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Modulation format independent blind polarization demultiplexing algorithms for elastic optical networks

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Abstract We demonstrate a novel modulation format independent algorithm for adaptive blind polarization demultiplexing for elastic optical networks (EONs). We compare the proposed algorithm with traditional constant modulus algorithm (CMA) and radius-directed algorithm (RDA), in terms of performance in PM-QPSK, PM-16QAM and PM-64QAM coherent system, by simulating in back-to-back (BTB) and transmission sceneries. The simulation result shows that the modulation format independent algorithm can achieve universal adaptive blind polarization demultiplexing for PM-mQAM signals and gain slightly better performance in condition of lower optical signal noise ratio (OSNR). Furthermore, we also carry out experiments to investigate the performance of the proposed algorithm in BTB and 800 km transmission scenarios for 16 GBaud PM-QPSK and PM-16QAM. The experimental results demonstrate the conclusion of the numerical simulations.

Keywords PM-mQAM, blind polarization demultiplexing algorithms, modulation format independence, coordinate transformation, elastic optical networks (EONs)

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1 Introduction

Future internet traffic tends to become dynamic, heterogeneous and unpredictable due to the rapid increase of high-speed optical network with various modulation formats and diverse bitrates [1]. Transmission reach and spectral efficiency can be traded off by dynamic adjusting the modulation formats such that the network infrastructure is optimally used [2]. Therefore, elastic optical networks (EONs) [3] with flexible transceivers [4] support multiple modulation formats, especially the polarization multiplexing m-ary quadrature amplitude modulation (PM-mQAM) [5] bringing the total line rate doubled, are key components to support future traffic patterns, enhance spectral efficiency and optimize network resource utilization. Another pivotal components in EONs are the flexible receiver digital signal processing (DSP) units supporting diverse bitrates [6], alterable bandwidths [7] and flexible modulation formats [8,9] without additional optical components. Thus, from the perspectives of receiver DSP design, EONs strongly

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desire an universal DSP platform which could adaptively and adequately accomplish equalization of various transmission impairments and realize adaptive blind polarization demultiplexing for arbitrary modulation formats [10].

Typically, based on coherent detection [11], the majority of the chromatic dispersion (CD) accumulated through propagation could be removed by a FIR filter in frequency domain at first [12]. Then an adaptive butterfly FIR filter implements polarization demultiplexing [13], meanwhile compensating for residue CD and polarization mode dispersion (PMD). Regularly, we can use the training sequence (TS) to achieve the same purpose [14]. However, the training sequence induces additional overhead making bandwidth efficiency decreased and potentially increase transceiver complexity. Modified constant modulus algorithm (MCMA) [15] with simple structure and robustness, could correct phase rotation, is the most famous one of blind equalization [16] and adaptive polarization demultiplexing algorithm. Nevertheless, it is not suitable for high-order PM-mQAM polarization demultiplexing, because PM-mQAM signals distribute in a few known radius. As a result, even when the channel equalization is perfectly implemented, the error function still cannot exactly approach zero. Thus cascade algorithm gets more attention in which MCMA is utilized to realize pre-convergence and radius-directed algorithm (RDA) [17] achieving further accurate convergence. However, this cascade scheme would increase the complexity of the DSP units. Therefore, designing a polarization demultiplexing algorithm with simple structure and low computational complexity is strongly desired.

In this paper, we focus on flexible transceivers supporting multiple modulation formats. Accordingly, we propose and demonstrate a useful modulation format independent algorithm for adaptive blind polarization demultiplexing for elastic optical networks (EONs). We describe the technique in detail, comparing the performance of the proposed algorithm with the CMA for PM-QPSK system and RDA for PM-16QAM and PM-64QAM coherent system. The remainder of this paper is as follows. A comprehensive principle description of the proposed algorithm is elaborated in Section 2. Section 3 shows the simulation setup and results, comparing performance in PM-QPSK, PM-16QAM and PM-64QAM coherent system, all in terms of back-to-back and transmission tolerance to optical signal noise ratio (OSNR). Section 4 verifies the performance of the proposed algorithm by 16 GBaud PM-QPSK and PM-16QAM experiments. Conclusion of the proposed algorithm is finally drawn in Section 5.

2 Principle of the proposed algorithm

According to the characteristics of the square QAM constellations, we propose a novel modulation format independent algorithm for adaptive blind polarization demultiplexing based on coordinate transformation (CT) of the butterfly FIR filter output signals, and take advantage of a modified constant modulus algorithm (MCMA) cost function to update the taps coefficients. The principle block diagram of the proposed algorithm is shown in Figure 1.

