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Nonlinear impairment compensation in multi-channel communication systems based on correlated digital backpropagation with separation of walk-off effect

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ARTICLE INFO

Keywords:
Nonlinearity compensation
Optical fiber communication
Walk-off effect

ABSTRACT

Digital backpropagation (DBP) is a commonly used method to compensate for the nonlinear impairments of optical fiber channels in the electrical domain, offering a new approach to enhancing the data capacity without affecting the system performance. However, due to the repeated Fourier transform and inverse transform of the split-step Fourier method (SSFM), the complexity of DBP algorithm has increased significantly. In this paper, a correlated backpropagation algorithm with the separation of the walk-off effect is developed, which improves the computational step and significantly reduces the complexity of the algorithm. Simulation results demonstrate that in a 6-channel PDM-16QAM system, the proposed hybrid algorithm reduces the computational complexity by 73.96 % compared to the traditional DBP algorithm for an 800 km transmission.

1. Introduction

With the development of cloud service and artificial intelligence technology, the era of the Internet of Everything (IoE) has brought massive data traffic, which puts forward higher requirements for the channel rate, transmission capacity, and distance of optical communication systems [1–3]. In coherent optical communication systems, the transmission capacity of the system can be improved by applying high-order modulation formats (e.g. m-QAM), polarization-division multiplexing (PDM), and wavelength-division multiplexing (WDM) techniques [4–7]. But these approaches also present some new challenges. For example, advanced modulation formats reduce the Euclidean distance between constellation points, thus requiring higher transmission power to maintain sufficient optical signal-to-noise ratio (OSNR), but the large launch power leads to increased nonlinear impairments. Moreover, PDM and WDM aggravate the nonlinear effects within and between channels, which in turn causes nonlinear impairments to the optical signals in the link, resulting in a severe degradation of signal quality. Nonlinear compensation is a research hotspot to increase the system capacity without affecting the system performance [8–11].

Nonlinear impairments in fibers include distortions caused by inelastic scattering effects and those caused by changes in the refractive index. The former cannot be estimated due to the energy transfer between light and medium, so we mainly consider the latter impairments of e.g. self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) caused by the Kerr effect [12–14]. The combination of digital signal processing (DSP) and coherent detection technology provides a new solution for the realization of high-speed, long-distance optical communication. It becomes the development direction of high-speed optical communication in the future, which can implement the impairment compensation in the electrical domain, thereby enhancing the transmission performance of the system and increasing the transmission distance of optical signals without relay [15,16].

DBP is an effective method in compensating for the nonlinear impairments caused by the Kerr effect in fiber, based on the nonlinear Schrödinger equation (NLSE). The core principle of DBP can be encapsulated by initiating the optical signals at the receiving end, and iteratively applying the linear and nonlinear transformations delineated by the split-step Fourier method (SSFM). This backpropagation continues through the optical fiber until the signal is retraced to the transmitting end, ultimately recovering the original signal. So far, DBP has played a

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significant role in many communication systems and has become one of the most commonly used algorithms to compensate for optical fiber nonlinear impairments [17–21]. However, due to the recursive characteristic of SSFM and the need to reduce the DBP step size as much as possible in order to improve the calculation accuracy, the number of calculating operations of the DBP algorithm is greatly increased. Thus, its further application in WDM or PDM systems is limited. One of the keys to the development of nonlinear compensation technology is to reduce the complexity of compensation algorithms.

To solve the problem of a large computing load of DBP, we propose a correlated digital backpropagation algorithm to mitigate SPM and XPM impairments in the PDM-WDM optical communication system by separating the walk-off effect. In this algorithm, the step size of the SSFM is enlarged by explicitly adding the walk-off effect in the process of nonlinear compensation calculation. While the step size increases, the dispersion should be considered in each step operation to ensure the calculation accuracy, which means adding the influence of the adjacent signal on the nonlinear phase shift of the current signal. In a 6-channel PDM-16QAM system, the proposed hybrid algorithm is proven to effectively reduce computational complexity and improve the performance of the communication system. Simulation results show that the computational cost of the proposed hybrid algorithm is reduced by 73.96 % compared with conventional DBP after the transmission of 800 km.

