New control algorithm for automatic PMD compensation system

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A new cross-tracking method is proposed to improve the convergent speed of the control algorithm in real-time polarization mode dispersion (PMD) compensation systems. The cross-tracking algorithm is compared with the previously used dithering particle swarm optimization (DPSO) and gradient particle swarm optimization (GPSO) algorithms, and it is proven to offer the best performance among the three algorithms. The transmission of a 43-Gb/s differential quadrature phase-shift keying (DQPSK) signal over a 1 200-km fiber span using a compensator based on digital signal processing (DSP) is demonstrated via the cross-tracking algorithm.

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Polarization mode dispersion (PMD) is a major contributor to signal distortion in high-speed communication systems with speeds beyond 40 Gb/s, and thus, it needs to be compensated[1,2]. PMD causes the two principal polarization components of a light signal to travel at different speeds. Hence, it spreads the bit width, increases the bit-error rate (BER), and causes service outage. Furthermore, the PMD of a signal channel randomly changes when the temperature or mechanical stress on the fiber cable changes. The main causes of transmission-system damage are the first- and second-order PMDs. the first-order PMD is defined as a differential group delay (DGD) between two principal states of polarization, and the second-order PMD is related to rotation, depolarization, and polarization depending on the dispersion. Adaptive PMD compensation (PMDC) is required for optical communication. However, achieving a stable polarization compensation is challenging. The logic control algorithm is a key factor that determines the speed of the adaptive PMDC. Thus, it should search and track rapidly without being trapped in submaximum. An artificial intelligence algorithm, the particle swarm optimization (PSO) algorithm, has been proven to be effective in PMDC[3].

To overcome premature convergence and improve the convergent speed in the tracking control process of real-time PMDC, a new tracking algorithm is proposed. The performance of the cross-tracking algorithm is theoretically analyzed and evaluated by comparing it with that of the dithering PSO (DPSO) and gradient PSO (GPSO) algorithms. The hardware operation times, numbers of failures, and degree of polarization (DOP) stabilities of the three algorithms in the tracking process are compared. Lastly, the transmission of a 43-Gb/s differential quadrature phase-shift keying (DQPSK) signal over a 1 200-km fiber span using a digital signal processing (DSP)-based PMD compensator employing the cross-tracking algorithm is demonstrated.

In the experiment, the PMDC mainly consists of three parts: the PMD monitoring, compensation, and logic control units. For the one-stage compensator, the compensation unit is composed of a polarization controller (PC) that transforms the state of polarization (SOP) of an input optical wave into its output state and a DGD line that eliminates the DGD of the input optical signals. Each compensator has several parameters to control. The DOP of the distorted optical signal is used as the feedback signal in the PMD monitoring unit because it can indicate the PMD variation in a fiber. The polarimeter outputs four voltages representing the Stokes parameters[4,5]. The automatic gain control technique is adopted to expand the subject power range of the input optical signal. The logic control unit adjusts the voltages to search for the optimum of the entire fiber link using a control algorithm. Denote the desired stable output SOPs as S1, S2, and S3. A special function F[(S1-S1')^2, (S2-S2')^2, (S3-S3')^2] with a single maximum or minimum point is designed, where S1', S2', and S3' are the SOPs detected by the polarimeter (PolaDetect™, General Photonics) in real time. The voltages are adjusted using the smart algorithm to determine the case where S1 = S1', S2 = S2', and S3 = S3'. Thus, the function reaches and maintains its maximum or minimum.

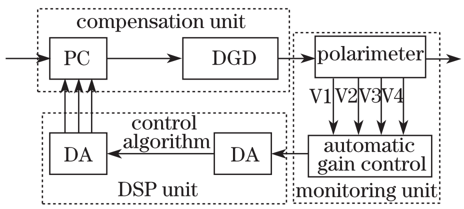

Fig. 1. Configuration of the one-stage compensator.

Figure 1 shows the configuration of the one-stage compensator.

The PSO algorithm was a community intelligence optimization method first proposed by Kennedy *et al.* in 1995[6]. Similar to other global optimization algorithms, the PSO algorithm tends to suffer from premature convergence. Thus, many improvements, such as GPSO and DPSO, have been suggested to overcome this problem in the control of real-time PMDC[7−12]. The main principle behind the GPSO and DPSO methods is the addition of a new gradient or dithering method to the PSO to improve performance. In the GPSO algorithm, a vector is calculated to determine the direction of the particle motion. Considering that the moving length is equal to amp (a constant), a new position is achieved, and the movement will continue only when the latter position is better than the former. As a result, the best position is found, and the gradient method is complete. Then, the PSO algorithm begins. The particle positions are updated using the PSO algorithm. The fitnesses of the current and best previous positions are compared, and a new best global position is determined. This procedure is repeatedly performed until the criterion is met. The DPSO process is similar to that of GPSO. Before updating the particle positions, the current position is compared with the best previous position to obtain the best position.