Where $x_{in}(k)$ and $y_{in}(k)$ are the received digital signals of two polarizations which are inputted to the butterfly FIR filter. The N taps input vectors of the digital signals can be defined by

$$\begin{aligned} x_{in}(k) &= [s_x(k), s_x(k-1), \ldots, s_x(k-N+1)]^{\mathrm{T}}, \\ y_{in}(k) &= [s_y(k), s_y(k-1), \ldots, s_y(k-N+1)]^{\mathrm{T}}. \end{aligned} \tag{1}$$

The N-taps weight vectors of the filter are denoted as

$$\begin{aligned} h_{xx}(k) &= [w_{xx1}(k), w_{xx2}(k), \ldots, w_{xxN}(k)]^{\mathrm{T}}, \\ h_{xy}(k) &= [w_{xy1}(k), w_{xy2}(k), \ldots, w_{xyN}(k)]^{\mathrm{T}}, \\ h_{yx}(k) &= [w_{yx1}(k), w_{yx2}(k), \ldots, w_{yxN}(k)]^{\mathrm{T}}, \\ h_{yy}(k) &= [w_{yy1}(k), w_{yy2}(k), \ldots, w_{yyN}(k)]^{\mathrm{T}}. \end{aligned} \tag{2}$$

The filters are applied as a time-domain convolution. The kth filtered output samples $x(k)$ and $y(k)$ for

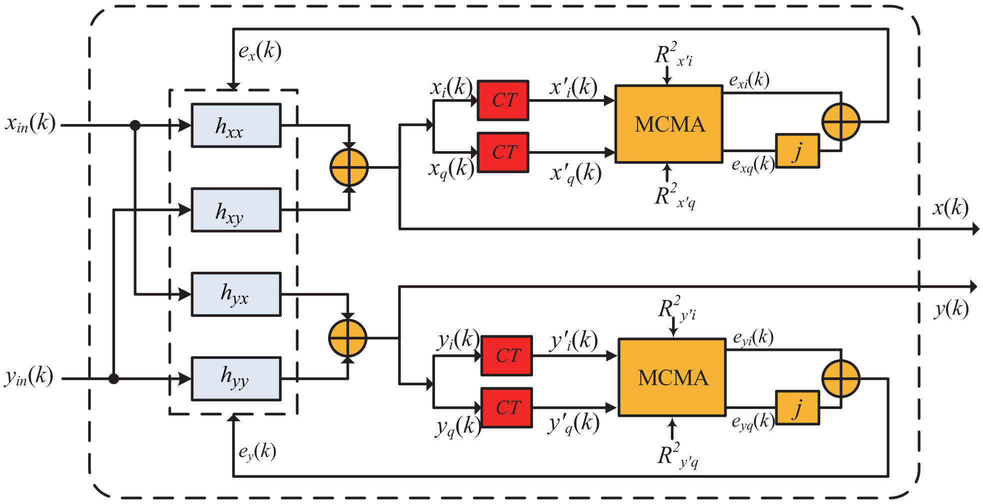

Figure 1 (Color online) Principle block diagram of the proposed algorithm.

the x and y polarizations can be represented as follows:

$$\begin{aligned} x(k) &= h_{xx}(k)^{\mathrm{T}} \cdot x_{in}(k) + h_{xy}(k)^{\mathrm{T}} \cdot y_{in}(k), \\ y(k) &= h_{yx}(k)^{\mathrm{T}} \cdot x_{in}(k) + h_{yy}(k)^{\mathrm{T}} \cdot y_{in}(k). \end{aligned} \tag{3}$$

To succinctly describe, we only analyze the x polarization here. Considering the robustness and easy implementation of MCMA, we make a transformation of the butterfly filter output signals so that the N-taps weight vectors could be updated in a constant-module way. The transform method can be expressed as follows:

$$\begin{aligned} x_i'(k) &= x_i(k) - 4 \cdot \mathrm{sign}\left[x_i(k)\right] - 2 \cdot \mathrm{sign}\left\{x_i(k) - 4 \cdot \mathrm{sign}\left[x_i(k)\right]\right\}, \\ x_q'(k) &= x_q(k) - 4 \cdot \mathrm{sign}\left[x_q(k)\right] - 2 \cdot \mathrm{sign}\left\{x_q(k) - 4 \cdot \mathrm{sign}\left[x_q(k)\right]\right\}, \end{aligned} \tag{4}$$

