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Yan Han
University of Central Florida

Guifang Li
University of Central Florida

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Coherent optical communication using polarization multiple-input-multiple-output

Yan Han and Guifang Li

College of Optics and Photonics / CREOL & FPCE, University of Central Florida
4000 Central Florida Blvd., Orlando, FL 32816
yanhan@creol.ucf.edu

Abstract: Polarization-division multiplexed (PDM) optical signals can potentially be demultiplexed by coherent detection and digital signal processing without using optical dynamic polarization control at the receiver. In this paper, we show that optical communications using PDM is analogous to wireless communications using multiple-input-multiple-output (MIMO) antennae and thus algorithms for channel estimation in wireless MIMO can be ready applied to optical polarization MIMO (PMIMO). Combined with frequency offset and phase estimation algorithms, simulations show that PDM quadrature phase-shift keying signals can be coherently detected by the proposed scheme using commercial semiconductor lasers while no optical phase locking and polarization control are required. This analogy further suggests the potential application of space-time coding in wireless communications to optical polarization MIMO systems and relates the problem of polarization-mode dispersion in fiber transmission to the multi-path propagation in wireless communications.

OCIS codes: (060.1660) Coherent communications; (060.4510) Optical communications; (060.5060) Phase modulation; (260.5430) Polarization; (070.6020) Signal processing

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1. Introduction

Wavelength-division multiplexing (WDM) can significantly increase the capacity of optical communication systems. The transmission cost per bit is reduced with the increase of capacity since the WDM channels share the same fiber and optical amplifiers. To accommodate more channels to further increase capacity, closer channel spacing and/or more wavelengths should

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be used. This may not only require the use of broadband optical amplifiers but also increase system complexity in terms of multiplexing, demultiplexing and dispersion management. Another potentially economical approach to increasing the overall capacity is to use advanced modulation formats with higher spectral efficiency. With the reduced symbol rates, systems using high-spectral efficiency modulation formats could be more tolerant to chromatic and polarization-mode dispersion. Generally, there exists a tradeoff between spectral efficiency and sensitivity of a modulation format. Coherent detection is usually considered necessary to alleviate this tradeoff. For example, quadrature phase-shift keying (QPSK) with coherent detection has the same sensitivity as binary phase-shift keying (BPSK), but doubles the spectral efficiency. Additionally, coherent detection can also facilitate channel demultiplexing and chromatic dispersion compensation in a WDM system [1, 2].

Optical phase locking and polarization control are generally required in coherent detection. Conventional phase locking uses costly optical phase-locking loops. With the advance of A/D converter, phase locking (or phase estimation) using digital signal processing (DSP) at 10 GSymbol/s has been recently reported [3]. Polarization dependence of coherent detection can be managed by using optical dynamic polarization control or polarization diversity receiver [4]. In a conventional polarization diversity receiver, two sets of receivers are used to independently detect signal components in the two orthogonal polarization states and the original signal is recovered after combining two components, which is rather inefficient in terms of hardware. However, when two PDM channels are simultaneously transmitted at orthogonal polarization states, polarization diversity receiver in principle can receiver both channels, for example, by using optical dynamic polarization control at the receiver. It has been suggested that PDM optical signals can potentially be demultiplexed by combining coherent detection and polarization/phase diversity [1]. In this paper, we show that optical communications using PDM is analogous to wireless communications using multiple-input-multiple-output (MIMO) antennae and thus algorithms for channel estimation in wireless MIMO can be ready applied to optical polarization MIMO (PMIMO). The effectiveness of this scheme when using commercial semiconductor lasers free of active optical controls is also investigated by simulations.