2. Principle

The signal is affected by the dispersion and nonlinear effects during its transmission in fiber, resulting in signal impairments. The process is described by NLSE in a standard single-mode fiber (SSMF). In the case of a PDM system, it can be described by the Manakov equation due to the influence of polarization mode dispersion (PMD) and cross-polarization effect [22]. When the nonlinear length of fiber is much larger than the birefringent beat length in an SSMF, the envelope evolution of the optical field is described as

$$-\frac{\partial E_{(x,y)}}{\partial z}+\frac{\alpha}{2}E_{(x,y)}+\frac{i\beta_2}{2}\frac{\partial^2 E_{(x,y)}}{\partial t^2}+i\frac{8}{9}\gamma\left(\left|E_{(x,y)}\right|^2+\left|E_{(y,x)}\right|^2\right)E_{(x,y)}=0 \tag{1}$$

where $E_{(x,y)}$ represents the optical signal envelope in two orthogonal polarization states of X and Y, α is the loss coefficient of fiber, β_2 is the dispersion coefficient, and γ is the nonlinear coefficient to describe the intensity of nonlinear effects in fiber. All deterministic nonlinear effects in the channel are included in this equation, including SPM, XPM, and FWM. However, FWM has a significant effect only when the phase-matching condition is satisfied. Therefore, in ordinary SSMF used in communication systems, where the dispersion coefficient is large and the transmission is far away from the phase matching point, FWM can usually be ignored to simplify the computational complexity.

DBP method is operated based on solving backward propagation NLSE and the commonly used method is SSFM. Actually, the dispersion effect and nonlinear effects occur simultaneously along the propagation in the fiber. SSFM solves NLSE by assuming that dispersion and nonlinear effects act sequentially at each step during the transmission of light. In the first step, there are nonlinear effects only, which can be solved in the time domain. Then the dispersion is considered only in the second step to realize the compensation in the frequency domain by means of Fourier transform. This approximation is valid when the step size is small enough.

In a PDM-WDM system, the light field is expressed as

$$E=\sum_{m=1}^{N}\widehat{E}_m\exp(im\Delta\omega t) \tag{2}$$

where m is the channel number and $\Delta f=\Delta\omega/2\pi$ is the channel spacing. Substituting it into the Manokov equation so we obtain the coupled equations as

$$\begin{aligned}-\frac{\partial\widehat{E}_{xm}}{\partial z}+\left(\frac{\alpha}{2}+L_m+iC_{xm}\right)\widehat{E}_{xm}+iK_m\widehat{E}_{ym}=0\\ -\frac{\partial\widehat{E}_{ym}}{\partial z}+\left(\frac{\alpha}{2}+L_m+iC_{ym}\right)\widehat{E}_{ym}+iK_m^*\widehat{E}_{xm}=0\end{aligned} \tag{3}$$

where L_m is the dispersion operator, $C_{(x,y)m}$ represents SPM and polarization-independent XPM terms, and K_m is the polarization mixing term, respectively, given by

$$L_m=D_{1m}\frac{\partial}{\partial t}+D_{2m}\frac{\partial^2}{\partial t^2} \tag{4}$$

$$C_{(x,y)m}=-\frac{8}{9}\gamma\left(P_{xm}+P_{ym}+\sum_{\forall q\neq m}R_{(x,y)q}\right) \tag{5}$$

$$K_m=-\frac{8}{9}\gamma\left(\sum_{\forall q\neq m}\widehat{E}_{yq}^*\widehat{E}_{xq}\right) \tag{6}$$

where $P_{(x,y)m}=\left|\widehat{E}_{(x,y)m}\right|^2$ and $R_{(x,y)m}=2P_{(x,y)m}+P_{(y,x)m}$. The dispersion parameters are given by $D_{1m}=m\beta_2\Delta\omega$ and $D_{2m}=i\beta_2/2$.

