Crossover Block Modulation with Complementary Codes Superposition

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Abstract

Coherent communication has been widely deployed with the assistance of digital signal processing. Dual-polarized quadrature phase-shift keying (DP-QPSK) is a standard solution for both long-haul and metro 100 Gb/s optical transport [1]. To optimize the spectral efficiency and the reach under each of these transmission conditions, both higher and lower order modulation have been investigated. Besides regular 2N quadrature amplitude modulation with polarization multiplexing for 2N bit/symbol, intermediate solutions are considered since 2N bit/symbol may not have enough granularity to maximize the system capacity in all cases. Polarization-switched quadrature phase-shift keying (PSQPSK)[2] is an early solution having an intermediate spectral efficiency of 3 bit/symbol, which is classified as part of a 4-dimensional modulation family. PS-QPSK shows good linear and reasonable nonlinear performance and efficiently fills the gap in spectral efficiency between DP-QPSK and DP binary phase-shift keying (DP-BPSK) [3]. Single paritycheck (SPC) coded DP-QPSK is equivalent to PS-QPSK. The coding-based solution is hardware-efficient because it does not require changes to the optical transmitters of a standard DP-QPSK configuration. In long-haul transmission, fiber nonlinearity and polarization dependency are critical factors limiting the reach. To reduce the degradation, state of polarization (SOP) management has been intensively investigated for non-coherent schemes [4]. Biasing the SOP increases degradations such as polarization dependent loss (PDL), polarization hole burning, and cross polarization modulation. We also have to be aware of this for polarization multiplexed coherent schemes [5]. PS-QPSK takes two SOPs with orthogonal linear polarizations and the SOP bias will depend on the bit sequence. Forward error correction (FEC) with bit-interleaving helps to mitigate the effects of PDL, but it is not enough.Diversity transmission such as phase-conjugate modulation and superposition demodulation [6-9] can help to reduce such degradation quite effectively. On the other hand, these signals have themselves so far provided either no or lower coding gain. The best mixture of diversity transmission would be with a concept like phase-conjugation modulation providing coding gain by increasing the Euclidean and/or Hamming distance by employing, e.g., high-dimensional modulation [10]. If we can realize not only SOP diversity and superposition but natural SOP management, additional performance improvement will be expected on transmission lines with strong nonlinearity and polarization dependent degradation. Although a solution for 2 bit/symbol has already been proposed [11], there has, however, so far been no reported solution for 3 bit/symbol transmission to the best of our knowledge. In this paper, we propose three novel 3 bit/symbol modulation schemes, one of which realizes SOP management by crossover superposition of two sets of SPC coded signals over two time slots and two polarizations. Through numerical simulation, we observed 0.8 dB improvement in the presence of interplay of fiber nonlinearity and PDL.

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Abstract: *We propose novel 3-bit/symbol modulation schemes which cross-connects two sets of coded signals over time and polarization. Simulations show 0.8 dB higher tolerance against interplay of fiber nonlinearity and PDL compared with conventional PS-QPSK.*
Keywords: *Coherent Communication, Fiber Nonlinearity, Modulation.*

I. INTRODUCTION

Coherent communication has been widely deployed with the assistance of digital signal processing. Dual-polarized quadrature phase-shift keying (DP-QPSK) is a standard solution for both long-haul and metro 100 Gb/s optical transport [1]. To optimize the spectral efficiency and the reach under each of these transmission conditions, both higher and lower order modulation have been investigated. Besides regular 2^N quadrature amplitude modulation with polarization multiplexing for $2N$ bit/symbol, intermediate solutions are considered since $2N$ bit/symbol may not have enough granularity to maximize the system capacity in all cases. Polarization-switched quadrature phase-shift keying (PS-QPSK) [2] is an early solution having an intermediate spectral efficiency of 3 bit/symbol, which is classified as part of a 4-dimensional modulation family. PS-QPSK shows good linear and reasonable nonlinear performance and efficiently fills the gap in spectral efficiency between DP-QPSK and DP binary phase-shift keying (DP-BPSK) [3]. Single parity-check (SPC) coded DP-QPSK is equivalent to PS-QPSK. The coding-based solution is hardware-efficient because it does not require changes to the optical transmitters of a standard DP-QPSK configuration.

