Electronic polarization-division demultiplexing based on digital signal processing in intensity-modulation direct-detection optical communication systems

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Abstract: We propose a novel configuration of optical receivers for intensity-modulation direct-detection (IM-DD) systems, which can cope with dual-polarization (DP) optical signals electrically. Using a Stokes analyzer and a newly-developed digital signal-processing (DSP) algorithm, we can achieve polarization tracking and demultiplexing in the digital domain after direct detection. Simulation results show that the power penalty stemming from digital polarization manipulations is negligibly small.

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1. Introduction

The dual-polarization (DP) transmission scheme has been introduced into practical optical communication systems for the first time by using recently-developed digital coherent receivers [1]. Controlling the state of polarization (SOP) of the DP signal in the digital domain, such receivers
can demultiplex two polarization tributaries in an adaptive manner [2]. The efficient SOP control based on digital signal processing (DSP) is owing to the phase information of the DP signal, which is obtained from coherent detection employing phase and polarization diversities [3].

On the other hand, it has been believed that in conventional intensity-modulation direct-detection (IM-DD) systems, we cannot manipulate the signal SOP even by using DSP, because the phase information of the DP signal is entirely lost after direct detection; therefore, in order to demultiplex the DP signal, we need to rely on bulky and slow optical polarization controllers, which prohibit practical implementation of DP-IM-DD systems.

Contrary to such a common belief, this paper proposes a novel configuration of direct-detection receivers, which enables polarization-division demultiplexing the DP-IM signal in the digital domain without using optical polarization controllers. Implementing the Stokes analyzer and low-complexity DSP in the receivers, we can achieve tracking of SOP fluctuations and polarization-division demultiplexing of the DP-IM signal in the digital domain. Simulation results show that the power penalty stemming from digital polarization manipulations is negligibly small even under very fast SOP fluctuations. This technique may be useful for 100-Gbit/s short-reach optical transmission systems based on the IM-DD scheme, because the 50-GS/s sampling rate of analog-to-digital converters (ADCs) is currently available [1] and the bit rate can easily be doubled with our proposed method.

The organization of the paper is as follows: Section 2 discusses the SOP of the DP-IM signal. Section 3 deals with the configuration of the proposed direct-detection receiver composed of the Stokes analyzer. In Sec.4, we discuss the polarization-tracking and polarization-demultiplexing algorithm used in the DSP circuit. Simulation results on the bit-error rate (BER) performance of the proposed receiver is described in Sec.5, and the effectiveness of the proposed algorithm is validated. Finally, Sec.6 concludes this paper.

2. SOP of the DP signal

Figure 1 shows the configuration of the DP-IM transmitter. We assume that two independent laser diodes, LD 1 and LD 2, are intensity-modulated with the same clock using either the direct-modulation method or the external modulation method. The two signals are polarization-multiplexed with a half-wave plate (λ/2) and a polarization beam combiner (PBC). The tributary 1 has the linear x polarization at the transmitter, whereas the tributary 2 does the linear y polarization. The intensity of the lasers is modulated in a binary manner. In a low logic level, the intensity of each tributary is zero. In the following analysis, we assume that the intensity of each tributary in a high logic level is two so that the average intensity is normalized to unity when both logic levels occur at the same probability of 1/2.

The total intensity of the DP-IM signal is classified into three cases shown in Table 1. In the case (I), logic levels of both of the polarization tributaries are low and the total signal intensity is zero. In the case (II), one tributary is in the high level, and the other in the low level; therefore, the total intensity is two. In the case (III), both of the tributaries are in the high level, and the total intensity is four.

Corresponding to these cases, the SOP of the DP-IM signal is classified as follows: In the case (I), we have no signal. The SOP in the case (II) at the transmitter is determined either from the linear x polarization ((II)(a)) or from the linear y polarization ((II)(b)). On the other hand, in the case (III), the DP signal never has a fixed SOP, because phases of the two tributaries are not correlated. Noting that intensities of x-polarization and y-polarization components of the DP signal are the same, we find that \( S_1 \) of the Stokes vector of the DP signal is zero, whereas \( S_2 \) and \( S_3 \) are fluctuating at the speed of the laser linewidth under the condition that \( S_2^2 + S_3^2 = 4 \). Thus, we have the relation of the three Stokes vectors shown in Fig. 2: Normalized Stokes vectors \( S_i / S_0 \) in cases (II)(a) and (II)(b) are pointed to opposite directions, and the normalized Stokes vectors...
Fig. 1. Configuration of the DP-IM transmitter. Intensities of two independent laser diodes (LDs) are modulated either by direct modulation or by external modulation with the same clock. The two signals are polarization-multiplexed by a half-wave plate ($\lambda/2$) and a polarization beam combiner (PBC).