In the linear part, the dispersion compensation is achieved by the Fourier transform

$$\widehat{E}_{(x,y)m}(t,z+h)=F^{-1}\left\{F\left[\widehat{E}_{(x,y)m}(t,z)\right]H_m(\omega,h)\right\} \tag{7}$$

The multi-channel transfer function H_m is given as

$$\begin{aligned}H_m(\omega,h)&=\exp\left[\left(D_{1m}i\omega+D_{2m}(i\omega)^2\right)h\right]\\&=\exp\left[i\beta_2h\left(\omega m\Delta\omega-\omega^2/2\right)\right]\end{aligned} \tag{8}$$

where h is the step size.

During the nonlinear operation, SPM and polarization-independent XPM term $C_{(x,y)m}$ only introduce the nonlinear phase shift, while polarization mixing term K_m couples the signal of X polarization with that of Y polarization, leading to a change in signal amplitude. The calculation formulas are

$$\begin{aligned}E_{xm}(t,z+h)&=E_{xm}(t,z)e^{i\phi_{xm}}\cos(|Q_m|)-iE_{ym}(t,z)e^{i\phi_{ym}}Q_m sinc(|Q_m|)\\E_{ym}(t,z+h)&=E_{ym}(t,z)e^{i\phi_{ym}}\cos(|Q_m|)-iE_{xm}(t,z)e^{i\phi_{xm}}Q_m^* sinc(|Q_m|)\end{aligned} \tag{9}$$

When the step length is short enough, there are approximations that

$$\phi_{(x,y)m}(t,z+h)=h_{eff}C_{(x,y)m}(t,z) \tag{10}$$

$$Q_m(t,z+h)=h_{eff}K_m(t,z) \tag{11}$$

where $h_{eff}=[exp(\alpha h)-1]/\lambda$ is the effective step size.

To guarantee the accuracy of calculation, the fluctuation of the optical power caused by the nonlinear phase shift and the dispersion in each step should be small enough. We generally choose the appropriate step size based on the dispersion length L_d, the nonlinear length L_{nl}, and the walk-off length L_{wo} of the system, given by

$$L_d=\frac{1}{|\beta_2|B^2}$$

$$L_{nl}=\frac{N}{\gamma P(2N-1)}$$

$$L_{wo}=\frac{1}{2\pi|\beta_2|(N-1)\Delta fB}$$

where β_2 is the dispersion coefficient, B is the bandwidth of the channel, γ is the nonlinear coefficient, P is the launch power, and Δf is the channel spacing. The nonlinear compensation will produce a significant error if the step size exceeds the dispersion length while the XPM error

increases when the step size is larger than the walk-off length. Therefore, an appropriate step size used in DBP is generally the minimum of the dispersion length L_d, the nonlinear length L_{nl}, and the walk-off length L_{wo}.

In order to improve the calculation requirements and reduce the algorithm complexity, considering that the walk-off length is usually small, the step size can be relaxed to the dispersion length by explicitly adding the walk-off effect to the nonlinear compensation calculation part as

$$C_{(x,y)m}(t,z) = -\frac{8}{9}\gamma\left(P_{xm}(t,z) + P_{ym}(t,z) + \sum_{\forall q\neq m} R_{(x,y)q}\left(t - d_{mq}z, z\right)\right) \tag{12}$$

$$K_m(t,z) = -\frac{8}{9}\gamma\left(\sum_{\forall q\neq m} E^*_{yq}\left(t - d_{mq}z, z\right)E_{xq}\left(t - d_{mq}z, z\right)\right) \tag{13}$$

where $d_{mq} = \beta_2(\omega_m - \omega_q)$ is the walk-off parameter.

