Improving nonlinearity tolerance of 112-Gb/s PDM OFDM systems with coherent detection using BLAST algorithm

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The use of Bell Laboratories layered space-time (BLAST) architecture as a digital signal processing algorithm is proposed in this letter. It is aimed at improving the nonlinearity tolerance of a polarization division multiplexing (PDM) coherent optical orthogonal frequency division multiplexing (CO-OFDM) system. The application of this channel estimation algorithm simulates system performance under different dispersion compensation (DC) maps. Simulation results show that, compared with intra-symbol frequency-domain averaging (ISFA) algorithm, at least 5-dB Q-factor improvement is achieved for the PDM CO-OFDM system at 112-Gb/s data rate over an 800-km standard single-mode fiber (SSMF) without DC.

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Orthogonal frequency division multiplexing (OFDM) is generally susceptible to fiber nonlinearity and phase noise due to its high peak-to-average power ratio (PAPR)[1]. Therefore, it is critical to investigate and improve the coherent optical OFDM (CO-OFDM) system transmission performance, including fiber nonlinearity, which affects all types of long-haul optical systems. Various compensation algorithms that aim to solve fiber nonlinearity have been proposed in recent years. Among these algorithms is the traditional but complex digital back propagation[2] algorithm. Fiber nonlinearity compensation implemented by periodic dispersion maps[3] has already been proposed. An optimized optical phase conjugation (OPC) configuration for nonlinear cancellation has also been presented[4,5]. The new method incorporates biased clipping OFDM[6]. However, all of the algorithms mentioned have a high degree of computational complexity. In this letter, we propose a channel estimation algorithm to enhance nonlinearity tolerance based on the Bell Laboratories layered space-time (BLAST) algorithm.

The layered space-time architecture proposed by Foschini[7], now known as BLAST, is one of the most important approaches in improving wireless spectrum efficiency in multiple-input multiple-output (MIMO) systems. This architecture was originally designed for the transmitter that lacked knowledge of the channel characteristic within a Rayleigh fading environment. This architecture yields a system with a capacity that increases linearly with n for both fixed bandwidth and fixed total radiated power[7]. This method is then used by Djordjevic *et al.*[8] as a polarization-mode dispersion (PMD) compensation scheme suitable for use in multilevel ($M \geqslant 2$) block-coded modulation schemes with coherent detection. This algorithm compensates for the PMD influence effectively, although it has not yet been used in estimating fiber nonlinearity.

The intra-symbol frequency-domain averaging (ISFA) algorithm, first proposed by Liu *et al.*[9], is an efficient channel estimation method for CO-OFDM. It is robust against various transmission impairments, such as optical noise, chromatic dispersion (CD), PMD, polarization-dependent loss (PDL), and fiber nonlinearity.

The BLAST algorithm is proposed in this letter to improve the nonlinearity tolerance in polarization division multiplexing (PDM) CO-OFDM systems. The algorithm is then compared with the ISFA. The application of this channel estimation algorithm enables the simulation of system performance under different dispersion compensation (DC) maps. The simulation results show that, compared with the ISFA algorithm[10], at least 5-dB Q-factor improvement is achieved for the PDM CO-OFDM system at a 112-Gb/s data rate over an 800-km standard single-mode fiber (SSMF) without DC.

Polarization-multiplexed quadrature phase-shift keying (QPSK) modulation transmission with a gross data rate of 112 Gb/s for CO-OFDM systems were simulated in VPI transmission Maker 7.6. This process was conducted to evaluate the system performance. Figure 1 illustrates the schematic of the optical OFDM transmitter and receiver setup.

Assuming a perfectly synchronized system, the received signal $\mathbf{R}(k)$ of the kth subcarrier is expressed as[3]

$$\mathbf{R}(k) = \mathbf{H}(k)\mathbf{X}(k) + \mathbf{n}(k),\ \mathbf{H}(k)\begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix}, \quad (1)$$

where $\mathbf{X}(k) = [x_{x,k}, x_{y,k}]^{\mathrm{T}}$ denotes the transmitted symbol vector, $\mathbf{n}(k) = [n_{x,k}, n_{y,k}]^{\mathrm{T}}$ represents the noise vector dominantly determined by the amplified spontaneous emission (ASE), and $\mathbf{H}(k)$ is the 2×2 channel matrix determined by training-aided[11] channel estimation.

