Adaptive digital backward propagation based on variance of intensity noise

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An adaptive digital backward propagation (ADBP) algorithm is proposed and experimentally demonstrated based on the variance of the intensity noise. The proposed algorithm can self-determine the unknown nonlinear coefficient γ and the nonlinear compensation parameter ξ. Compared to the scheme based on the variance of phase noise, the proposed algorithm can avoid the repeated frequency offset compensation and carrier phase recovery. The simulation results show that the system's performance compensated by the proposed method is comparable to conventional ADBP schemes. The performance of the proposed algorithm is simulated in 40/112 Gb/s polarization-division multiplexing (PDM)-quadrature phase-shift keying (QPSK) and 224 Gb/s PDM-16-quadrature amplitude modulation (QAM) systems and further experimentally verified in a 40 Gb/s PDM-QPSK coherent optical communication system over a 720 km single-mode fiber.

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In recent years, both the system capacity and the spectral efficiency have been significantly improved to meet the demands of the ever-growing data traffic[1–3]. Optical transmission schemes based on coherent detection and digital signal processing (DSP) for polarization-division multiplexing (PDM) combined with advanced modulation formats are being considered or deployed for the next generation optical networks[2]. In principle, enhanced DSP technology can perfectly compensate for all linear impairments, such as chromatic dispersion (CD) and polarization-mode dispersion (PMD)[4–7]. However, Kerr nonlinear effects, including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), in optical fibers are viewed as the main obstacles in the overall transmission capacity and performance.

So far, various nonlinear compensation methods have been proposed, including phase-conjugated twin waves[8], mid-link optical phase conjugation[9], a Volterra-series nonlinear equalizer[10], digital backward propagation (DBP)[11–21], and so on. Among them, DBP has attracted significant attention since in principle, it can compensate for any deterministic propagation impairment. DBP is typically implemented by solving an inverse nonlinear Schrödinger equation[22] with full knowledge of the link parameters. However, the link information might not be accurately gained in reconfigurable and time-varying systems. For these scenarios, semi-blind DBP or adaptive DBP (ADBP)[19] may be desirable, preferably with a reduced computation complexity to meet the requirements of real-time processing. An efficient ADBP algorithm[19], which only self-determines the unknown fiber nonlinear coefficient γ, was demonstrated based on phase-noise variance.

In this Letter, we propose a new ADBP algorithm, which uses the variance of the intensity noise to estimate the optimized product $\gamma * \xi$. The proposed algorithm can obtain the optimal value of $\gamma * \xi$ even in the case of an incorrect nonlinear coefficient and inaccurate fiber output power. The proposed algorithm will be a new alternative solution for estimating nonlinear coefficient γ and nonlinear compensation parameter ξ. The performance of the proposed algorithm is verified by both simulations (i.e., 40/112 Gb/s PDM-quadrature phase-shift keying (QPSK) and 224 Gb/s PDM-16-quadrature amplitude modulation (QAM) transmission over different lengths of single-mode fibers (SMFs)) and experiments (i.e., 40 Gb/s PDM-QPSK over a 720 km SMF).

Figure 1(a) shows the block diagram of the proposed ADBP. The received signal is first converted from analog to digital by the analog-to-digital converter. The digital signal passes through the ADBP compensator to compensate for CD and nonlinear effects. Afterwards, the demultiplexing of the PDM signal (PDM_DEMUX) uses the constant-modulus algorithm to accomplish polarization demultiplexing and PMD compensation. After the PDM_DEMUX module, the intensity noise variance function CF[23] is defined as $\sigma^2[\delta I(nT)]$, where the intensity fluctuation can be expressed as

$$\delta I(nT) = |E_d(nT)|^2 - \overline{|E_d(nT)|^2}, \quad (1)$$

where $E_d(nT)$ is the output signal of the PDM_DEMUX that performs the polarization demultiplexing. T is the

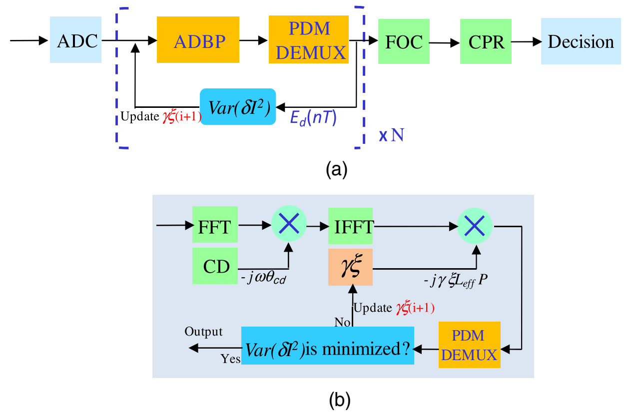

Fig. 1. (a) Block diagram and (b) principle of proposed ADBP algorithm. ADC: analog-to-digital conversion; FOC: frequency-offset compensation.

