

Performance Analysis of Time–Polarization Multiplexed 40-Gb/s RZ-DPSK DWDM Transmission

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Abstract—The performance of return-to-zero differential phase-shift-keyed dense wavelength-division-multiplexing transmission with time–polarization multiplexing or interleaving is investigated. Polarization interleaving enables further reduction of nonlinear penalties, especially in high-bit-rate transmissions where intrachannel nonlinear effects dominate. We show numerically that transmission distance can be much increased with this scheme in a 40-Gb/s system. Polarization scattering resulting from polarization-mode dispersion and cross-phase modulation is also much reduced as compared to that in ON–OFF keying systems, making it possible for effective polarization demultiplexing that may also reduce system cost.

Index Terms—Differential phase-shift keying (DPSK), optical communication, polarization interleaving.

I. INTRODUCTION

DIFFERENTIAL phase-shift keying (DPSK) has recently attracted renewed interest in high-speed transmissions [1], owing to its high receiver sensitivity and high tolerance to intrachannel nonlinear effects such as cross-phase modulation (XPM) and four-wave mixing (FWM) [2], [3]. Dense wavelength-division-multiplexing (DWDM) 40-Gb/s transmission with ultralong-haul transmission distance of 10 000 km [4] and ultrahigh capacity of 6.4 Tb/s [5] have recently been demonstrated using DPSK. Polarization bit multiplexing (P-MUX) or interleaving [6], [7] has been shown to reduce the nonlinear penalty and intersymbol interference resulting from chromatic dispersion and polarization-mode dispersion (PMD). In this letter, we study the performance of return-to-zero (RZ)-DPSK in which P-MUX is applied to further reduce intrachannel FWM and XPM. In this scheme, adjacent bits are orthogonally polarized, and the FWM among these adjacent bits is greatly weakened due to fiber birefringence. The orthogonality of the polarization states between adjacent bits can be well maintained over long distance in the DPSK scheme, effectively suppressing the FWM along the entire transmission. This is enabled by the fact that, unlike in ON–OFF keying (OOK) systems [8], the degree of polarization (DOP) of each polarization state is well maintained due to the reduction of the nonlinear polarization rotation induced from XPM (both interchannel and intrachannel) and PMD. We show numerically that transmission distance can be much increased

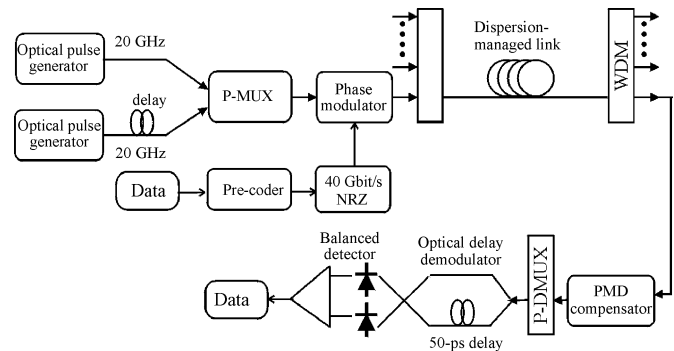


Fig. 1. Schematic of the proposed time–polarization multiplexed DPSK scheme. DL: optical delay line. P-(D)MUX: polarization (de)multiplexer.

with the P-MUX DPSK scheme, nearly doubling the reach of similar RZ transmissions with OOK format. We recently also showed that P-MUX can be used in dispersion-managed soliton systems (where adjacent bits have little overlap) to double its capacity with very small sacrifice in transmission distance [9].

II. PRINCIPLE AND IMPLEMENTATION

The schematic of the P-MUX DPSK transmission system is shown in Fig. 1. Two optical pulse generators generate two orthogonally polarized RZ pulse trains with 20-GHz repetition rate. The two pulse trains are polarization multiplexed to 40 GHz by an adjustable delay line and a polarization combiner. A precoder is used to ensure that the received data or data tributaries can be properly decoded. Different WDM channels are then multiplexed before launching into a dispersion-managed link, which consists of a predispersion compensator, dispersion-compensated (not necessarily fully compensated) spans, and a postdispersion compensator.