The Fourier transform is used for processing as

$$C_{(x,y)m}(\omega,z) = -\frac{8}{9}\gamma\left(P_{xm}(\omega,z) + P_{ym}(\omega,z) + \sum_{\forall q\neq m} R_{(x,y)q}(\omega,z)e^{-id_{mq}\omega z}\right) \tag{14}$$

$$K_m(\omega,z) = -\frac{8}{9}\gamma\left(\sum_{\forall q\neq m} E^*_{yq}(\omega,z)E_{xq}(\omega,z)e^{-id_{mq}\omega z}\right) \tag{15}$$

According to the above equations, we get

$$\phi_{(x,y)m}(t,z+h) = -\frac{8}{9}\gamma\left[\left(P_{xm}(t,z) + P_{ym}(t,z)\right)h_{eff} + F^{-1}\left\{\sum_{\forall q\neq m} R_{(x,y)q}(\omega,z)W_{mq}(\omega,h)\right\}\right] \tag{16}$$

$$Q_m(t,z+h) = -\frac{8}{9}\gamma\left[F^{-1}\left\{\sum_{\forall q\neq m} \widehat{E}^*_{yq}(\omega,z)\widehat{E}_{xq}(\omega,z)W_{mq}(\omega,h)\right\}\right] \tag{17}$$

where

$$W_{mq}(\omega,h) = \frac{e^{\alpha h - id_{mq}\omega z} - 1}{\alpha - id_{mq}\omega}$$

The step size of SSFM can be increased to the dispersion length after the above processing. Although the Fourier transform and inverse Fourier transform are added in each step, the significant increase in step size ultimately reduces the computational requirements. Actually, this algorithm is called as walk-off algorithm due to the separation of walk-off effect and was firstly introduced in [23].

However, dispersion will broaden the signal pulse when the step size is increased. Therefore, the overlapping of adjacent pulses will interfere with each other through nonlinear effects, which affects the calculation accuracy of nonlinear phase shifts. In this case, the nonlinear phase shift of the current signal can be regarded as the result of the joint action of adjacent signal pulses. In the calculation, the intensity of adjacent pulses is added with a certain weight as the power of the current signal to calculate the nonlinear phase shift and compensate. That is

$$P'_{(x,y)m} = \sum_k c_k\left(aP_{(x,y)m} + bP_{(y,x)m}\right) \tag{18}$$

$$R'_{(x,y)m} = 2P'_{(x,y)m} + P'_{(y,x)m} \tag{19}$$

where c is the correlation coefficient between adjacent signals, and a and b are the weight factors of parallel polarization and vertical polarization, respectively.

The correlation coefficient c between adjacent signals should be determined by the time-domain relationship of nonlinear impairments between the nearest neighboring signals, which can be obtained via the perturbation-based nonlinearity compensation method [24]. In the dual-polarization channel, it can be concluded that the nonlinear perturbation term caused by all adjacent signal pulses to the signal at the current time $t = 0$ according to the Manakov equation is described as

$$\Delta u_x = \sum_{m,n} P_0^{3/2}\left(A_{n,x}A^*_{m+n,x}A_{m,x} + A_{n,y}A^*_{m+n,y}A_{m,x}\right)C_{m,n} \tag{20}$$

$$\Delta u_y = \sum_{m,n} P_0^{3/2}\left(A_{n,y}A^*_{m+n,y}A_{m,y} + A_{n,x}A^*_{m+n,x}A_{m,y}\right)C_{m,n} \tag{21}$$

where the perturbation coefficient of the effect of Intra-channel Four-wave Mixing (IFWM) is

$$C_{m,n} = j\frac{8}{9}\frac{\gamma\tau^2}{\sqrt{3}|\beta_2|}E_1\left(-i\frac{mnT^2}{\beta_2 L}\right)\ m \neq 0, n \neq 0 \tag{22}$$

where τ is the width of the pulse, T is the reciprocal of the symbol rate, L is the transmission length, m and n are the symbol index, and $E_1(\cdot)$ is the exponential integral function. And the perturbation coefficient of Intra-channel Cross-phase Modulation (IXPM) is

$$C_{m,n} = j\frac{8}{9}\frac{\gamma\tau^2}{\sqrt{3}|\beta_2|}\frac{1}{2}E_1\left(\frac{(n-m)^2T^2\tau^2}{3|\beta_2|^2L^2}\right)\ m \text{ or } n = 0 \tag{23}$$

and the perturbation coefficient of SPM is

$$C_{0,0} = j\frac{8}{9}\frac{\gamma\tau^2}{\sqrt{3}|\beta_2|}\int_0^L dz\frac{1}{\sqrt{\tau^4/(3\beta_2^2) + z^2}} \tag{24}$$

Due to the excessive number of IFWM terms, which brings a huge number of calculations, it is usually possible to discard IFWM terms that have a small impact but multiple calculations.