symbol interval, and n is the number of samples. $|E_d(nT)|^2$ is the mean value of the power signal. When the signal passes through a multi-span transmission system, the intensity noise is converted to the phase noise by SPM effect[23]. At the receiver, the intensity noise correlates partially with the phase noise, and the variance of phase noise is proportional to that of the intensity noise. Therefore, compared to the scheme based on the variance of the phase noise, the intensity noise variance is also an effective indicator of signal quality. For example, the signal quality becomes worse when the intensity noise variance becomes larger. Meanwhile, the proposed method can avoid frequency offset compensation and carrier phase recovery (CPR).

Afterwards, the proposed algorithm makes a judgment on whether *CF* is minimized. If the minimum is not found, the proposed algorithm uses the update rule of the steepest descent algorithm to search for the optimized product $\gamma\xi = \gamma * \xi$, which is expressed as

$$\gamma\xi(i+1) = \gamma\xi(i) + \mu_{\mathrm{adap}}\partial CF(i), \tag{2}$$

where $\gamma\xi(i)$ and $\partial CF(i)$ represent the optimized product $\gamma\xi$ and the gradient of *CF* at the iteration i, respectively. The parameters γ and ξ are the nonlinear coefficient and nonlinear compensation parameter. The convergence speed factor μ_{adap} used in the proposed algorithm is 0.01. The formula $\partial CF(i)$ is defined as $\partial CF(i) = [CF(i) - CF(i-1)]/[\gamma\xi(i) - \gamma\xi(i-1)]$. When the sign of $\partial CF(i)$ is observed with a positive and negative change, the minimized *CF* is obtained. Therefore, the algorithm will stop, and then the optimal product of $\gamma * \xi$ can be obtained. The nonlinear compensator in the proposed algorithm can be defined as $H = \exp(-j\xi\gamma P L_{\mathrm{eff}})$, as shown in Fig. 1(b), where P is the signal power after CD compensation. In this case, the signal can be out of the loop and enter frequency offset compensation and CPR, as shown in Fig. 1(a). The number of iterations is mostly less than 5 in our experiments, and is generally determined by the level of inaccuracy of the nonlinear coefficient. Meanwhile, the CPR module uses the Viterbi–Viterbi phase estimator to compensate for the laser phase noise. Finally, the data decision module is applied to evaluate the system's performance by counting the bit errors.

To compare the performance between experiments and simulations, we firstly simulate the 40 Gb/s PDM-QPSK coherent optical communication system over a 720 km SMF transmission, as shown in Fig. 2. At the transmitter, the light from the external cavity laser oscillating with ~100 kHz linewidth at ~1550.0 nm is modulated by an in-phase/quadrature (IQ) modulator with a 10 Gb/s $2^{31} - 1$ pseudo-random bit sequence (PRBS) to generate a 20 Gb/s QPSK signal. The encoded signals are polarization multiplexed to generate 40 Gb/s PDM-QPSK signals by employing an interleave scheme that is composed of a coupler, two polarization controllers (PCs), a variable optical attenuator (VOA), a 1 km SMF, and a polarization beam combiner (PBC). Here, the two PCs, 1 km SMF, and the VOA are used to generate two data streams with orthogonal states of polarization, decorrelate two data streams, and balance the optical power between two arms, respectively. The transmission optical link is comprised of 9×80 km spans of SMFs (720 km), whose dispersion parameter, attenuation, and nonlinearity factor are $D = 16.5$ ps/nm/km, $\alpha = 0.2$ dB/km, $\gamma = 1.27\ \mathrm{km}^{-1} \bullet \mathrm{W}^{-1}$, respectively. It is noted that the dispersion D is known in all simulations and experiments. The fiber loss of each span is completely compensated per span using an erbium-doped fiber