After transmission, the WDM channels are demultiplexed. Each individual channel can either be polarization demultiplexed (P-DMUX) to two 20-Gb/s channels before being detected by two 20-Gb/s DPSK receivers, or detected a 40-Gb/s DPSK receiver without the P-DMUX. A PMD compensator is required when P-DMUX is not applied since PMD makes the spacing between adjacent bits alternating between $T + \langle \text{DGD} \rangle$ and $T - \langle \text{DGD} \rangle$, where T is the bit period (i.e., 25 ps) and $\langle \text{DGD} \rangle$ is the mean link PMD, and thus, makes it impossible for optimum decision in the 40-G receiver. Both the 20- and 40-Gb/s DPSK receivers include an optical delay demodulator with 2-bit (or 50 ps) delay (to ensure the same polarization of the two interfering bits in the demodulator) and a balanced detector. Electrical deinterleaving of the 40-Gb/s data into two 20-Gb/s data tributaries is needed when using the 40-Gb/s receiver.

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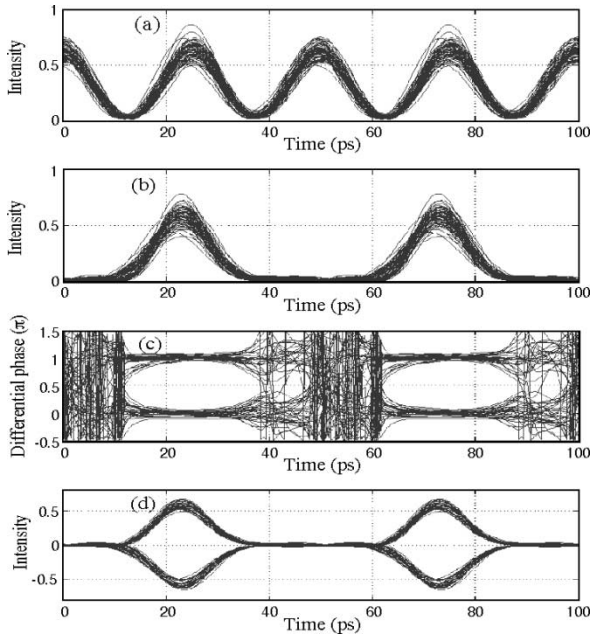


Fig. 2. Eye diagrams of the center wavelength channel after 4000-km P-MUX DPSK transmission. (a) Undecoded optical eye diagram before P-DMUX, (b) after P-DMUX, (c) differential phase diagram, and (d) after the differential phase detection (without electrical filtering).

III. SIMULATIONS

We model the nonlinear propagation by the standard split-step Fourier method. Nine 100-GHz spaced 40-Gb/s WDM channels, each assigned a 128-bit random data sequence with adjacent bits orthogonally polarized, are used. All the modulators are assumed to be ideal. The dispersion managed link consists of 100-km fiber spans with $D = 4$ ps/km/nm and $\gamma = 1.79/\text{W}/\text{km}$, and 4 km of dispersion-compensating fiber which gives a path-averaged dispersion (D_{avg}) ranging from 0 to 0.15 ps/nm/km. The predispersion compensation value is -200 ps/nm, and the postdispersion compensation makes the net dispersion of the entire system zero. The span fiber loss is 21 dB, and is compensated by distributed Raman amplification with 50% forward and 50% backward Raman gains. The effective amplified spontaneous emission (ASE) noise corresponding to the distributed Raman amplification with $\text{NF} = 3.5$ dB is added after each span. PMD is simulated by a coarse step method [6], [10] with the PMD parameter chosen to be 0.1 ps/ $\sqrt{\text{km}}$. After transmission, the channels are demultiplexed by an 85-GHz fourth-order Gaussian filter, followed by PMD compensation. We define a differential phase Q factor as π over the sum of the standard deviation of the differential phases (between two adjacent bits with the same polarization) [11]. It was found that the intrachannel FWM-induced phase noise is nearly Gaussian distributed [4], therefore, the differential phase Q factor as expected is found to be closely related to bit-error rate (BER), as was verified by more extensive simulations with direct error counting at high BERs. Fig. 2 shows the eye diagrams of the center wavelength after 4000-km transmission with $D_{\text{avg}} = 0.1$ ps/km/nm and -4 -dBm channel power (which is found to give \sim maximum distance with $Q = 6$). It shows the undecoded optical eyes right before and after P-DMUX, differential phase eyes, and