Using a 512-sized fast Fourier transform (FFT), 112-Gb/s data bits at the transmitter were encoded into the baseband OFDM signals. The cyclic prefix (CP) ratio was 1/8, which meant that 64 subcarriers were copied from the back of an OFDM symbol to the front. Meanwhile, the zero-padding ratio was maintained at 1/8, thus

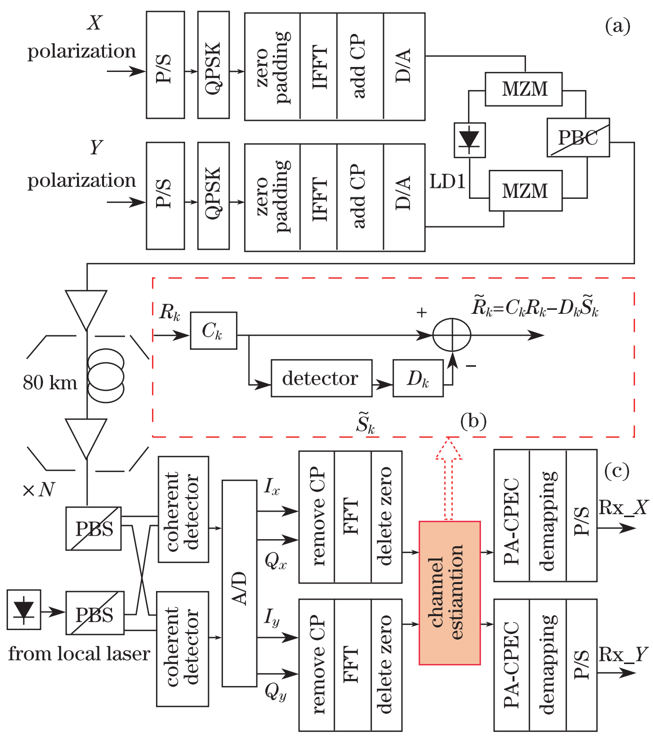

Fig. 1. 112-Gb/s PDM CO-OFDM system architecture. (a) Transmitter, (b) BLAST type nonlinearity mitigation scheme, and (c) receiver. PBS: polarization beam splitter (combiner), MZM: dual-drive Mach-Zehnder modulator.

avoiding the influence of un-ideal filters[12]. An optical IQ modulator was used to convert the baseband signal directly to the optical domain.

A transmission link consisting of 8 spans was employed. Each span included 100-km SSMF and an Erbium-doped fiber amplifier (EDFA), which compensated for the fiber loss. SSMF has a loss of 0.2 dB/km, a nonlinearity coefficient, n_2, of 2.6×10^{-20} m^2/W, and an effective cross section of 80 μm^2.

The two polarization signals consisted of an arbitrary mix of each transmitted signal after transmitting through the SSMF fiber at the receiver. Two coherent optical detectors were used to convert the signals from the optical to electrical domain. Four analog-to-digital (A/D) converters were used to generate the digital signal. We obtained channel estimation, the most important module, after removing the CP of these two polarizations, allowing them to pass through FFT, and deleting the zero padding. In this module, the previously known signals[10], along with the received ones, were applied to demultiplex the rotated polarization signals and obtain the estimation value of the original signals. A total of 32 subcarriers used as pilot signals were inserted periodically into the OFDM sequence for phase estimation[13,14] in the receiver. This process was carried out to examine the phase noise caused by the un-ideal apparatus. BER was estimated from the electrical signal quality measured from the constellation Q-factor using BER $= \frac{1}{2}\mathrm{erfc}(q/\sqrt{2})$. The results are presented in dB scale using $Q = 20\lg(q)$ due to the large spread in the values of q[15]. Meanwhile, Monte Carlo method was employed to evaluate system performance.

The configuration of nonlinearity cancellation scheme using the BLAST algorithm is shown in Fig. 1(b). Here, $\mathbf{R}_k = \begin{bmatrix} R_{x,k} & R_{y,k} \end{bmatrix}^{\mathrm{T}}$ represents the received signal on two polarizations, while $\widetilde{\mathbf{R}}_k = \begin{bmatrix} \widetilde{R}_{x,k} & \widetilde{R}_{y,k} \end{bmatrix}^{\mathrm{T}}$ represents the estimated signal through BLAST algorithm. The matrices $\mathbf{C}_k$ and $\mathbf{D}_k$ in the presence of ASE noise are determined by minimizing the mean square error, which leads to[8]