2. Optical polarization MIMO

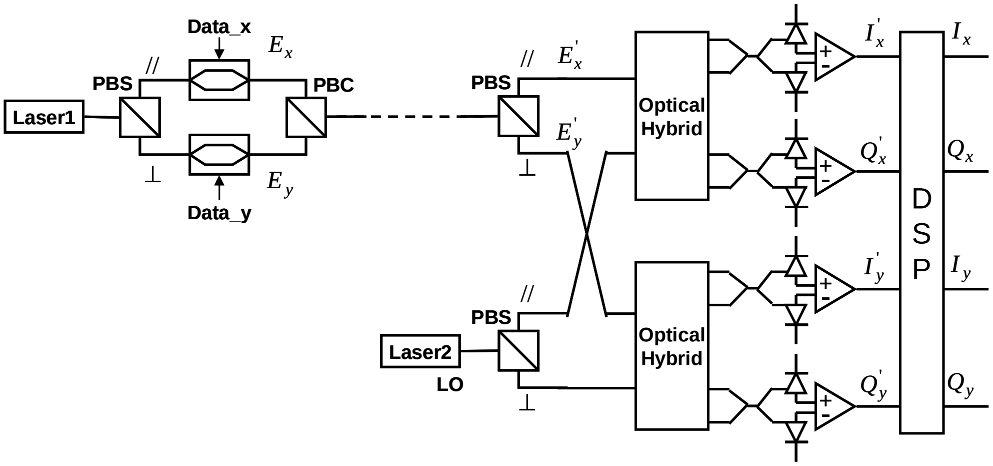

Fig. 1. Schematic of an optical polarization MIMO system. PBS: polarization beam splitter; PBC: polarization beam combiner; LO: local oscillator.

The schematic of an optical polarization MIMO system is shown in Fig. 1. In the transmitter, two synchronous data are modulated in orthogonal polarizations. The modulation format can be amplitude and/or phase modulation. E_x and E_y are the complex representation of the modulated signal in the parallel and perpendicular polarization state. After transmission

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through fiber, the polarization of lightwave is usually not preserved. For an arbitrary orientated PBS, the received signal, $E_x^{'}$ or $E_y^{'}$, contains significant crosstalk between the original signals in the two orthogonal polarization states. The output electrical field can be related to the input electrical field by

$$\begin{pmatrix} E_x^{'} \\ E_y^{'} \end{pmatrix} = L \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = JL \begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{1}$$

where L is a real scalar to describe the optical loss from the input to the output and the polarization change due to fiber is described by a unitary Jones matrix J. (For simplicity of analysis, polarization-mode dispersion (PMD) and polarization dependent loss (PDL) of fiber and other inline optical components are neglected.) Equation (1) describes a two-input and two-output MIMO system. Since J is a unitary matrix, this MIMO system, in theory, can transmit two synchronous channels without any penalty [5]. Due to environment variations, the polarization of lightwave in fiber generally drifts with the time. The rate of this polarization drift is generally much slower than the transmission data rate. Therefore, the system can be designed to estimate the Jones matrix J for the entire frame using a training sequence in the preamble of each frame to remove polarization crosstalk. Various channel estimation algorithms can be used to estimate J. Considering the high date rate used in optical communications, the LMS (least-mean-squares) algorithm is chosen in this paper because of its simplicity [6]. The J can be estimated by using the following iterative algorithm.

$$J_i = J_{i-1} + \mu \times \left[\left. \begin{pmatrix} E_x^{'} \\ E_y^{'} \end{pmatrix} \right|_i - J_{i-1} L \left. \begin{pmatrix} E_x \\ E_y \end{pmatrix} \right|_i \right] \times L \left. \begin{pmatrix} E_x \\ E_y \end{pmatrix} \right|_i^{'}, \quad i \geq 0, \quad J_{-1} = \text{initial guess} \tag{2}$$

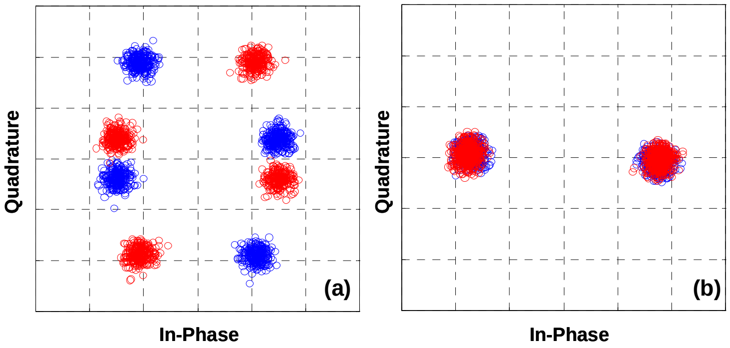

Fig. 2. Signal constellations. (a) Received signal; (b) after applying the estimated Jones matrix. No laser phase noise and frequency offset.