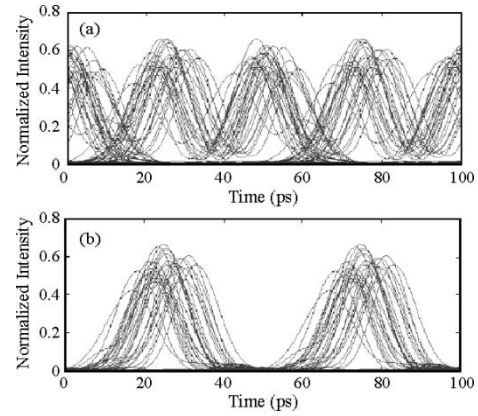


Fig. 3. Eye diagrams of the center channel after 4000-km P-MUX OOK transmission. Optical eye diagrams (a) before and (b) after P-DMUX.

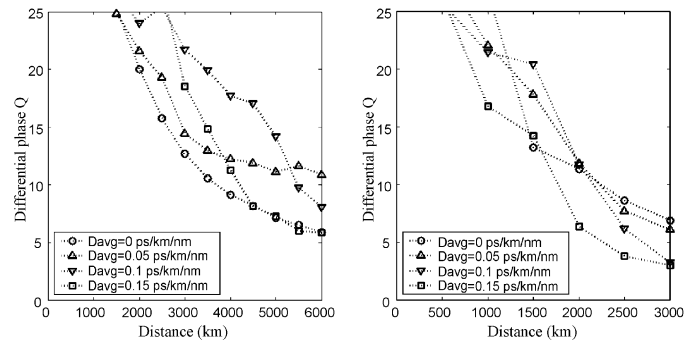


Fig. 4. Dependence of system Q factors on propagation distance in P-MUX DPSK RZ (left) and P-MUX OOK (right) transmissions with four different path-averaged dispersion values. Path-averaged channel power = -4 dBm.

the decoded eye diagram after the differential phase detection. The differential phase Q factor is estimated to be ~ 13 .

As a comparison, Fig. 3 shows the optical eye diagrams after 4000-km transmission in an OOK system with the same parameters as those used in Fig. 2. The upper and lower plots show the optical eyes before and after P-DMUX, respectively. Evidently, XPM in OOK system causes large timing and amplitude jitters which close the eyes. To show in more detail the improved system performance of DPSK scheme over OOK scheme, we plot in Fig. 4 the dependence of Q on transmission distance for both DPSK [Fig. 4(a)] and OOK [Fig. 4(b)] schemes. We also vary D_{avg} from 0 to 0.15 ps/km/nm to see the system tolerance to different path-averaged dispersions. For OOK, lower D_{avg} gives better performance, due to the reduced pulse overlap and consequently reduced intrachannel XPM and FWM penalties. For DPSK, however, lower D_{avg} does not necessarily give better performance since at low D_{avg} , the pulse spreading will be smaller and self-phase modulation becomes stronger, which leads to larger Gordon-Mollenauer phase noise [12]. We also note that the interchannel nonlinear effects are found to be negligible in the 40-Gb/s DPSK system studied here. In short, the OOK transmissions simulated are limited to a reach of ~ 3000 km for a BER of 10^{-9} , and the DPSK transmissions can reach ~ 6000 km. It is worth mentioning that without P-MUX, DPSK transmission is limited to ~ 4000 km [2]. Together with the use of advanced forward-error correction and transmission fibers with low nonlinearity [4], the P-MUX DPSK transmission distance may be extended well beyond 10 000 km.