$$\mathbf{C_k} = \mathrm{diag}^{-1}(\mathbf{S}_k)(\mathbf{S}_k^*)^{-1}\mathbf{H}_k, \mathbf{D}_k = \mathrm{diag}^{-1}(\mathbf{S}_k)\mathbf{S}_k - \mathbf{I}, \tag{2}$$

where $\mathbf{I}$ is the identity matrix, and diag denotes the diagonal elements of $\mathbf{S}_k$. In addition, $\mathbf{S}_k$ is the upper triangular matrix obtained by Cholesky factorization of $\mathbf{H}_k^*\mathbf{H}_k + \mathbf{I}/\mathrm{SNR} = \mathbf{S}_k^*\mathbf{S}_k$, where SNR denotes the corresponding electrical SNR. We use $*$ to denote, conjugate, and transpose. The Euclidean detector was also used to create the preliminary decisions to obtain $\widetilde{\mathbf{S}}_k$.$\mathbf{H}_k$ is the transmission matrix obtained by training OFDM symbols[10]. Using Eq. (1), we obtain[8]

$$\begin{aligned} \widetilde{\mathbf{R}}_k &= \mathbf{C}_k\mathbf{R}_k - \mathbf{D}_k\widetilde{\mathbf{S}}_k \\ &= \mathrm{diag}^{-1}(\mathbf{S}_k)\,\mathbf{S}_k\mathbf{X}_k - \left[\mathrm{diag}^{-1}(\mathbf{S}_k)\,\mathbf{S}_k - \mathbf{I}\right]\widetilde{\mathbf{S}}_k \\ &\quad + N_k - \mathrm{diag}^{-1}(S_k)\,(S_k^*)^{-1}(I/\mathrm{SNR})X_k, \end{aligned} \tag{3}$$

where $\mathrm{diag}^{-1}(S_k)\,\mathrm{S}_k$ is the upper triangular matrix. The main diagonal of $\mathrm{diag}^{-1}(\mathbf{S}_k)\,\mathbf{S}_k - \mathbf{I}$ is zero and the last two parts in Eq. (3) are the noises that tend toward zero. From this, the estimated original signals were obtained.

After obtaining the transmission matrix in the ISFA algorithm, we averaged the estimated channel matrices for multiple adjacent frequency subcarriers in the same training symbol. We obtain[10]

$$\begin{bmatrix} h_{xx}(k') & h_{xy}(k') \\ h_{yx}(k') & h_{yy}(k') \end{bmatrix} = \frac{1}{\max(k_{\max},\, k'+m) - \max(k_{\min},\, k'-m) + 1} \sum_{k=k'-m}^{k'+m} \cdot \begin{bmatrix} h_{xx}(k) & h_{xy}(k) \\ h_{yx}(k) & h_{yy}(k) \end{bmatrix}, \tag{4}$$

where m is the average between $(2m+1)$ adjacent subcarriers. The signals out of the range are set to zero[10].

Next, we obtained the final channel transfer matrix, which was inversed and applied to other receiving signals to obtain the estimation of the original signal.

First, we evaluated the system in a back-to-back (B2B) configuration without using the fiber transmission line, after which we analyzed the system penalty using BLAST algorithm. Figure 2 shows the Q factor as a function of optical signal-to-noise ratio (OSNR) for 112-Gb/s PDM CO-OFDM systems in two situations. In the first case, we obtain the simulated value when the BLAST algorithm is applied. In the second case, the theoretical value is obtained while the BLAST algorithm is absent.

The theoretical value was obtained under the ideal conditions, which meant that fiber nonlinearity, CD, and PMD were not present in the transmission fiber (Fig. 2). This finding is demonstrated as

$$Q = 20 \times \lg\left[\sqrt{2} \times \mathrm{erfcinv}(2 \times \mathrm{BER})\right]. \tag{5}$$

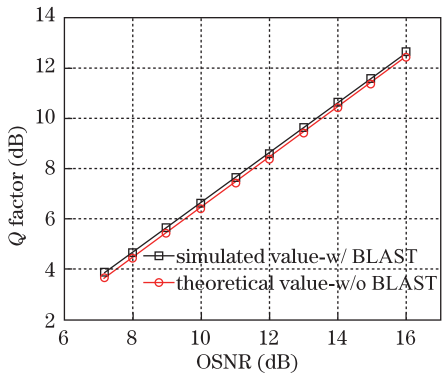

Fig. 2. Q factor as a function of OSNR for 112-Gb/s PDM CO-OFDM systems.

