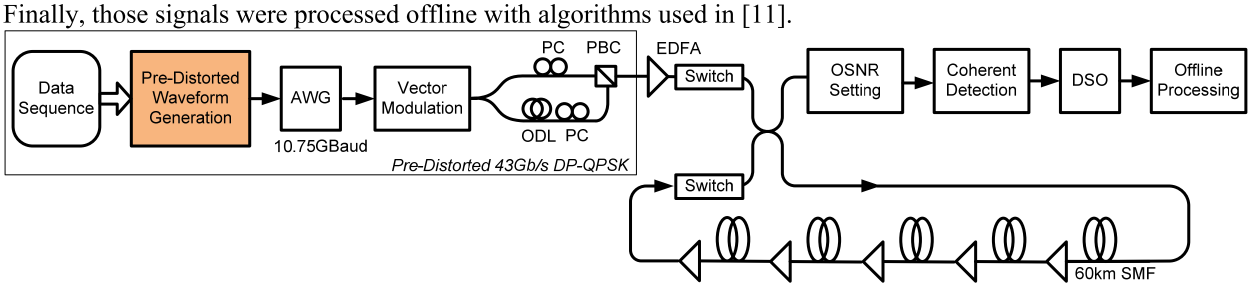

Fig. 1. Experimental setup. AWG: arbitrary waveform generator. PC: polarization controller. ODL: optical delay line with half PRBS period delay. PBC: polarization beam combiner. SMF: single mode fiber. EDFA: erbium-doped fiber amplifier. DSO: digital storage oscilloscope.

The proposed pre-distortion method was compared to BP with one stage per span (BP-1s). Fig. 2(a) shows the performance of the two methods at the launch power of 2dBm with various OSNR. Both of them achieved nearly 2dB Q improvement when OSNR was 13dB. In lower OSNR region, the proposed pre-distortion method outperformed BP-1s, which may be attributed to the error in the BP calculation due to the additional ASE noise loaded at the receiver that has no contribution to the nonlinear propagation. Fig. 2(b) shows the performance comparison at different launch powers with the fixed OSNR of 11dB. The proposed pre-distortion method had the comparable performance as BP-1s when the launch powers increased from 0dBm to 3dBm. The slight performance degradation at 3dBm might be ascribed to the assumption in the derivation of (2) that the nonlinearity should be small.

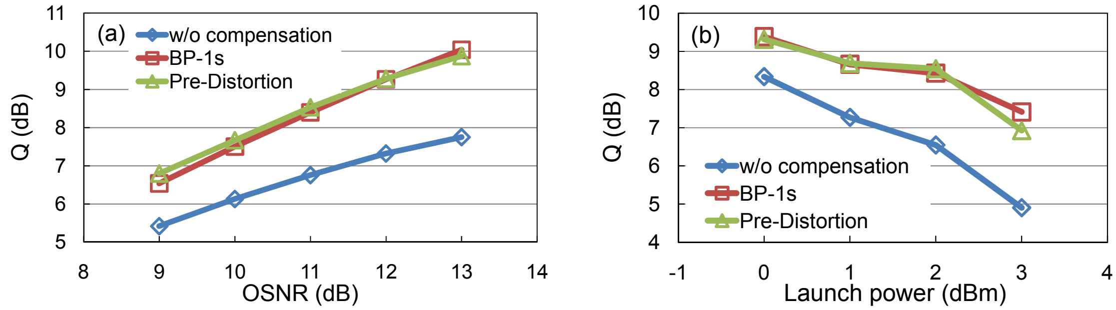

Fig. 2. Performance comparison between the proposed pre-distortion method and BP with 1 step per stage (BP-1s).
(a) OSNR dependency with a fixed launch power of 2dBm, (b) Launch power dependency with fixed OSNR of 11dB.

During the implementation of the proposed pre-distortion method, there is a trade-off between the complexity and the performance with respect to the number of terms included in the perturbation calculation. Fig. 3(a) shows the normalized amplitudes of the coefficients on a plane defined by the pulse indices (m, n). The closest pulses have the largest contribution to the perturbation and the number of terms inside of every 10dB region grows exponentially. Fig. 3(b) shows the Q improvement as a function of the total number of terms included. When the term cut-off threshold is set to -40dB, which is the default setting in pre-distorted waveform generation, the number of terms is 1413 and the performance is approaching saturation. Fig. 3(c) shows the individual contributions of IFWM-SP and IFWM-OP to the total Q improvement. It is found that the compensation of IFWM from only one polarization almost halves the Q improvement and both of them should be included together in the calculation of perturbation terms in DP scenarios.

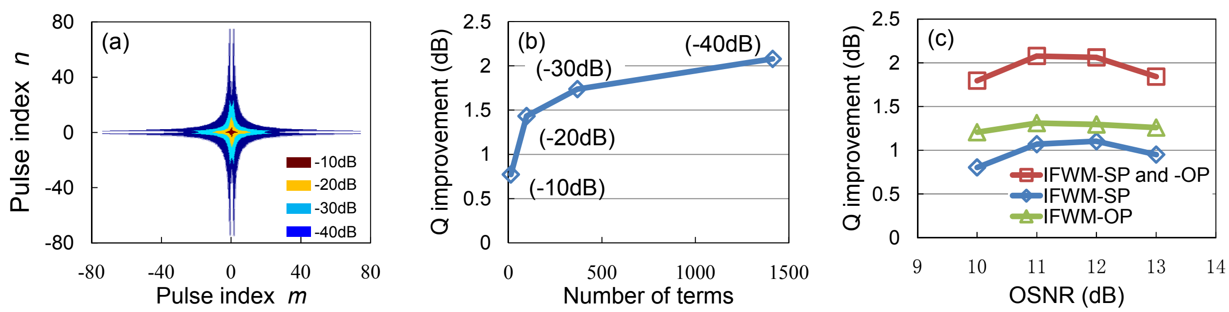

Fig. 3. (a) Magnitude of the coefficient (shown by the color gradient) as a function of the pulse indices (m, n). (b) Q improvement vs. number of terms included in the perturbation calculations measured with OSNR of 11dB at the launch power of 3dBm. Numbers in the brackets shows the corresponding cut-off threshold of the coefficient magnitude. (c) Performance comparison with only IFWM-SP, only IFWM-OP and the both in perturbation calculations with launch power of 3dBm.

4. Summary

It was shown experimentally that the intra-channel nonlinearity was compensated by a multiplier-free pre-distortion method based on symbol rate operation in a 43Gb/s DP-QPSK system without in-line dispersion compensation. The relationship between Q improvement and the number of the perturbation terms was analyzed in detail. It was also shown that both IFWM-SP and IFWM-OP should be included in the pre-distorted waveform calculation.

5. References

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