where sign$(\cdot)$ denotes sign function. $x_i(k)$ and $x_q(k)$ are the in-phase and quadrature parts of the origin coordinates of the butterfly filter output signal $x(k)$, respectively. $x_i'(k)$ and $x_q'(k)$ are the in-phase and quadrature parts of the new signals transformed from $x_i(k)$ and $x_q(k)$. Obviously, via such coordinate transformation, square QPSK, 8QAM, 16QAM, 32QAM and 64QAM signals with known radius of ± 1, ± 3, ± 5 and ± 7, can be adjusted to a constant modulus of QPSK. The cost function of the proposed algorithm is expressed as

$$J(k) = E[|x_i'(k)|^2 - R^2{}_{x'i}] + E[|x_q'(k)|^2 - R^2{}_{x'q}]. \tag{5}$$

The constant modulus $R^2{}_{x'i}(k)$ and $R^2{}_{x'q}(k)$ are given by the following transformation formulas:

$$R^2_{x'i} = \frac{E\{|s'_{xi}(k)|^4\}}{E\{|s'_{xi}(k)|^2\}}, \quad R^2_{x'q} = \frac{E\{|s'_{xq}(k)|^4\}}{E\{|s'_{xq}(k)|^2\}}, \tag{6}$$

where $s_{xi}'(k)$ and $s_{xq}'(k)$ are the in-phase and quadrature parts of the new signals transformed from $s_{xi}(k)$ and $s_{xq}(k)$ of standard PM-mQAM, respectively. The following is the error function of the proposed algorithm:

$$e_{xi}(k) = x_i(k)\left(|R_{x'i}|^2 - |x_i'(k)|^2\right), \quad e_{xq}(k) = x_q(k)\left(|R_{x'q}|^2 - |x_q'(k)|^2\right), \tag{7}$$

$$e_x(k) = e_{xi}(k) + je_{xq}(k), \tag{8}$$

where $e_{xi}(k)$ and $e_{xq}(k)$ are the real and imaginary parts of the error function $e_x(k)$. The tap coefficients of the filter are updated by

$$\begin{aligned} h_{xx}(k+1) &= h_{xx}(k) + \mu \cdot e_x(k) \cdot x_{in}{}^*(k), \\ h_{xy}(k+1) &= h_{xy}(k) + \mu \cdot e_x(k) \cdot y_{in}{}^*(k), \\ h_{yx}(k+1) &= h_{yx}(k) + \mu \cdot e_y(k) \cdot x_{in}{}^*(k), \\ h_{yy}(k+1) &= h_{yy}(k) + \mu \cdot e_y(k) \cdot y_{in}{}^*(k), \end{aligned} \tag{9}$$

where $x_{in}{}^{*}(k)$ and $y_{in}{}^{*}(k)$ are the complex conjugates of $x_{in}(k)$ and $y_{in}(k)$, respectively. μ means the step size, changing from large to small in different iteration loop during the implementation of the DSP. A larger step means faster convergence while a smaller one achieves more accurate operation. As a brief review, the polarization demultiplexing principle can be expressed as the following matrix equation:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix} \begin{bmatrix} x_{in} \\ y_{in} \end{bmatrix} = H \begin{bmatrix} x_{in} \\ y_{in} \end{bmatrix}. \tag{10}$$

The aims of the filter is adjusting the coefficients of the butterfly FIR filter matrix H to adequately achieve adaptive polarization demultiplexing for the arbitrary modulation formats.

It should be noticed that computational complexity of the equalizer is a key concern to prove a cost-efficient solution and enable power efficient implementation. As shown in literature [18], making sign(·) of the output symbol requires only addition operations. Accordingly, we evaluate the complexity of the proposed algorithm and make comparisons with CMA and RDA. The calculation results show that per output symbol requires $8N{+}2$ (N is the filter taps number) times real multiplications and $8N$ times real additions for CMA, $8N{+}2$ times real multiplications and $8N{+}6$ times real additions for RDA to achieve polarization demultiplexing of PM-16QAM signals while it is $8N{+}2$ times real multiplications and $8N{+}18$ times real additions of PM-64QAM signals, and $8N{+}4$ times real multiplications and $8N{+}14$ times real additions for the proposed algorithm. From the complexity analysis, when N is equal to a typical value of 13, we can see that the proposed algorithm slightly increases the computational complexity by less than 2% compared with traditional CMA as well as RDA. Therefore, the proposed algorithm could be a candidate for achieving modulation format independent polarization demultiplexing of multi-modulus PM-mQAM ($m \leqslant 64$) signals in elastic optical networks.