where μ is a positive step-size, i is the label of training sequences and L can be obtained from the received average power. Since $E_x^{'}$ and $E_y^{'}$ are generally complex, 90° optical hybrids are used to simultaneously measure the in-phase $I_x^{'}$ and $I_y^{'}$ and quadrature $Q_x^{'}$ and $Q_y^{'}$ components. If the 90° hybrid is polarization-insensitive, the receiver in Fig. 1 can be further simplified by using only one hybrid followed by PBSs. The state of polarization of LO is chosen so that its power is equally split between orthogonal polarizations. In this section, laser2 is assumed phase-locked to the laser1. The inverse of estimated J can then be applied to the received signals to recover the transmitted data I_x, I_y, Q_x and Q_y. Because J is a unitary matrix, the inversion equals the conjugate transpose. In optical polarization MIMO

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systems, the received signal polarization estimation and tracking is performed by DSP algorithm and no optical dynamic polarization control is required at the receiver. A different scheme named digital endless polarization control using nine-hypotheses gradient search algorithm was proposed in [7].

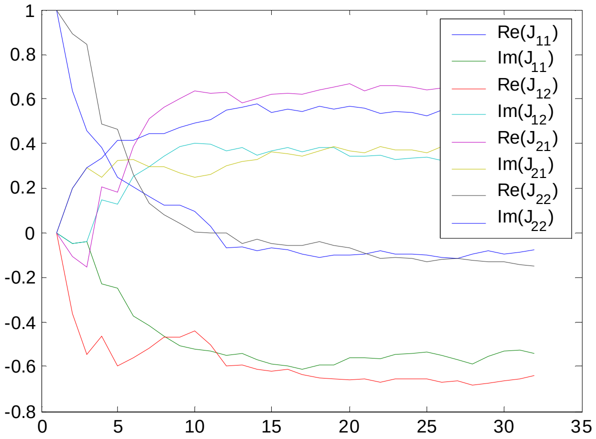

Fig. 3. Learning curves of the LMS algorithm used to estimate the Jones matrix.

The performance of the proposed polarization MIMO system is evaluated by numerical simulations. The transmitter and receiver are the same as in Fig. 1. As an example, BPSK modulation format is attempted, which is generated by an ideal phase modulator. The symbol rate is 10 GSymbol/s. The transmission fibers comprise 100 km standard single-mode fiber (with a dispersion of -16 ps/nm/km, a loss of 0.2 dB/km and a core area of 80 μm^2) and matching 20 km dispersion compensating fiber (with a dispersion of 80 ps/nm/km, a loss of 0.5 dB/km and a core area of 20 μm^2) with randomly varying birefringence simulated by the coarse-step method [8]. The PMD coefficient of the fibers is 0.1 ps/$\sqrt{km}$. The fiber nonlinear-index coefficient is 2.6x10^{-20} m^2/W. An optical amplifier is used to amplify the received signal emulating the ASE-dominated scenario. The received power before optical amplifier is -30 dBm, corresponding to a 0 dBm launch power. The noise figure of the optical amplifier is 5 dB. The optical filter before receiver is a Gaussian filter with a 3 dB bandwidth of 25 GHz. The frame length in simulations is set to 1024 symbols. The length of training sequence in the preamble is 32 symbols. The constellations of received signals in orthogonal polarizations are shown in Fig. 2(a), where significant crosstalk exists. In this paper, the blue and red symbols represent the parallel and perpendicular polarization states, respectively. After applying the Jones matrix J that is estimated from the training sequence, the crosstalk is removed and BPSK constellations are obtained in Fig. 2(b). The learning curve of LMS algorithm is shown in Fig. 3. The eight lines represent the real and imaginary components of Jones matrix J_i in the iterative algorithm. A unit matrix is used as the initial guess. The algorithm reaches the steady state after ~20 iterations. There is a tradeoff between the accuracy and convergence speed in LMS algorithm [6].