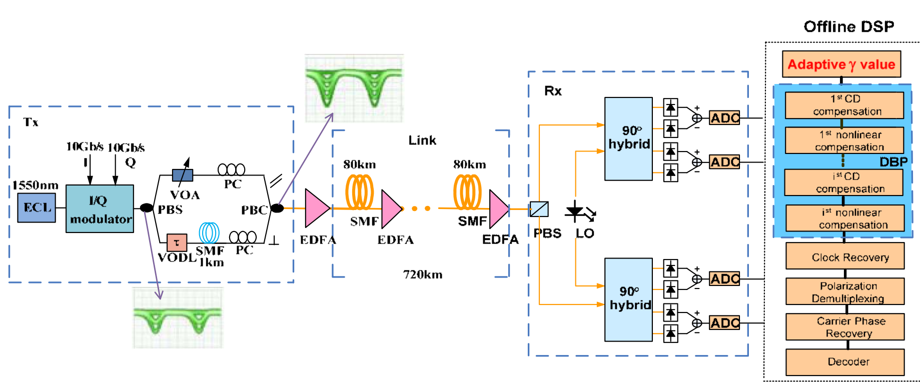

Fig. 2. Flowchart of the proposed ADBP.

amplifier with a noise figure of 5 dB. At the coherent homodyne receiver side, the received signal and the local oscillator are combined using the optical 90° hybrid. The electrical signals passing through a pair of balanced photodiodes are processed using a MATLAB code in the offline DSP module.

Figure 3(a) depicts the normalized intensity noise variance for the 40 Gb/s PDM-QPSK system with different products $\gamma * \xi$ under the different fiber output powers p. In traditional DBP algorithms, accurate fiber output power is an important parameter to achieve a high compensation performance. But in practical systems, such a value would vary with time or usually changes in different applications. As shown in Fig. 3(a), different fiber output powers p correspond to different minimum intensity noise variances when the launch power is 5 dBm. Therefore, the proposed algorithm utilizes the intensity noise to search for the optimal products $\gamma * \xi$. The corresponding constellation diagrams with different intensity noise variances under different products $\gamma * \xi$ are shown in Fig. 3(a). Figure 3(b) shows the simulated bit error rate (BER) performance by employing different compensation schemes for the 40 Gb/s PDM-QPSK system. The system performance with an inaccurate product (i.e., $\gamma * \xi = 2.1$) would degrade significantly. Compared to linear equalizer (LE) compensation (i.e., only CD compensation), the

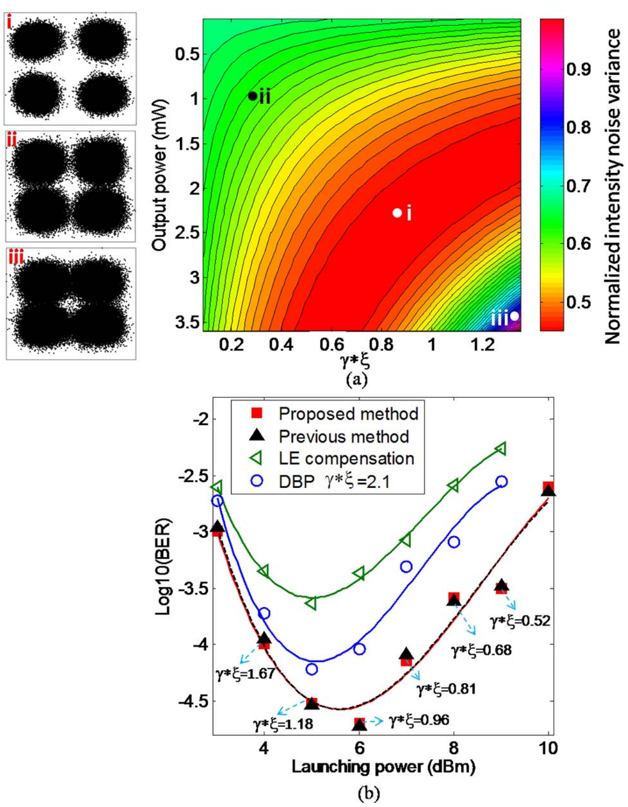

Fig. 3. Simulated performance: (a) normalized intensity noise variance with different products of $\gamma * \xi$ under the different fiber output powers p for the 40 Gb/s PDM-QPSK; (b) BER versus launching power over 720 km SMF link with LE compensation, conventional DBP, and proposed ADBP.

power penalty improvement of up to ∼2 dBm is achieved when the BER is 10^{-3}. The normalized intensity noise variance is defined as $nCF(i) = CF(i)/\max(CF)$.