The cross-tracking algorithm is proposed to improve the convergent speed in the control of the tracking process in PMDC. It simplifies the calculation flow and reduces the time spent in adjusting the hardware, thus achieving faster response and cross-tracking convergence speeds than those of the previously used algorithms, such as DPSO and GPSO. The detailed process of the cross-tracking method is as follows.

Step 1: choose the last best position G_{best} as the cross center. In the cross center, according to the prior amplitude, generate new positions as

$$xx_i^d = G_{\text{best}}^d \pm \text{amp}, \tag{1}$$

where i is the serial number of the new positions, d is the dimensionality, xx is the new position (coordinate), G_{best} is the last best global optimal position obtained by the cross-tracking algorithm, and amp is the half-length of the cross.

Step 2: calculate and compare the fitnesses of all new positions to determine the global optimal position using the following formula. This process is called "group learning".

$$f\left(G_{\text{best}}\right) = \max[f\left(xx_i\right)]. \tag{2}$$

Step 3: if the new optimal position is better than the existing one, it becomes the global optimal position.

Step 4: stop the algorithm if the global optimal position meets the condition. Otherwise, continue.

As an example, a two-dimensional (2D) problem is discussed below. The best prior global position ($A_0(X_0, Y_0)$) is chosen as the center position. For the x-dimension, two symmetrical positions are chosen on the left and right sides of the center position. The two positions are $A_1(X_0\text{-amp}, Y_0)$ and $A_2(X_0\text{+amp}, Y_0)$. For the y-dimension, another two symmetrical positions $A_3(X_0, Y_0-\text{amp})$ and $A_4(X_0, Y_0+\text{ amp})$ are chosen. Then, the fitnesses of the five positions are compared with obtain the best position. If the best position is not at the center, it is chosen as the new center position and the process is repeated. When the best position is found, the cross-tracking method is ended.

All three algorithms above can obtain an optimal position (P_{a}) via different ways in controlling the tracking process, such as the dithering method in DPSO, the gradient method in GPSO, and the cross-tracking method in cross-tracking algorithm. The PSO algorithm must be performed in the DPSO and GPSO algorithms to get another position (P_{b}), and the final position is the better one between P_{a} and P_{b}. However, the P_{a} is already the final position in the cross-tracking algorithm, and hence, the PSO does not need to be performed.

Figure 2 shows the DOP surface map of the PMDC system, which indicates the relationship between the DOP and the PC voltage. The two voltages V_1 and V_2 (corresponding to X and Y) range from 0 to 140 V. Figure 2 shows several submaxima beside a global maximum in the search space. Moreover, the DOP surface is not smooth because of the noise in the fiber link.

The data collected from the automatic PMDC experiment were used to test the cross-tracking, DPSO, and GPSO algorithms. The threshold value of the search function (DOP) was set to 0.98. The simulation was conducted 50 times, and the maximum number of iterations for each trial was 50. If the DOP was larger than the threshold value, the tracking algorithm was terminated and the number of iterations was recorded.

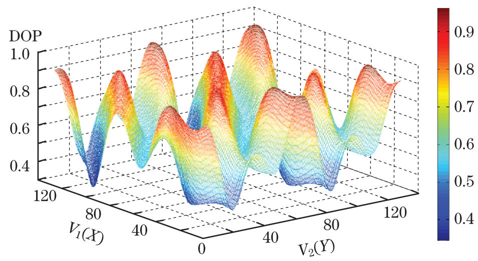

Fig. 2. DOP surface map of the PMDC system.