3. Optical polarization MIMO with phase estimation

In Section 2, the transmitter laser and LO (laser1 and laser 2) have been assumed to be phase-locked. In practice, phase locking can be performed using DSP algorithms without modification to Fig. 1. The algorithm then comprises two steps: i) Estimate J using a training sequence and remove polarization crosstalk as in Section 2; ii) Phase drift of LO within a frame is estimated using an algorithm similar to [3]. The phase estimation algorithm squares received signals (quadruples the signal for QPSK signals) to remove the intended phase

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modulation and track the LO phase relative to carrier. Signals in each frame are separated into 16-symbol blocks. The estimated LO phase within each block is averaged. In experiments reported in [3], the frequency offset between laser1 and laser2 are controlled within 10 MHz and the algorithm did not distinguish the phase drift due to phase noise or frequency offset.

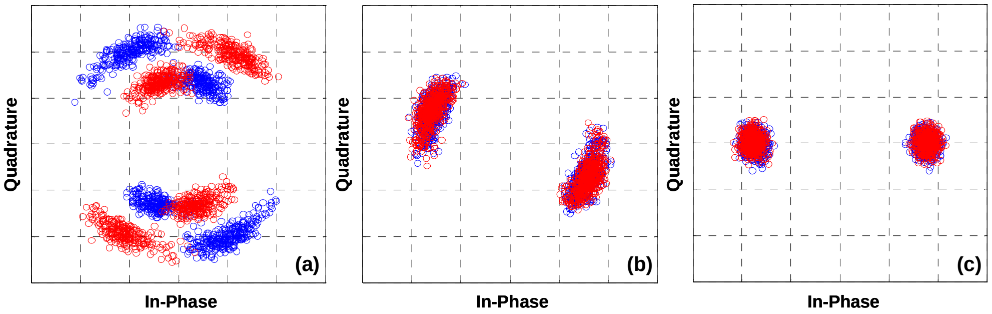

Fig. 4. Signal constellations. (a) Received signal; (b) step-1: remove polarization crosstalk; (c) step-2: phase estimation. 1 MHz laser linewidth and no frequency offset.

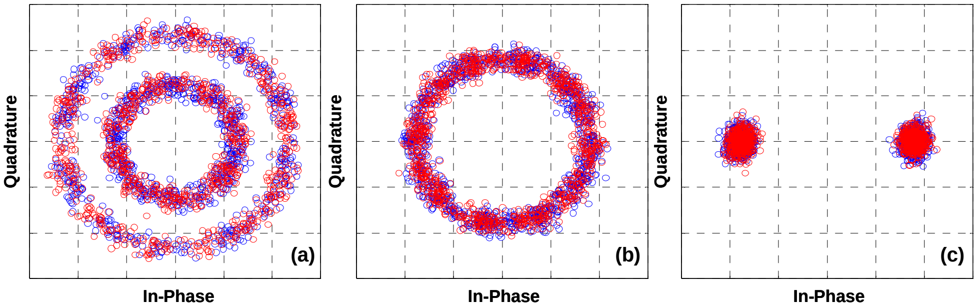

Fig. 5. Signal constellations. (a) Received signal; (b) step-1: remove polarization crosstalk; (c) step-2: phase estimation. 1 MHz laser linewidth and 10 MHz frequency offset.

The simulation parameters are the same as in Section 2 except that the laser linewidth is assumed to be 1 MHz, which is typical for commercially available semiconductor lasers. The results are shown in Fig. 4. After removing the crosstalk between orthogonal polarizations (Fig. 4(b)), the resultant constellations contain significant phase noises. Using the phase estimation algorithm described above, BPSK constellations in Fig. 4(c) are obtained. In Fig. 4, laser frequency offset is neglected. If laser frequency offset is small, it can be treated as laser phase noise. For a 10 MHz frequency offset, the same algorithm is still effective and the results are shown in Fig. 5. The slight asymmetry in the constellations is due to 5.8^o of phase rotation in the 16-symbol block corresponding to 10 MHz frequency offset. This phase error increases with the frequency offset and can be reduced by using block length shorter than 16 symbols, but as a tradeoff, the estimated phase error due to laser linewidth increases.