In long-haul transmission, fiber nonlinearity and polarization dependency are critical factors limiting the reach. To reduce the degradation, state of polarization (SOP) management has been intensively investigated for non-coherent schemes [4]. Biasing the SOP increases degradations such as polarization dependent loss (PDL), polarization hole burning, and cross polarization modulation. We also have to be aware of this for polarization multiplexed coherent schemes [5]. PS-QPSK takes two SOPs with orthogonal linear polarizations and the SOP bias will depend on the bit sequence. Forward error correction (FEC) with bit-interleaving helps to mitigate the effects of PDL, but it is not enough. Diversity transmission such as phase-conjugate modulation and superposition demodulation [6–9] can help to reduce such degradation quite effectively. On the other hand, these signals have themselves so far provided either no or lower coding gain. The best mixture of diversity transmission would be with a concept like phase-conjugation modulation providing coding gain by increasing the Euclidean and/or Hamming distance by employing, e.g., high-dimensional modulation [10]. If we can realize not only SOP diversity and superposition but natural SOP management, additional performance improvement will be expected on transmission lines with strong nonlinearity and polarization dependent degradation. Although a solution for 2 bit/symbol has already been proposed [11], there has, however, so far been no reported solution for 3 bit/symbol transmission to the best of our knowledge.

In this paper, we propose three novel 3 bit/symbol modulation schemes, one of which realizes SOP management by crossover superposition of two sets of SPC coded signals over two time slots and two polarizations. Through numerical simulation, we observed 0.8 dB improvement in the presence of interplay of fiber nonlinearity and PDL.

II. PRINCIPLES OF THE PROPOSED MODULATION SCHEME

In this paper we examine the three types of modulation scheme shown in Figure 1. X1 and X2 are the electric fields of the first and second time slots of the X-polarization, while Y1 and Y2 are those of the Y-polarization. For efficient implementation, we use 3-bit to 4-bit conversion with SPC. Although the coding is 3 bits in 4-D, the modulation acts like 6 bits in 8-D. Using a block of 6-bit data, b_0, b_1, …, b_5 are mapped onto two time slots and two polarizations. Table I shows the coding rules for the proposed scheme. To realize a spectral efficiency of 3 bit/symbol, we use not only an SPC code for converting 3 bits into 4 bits as shown in Table I (A), but also the complementary version of the SPC code shown in Table I (B). This complementary version is equivalent to partial phase conjugation [9]. Therefore, phase conjugate coding and coded modulation are strongly related to each other.

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A. Cross Polarization- and Time-Block Coding (X-PTBC)

Figure 1 (a) shows the first case: cross polarization- and time-block coding (X-PTBC). Two sets of 3-bit 4-D block-coded signals are mapped onto two time slots and two polarizations. Electric fields A and B in Table I (A) are mapped onto X1 and Y2, and C and D in Table I (B) are mapped onto Y1 and X2. The SOPs of the two time slots are always different. One time slot is linearly polarized (at S2 on the Poincaré sphere; 0 or 180 degree optical phase difference between the X and Y polarizations) and the other time slot is circularly polarized (S3 on the Poincaré sphere; +/-90 degree optical phase difference between X and Y polarizations).

B. Parallel Time-Block Coding (P-TBC)

Figure 1 (b) shows the second case: parallel time-block coding (P-TBC). Two-set of 3-bit 4-D block-coded signals are mapped on two time slots, the first set on the X-polarization and the second set on the Y-polarization. Electric fields A and B in Table I (A) are mapped onto X1 and X2, and C and D in Table I (B) are mapped onto Y1 and Y2. One time slot is linearly polarized (at S2) and the other time slot is circularly polarized (at S3), just as with X-PTBC.

C. Parallel Polarization-Block Coding (P-PBC)

Figure 1 (c) is the third case: parallel polarization-block coding (P-PBC). Two sets of 3-bit 4-D block-coded signals are mapped onto two polarizations. Electric fields A and B in Table I (A) are mapped onto X1 and Y1, and C and D in Table I (B) are mapped onto X2 and Y2. The first time slot is linearly polarized (at S2 on the Poincaré sphere) and the second time slot is circularly polarized (at S3). The SOP randomization helps to reduce inter-channel polarization dependent degradation. However, there is no gain from superimposing over two time slots having different SOP.