By employing this perturbation-based approach, the correlation coefficient between adjacent signals can be calculated, enabling a more accurate estimation of the current signal power. The greater the number of perturbations considered, the more accurate the calculation results are, but the complexity of the algorithm also increases. So it is necessary to select the perturbation terms used in the calculation according to certain rules.

In the WDM system, the step size constraint imposed by the walk-off length can be overcome by separating the walk-off effect. The influence of dispersion is introduced, that is, the power weighting of the adjacent signal is substituted into the nonlinear phase shift calculation process as the power of the current signal, and the nonlinear compensation is finally realized. In the following article, we call this algorithm the hybrid algorithm because it combines the characteristics of the walk-off algorithm and the perturbation-based method.

3. Simulation results

In the simulation experiment, we simulate a dual-polarization WDM system with six channels in VPI TransmissionMaker as shown in Fig. 1, where 16QAM modulated signals are transmitted over a 10 × 80 km link. The symbol rate equals 30 GBaud, the center wavelength is 1550 nm and 50 GHz channel spacing is applied. The transmitter uses a PRBS sequence of 2^{15} symbols, which is pulse-shaped by a root-raised cosine (RRC) filter with a roll-off coefficient of 0.18. The symbols are then input to an IQ modulator with a continuous laser carrier to generate the optical signal of 16QAM. The system adopts a SSMF with a dispersion coefficient of $D = 17ps/nm/km$ and a nonlinear coefficient of $1.3/W/km$. The loss in each span is compensated by EDFA, which has a noise figure of 4 dB and a power gain of 14 dB.

At the receiving end, the incident signal is coherently mixed with the local oscillator (LO) light to realize the coherent detection of in-phase

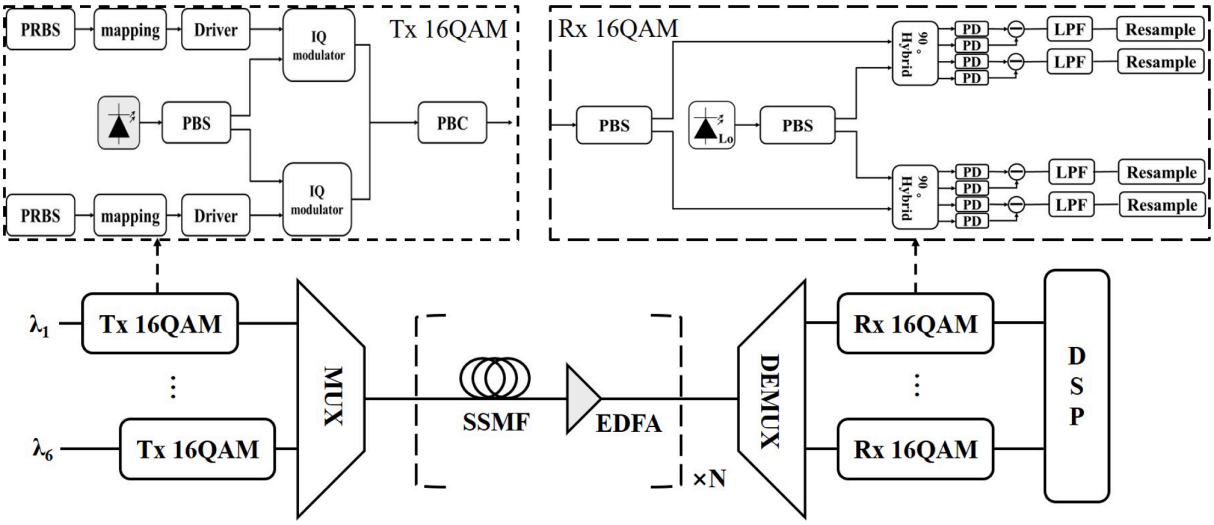


Fig. 1. Simulation system architecture. Tx: transmitter, PBS: polarization beam splitter, PBC: polarization beam combiner, PD: photodiode, LPF: low-pass filter, MUX: wavelength multiplexer, EDFA: Erbium-doped fiber amplifier, DEMUX: wavelength demultiplexer, Rx: receiver.