3 Numerical simulations and results

3.1 Simulation setting

To evaluate the performance of our propose algorithm, numerical simulations of 16 GBaud PM-QPSK, 16 GBaud PM-16QAM and 16 GBaud PM-64QAM have been carried out using CMA for PM-QPSK and RDA for PM-16QAM/64QAM for polarization demultiplexing in the back-to-back (BTB) and 800 km transmission scenario, respectively.

The setup of the transmitter, the fiber channel and the coherent receiver for both of PM-QPSK, PM-16QAM and PM-64QAM are shown in Figure 2. We use $2^{15}-1$ pseudo-random bit sequence (PRBS) to generate Gray mapped two-level PM-QPSK, four-level PM-16QAM and eight-level PM-64QAM signals with the same symbol rate of 16 GBaud. Each polarization state of the laser output from the continuous wave (CW) with 100 kHz line-width is modulated. Then, the mapped QAM signals drive two IQ-modulators (IQMs) [19] followed with a Bessel filter with 12 GHz 3 dB bandwidth to limit the bandwidth of the signals. Polarization beam combiner (PBC) combines the orthogonal polarizations of the modulated signals from the two IQMs. The local oscillator laser line-width is 100 kHz and the frequency offset between signal carrier and LO is 1 GHz. In transmission simulation, the attenuation of fiber is 0.2 dB/km and the dispersion coefficient is 16 ps/nm/km while PMD coefficient is 0.1 ps/km$^{1/2}$. Noise from the erbium-doped fiber amplifiers (EDFA) is added at each amplifier and the fiber link is composed of 800 km SSMF spans with 0.2 dB/km attenuation and each span loss is completely compensated by an EDFA. To easily adjust the optical signal-to-noise ratio (OSNR), an attenuator (Att) and an EDFA before an optical band-pass filter (OBPF) are used to adjust the optical signal-to-noise ratio (OSNR) of the signals. Before the optical signals splitted by a polarization beam splitter (PBS), the amplified spontaneous emission (ASE) noise is suppressed by the 0.2 nm bandwidth OBPF.

We use the same hardware for all above modulation formats at coherent receiver end. The polarization diversity is obtained by two optical 90° hybrids. Four couple balanced photo detectors (PD) achieve photoelectric conversion. Digital to analog conversion (ADCs) realize sampling at 2 sample per symbol.

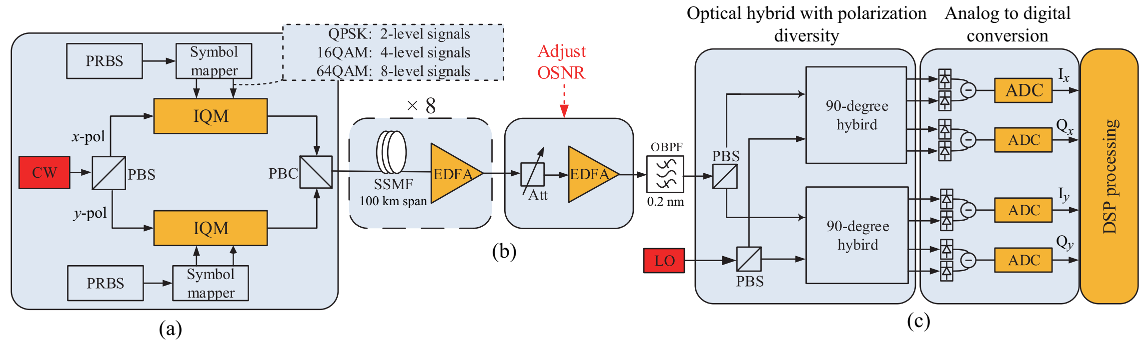

Figure 2 (Color online) Block diagram of the simulation setup for PM-QPSK/16QAM/64QAM. (a) Transmitter; (b) fiber link; (c) coherent receiver.