Table 1. Classification of the state of the DP-IM signal based on the total peak intensity.

| Logic level | (I) | (II) | (III) |
|-------------|-----|------|-------|
| tributary 1: Low | tributary 1: High | tributary 1: High |
| tributary 2: Low | tributary 2: Low | tributary 2: High |
| Total peak intensity | 0 | 2 | 4 |

vector in the case (III) is orthogonal to these vectors in spite of its fluctuations. This orthogonal relation among the three normalized Stokes vectors is unchanged at the receiver although these vectors walk around on the Poincaré sphere due to fluctuations of fiber birefringence.

Fig. 2. Relation among normalized Stokes vectors in cases (II)(a), (II)(b), and (III). Normalized Stokes vectors in cases (II)(a) and (II)(b) are pointed to opposite directions, whereas the normalized Stokes vector in the case (III) is orthogonal to these vectors. The vector $v(n)$ denotes the reference Stokes vector discussed in Sec. 4.

3. Receiver configuration

Figure 3 shows the schematic diagram of our proposed receiver. The incoming DP-IM signal is equally split into four branches after optical pre-amplification and optical filtering if necessary. In the first branch, we measure the signal intensity $I_x$. Inserting a polarizer ($0^\circ$ Pol), whose transmission axis is the $x$ axis, we measure the intensity of the $x$-polarization component $I_x$ in...
the second branch. Using a polarizer (45° Pol), whose transmission-axis is rotated by 45° with respect to the positive x axis, we detect the intensity of the 45° linearly-polarized component \( I_{45°} \) in the third branch. With a quarter-wave plate (\( \lambda/4 \)), whose fast axis is aligned to the x axis, and a 45°-rotated polarizer (45° Pol), we measure \( I_R \), which is the intensity of the right-circularly-polarized component, in the fourth branch. This configuration is known as the Stokes analyzer, which determines Stokes parameters from \( I_t \), \( I_x \), \( I_{45°} \), and \( I_R \) [4] as

\[
S_0 = I_t , \\
S_1 = 2I_x - S_0 , \\
S_2 = 2I_{45°} - S_0 , \\
S_3 = 2I_R - S_0 .
\]

The four outputs of photodiodes (PDs) in Fig. 3 are converted to digital data using four-channel ADCs. The clock (CLK) extracted from the first branch of the Stokes analyzer controls sampling instances of the ADCs. The sampling rate is one sample/bit. The sampled data are sent to the DSP circuit.

4. DSP circuit

In the DSP circuit shown by Fig. 4, after calculations of Stokes parameters using Eqs. (1)-(4), polarization tracking and demultiplexing are done by the algorithm given in the following.

![Fig. 3. Receiver configuration for polarization-division demultiplexing the DP-IM signal. The part surrounded by broken lines represents the Stokes analyzer. Four outputs from photodiodes (PDs) are sent to the DSP circuit.](image)

![Fig. 4. DSP circuit for polarization-division demultiplexing the DP-IM signal. The intensity discriminator determines the case (I) shown in Table 1. Cases (II)(a), (II)(b), and (III) in Table 1 are separated through discrimination of the Stokes-vector amplitude along the reference Stokes-vector direction.](image)
where \( \mu \) is modified by using the error signal \( \varepsilon = S(n)/S_0(n) - v(n) \) and tracks the SOP of the tributary 1 even when it fluctuates on the Poincaré sphere due to the random change in fiber birefringence. A smaller value of \( \mu \) improves the signal-to-noise ratio of \( v(n) \) but reduces the SOP tracking speed; therefore, we need to choose an optimum value of \( \mu \), depending on the SOP fluctuation speed.

On the other hand, when \( u(n) \leq -u_{th} \), we decide that the measured sample belongs to the tributary 2. In such a case, the tributary 1 is in the high level, whereas the tributary 2 is in the low level. Reversing the sign of the normalized Stokes vector in Eq. (6), we have the update formula for \( v(n) \) given as

\[
v(n + 1) = \frac{v(n) + \mu \left[ -S(n) - S_0(n) \right]}{v(n) + \mu \left[ -S(n) - S_0(n) \right]},
\]

where the error signal \( \varepsilon = -S(n)/S_0(n) - v(n) \) controls the reference Stokes vector.

When \( |u(n)| < u_{th} \), both of the tributaries are in the high level. We do not update the reference Stokes vector, because the SOP is not fixed in such a case. It should be noted that in cases (I) and (III), we do not update the reference Stokes vector and keep that defined in the nearest preceding case of (II); however, since the fluctuation speed of the reference Stokes vector is much slower than the bit rate, such thinned-out operation of the update process never degrades the BER performance as shown in 5.3.