4. Optical polarization MIMO with frequency and phase estimation

In Fig. 4 and 5, the LMS algorithm used to estimate J is almost not affected by the phase rotation due to small frequency offset because the adaptive LMS algorithm can track this phase rotation. In the presence of large frequency offset, the expected J becomes periodic, corresponding to the offset frequency. Simulations show that the LMS algorithm is still effective with a frequency offset of 100 MHz (1% symbol rate), but fails when the offset is 1 GHz (10% symbol rate). Therefore, for an offset as large as 1 GHz, additional frequency estimation algorithm should be employed. The overall algorithm then comprises three steps: i) frequency estimation, ii) polarization MIMO channel estimation and iii) phase estimation. The MIMO channel estimation and phase estimation are the same as the steps described in Section

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3. In this paper, the following simple frequency estimation method is used. To avoid unknown crosstalk between orthogonal polarizations in frequency estimation, an additional training sequence comprises 32 symbols of 1's in both polarizations. The phase rotation due to frequency offset is estimated by calculating the phase difference of adjacent received signals and averaged over 32 symbols. Using this algorithm, the simulation results for a 1 GHz frequency offset and 1 MHz laser linewidth are shown in Fig. 6. The clear BPSK constellations in Fig. 6(d) demonstrate the effectiveness of algorithm to demodulate PDM BPSK signals without using optical phase locking and polarization control.

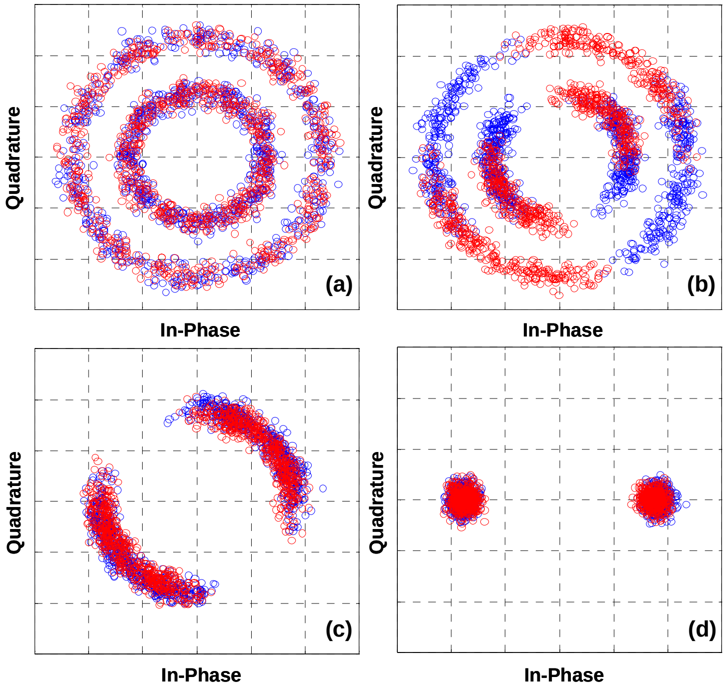

Fig. 6. Signal constellations. (a) Received signal; (b) step-1: frequency estimation; (c) step-2: remove polarization crosstalk; (d) step-3: phase estimation. 1 MHz linewidth and 1 GHz offset.

Since both in-phase and quadrature components are received in optical polarization MIMO, it is natural to transmit two QPSK signals in the two orthogonal polarizations and each of four balanced receivers receives a tributary. Four-fold increase of capacity is readily achieved. For a 1 GHz laser frequency offset and 1 MHz laser linewidth, the results are shown in Fig. 7. In the third step of phase estimation, the received QPSK signal is quadrupled, instead of squared. The results show the potential of optical polarization MIMO system to quadruple the spectral efficiency of existing optical communication systems using PDM QPSK format, coherent detection and simple DSP almost free of power penalty. More complicated formats, such as 8-level phase-shift keying and quadrature amplitude modulation can also be used with optical polarization MIMO.

5. Discussion

Since the LMS algorithm can track the variations of MIMO channel, it estimates both J and the phase difference between laser1 and laser2 in the preamble. Therefore, if the laser linewidth is sufficiently narrow that phase drifts within a frame can be neglected, no phase estimation is required at all. For example, the algorithm used in Fig. 2 (without phase estimation) is still effective when the laser linewidth is set to 10 kHz, which corresponds to solid state lasers or fiber lasers. The standard deviation of phase drift during a frame can be

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calculated as $\sqrt{2\pi\Delta\nu T}$, where T is the length of frame and $\Delta\nu$ is the beat linewidth of laser1 and laser2. The calculated standard deviation for 20 kHz beat linewidth is only 6.5^o.