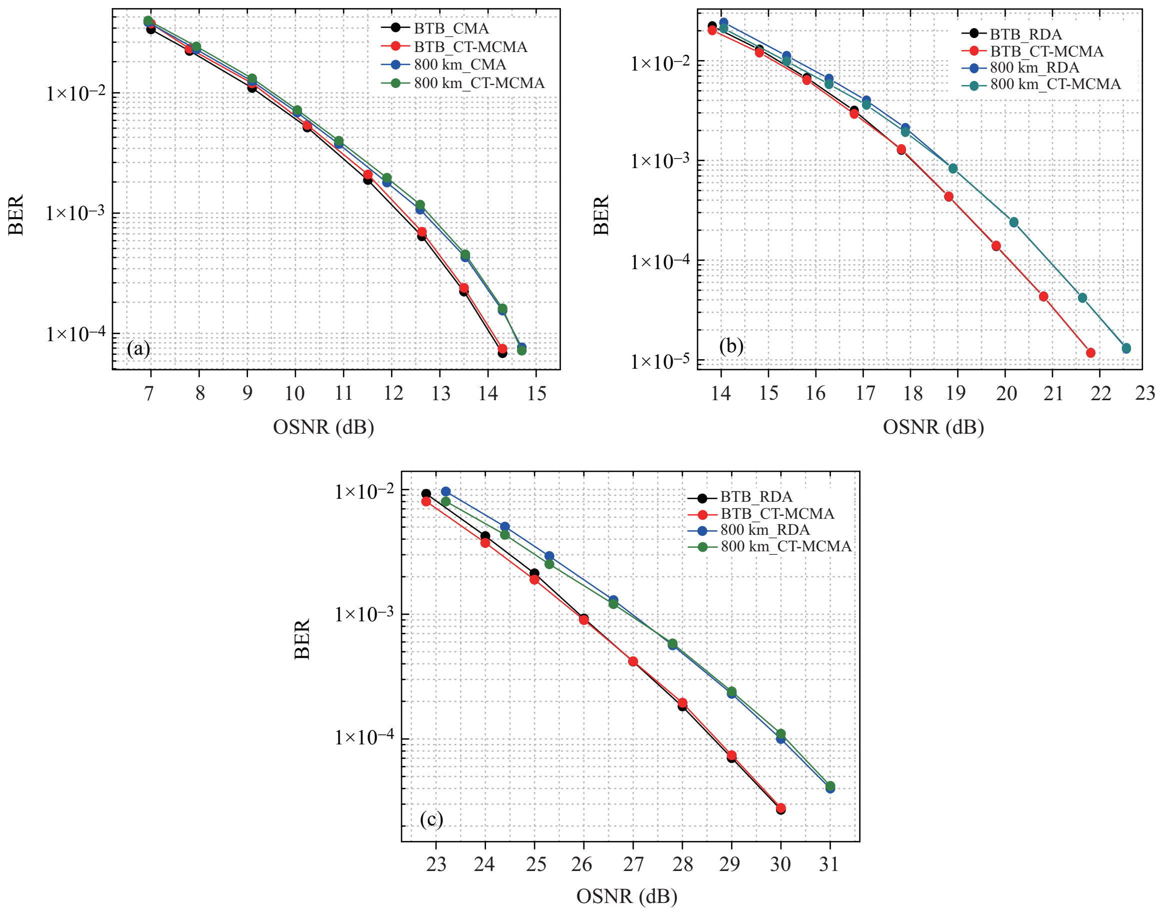

Figure 3 (Color online) Simulation results in back-to-back (BTB) and 800 km transmission scenario. (a) PM-QPSK; (b) PM-16QAM; (c) PM-64QAM.

Finally, the up-sampling signals send into DSP platform. It should be noted that, the initial step-size and tap numbers of the butterfly FIR filter are optimized when dealing with different modulation formats.

3.2 Simulation results

To straightforwardly evaluate the performance of our propose algorithm, we use CMA and RDA as comparisons for the proposed algorithm. The OSNR is ranging from 7–14.8 dB for PM-QPSK, 13.7–23 dB for PM-16QAM and 22.8–31 dB for PM-64QAM, respectively.

Figure 3(a) shows the BER vs. OSNR curves for 16 GBaud PM-QPSK in back-to-back and 800 km transmission, polarization demultiplexed by the proposed algorithm (hereinafter be referred to as CT-

MCMA) and CMA. The OSNR for PM-QPSK is around 12.1 dB to achieve a BER of 1E−3 in back-to-back scenario for the proposed algorithm as well as CMA. In 800 km transmission scenario, it requires around 12.6 dB OSNR for the proposed algorithm as well as CMA to achieve a BER of 1E−3, resulting in 0.5 dB transmission cost.