and orthogonal signals. DSP is operated after the signal conversion from optical to electrical signals. During the offline DSP, the Samples per Symbol (SpS) is set to 2. $Q^2 = 20\log_{10}\sqrt{2}erfc^{-1}(2BER)$ is used to evaluate the system performance, where $erfc(\cdot)$ is the complementary error function. In the hybrid algorithm, we ignore the influence of the polarization direction and take the weight factors of parallel polarization a and vertical polarization b as 1 in Eq. (19). We consider only the influence of the nearest 10 pulses for each pulse since only the nearest signal has a noticeable effect on the current pulse.

Fig. 2 shows the average value of Q^2 factor of the WDM channels after the compensation using this proposed algorithm and traditional DBP under different launch powers when the step number per span equals 5. The higher the launch power, the higher the OSNR of the system. However, due to the existence of nonlinear effects, high launch power will bring more severe nonlinear impairments. Simulation results illustrate that the optimal launch power is 0 dBm per channel, and the Q^2 factor of the proposed hybrid algorithm is significantly better than that of DBP.

At the optimal launch power of 0 dBm, we compared the system performance improvement brought by the traditional DBP algorithm, the walk-off algorithm, and the proposed hybrid algorithm at different number of steps per span. To illustrate the performance improvement caused by nonlinear compensation, we consider the linear algorithm, which only operates the linear impairments compensation. From Fig. 3, it is evident that when the step number per span is small, the Q^2 factor of the system increases with the number of steps. Furthermore, the Q^2 factor obtained by the proposed hybrid algorithm is higher than that of the conventional DBP and walk-off algorithms under different steps. Compared with DBP, the walk-off algorithm relaxes the step size by approximately 3.3 times to achieve the same performance improvement. On the basis of the walk-off algorithm, the influence of adjacent pulses in each step on the current signal pulse is considered, so that the Q^2 factor is further improved. Finally, the hybrid algorithm brings a Q^2 factor improvement of 1.94 dB compared with DBP when the step number equals 5 per span.

At the optimal launch power of 0 dBm, the performance of the signal transmission over different distances was investigated in Fig. 4. Each

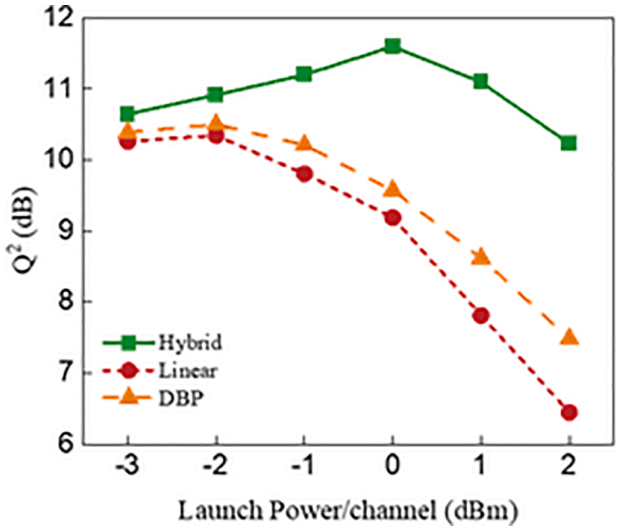


Fig. 2. The relationship between Q^2 of the system and the launch power under different nonlinear compensation methods.