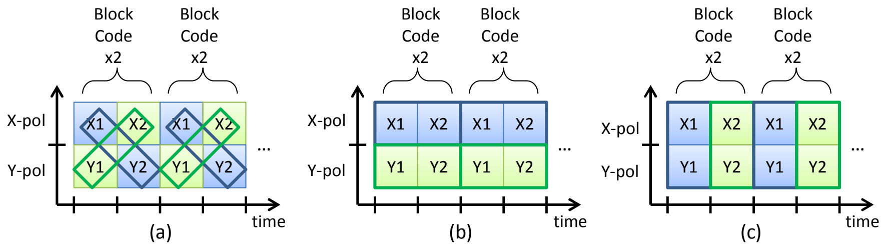

Fig. 1. The three types of modulation scheme considered; (a) cross polarization- and time-block coding (X-PTBC), (b) parallel time-block coding (P-TBC), (c) parallel polarization-block coding (P-PBC).

TABLE I
CODING RULES; (A) SINGLE PARITY CHECK AND (B) COMPLEMENTARY SINGLE PARITY CHECK

(A)

b_0	0	0	0	0	1	1	1	1
b_1	0	0	1	1	0	0	1	1
b_2	0	1	0	1	0	1	0	1
A (E_1)	(+1,+1)	(+1,+1)	(+1,-1)	(+1,-1)	(-1,+1)	(-1,+1)	(-1,-1)	(-1,-1)
B (E_1 or $-E_1$)	(+1,+1)	(-1,-1)	(-1,+1)	(-1,+1)	(+1,-1)	(-1,+1)	(+1,+1)	(+1,+1)

(B)

b_3	0	0	0	0	1	1	1	1
b_4	0	0	1	1	0	0	1	1
b_5	0	1	0	1	0	1	0	1
C (E_2)	(+1,+1)	(+1,+1)	(+1,-1)	(+1,-1)	(-1,+1)	(-1,+1)	(-1,-1)	(-1,-1)
D (E_2^* or $-E_2^*$)	(+1,-1)	(-1,+1)	(+1,+1)	(-1,-1)	(+1,+1)	(-1,-1)	(+1,-1)	(-1,+1)

III. SIMULATION

To verify the transmission performance, we have conducted a set of numerical simulations whose parameters are listed below. The modulation schemes tested were X-PTBC, P-TBC, and P-PBC, and for comparison, PS-QPSK and DP-QPSK were also examined. The gross bit rate, including FEC parity, pilot symbols and frame overhead was 140 Gb/s. The baud rate was set to 46.67 Gbaud except for DP-QPSK (which used 35 Gbaud to ensure equal bit rate), and their signals were root-raised cosine (RRC) filtered with a roll-off factor of 0.1. Nine-channel wavelength division multiplexed with a channel spacing of 53.67 GHz (= 46.67 GHz x 1.15) were created. As we were focused on highly nonlinear conditions, the transmission line consisted 25 spans of non-zero dispersion-shifted fiber (NZDSF) having a loss of 0.2 dB/km, a span length of 80 km , a local chromatic dispersion (CD) of 3.9 ps/nm/km, and a nonlinear index of 1.6 $W^{-1}km^{-1}$. CD compensation was applied at a rate of 50% of residual dispersion at the transmitter and 90% in-line per span. Erbium-doped fiber amplifiers were used for span loss compensation with a noise figure of 5 dB. All amplified spontaneous emission noise was loaded at the receiver side to adjust optical signal-to-noise ratio (OSNR). The performance was evaluated using the span loss budget [12], calculated from Required OSNR(ROSNR), needed to achieve the target normalized generalized mutual information [13] of 0.85 assuming use of a soft-decision FEC [14].

Figure 2 shows the simulation result; Fig. 2 (a) is the span loss budget, and Fig. 2 (b) is the gain compared to PS-

QPSK. Under linear conditions where the launched power was less than -4 dBm/ch, there was no difference between the performances of the various 3 bit/symbol modulation schemes. On the other hand, under highly nonlinear conditions where the launched power was higher than -3 dBm/ch, all the proposed formats outperformed the conventional PS-QPSK. The maximum span loss budget was improved by 0.3 dB. Although SOP-managed X-PTBC shows the best performance of the three proposed types, the difference is not particularly significant.