Figure 3(b) gives the BER vs. OSNR curves for 16 GBaud PM-16QAM, polarization demultiplexed by the proposed algorithm and RDA. The OSNR for PM-16QAM is around 18 dB to achieve a BER of 1E−3 in back-to-back scenario for the proposed algorithm as well as RDA. In 800 km transmission scenario, it requires around 18.7 dB for the proposed algorithm as well as RDA to achieve a BER of 1E−3, resulting in 0.7 dB transmission cost.

Figure 3(c) is the BER vs. OSNR curves for 16 GBaud PM-64QAM in back-to-back and 800 km transmission, polarization demultiplexed by the proposed algorithm and RDA. The measured required OSNR for PM-64QAM is around 25.8 dB to achieve a BER of 1E−3 in back-to-back scenario for the proposed algorithm as well as RDA. In 800 km transmission scenario, it requires around 27 dB for the proposed algorithm as well as RDA to achieve a BER of 1E−3, resulting in 1.2 dB transmission cost.

Particularly, both in PM-QPSK, PM-16QAM and PM-64QAM polarization multiplexing coherent detection system, the simulation results confirm that the proposed algorithm can achieve universal adaptive blind polarization demultiplexing, and it gains slightly better performance than RDA in condition of low OSNR.

4 Experiments and results

4.1 Experiments setting

To further confirm the simulation results, including BTB and 800 km transmission, we carry out experimental investigations for 16 GBaud PM-QPSK and 16 GBaud PM-16QAM.

Figure 4 shows the schematic of experimental setup for PM-QPSK and PM-16QAM including the transmitter, the fiber channel and the coherent receiver. At the transmitter, as shown in Figure 4(a), we use $2^{15} - 1$ pseudo-random bit sequence (PRBS) to generate Gray mapped PM-QPSK and PM-16QAM signals. The four field components of the PM-QPSK and PM-16QAM signals, corresponding to I- and Q-components of both x- and y-polarizations, are sent into four synchronized 8-bit digital-to-analog converters (DACs) with 13 GHz 3 dB analog bandwidth and work at 64 GSa/s. Fourfold oversampling is used to generate 16 GBaud signals, and these signals are used to drive a polarization multiplexed I/Q modulator. Consider that the nonlinearity effects from modulators could cause signals distortion, in order to alleviate this effect, the pre-distortion method was performed. The optical carrier is from an external cavity laser (ECL) at 193.475 THz with a linewidth of 100 kHz.

In transmission experiments, the signal is launched with a power of 0 dBm, and the link is composed of 800 km SSMF spans with 0.159 dB/km attenuation and each span loss is completely compensated by an EDFA. Figure 4(b) illustrates the optical spectrum of 16 GBaud PM-16QAM. As shown in Figure 4(c), an attenuator (Att) and an EDFA before an optical band-pass filter (OBPF) are used to adjust the optical signal-to-noise ratio (OSNR) of the signals. The OBPF with 0.2 nm bandwidth is used to suppress amplified spontaneous emission (ASE) noise outside the signal spectrum. The linewidth of the ECL used as the local oscillator for coherent detection is less than 100 kHz. The received signals are sent to a commercial integrated polarization-diverse coherent receiver (U2T CPRV1220A, 3 dB electric bandwidth 25 GHz), and the four output RF signals of the coherent receiver are sampled at 80 GSa/s sample rate by the Lecroy WaveMaster-8-Zi Real-time sampling oscilloscope and transferred to a computer for offline DSP processing.

As shown in Figure 4(d), the received signal is first upsampling to 2 samples/symbol, and I/Q imbalance compensation, chromatic dispersion (CD) compensation and clock recovery [20], and then passed through the butterfly FIR filter to implement polarization demultiplexing. A 4th power frequency-domain algorithm [21] is used to estimate the frequency offset between signal carrier and LO (in fact, the frequency offset is less than 100 MHz in the experiment). The Viterbi-Viterbi algorithm [22] (using blocks