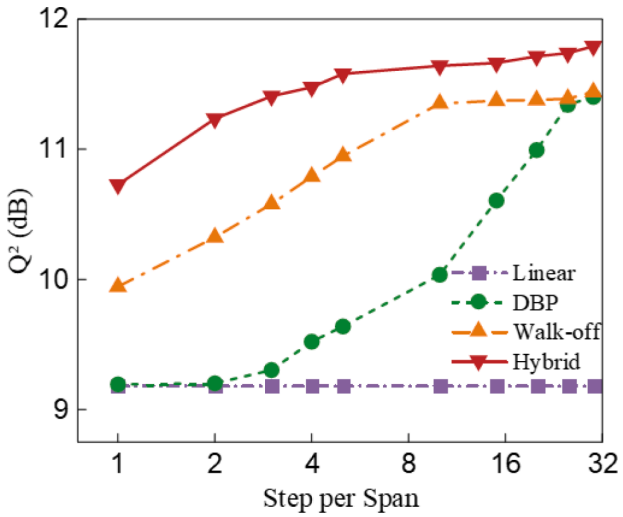


Fig. 3. The relationship between Q^2 of the system and the number of steps per span under different nonlinear compensation methods.

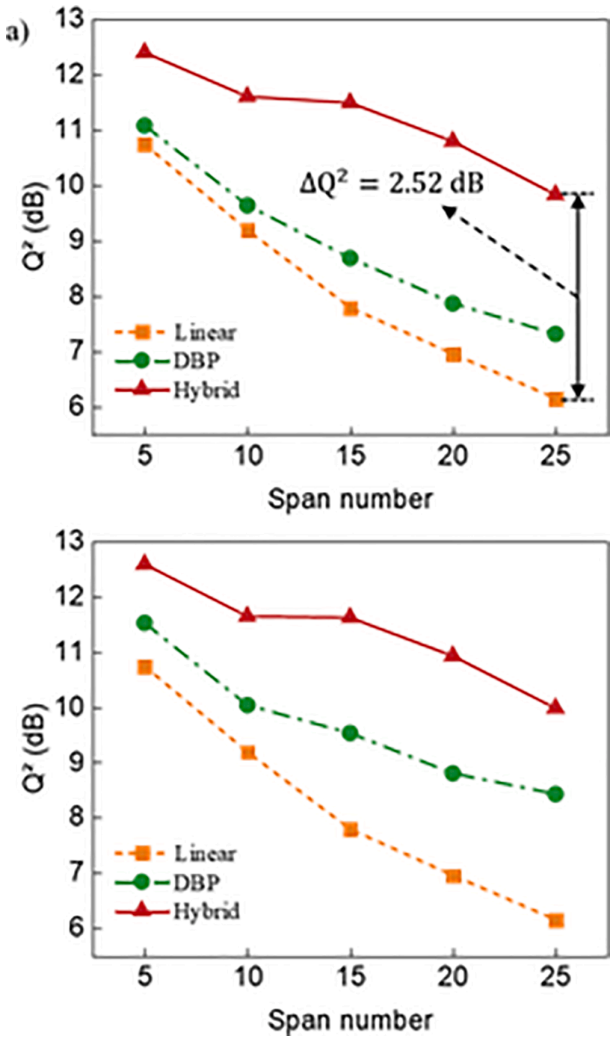


Fig. 4. The relationship between Q^2 of the system and the number of spans of transmission fiber under different nonlinear compensation methods when a) steps per span is 5 and b) steps per span is 10.

span is 80 km long, and the abscissa represents the number of spans. The hybrid algorithm exhibits characteristics similar to conventional DBP, where the system performance deteriorates as the transmission distance becomes larger, and the performance improvement brought by nonlinear compensation also increases. When the number of steps per span is 5 and 10, the Q^2 factors brought by the hybrid algorithm are higher than those of DBP in the transmission distance of 400 km, 800 km, 1200 km, 1600 km, and 2000 km, respectively. When the transmission distance reaches 2000 km and the number of steps is 5 in each span, the hybrid compensation algorithm can obtain a Q^2 improvement of 2.52 dB compared with conventional DBP.

