A Dispersion-Tolerant Symbol Constellation of Stokes-Vector Modulation for Short-Reach Fiber Links

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SUMMARY We propose a novel 16-ary constellation of Stokes-vector modulation. It consists of two concentric cubic lattices of different sizes, one rotated by 45-degrees in longitudinal direction. Numerical simulations of 25-Gbaud signal transmission show the proposed constellation having better dispersion-tolerance than does the conventional one.
keywords: *Optical fiber communications, Polarization of Light, Stokes vector modulation, Stokes vector receivers, Direct detection.*

1. Introduction

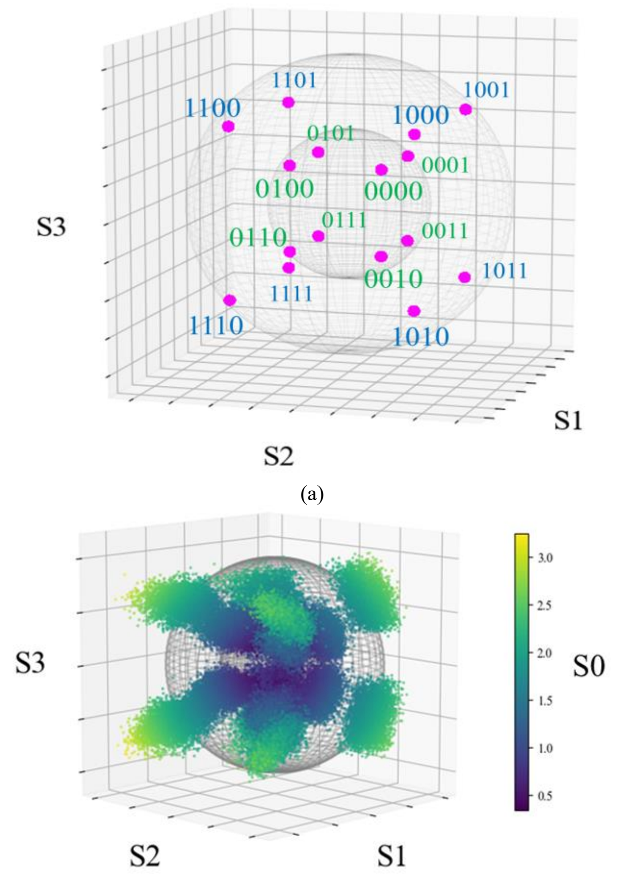
Caused by the wide spread of mobile systems and advanced network services in recent years, the data traffic within intra- and inter-data centers has been rapidly increased. To meet demands for such short-reach, high-capacity and cost-effective optical links that span no more than several kilometers, Stokes vector modulation (SVM) / direct-detection (DD) systems have been proposed as an alternative to multi-level intensity modulation (IM) / DD systems [1-6].

The transmission performance of several tens of gigabaud signals in several kilometres of fibers can be limited by fiber dispersion [4]. Since DD includes a nonlinear operation on the field amplitude, digital linear equalizers available for coherent detection do not function properly for DD-Stokes vector reception. Besides, dispersion compensation in the optical domain seems not realistic in such use cases for its high cost and lack of versatility. Taking advantage of an additional degree of freedom, it is practical for SVM/DD systems to arrange signal constellation in Stokes space in order to improve the dispersion tolerance.

In this paper, we propose a 16-ary signal constellation in 3D Stokes space that has larger dispersion tolerance than does the conventional one proposed in Ref. [2] and study the performance of the proposed SVM signal using numerical simulations.

2. Principle

Since the phase modulation is essential for SVM that needs to change the relative phase between two polarizations, SVM signals are more susceptible to fiber dispersion than IM signals. Figure 1 (a) shows the 3D constellation of a 16-ary SVM signal proposed in Ref. [2] (hereafter we will refer to this constellation as "conventional"). This scheme uses two concentric Poincare spheres having different radiuses. Each sphere contains eight signal points that are vertices of a cubic lattice inscribed in the sphere. The longitude and latitude of signal points on one of the spheres are the same as those on the other sphere. Figure 1 (b) shows the constellation affected by the accumulated dispersion of −160 ps^2. The signal points are spread both in radial and spherical directions in the Stokes space.



(a)

(b)

Fig. 1: (a) 3D constellation of conventional 16-ary SVM signal [2]. (b) constellation of 25 Gbaud conventional 16-ary SVM signal affected by dispersion of -160 ps^2.