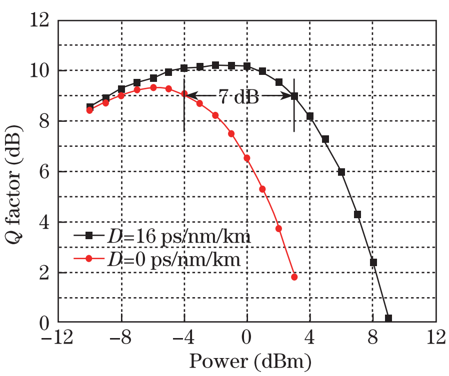

Fig. 3. Q factor after transmission over 16×80-km fiber spans verusu signal launch power with and without the consideration of fiber dispersion. OSNR is assumed to be fixed at 14 dB.

In this letter, QPSK modulation was used to perform symbol mapping. If the probabilities for transmitting 1 and 0 are equal, then the average BER for the best receive can be expressed as

$$P_{\mathrm{b}} = \frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_{\mathrm{b}}}{N_0}}\right). \quad (6)$$

The following formula is obtained by calculating the relationship between BER and OSNR as

$$\begin{aligned} Q &= 20 \times \lg\left(\sqrt{\frac{2E_{\mathrm{b}}}{N_0}}\right) = 20 \times \lg\left(\sqrt{4 \times \frac{B_{\mathrm{ASE}}}{R} \times \mathrm{OSNR}}\right) \\ &= 20 \times \lg\left(\sqrt{4 \times \frac{B_{\mathrm{ASE}}}{R} \times 10^{\left(\frac{1}{10}\mathrm{OSNR}\right)}}\right), \end{aligned} \quad (7)$$

where B_{ASE} =12.5 GHz is the bandwidth of the ASE noise, R =112 Gb/s represents the net bit rate. Thus, we obtained the relationship between theoretical Q and OSNR shown in Fig. 2.

The simulated value is quite consistent with the theoretical value, while the system penalty becomes less than 0.5 dB when BLAST algorithm is applied (Fig. 2). This result is acceptable when this algorithm is used. Meanwhile, in the dispersion-unmanaged single channel transmission system, the Q factor of the recovered signal derived from the calculated BER serves as a function of the signal power (Fig. 3). At the same time, the allowed signal power is 3 dBm with the consideration of fiber dispersion, which is 7-dB higher than when fiber dispersion is not considered.

This dispersion-induced nonlinear tolerance improvement can be explained by dispersion-induced broadening of high-power peaks in the OFDM signal waveform and the consequent removal of persistent high-power peaks[16]. This improvement is also explained by dispersion-induced phase mismatching in the four-wave mixing (FWM) interactions among the subcarriers.

Similar to most installed long-haul transport systems, in-line optical dispersion management was applied in this letter. On one hand, optical dispersion compensating fiber is commonly inserted in the optical amplifier that follows each transmission fiber span to compensate for the CD of the span. Thus, it is important to assess the nonlinear tolerance of CO-OFDM in dispersion-managed systems. On the other hand, the larger residual dispersion per span is known to lead to large overall dispersion excursion, suppressing the nonlinear interactions among the OFDM subcarriers[17]. Thus, we analyzed the system performance under different DC maps.

The penalty induced by self-phase modulation (SPM) becomes larger in a dispersion-managed single-channel transmission system. Two DC maps are considered in this study (Fig. 4), which shows the length of the fiber per span at 80 km. The red line shows the DC map 1 when the DC rate is 105%; the virtual red line is the reflection of the residual dispersion (RD) map per span. Meanwhile, the blue line shows the second condition when the DC rate is 80%; the virtual blue line is the reflection of RD map per span.

Figure 5 shows the simulated Q factor (derived from BER) of the 112-Gb/s PDM CO-OFDM signal after applying dispersion-managed transmission over the two dispersion maps. The constellation diagrams under varied input powers in different dispersion maps are shown in Figs. 5 (a)–(c). Figure 5 also shows the second dispersion map used in this work. Power tolerance is further increased by 1 to 0 dBm, which is 3-dB lower than in dispersion-unmanaged transmission. This indicates that the single-channel nonlinearity does not prevent PDM CO-OFDM system from undergoing dispersion-managed