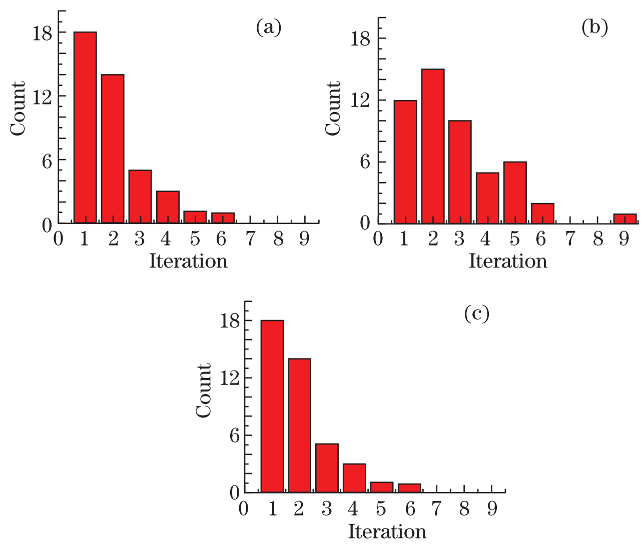

Fig. 3. Number of iteration records versus iteration. (a) DPSO; (b) GPSO; (c) cross-tracking algorithm.

Figure 3 shows the number of iteration records with its corresponding iteration. The number was obtained by adding a variable in the program. From Fig. 3, the mean convergence iteration numbers of the GPSO and DPSO algorithms were obtained as 2.86 and 2.5, respectively, and that of the cross-tracking method was 1.68. Few iterations were used to determine the threshold. Moreover, the cross-tracking algorithm spent the least time for each iteration. Thus, the simulation results show that the cross-tracking method performs faster than the GPSO and DPSO algorithms.

The cross-tracking algorithm was also experimentally evaluated. The experimental setup is shown in Fig. 4. A 43-Gb/s return-to-zero (RZ) DQPSK signal (at 193.1 THz) is generated using a 31-GHz I/Q modulator and a chirp-free Mach-Zehnder modulator for a 50% duty-cycle pulse carving. The I/Q modulator is driven by 2^{11}-1 precoded non-RZ (NRZ) binary sequences and fed into wavelength-division multiplexing (WDM) channels with a 0.8-nm spacing. A polarization scrambler (PS), followed by a PMD emulator, is placed in front of the link. The PS is used to simulate the SOP changes and is set to scan rate 8 of HP11896A, that is, the average SOP variation is about 85 rad/s[13]. A variable optical attenuator and an erbium-doped fiber amplifier (EDFA) are used to vary the optical signal-to-noise ratio (OSNR) going into the receiver. A 1 200-km standard single-mode fiber (SSMF) link is employed to evaluate the performance of the PMDCs. The straight link consists of 16 spans of SSMF spools, and each span has a length of 75 km and a loss of 23 dB. The dispersion of the link is compensated using dispersion-compensating fibers. The signal is compensated by the PMDC after demultiplexing and is then used to obtain the BER. The OSNR is measured before the signals enter the interleaver.

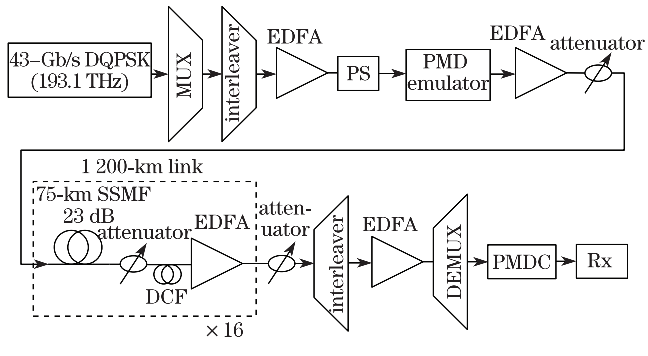

Fig. 4. Experimental setup.

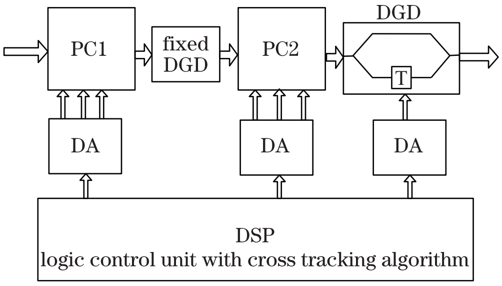

Fig. 5. Configuration of the two-stage compensator.

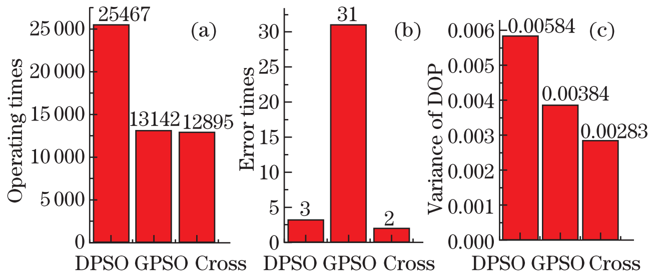

Fig. 6. Performances of the different control algorithms. (a) Hardware operation times; (b) number of failures; (c) variance.

