Stokes Vector Direct Detection with 3×3 Coupler in Short-reach Optical Communication

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Abstract. The authors propose a detection scheme called Stokes vector direct detection (SV-DD) to realize high electrical spectral efficiency and cost-effective optical communication, which is more suitable than coherent detection for short-reach. At reception, the signal is detected in Stokes space. In this paper, the authors experimentally demonstrate the SV-DD scheme in single-carrier system by using a 3×3 coupler with three photodetections in the receiver.

Introduction

With the arrival of coherent communications, long-haul optical fiber transmission has been extensively studied during the last ten years. The emergence of many spectacular personal Internet devices and many Internet-centric applications such as cloud computing makes the Internet become an essential element to today's society and the high-speed optical transport being much more needed. Short-reach networks, such as data center interconnects within a distance of hundreds of kilometers, need to upgrade their capacity per wavelength to meet the ever-increasing traffic demand. As the short-reach applications require a massive number of transceivers to be deployed across the wide geographic areas, the transceiver cost becomes a consideration. Compared with the coherent detection, the optical direct detection (DD) technology, especially a host of self-coherent system can give a very suitable solution because of the low system cost and the realization of both high data rate and moderate reach. It requires simpler transceiver structure, neither polarization diversity nor local oscillator, and the digital processing is also much simpler because of no laser frequency offset or laser phase noise.

DD systems use double sideband modulation due to chromatic dispersion (CD) induced fading. Single sideband modulation is an efficiency way to avoid CD induced fading, but it halves the electrical spectral efficiency of transmitter. Additionally, the self-coherent systems suffer from the signal-to-signal beat noise (SSBN) due to intrinsic 2nd order nonlinearity of photodiodes. Many techniques have been proposed to remove the SSBN at the sacrifice of SE or making digital signal processing (DSP) complex. To further increase the SE, the Stokes vector DD (SV-DD) is proposed recently, where the signal is detected in Stokes space. The Stokes vector receiver may achieve 3-dimensional detection with phase diversity and canceling the 2nd order noise. In this paper, the authors analyze the performance of conventional SV-DD system and propose a novel SV-DD system, which is compared with the conventional structure in receiver. This system can reduce the SSBN by using a 3×3 coupler instead of the 90° hybrid.

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Principle of Stokes Vector Direct Detection

An optical signal with arbitrary polarization state can be converted to the Stokes space, as they are homomorphic. Then the authors can express the signal by a Stokes vector,

$$SV = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} S \cdot S^* \cdot C \cdot C^* \\ S \cdot C^* + S^* \cdot C \\ j(S \cdot C^* - S^* \cdot C) \end{bmatrix} = \begin{bmatrix} |S|^2 - |C|^2 \\ \text{Re}(S \cdot C^*) \\ \text{Im}(S \cdot C^*) \end{bmatrix},$$

Where $\text{Re}()$ and $\text{Im}()$ represent for the real part and imaginary part of a complex number.

In SV-DD system, there are two parts, the signals(s) and the carrier(c) loaded onto orthogonal polarizations. Then the two polarizations are randomly coupled with each other during the transmission. S and C are combined with a polarization beam combiner (PBC). The authors measure the received SV by using DD subsystems as shown in Fig. 1. The signal is split with a polarization beam splitting (PBS) into two outputs of X and Y. Since the signal polarization has been randomly rotated in the fiber, the received signals X and Y are the mixture of the transmitted signals of S and C. Both X and Y are split with 3 dB couplers, resulting in 4 output ports. Ports 1 and 4 are fed into two PDs directly and operated in DSP to get S_1 . Ports 2 and 3 are as the two inputs to the 3*3 coupler. Then the outputs are fed into three PDS. The outputs electrical signals are sent into two operational amplifiers to get S_2 and S_3 . The authors can also use DSP instead of operational amplifiers.

Fig. 1 Receiver Structure of DD Subsystems for Measuring SV. PBS, Polarization Beam Splitter; PD, Photodetector.

To recover the signal, the receiver needs to acquire a polarization rotation represented by a 3*3 rotation matrix (RM) after the fiber transmission in the Stokes space. The training symbol can be used to get the RM. It can be done by adding a special training symbol.