4. Discussion

The computational complexity of DSP algorithms can be described by the number of multiplications used in the compensation process. Each calculation step includes a dispersion compensation and a nonlinear compensation. In the dispersion compensation part, each channel needs to operate two Fourier transforms, and the number of required multiplications is $2(N\log_2 N + N) \times M$, where N is the number of signals in one channel and M is the number of channels. The dispersion compensation procedures performed in DBP and the proposed hybrid algorithm are identical.

In the nonlinear compensation part, because the traditional DBP algorithm has to calculate the power and nonlinear phase shift, the required number of multiplications is $16NM$. In the walk-off algorithm, the performed number of complex multiplication operations is $3NM + 3NM(M - 1 + \log_2 N) + 10NM$ considering the Fourier and inverse Fourier transforms in the calculation of nonlinear phase shift and the calculation of the walk-off factor. On this basis, the hybrid algorithm considers the effect of $2k$ adjacent signals on the current signal. Hence, the number of multiplications is $3NM + 3NM(M - 1 + \log_2 N) + 10NM + 4kNM$.

Take $N = 2^{15}$, $k = 10$ and $M = 6$, the required numbers of multiplications for each step in the three algorithms are $288N$, $630N$, and $750N$, respectively. The required numbers of steps for the three algorithms to achieve the same Q^2 factor of 11.4 dB are 30, 10, and 3, respectively. Therefore, as shown in Fig. 5, the number of complex multiplication operations performed by this algorithm is reduced by 73.96 % compared with DBP and 64.29 % compared with the walk-off algorithm introduced in [23].

5. Conclusion

A hybrid algorithm for compensating the nonlinear impairments of SPM and XPM in the PDM-WDM optical communication system is proposed in this paper. Based on the solution of Manakov equations in the WDM system, the step size is relaxed and the computational complexity is reduced by separating the walk-off effect, and then the impact of adjacent signals on the current signal is further introduced to improve the compensation effect. By simulating a PDM-16QAM 30-Gbaud system with six channels over a 10 × 80 km link, we achieved a 1.94 dB improvement of the Q^2 factor at 5 steps per span. The computational complexity of the algorithm is also discussed, and the number of multiplication operations of the proposed hybrid algorithm is reduced by 73.96 % compared to the conventional DBP when the same compensation performance is achieved for an 800 km transmission.

CRediT authorship contribution statement

Jian Zhao: Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization. **Mingyu Chang:** Writing – original draft, Validation, Software, Methodology, Investigation. **Yuqing Yang:** Methodology, Investigation. **Xutao Wang:** Methodology, Investigation. **Sheng Li:** Methodology, Investigation. **Tianhua Xu:** Writing – review & editing, Supervision, Formal analysis.

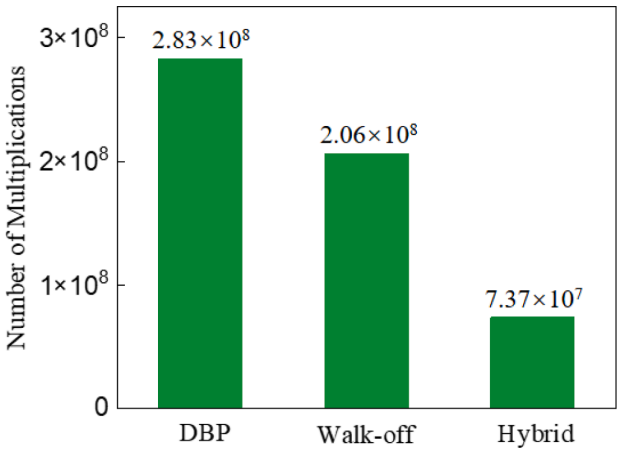


Fig. 5. The number of multiplications required by different algorithms to reach the same Q^2 factor in the transmission distance of 800 km.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the National Key Research and Development Program of China under Grant 2022YFE0202100, EU Horizon 2020 Project under Grant 101008280 (DIOR) and UK Royal Society under Grant IES\R3\223068.

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