Figure 5 shows the configuration of the automatic polarization compensator in the experiment. Each stage of the two-stage PMD controller has an electrically controlled PC and a delay line. Each electrically controlled PC has four cells adjusted at 0 to 140 V. The fixed DGD is about 16 ps and varies from −30 to +30 ps.

The logic control unit adjusts the voltages to search for the optimum of the entire fiber link by using the DPSO algorithm and the SOP feedback signals. THS1207 was used to obtain four simultaneous samples from an in-line polarimeter in the PMD monitoring unit. The DA chip TLC7226 outputs three voltage signals to adjust three for each PC. The TMS320C6720 was used as the signal processor.

The hardware operation times and the numbers of failures of the three control algorithms during the one tracking process were recorded (Fig. 6(a)). The cross-tracking method had the least hardware operation time, which is equal to that of GPSO and half that of DPSO. The DPSO searches for the position more accurately, whereas the GPSO and cross-track algorithms perform more effectively. As aforementioned, the cross-tracking algorithm spent the least time for each iterative process. Therefore, it is the fastest among the three. Furthermore, when the original particles were reduced to five (commonly 20) to increase the probability of failure, the number of failures of the cross-tracking algorithm was the least among the three algorithms (Fig. 6(b)). The particles move along the direction calculated by the last position. Compared with those of the DPSO and cross-tracking algorithms, the tracking area of the GPSO is the smallest. Thus GPSO has the highest number of errors.

The DOP variance was also evaluated. Figure 6(c) shows that the variance for the cross-tracking algorithm is 0.00283, whereas those of the DPSO and GPSO are 0.000584 and 0.000384, respectively. The PMDC system achieved its most stable performance upon using cross-tracking method because of its minimal DOP variance. Thus, the cross-tracking algorithm is the most suitable method for fast tracking in PMDC systems.

The OSNR penalties of the 43-Gb/s RZ-DQPSK signals at BER $= 10^{-3}$ are also measured for different DGDs with and without PMDC, and the results are shown in Fig. 7. When the DGD is less than 10 ps, the differences between the performances with and without compensation are insignificant. However, the PMD tolerance could be increased from 16 to 45 ps using the PMD compensator with a 1-dB OSNR penalty. Therefore, the PMD compensator using the cross-tracking algorithm

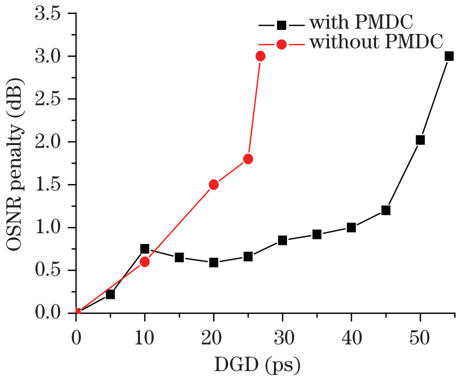

Fig. 7. OSNR penalty versus DGD.

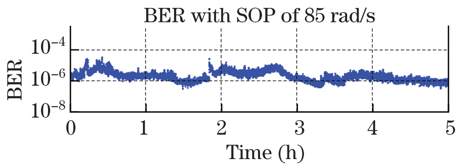

Fig. 8. Performance stability test over 5 h.

significantly increases the PMD tolerance of the system.

With the PS set to an 85-rad/s maximum speed, the long-term stability of the transmission performance (over 5 h) was tested (Fig. 8), and a better performance than that in Ref. [14] was achieved. A little fluctuation within one decade around a mean value of 10^{-5} was seen, and the BER remained below 10^{-13} with a 7% forward error correction overhead. The variations were mainly attributed to the OSNR fluctuations caused by the polarization-dependent loss. The results indicate that the cross-tracking method achieved a stable performance in the long-term test.

In conclusion, a new cross-tracking algorithm is proposed to improve the speed of real-time PMDC. The performances of the cross-tracking and other control algorithms are evaluated via simulation and experiment. The cross-tracking algorithm provides significant improvements in timing and accuracy, and thus, it is a promising control algorithm for real-time PMDC.

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