Extending inter-symbol distance is effective to reduce detection errors. The proposed 3D-signal constellation is shown in Fig. 2. The difference from the conventional one is the longitudes of the eight signal points on the outer Poincare sphere, where their longitudes are shifted by 45 degrees from those on the inner Poincare sphere. The

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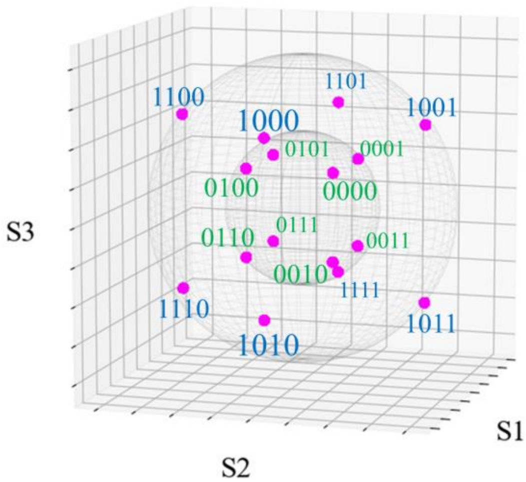

Fig. 2: 3D constellation of proposed 16-ary SVM signal.

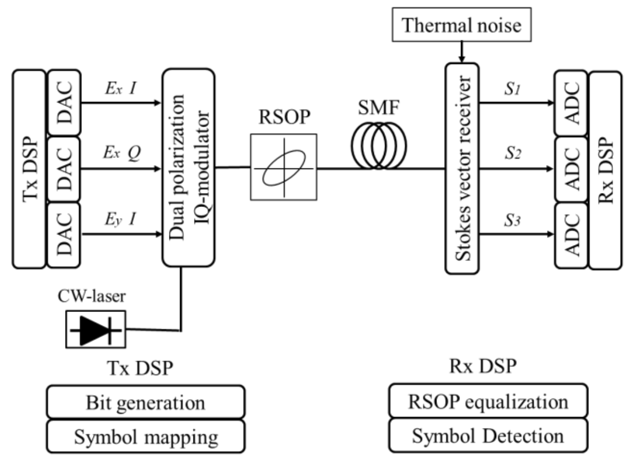

Fig. 3: Simulation setup.

distance between a signal point on the inner sphere and its neighbors on the outer sphere is then extended and dispersion tolerance is enhanced.

The symbol mappings of four bits assumed in this paper are depicted in Fig. 1 (a) and Fig. 2. In both constellations, the eight points on the inner sphere and the eight points on the outer sphere are each arranged in a grey code of three bits, with the most significant bit being 0 for the signal points on the inner sphere and 1 for the points on the outer sphere. All signal points of the conventional constellation have neighboring signal points coded with one-bit difference. In the proposed constellation, on the other hand, one of the neighbors of a signal point on the inner sphere is coded with two-bit difference. For example, the neighbors of 0000 (inner sphere) are 0001, 0100, 0010 (inner sphere), 1000 and 1001 (outer sphere), the last of which is different by two bits. This may cause additional bit errors for the case with large inter-symbol interference, as will be discussed in Section 4.

In Ref. [3], another type of 16-ary SVM constellation, "suboptimum 3D-signal constellation" was proposed, based on face centered cubic lattices. This scheme maximizes the squared minimum Euclidean distance between symbols for a given average energy. In our preliminary simulations, however, the low symmetry of this 3D-signal constellation made it difficult to equalize the rotation of the state of polarization (RSOP) by using a three-input three-output adaptive FIR filter in Stokes vector space [4]. We will report elsewhere the comparison between and our proposal and the "suboptimum 3D-signal constellation" after resolving this problem in equalization.

3. Simulation Condition

The system configuration studied in our simulation is shown in Fig. 3. 25-Gbaud 16-ary SVM signal is generated by using a transmitter depicted in Fig. 3. 3D Stokes vector signals are generated by using a dual-polarization IQ modulator (DPIQM) as shown in Fig. 4 [2]. If we assume perfectly polarized field, the Stokes vector of the output field is

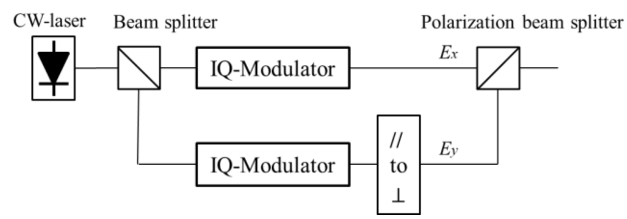

Fig. 4: Stokes-vector transmitter with dual polarization IQ-modulator [2].