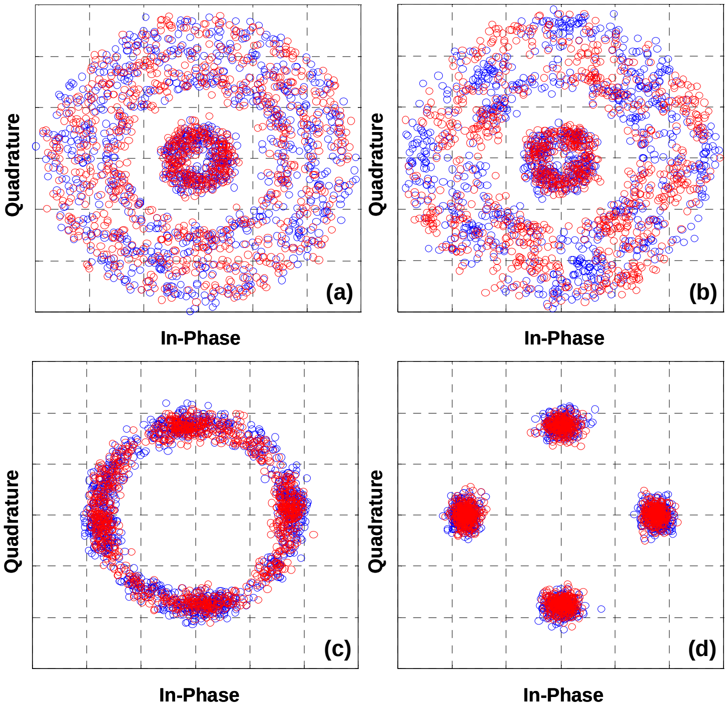

Fig. 7. Signal constellations. (a) Received signal; (b) step-1: frequency estimation; (c) step-2: remove polarization crosstalk; (d) step-3: phase estimation. 1 MHz linewidth and 1 GHz offset.

The maximum frame duration is determined by the speed of polarization fluctuations. In the proposed scheme, polarization fluctuations within a frame are assumed to be small so that the estimated J based on the training sequence is applicable for the entire frame. In field measurements, the fastest recorded polarization fluctuations are on the order of a few milliseconds. By contrast, the frame duration of a SONET/SDH frame is 125 microseconds. Therefore, optical polarization MIMO should be applicable to SONET/SDH if the training sequences can be included in the frame overhead and dedicated DSP chips are developed.

In Eq. (1), the PMD and PDL are neglected for simplicity of analysis. Although the PMD is included in the simulation, the amount of PMD is small for a 10 Gsymbol/s system and has a negligible impact on the signal quality. Since PMD and PDL can cause the depolarization of lightwave, it is potentially detrimental for optical polarization MIMO. The impact of non-negligible PMD and PDL in optical polarization MIMO needs further investigations. Similarly, optical nonlinearities such as cross-phase modulation in the WDM transmission may also depolarize the lightwave and their effects need further investigations.

The analogy between optical polarization MIMO and wireless MIMO has more profound implications than polarization demultiplexing. A potential application of this analogy is the use of space-time coding in optical polarization MIMO. Various space-time codes in [5] can be potentially adapted for optical polarization MIMO and novel codes dedicated to optical polarization MIMO may be found in the future. Another important application of this analogy is to relate the PMD in fiber transmission to the multi-path propagation in wireless communications. To the first order, PMD can be described by the differential group delay between two principle states of polarization. This simply corresponds to two different paths from the input to the output in wireless communications. The concept and tools developed in wireless communications should be useful to study the PMD-related effects. For the WDM

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system, the 2x2 model developed in this paper can be extended to more than two inputs and two outputs for mitigating the linear and nonlinear crosstalk between channels.

The proposed optical polarization MIMO scheme can also be applied to free space and multimode fiber optical communications.

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