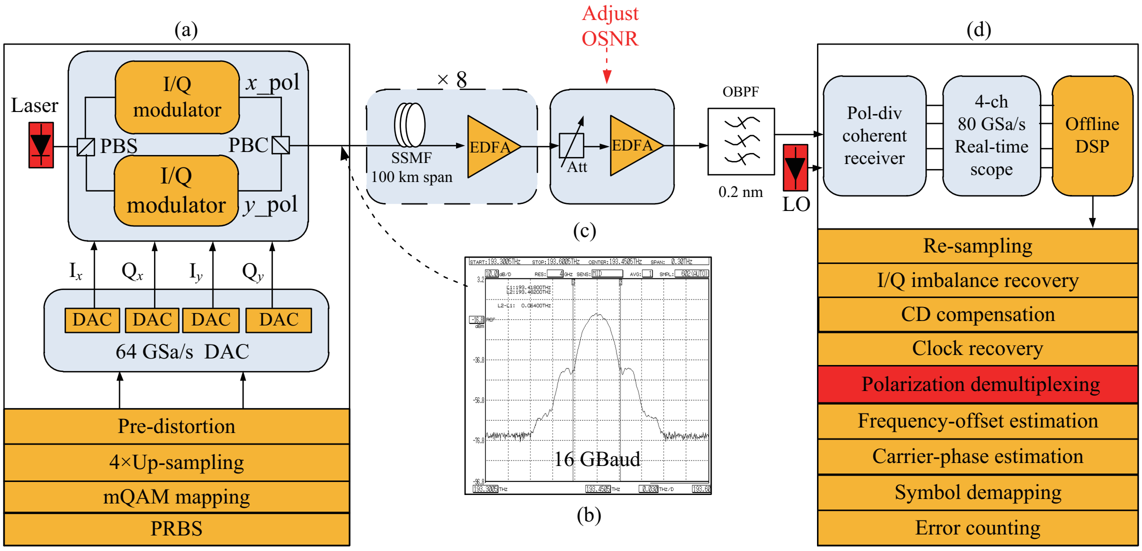

Figure 4 (Color online) Experimental setup for 16 GBaud PM-QPSK/PM-16QAM. (a) Transmitter; (b) spectrum; (c) fiber link; (d) receiver.

of 32–64 samples) and the blind phase search algorithm [23] (using blocks of 64 samples and 64 test phase angles) are used to achieve carrier-phase estimation for PM-QPSK and PM-16QAM, respectively. Finally, hard decision is made prior to BER estimation. In order to compare the performance, we use the proposed algorithm named CT-MCMA and conventional constant modulus algorithm (CMA) to implementing polarization demultiplexing for PM-QPSK, and adopt the proposed algorithm and the radius directed algorithm (RDA) for PM-16QAM, respectively.

4.2 Experiments results

Figure 5(a) shows the BER vs. OSNR curves for 16 GBaud PM-QPSK in back-to-back and 800 km transmission, polarization demultiplexed by the proposed algorithm and CMA. The results show that the PM-QPSK system requires around 13.1 dB OSNR to achieve 1E−3 BER in back-to-back scenario for both of CT-MCMA and CMA. Meanwhile, as for 800 km transmission scenario, it requires around 13.6 dB OSNR for the proposed algorithm as well as CMA to achieve a BER of 1E−3, resulting in 0.5 dB transmission cost. Figure 5(b) shows the measured 800 km transmission constellations of PM-QPSK at 1E−3 BER. Furthermore, it can be seen that by adopting the proposed algorithm, we can obtain an equal performance compared with CMA.

The BER vs. OSNR curves for 16 GBaud PM-16QAM in back-to-back and 800 km transmission are depicted in Figure 5(c). The PM-16QAM system requires around 19.5 dB OSNR, using the proposed algorithm and RDA in back-to-back scenario, to achieve a BER of 1E−3. Meanwhile, as for 800 km transmission scenario, it requires around 20.5 dB OSNR for the proposed algorithm as well as RDA to achieve a BER of 1E−3, resulting in 0.5 dB transmission cost. Figure 5(d) shows the measured 800 km transmission constellations of PM-16QAM at 1E−3 BER. Furthermore, it can be seen that by adopting the proposed algorithm, we can obtain an equal performance compared with RDA. The experimental results shows that the modulation format independent algorithm can achieves flexible and adaptive blind equalization and polarization demultiplexing, and gains slightly better performance in condition of lower optical signal noise ratio than RDA in all above systems.