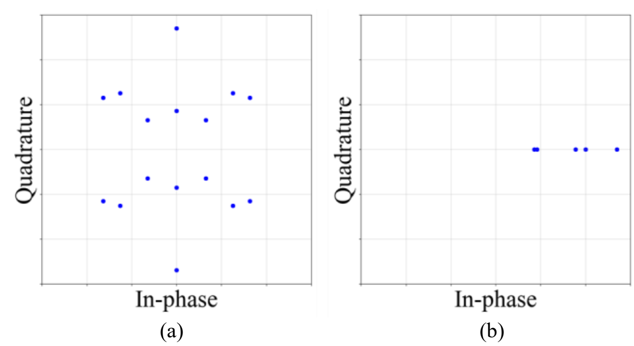

Fig. 5: Complex Jones field constellation of proposed SVM signal, (a) X-polarization and (b) Y-polarization.

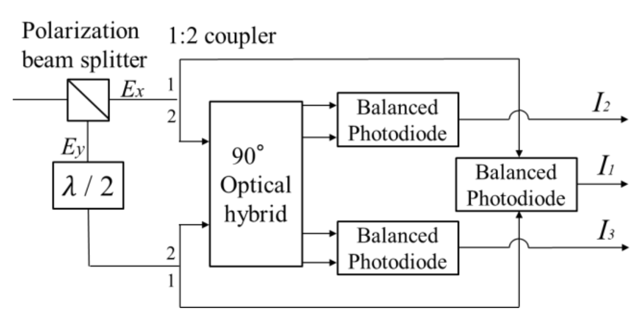

Fig. 6: Direct-detection Stokes vector receiver [5].

written as

$$\mathbf{S} = \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} |E_x|^2 - |E_y|^2 \\ 2\mathrm{Re}(E_x^* E_y) \\ 2\mathrm{Im}(E_x^* E_y) \end{bmatrix}, \quad (1)$$

$$S_0^2 = S_1^2 + S_2^2 + S_3^2, \quad (2)$$

where and E_x and E_y are the electrical field of X- and Y-polarization, respectively. Since the number of controllable field parameters is four (amplitude and phase of each polarization), we spare one degree of freedom to realize a target Stokes vector. Figures 5 (a) and (b) show the complex Jones field constellations of our realization of the proposed SVM signal, where Figs. 5 (a) and (b) are constellations of X- and Y- polarization, respectively [3]. With the aim of reducing the depth of phase modulation, we restrict IQ modulation to the X-polarization and apply only amplitude modulation to the Y-polarization.

The transmission link is assumed to be a single-mode fiber, the parameters of which are as follows: loss coefficient α= 0.2 dB/km, chromatic dispersion coefficient β_2 = –20 ps^2/km, nonlinear parameter γ = 1.27 W^{-1}km^{-1}, and polarization mode dispersion parameter δ = 0.02 ps/km$^{1/2}$. The fiber birefringence that causes the RSOP is modelled by coupling of polarization maintaining fibers, which have a length of 100 meter and have the eigenaxis randomly rotated at every connection point. The evolution of the light field in the fiber is calculated by solving coupled nonlinear Schrödinger equation using split-step Fourier method.

Figure 6 shows the configuration of the DD Stokes vector receiver (SVR) assumed in our simulations [5]. It consists of a polarization beam splitter, a half-wave plate, two 1:2 couplers, a 90-degree optical hybrid, and three balanced photodiodes. Output photocurrents I_1, I_2 and I_3 obtained from three balanced photodiodes are proportional to the Stokes parameters S_1, S_2 and S_3, respectively. As a noise source, we consider the thermal noise of load registers that follow the balanced receivers. The responsivity of a photodiode is assumed to be 0.6 A/W. The load resistance is assumed 1 kΩ operated at the temperature of 300 K. RSOP during transmission is equalized by using a three-input three-output adaptive FIR filter [4], which is trained by 512 symbols out of 262,656 transmission symbols in total. The decision of 3D symbols is performed by using fixed threshold planes that are perpendicular bisector planes between two signal points.

4. Simulation Results

Figure 7 shows the bit-error-ratio (BER) as a function of signal-to-noise ratio (SNR) of the back-to-back result, where the result of the conventional constellation and that of the proposed constellation are indicated by blue and red plots, respectively. The proposed constellation shows better sensitivity than does the conventional one. The SNR to achieve 7 % forward error correction (FEC) threshold by "Continuously interleaved BCH" [7,8] and 5.8 % FEC

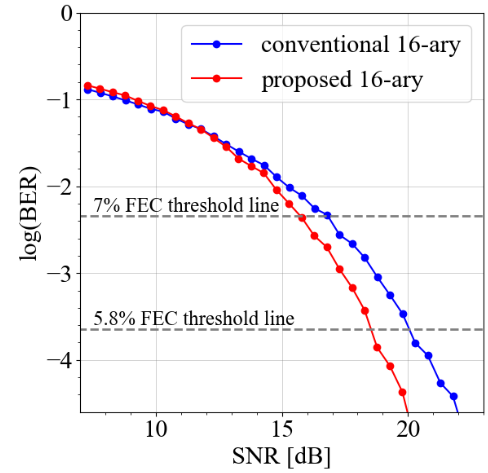

Fig.7: BER as a function of SNR when using conventional and proposed 16-ary 3D-signal constellation after back-to-back transmission.