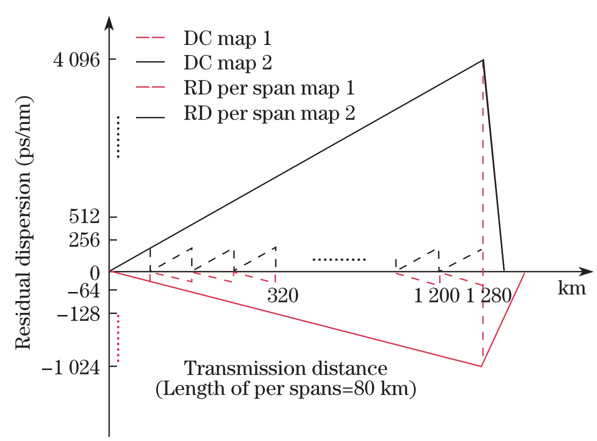

Fig. 4. (Color online) Two dispersion maps considered: (1) DC map 1: 105% DC rate; (2) DC map 2: 80% DC rate.

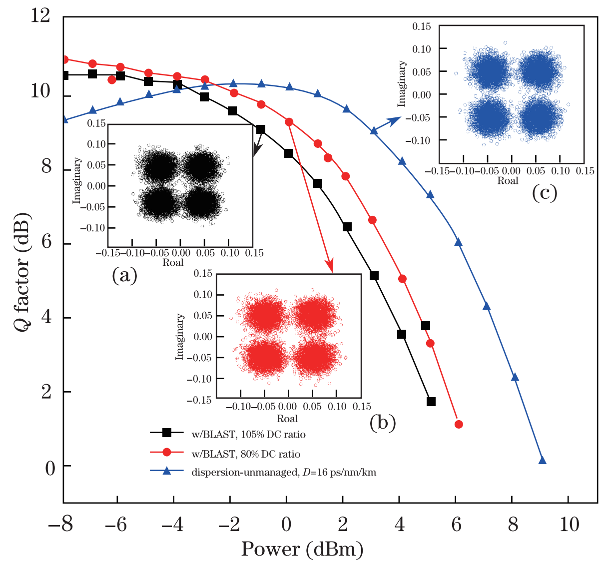

Fig. 5. Simulated Q factor of the 112-Gb/s PDM CO-OFDM signal after dispersion-managed transmission over 16×80 (km) SSMF spans with BLAST algorithm. (a) Constellation diagram for 105% DC ratio when input power equals –1 dBm; (b) constellation diagram for 80% DC ratio when input power equals 0 dBm; (c) constellation diagram for dispersion-unmanaged system when input power equals 3 dBm.

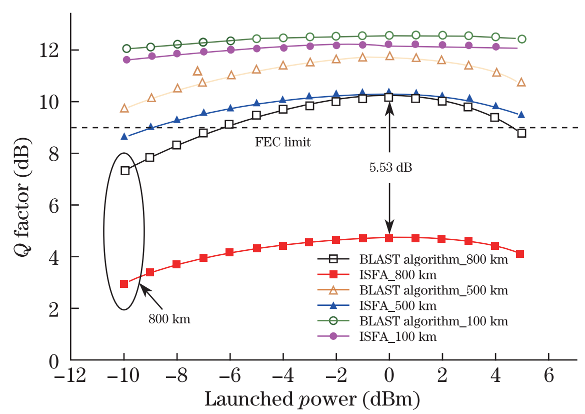

Fig. 6. Comparisons between the ISFA and BLAST algorithms for a 112-Gb/s PDM CO-OFDM system (OSNR =16 dB).

transmission.

Figure 6 plots the Q factor as a function of launched power and provides a comparison between the ISFA and BLAST methods.

This is under the condition that OSNR is set to 16 dB. Q factor increased from 4.72 to 10.25 dB when the fiber length is equal to 800 km (Fig. 6). Optimal Q also increased to 5.53 dB, indicating that the BLAST method eliminates most of the fiber nonlinearity influence. Additionally, when the launched power is in the range of –6–4 dBm, all BLAST tones achieved a Q factor that is higher than 9 dB. This Q factor is equivalent to BER of 2×10^{-3}, which is the FEC threshold with 7% overhead. No observable penalty is noted for an 800-km system transmission in this range.

In conclusion, we propose the application of BLAST algorithm as a channel detection algorithm in enhancing the fiber nonlinearity tolerance of the CO-OFDM system. System performance is simulated under different DC maps upon the application of the BLAST algorithm. Simulation results demonstrate that the proposed method significantly improves system performance. Compared with the ISFA algorithm, the BLAST algorithm achieved a 5-dB Q factor improvement for the PDM CO-OFDM system at a date rate of 112-Gb/s data over an 800-km SSMF without DC.

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