In order to clarify the benefits of the SOP management of the proposed schemes, we simulated their tolerance to a combination of fiber nonlinearity and PDL. After adding 2 dB of PDL at the transmitter side on axes S1, S2, and S3 of the Poincaré sphere, the nonlinearity degradation was simulated in the cases of -10 dBm (linear condition) and -3 dBm (nonlinear condition) launched power. Table II shows the ROSNRs (in dB with 0.1 nm noise bandwidth) for each modulation format, launched power, and PDL condition. Here we can see that X-PTBC and P-TBC perform better than the others. When we consider the worst PDL conditions, the benefit of X-PTBC reaches nearly 0.3 dB and 0.8 dB under linear and nonlinear conditions, respectively. While all three proposed schemes have SOP diversity (traversing the S2 and S3 axes in two time slots), only X-PTBC and P-TBC superpose the different SOP signals at the receiver. Having both transmitter-side diversity and receiver-side superposition is key to reducing PDL and nonlinearity penalties.

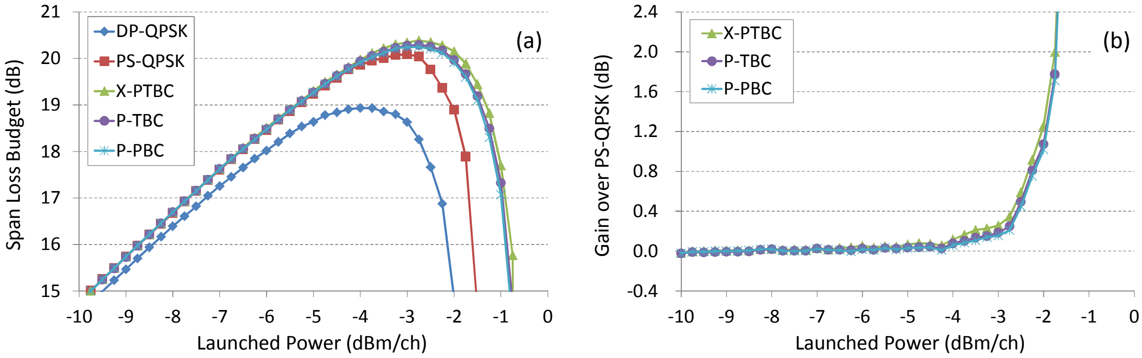

Fig. 2. Simulated transmission performance; (a) comparison of span loss budget, and (b) gain over PS-QPSK.

TABLE II
ROSNR WITH FIBER NONLINEARITY AND PDL

Launched Power		-10 dBm					-3 dBm				
PDL		0 dB	2 dB S1	2 dB S2	2 dB S3	2dB Worst	0 dB	2 dB S1	2 dB S2	2 dB S3	2dB Worst
Modn. Format	X-PTBC	9.49	9.69	9.64	9.64	9.68	10.91	11.08	11.29	11.31	11.31
	P-TBC	9.50	9.68	9.65	9.64	9.68	10.98	11.20	11.34	11.36	11.36
	P-PBC	9.50	9.84	9.66	9.64	9.84	11.00	11.34	11.35	11.41	11.41
	PS-QPSK	9.47	9.84	9.68	9.68	9.84	11.16	11.43	12.13	11.32	12.13
	DP-QPSK	9.73	10.00	9.91	9.91	10.00	12.62	12.92	13.64	13.72	13.72

IV. CONCLUSIONS

Novel 3 bit/symbol modulation schemes have been proposed. Due to SOP diversity at the transmitter side and superposing the signals across time slots and polarizations, the proposed schemes can reduce the degradation due to fiber nonlinearity and PDL. Our numerical simulations have shown that the performance of the proposed methods compared with PS-QPSK is the same under linear conditions and 0.3 dB better under highly nonlinear conditions comparing maximum span loss budget. In the presence of 2 dB of PDL with nonlinearity, the performance gain is increased to 0.8 dB.

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