The transmission matrix of 3*3 coupler is

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} = \begin{pmatrix} a & b & b \\ b & a & b \\ b & b & a \end{pmatrix} \cdot \begin{pmatrix} S \\ C \\ 0 \end{pmatrix}$$

Where, $a = \frac{2}{3} \exp(jkl) + \frac{1}{3} \exp(-2jkl)$, $b = \frac{1}{3} \exp(-2jkl) - \frac{1}{3} \exp(-jkl)$, j is the imaginary part of complex, k is the coupling coefficient, l is the coupling length of optical fiber. After 3*3 coupler, the authors definition the outputs from three PDs, I_1, I_2, I_3 .

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} |S|^2 + |C|^2 \\ |S|^2 + |C|^2 \\ |S|^2 + |C|^2 \end{pmatrix} + \frac{2}{3} \begin{pmatrix} |S||C|\cos(\varphi + 2/3\pi) \\ |S||C|\cos(\varphi - 2/3\pi) \\ |S||C|\cos(\varphi) \end{pmatrix}$$

φ is the phase difference between vibration signal light and the light.

$$S_2 = |S \cdot C^*| \cos \Delta\theta = \text{Re}(S \cdot C^*)$$

$$S_3 = |S \cdot C^*| \sin \Delta\theta = \text{Im}(S \cdot C^*)$$

$\Delta\theta$ is the phase difference between signal and carrier.

Fig. 2 shows the receiver structure of conventional SV-DD system with a 90° optical hybrid.

Fig. 2 Receiver Structure of Conventional SV-DD System with a 90° Optical Hybrid. B-PD, Balance Photodetector

The outputs of the balance receiver are

$$|X+Y|^2 - |X-Y|^2 = 4\text{Re}(X \cdot Y^*)$$

$$|X-iY|^2 - |X+iY|^2 = 4\text{Im}(X \cdot Y^*)$$

They are S2 and S3, respectively [6, 7]. After acquiring the RM, the authors multiply the received SV with the inverse of the RM

$$\begin{bmatrix} |S|^2 - |C|^2 \\ \text{Re}(S \cdot C^*) \\ \text{Im}(S \cdot C^*) \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix}^{-1} \cdot \begin{bmatrix} |X|^2 - |Y|^2 \\ \text{Re}(X \cdot Y^*) \\ \text{Im}(X \cdot Y^*) \end{bmatrix}$$

Furthermore, the 2nd order nonlinear terms of signal are all included in the 0th and 1st components of SV. Therefore, SSBN does not affect the signal recovered from 2nd and 3rd SV components.0

Experimental setup and Results

At transmitter, the state of polarization will change after optical fiber transmission. It is shown on Poincare sphere like Fig. 4. The relation of frequency-power will also change after optical fiber transmission. When there is no insert loss, the relation curve of frequency-power is much better than after 160km transmission, and the longer the optical fiber is, the more tanglesome the constellation is. It is shown in Fig. 5.

Fig. 4 Spheres Showing the State of Polarization:(a) There is No Loss;(b) after 160km Transmission.

Fig. 5 Relation of Frequency-power and the Constellation(a) No Insert Loss and no Fiber;(b) after 160km Transmission.

At reception, the optical signal is split into a PBS and polarization X and Y, which are equally split into two branches by using two 3 dB couplers. Parts 1 and 4 are fed into two photodetections. Parts 2 and 3 are fed into a 3*3 coupler. Then the authors send them to three photodetections and operate in two amplifiers. It is shown in Fig. 6.

Fig. 6 Experimental Setup for SV-DD (2)

The authors measure the bit error rate (BER) as the function of the fiber launch power, as shown in Fig. 7, in order to identify the fiber nonlinearity tolerance for this system. The blue line represents the SV-DD (1) and the red line represents the SV-DD (2). The authors can know that SV-DD (2) has better performance than SV-DD (1), and the optimum launch power is 6 dBm.

Fig. 7 BER Performance as a Function of Fiber Launch Power for Different SV-DD Structures

Conclusion

The authors have experimentally demonstrated 160-Gb/s reception over 160-km SSMF by using the SV-DD algorithm in single-carrier system and a 3*3 coupler with 100% spectrum efficiency with reference to coherent detection. SV-DD may provide a cost-effective solution to achieve 100G short-reach transmission with high spectral efficiency and low system complexity. The receiver with a 3*3 coupler has better performance than the receiver with 90° optical hybrid.

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