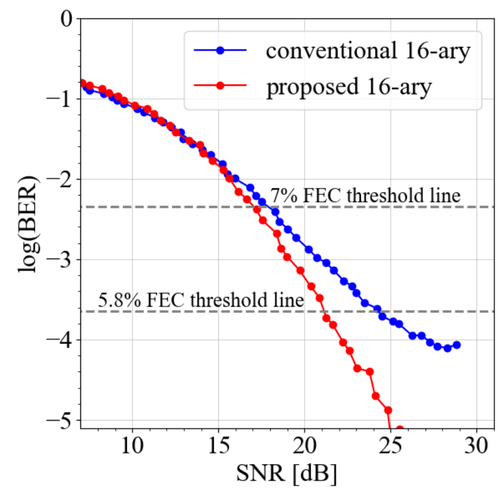

Fig. 8: BER as a function of SNR when using conventional and proposed 16-ary 3D-signal constellation after 4 km transmission.

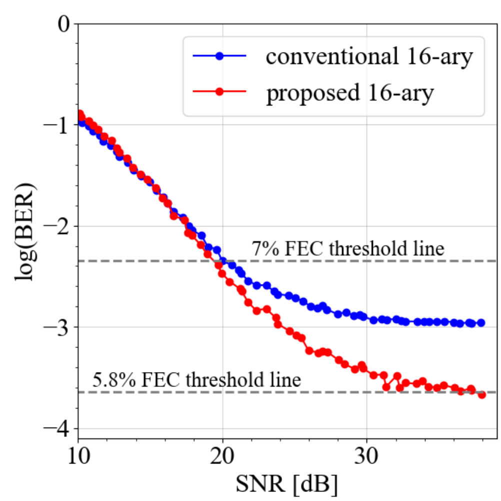

Fig. 9: BER as a function of SNR when using conventional (blue) and proposed (red) 16-ary 3D-signal constellation after 6 km transmission.

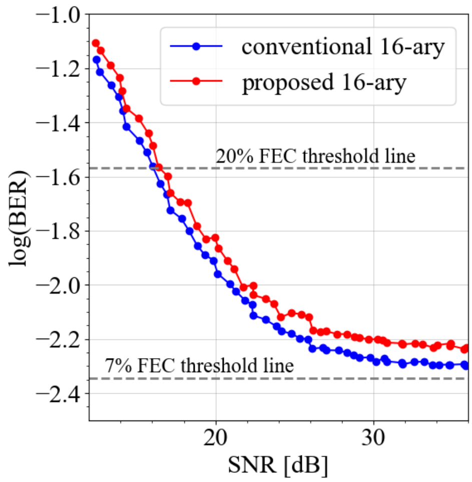

Fig. 10: BER as a function of SNR when using conventional (blue) and proposed (red) 16-ary 3D-signal constellation after 8 km transmission.

threshold by "RS (544, 514)" [7,9] are improved by 1.1 dB and 1.5 dB, respectively. This improvement can be attributed to the extended distance between signal points on the outer sphere and those on the inner sphere.

Figure 8 shows the BER after 4 km transmission as a function of SNR. The effect of the distance extension is more clearly seen in the results of 4 km transmission. For the SNR beyond 25 dB, the BER plots of the conventional constellation shows a clear error floor. Meanwhile, the plots of the proposed constellation do not show such an error floor, at least in the presented BER range. The power penalty of 4 km transmission at 7 % FEC threshold and 5.8 % FEC threshold are 0.8 dB and 3.2 dB, respectively.

Figure 9 shows the BER after 6 km transmission as a function of SNR. Despite the presence of the error floor, the proposed method can achieve BER below the 5.8 % FEC threshold, which cannot be achieved by the conventional constellation. However, the BER performance of the proposed constellation becomes even worse than the conventional one after 8 km transmission as shown in Fig. 10, where both constellations cannot achieve BER below 7 % FEC threshold. The reason for the loss of advantage would be in the increase of the two-bit errors caused by the interference between the symbols on the inner sphere and those on the outer sphere.

5. Conclusion

In this paper, we have proposed a dispersion-tolerant 16-ary 3D constellation of SVM, where two concentric cubic lattices of different sizes have been employed. The proposed constellation has been comprised of the eight signal points on the outer Poincare sphere, the longitudes which have been shifted by 45 degrees from those on the inner Poincare sphere. Numerical simulations have shown that the wider inter-symbol distance of the proposed constellation has offered not only better sensitivity but also better tolerance to fiber dispersion compared with the conventional one.

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