To further investigate the performance of the proposed algorithm, we simulate the transmission of the 112 Gb/s PDM-QPSK and 224 Gb/s PDM-16-QAM signals. Figure 4(a) shows the simulated BER performance by employing different compensation schemes, including an LE, conventional DBP, and the proposed ADBP for the 112 Gb/s PDM-QPSK system. Here, the transmission distance and nonlinear compensation parameter ξ are 40×100 km and 0.9, respectively. For the conventional DBP algorithm, the compensation performance of the system would degrade significantly when the product $\gamma * \xi$ is inaccurate (i.e., the upper triangle in black). Compare to the LE compensation, the proposed algorithm can improve the nonlinear compensation performance. Figure 4(b) shows the normalized intensity noise variance for the 224 Gb/s PDM-16-QAM with different products of $\gamma * \xi$ when the launch power is 5 dBm. As indicated in Fig. 4(b), the proposed ADBP algorithm based on the intensity noise variance can also be applied to higher-order modulation formats (i.e., 16-QAM). A previous ADBP algorithm[19] effectively demonstrated the performance improvement in a multi-channel (i.e., 10-channel), 224 Gb/s symbol rate, PDM-16-QAM data transmission over a 8×82 km link. Compared to the previous method with N-time frequency-offset compensation (FOC) and CPR process and self-determining unknown nonlinear

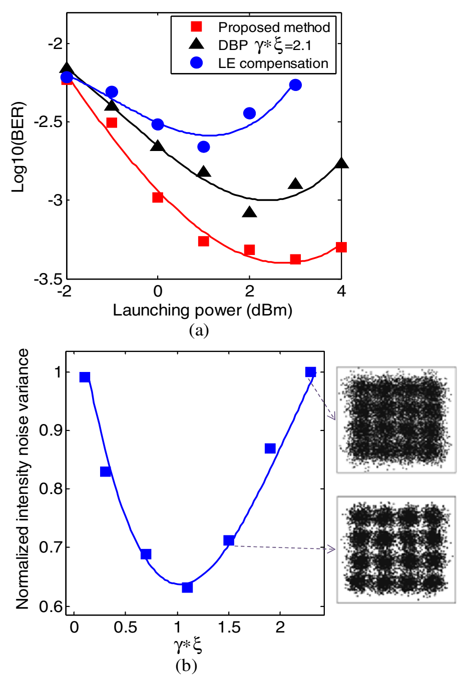

Fig. 4. Simulated performance: (a) BER versus launching power over 40×100 km SMF link for LE, standard DBP, and proposed ADBP for the 112 Gb/s PDM-QPSK. (b) Normalized intensity noise variance with different products of $\gamma * \xi$ and corresponding constellation diagrams (20×100 km SMF link) for the 224 Gb/s PDM-16-QAM.

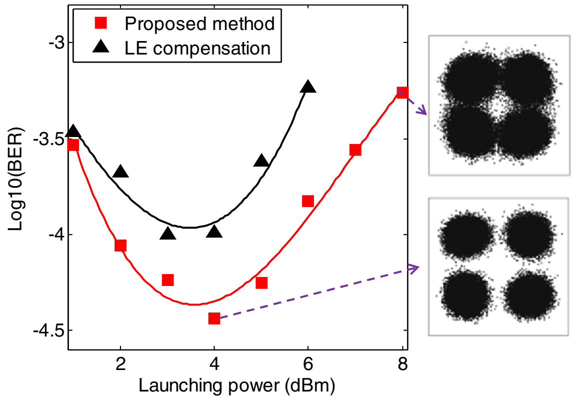

Fig. 5. Experimental results of BER versus launching power over 720 km SMF for LE and new ADBP.

coefficient γ, the proposed algorithm performs only one FOC and CPR process, and self-determines the unknown nonlinear coefficient γ and nonlinear compensation parameter ξ. Therefore, the proposed algorithm can decrease the calculation complexity with the same performance. Note that we only consider the single-channel case with SPM effects. It is desirable to investigate the performance of multi-channel case with SPM, XPM, and FWM effects in the near future.