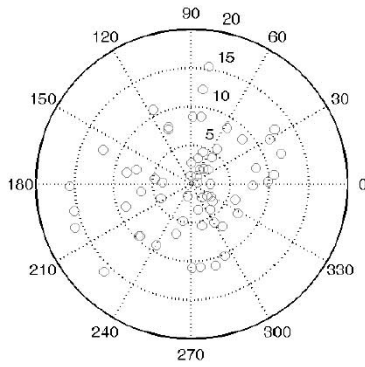


Fig. 5. Scatter plot of the ends of the Stokes vectors of individual bits at 4000 km, looking directly at the average vector, on the Poincaré Sphere.

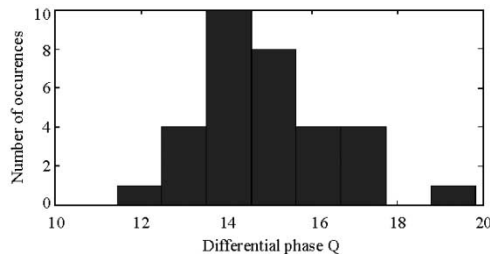


Fig. 6. Distribution of the differential phase Q factor at 4000 km. Here, $(DGD) = 6.3$ ps and $D_{avg} = 0.1$ ps/nm/km.

IV. POLARIZATION SCATTERING AND PMD

To illustrate the well-maintained DOP in the DPSK scheme, Fig. 5 shows the scatter plot of the Stokes vectors for many individual pulses after 4000 km. The standard deviation of the angles between these vectors and the mean vector is 8.4° , corresponding to a polarization extinction ratio of ~ 23 dB which is sufficient to suppress the crosstalk between the orthogonal states at the P-DMUX. On the other hand, the DOP scattering is nearly doubled in the corresponding OOK system.

The fact that the DOP of each of the two polarization states and their orthogonality are well maintained leads to two benefits. First, the nonlinear effects such as XPM and intrachannel FWM are effectively reduced along the entire transmission. Secondly, P-DMUX can be applied due to the maintained high polarization extinction ratio. The use of P-DMUX reduces the bit rate to 20 Gb/s, and thus, increases the receiver tolerance to PMD and chromatic dispersion and reduces the bandwidth requirement of the detectors. For example, PMD compensation is required after ~ 1000 -km transmission with 40-Gb/s receiver and 0.2 -ps/ $\sqrt{\text{km}}$ PMD, as compared to ~ 4000 km with 20-Gb/s receiver. The savings obtained by removing the need for PMD compensation and dynamic dispersion compensation and by using lower bandwidth detectors may outweigh the cost of the P-DMUX.

To estimate the impact of PMD and data pattern on system performance, many runs of simulations with different link PMDs (which are Maxwellian-distributed with a mean of 6.3 ps) and data patterns are performed to obtain the statistics of the differential phase Q factor. We performed 32 simulations with the same physical conditions as used above, but with different random orientations of fiber local birefringent axes, different data patterns, and different random ASE noises. The distributions of the differential Q factor at 4000 km is shown in Fig. 6. The Q factor

distribution is single peaked with a mean of ~ 15 and a standard deviation of ~ 1.7 .

V. CONCLUSION

We have investigated the performance of a time-polarization multiplexed DPSK transmission scheme. It is found that as compared to OOK, DPSK is better suited for P-MUX, thanks to the weak polarization scattering effect in high-speed DPSK systems. The combination of DPSK and P-MUX further reduces intrachannel XPM and FWM nonlinear penalties, and may provide a way for further performance improvement in high-speed transmissions.

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