5 Conclusion

In this paper, we demonstrate a novel modulation format independent algorithm for adaptive blind polarization demultiplexing using numerical simulations and experiments in back-to-back and transmission

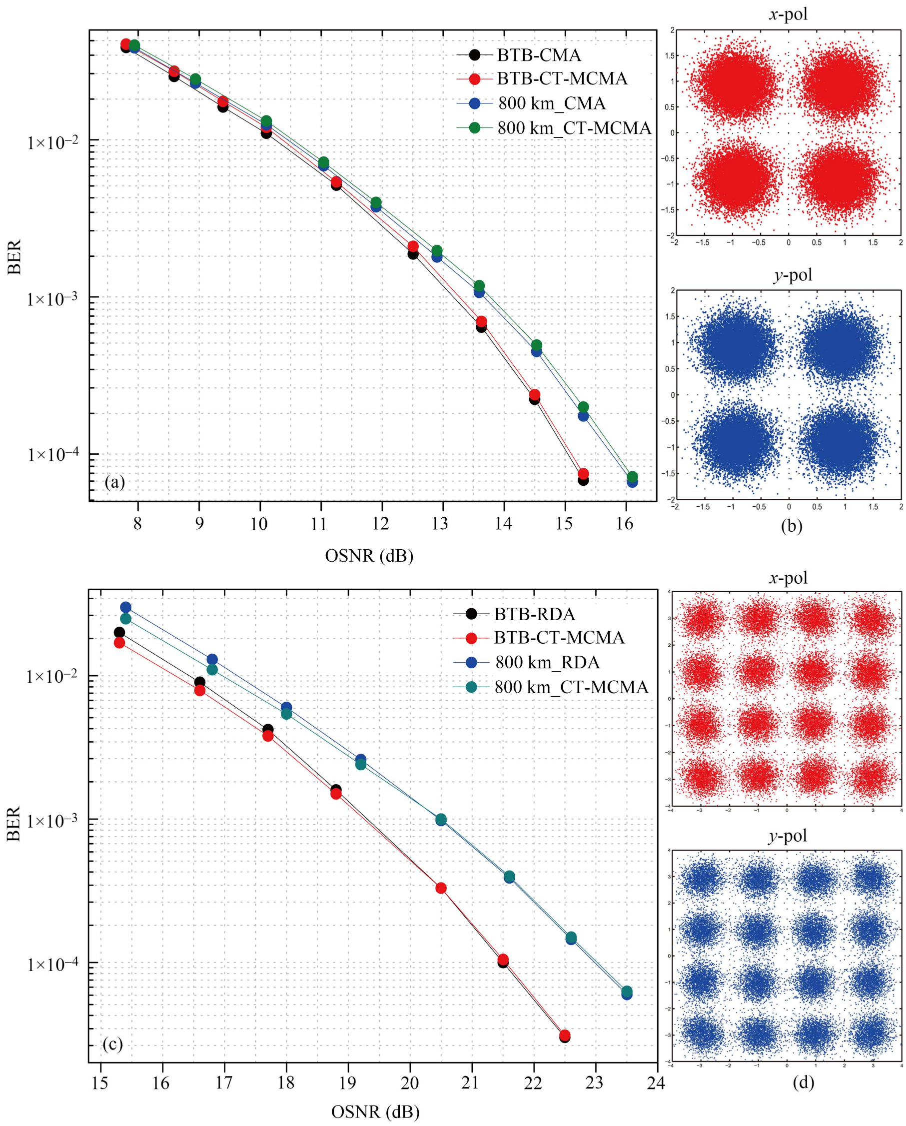

Figure 5 (Color online) Experimental results for PM-QPSK and PM-16QAM in back-to-back (BTB) and 800 km transmission scenario, respectively. (a) BER vs. OSNR curve for PM-QPSK; (b) experimentally measured constellations for PM-QPSK at 1E−3 BER; (c) BER vs. OSNR curve for PM-16QAM; (d) experimentally measured constellations for PM-16QAM at 1E−3 BER.

scenarios. The numerical simulations results for 16 GBaud PM-QPSK/PM-16QAM/PM-64QAM indicate that the proposed algorithm can achieve flexible adaptive blind polarization demultiplexing for PM-mQAM ($m \leqslant 64$) and has a slightly better performance than RDA at lower OSNR condition. Moreover, we also experimentally investigate the back to back and 800 km transmission performance of the proposed algorithm in 16 GBaud PM-QPSK/PM-16QAM coherent system. The experimental results further confirm the numerical simulation. In conclusion, the novel modulation format independent algorithm is a very attractive candidate for bind flexible adaptive polarization demultiplexing of alterable modulation formats in elastic optical networks.

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Conflict of interest The authors declare that they have no conflict of interest.

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