In order to further verify the proposed ADBP algorithm, we experimentally investigate the system performance of 40 Gb/s PDM-QPSK signals. The experimental setup is same as the simulation (Fig. 2) and has similar system parameters (i.e., 720 km SMF fiber length, $D = 16.5\,\text{ps/nm/km}$, $\alpha = 0.2\,\text{dB/km}$, $\gamma = 1.27\,\text{km}^{-1} \bullet \text{W}^{-1}$). Figure 5 shows the experimental results of employing an LE and the proposed ADBP. The proposed algorithm can provide an adaptive compensation performance, even if the initial value of $\gamma * \xi$ is 2.7. Compared to the LE's compensation (i.e., only CD compensation), the proposed method can improve the power penalty up to ~2 dBm when the BER is $10^{-3.5}$. Since the simulation is more ideal than the experimental case, there is a ~2 dBm launching power (at the BER value of 10^{-4}) difference between the simulation (Fig. 3b) and the experiment (Fig. 5).

In conclusion, we propose an efficient ADBP algorithm based on the variance of the intensity noise to estimate the optimum product of $\gamma * \xi$. Even under the assumption of incorrect nonlinear values and unknown received optical power, the proposed algorithm can effectively obtain the optimal product of $\gamma * \xi$. Whether accurate or not, our proposed method can self-adjust to optimize the system performance by deriving the correct product of $\gamma * \xi$. The effectiveness of the proposed algorithm is validated with different modulation formats (i.e., QPSK and 16-QAM) and different distances (i.e., 720, 2000, and 4000 km).

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References

1. L. S. Yan, X. Liu, and W. Shieh, IEEE Photon. J. **3**, 325 (2011).
2. P. J. Winzer, IEEE Commun. Mag. **48**, 26 (2010).
3. Z. Chen, L. Yan, W. Pan, B. Luo, Y. Guo, H. Jiang, A. Yi, Y. Sun, and X. Wu, Opt. Express **21**, 11590 (2013).
4. M. G. Taylor, IEEE Photon. Technol. Lett. **16**, 674 (2004).
5. M. Kuschnerov, F. N. Hauske, K. Piyawanno, B. Spinnler, M. S. Alfiad, A. Napoli, and B. Lankl, J. Lightwave Technol. **27**, 3614 (2009).
6. S. J. Savory, IEEE J. Sel. Top. Quantum Electron. **16**, 1164 (2010).
7. Q. Sui, A. P. T. Lau, and C. Lu, J. Lightwave Technol. **31**, 306 (2013).
8. X. Liu, A. R. Chraplyvy, P. J. Winzer, R. W. Tkach, and S. Chandrasekhar, Nat. Photon. **7**, 560 (2013).
9. S. Kumar and L. Liu, Opt. Express **15**, 2166 (2007).
10. F. P. Guiomar and A. N. Pinto, J. Lightwave Technol. **31**, 3879 (2013).
11. E. Ip and J. M. Kahn, J. Lightwave Technol. **26**, 3416 (2008).
12. F. Yaman and G. Li, IEEE Photon. J. **1**, 144 (2009).
13. L. Zhu and G. Li, Opt. Express **19**, 5953 (2011).
14. L. B. Du and A. J. Lowery, Opt. Express **18**, 17075 (2010).
15. C. Lin, R. Asif, M. Holtmannspoetter, and B. Schmauss, Chin. Opt. Lett. **10**, 020605 (2012).
16. Z. Huang, F. Zhang, and Z. Chen, Chin. Opt. Lett. **11**, 060601 (2013).
17. J. Yang, S. Yu, M. Li, Z. Chen, Y. Han, and W. Gu, Opt. Commun. **312**, 80 (2014).
18. T. Hoshida, T. Tanimura, S. Oda, T. Tanaka, H. Nakashima, Z. Tao, L. Li, L. Liu, W. Yan, and J. C. Rasmussen, in *Proceedings of OFC* OTuE5 (2010).
19. C. Lin, A. Napoli, B. Spinnler, V. Sleiffer, D. Rafique, M. Kuschnerov, M. Bohn, and B. Schmauss, in *Proceedings of OFC* M3C4 (2014).
20. J. Zhang, X. Li, and Z. Dong, J. Lightwave Technol. **31**, 3546 (2013).
21. L. Li, Z. Tao, L. Dou, W. Yan, S. Oda, T. Tanimura, T. Hoshida, and C. Jens, in *Proceedings of OFC* OWW3 (2011).
22. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nded. (Academic, 1995).
23. K. Kikuchi, M. Fukase, and S. Y. Kim, in *Proceedings of OFC* OTuA2 (2007).