Although we have assumed that \( v(n) \) is known, the update process using Eqs. (6) and (7) can start from an arbitrary reference vector in the blind mode. However, depending on the initial choice of the reference Stokes vector, the tributaries 1 and 2 may be exchanged. After a sufficient number of iteration with the proper choice of \( \mu \), the initial tracking process is converged and we can find an accurate estimate for \( v(n) \) even under very fast SOP fluctuations.
Thus, we can discriminate the four cases (I), (II)(a), (II)(b), and (III). Finally, we complete the
demodulation process, aligning bit sequences of the tributaries.

5. Simulation results

5.1. Simulation model

In computer simulations, we generate IM signals having binary random bit patterns for the two
polarization tributaries. The number of bits for each tributary is \( N = 2^{20} \). The Jones vector of
the DP signal at the transmitter is written as

\[
E_{\text{in}}(n) = \begin{bmatrix}
E_{\text{in}, x}(n) \\
E_{\text{in}, y}(n)
\end{bmatrix}.
\]  

Complex amplitudes of electric fields \( E_{\text{in}, x}(n) \) and \( E_{\text{in}, y}(n) \) are given as

\[
E_{\text{in}, x}(n) = s_x(n) \exp \left[ i \phi_x(n) \right] + n_x(n),
\]

\[
E_{\text{in}, y}(n) = s_y(n) \exp \left[ i \phi_y(n) \right] + n_y(n).
\]

In these equations, \( s_x(n) \) and \( s_y(n) \) are signal amplitudes, which are either \( \sqrt{2} \) (High level) or
0 (Low level) so that the average intensity of each polarization is unity. Parameters \( n_x(n) \) and
\( n_y(n) \) are complex-valued Gaussian noises. The variance of the real part of \( n_x, y(n) \) and that of
the imaginary part of \( n_x, y(n) \) are represented as \( \sigma^2 \). Then, the carrier-to-noise ratio (CNR) of
each polarization is expressed as

\[
\text{CNR/pol} = \frac{1}{2\sigma^2}.
\]

The value of CNR/pol is controlled by the amount of Gaussian noise, while the average signal
intensity is kept at a unity for each tributary. We do not take the CNR reduction by branching of
the signal into account. This is valid for the optically pre-amplified signal [5].

Parameters \( \phi_x(n) \) and \( \phi_y(n) \) are phase noises of the lasers LD 1 and LD 2, respectively. We
express them as

\[
\phi_x(n+1) = \phi_x(n) + \Delta \phi_x(n),
\]

\[
\phi_y(n+1) = \phi_y(n) + \Delta \phi_y(n).
\]

Parameters \( \Delta \phi_x(n) \) and \( \Delta \phi_y(n) \) are real-valued Gaussian noises and their variance \( \sigma_p^2 \) is given [6] as

\[
\sigma_p^2 = 2\pi \delta f \cdot T,
\]

where \( \delta f \) is the 3-dB spectral width of the lasers and \( T \) the bit duration.

After suffering from the random change in fiber birefringence, the Jones vector of the DP
signal at the receiver is given as

\[
E_{\text{out}}(n) = J(n)E_{\text{in}}(n),
\]

where \( J(n) \) is the Jones matrix of the fiber for transmission. From \( E_{\text{out}}(n) \), Stokes parameters
of the received signal is obtained [4] as

\[
S_0(n) = |E_{\text{out}, x}(n)|^2 + |E_{\text{out}, y}(n)|^2,
\]

\[
S_1(n) = |E_{\text{out}, x}(n)|^2 - |E_{\text{out}, y}(n)|^2,
\]

\[
S_2(n) = 2|E_{\text{out}, x}(n)|E_{\text{out}, y}(n) \cos [\delta(n)],
\]

\[
S_3(n) = 2|E_{\text{out}, x}(n)|E_{\text{out}, y}(n) \sin [\delta(n)],
\]
where \( \delta(n) = \arg [E_{out,y}(n)/E_{out,x}(n)] \). Equations (16)-(19) are equivalent to Eqs. (1)-(4).

When we scramble the SOP of the signal to emulate random fluctuations of fiber birefringence, the Jones matrix is expressed as

\[
J(n) = \begin{bmatrix}
\exp \left[ \frac{i \phi_r(n)}{2} \cos \left( \frac{\theta_r(n)}{2} \right) \right] & -\sin \left( \frac{\theta_r(n)}{2} \right) \\
\sin \left( \frac{\theta_r(n)}{2} \right) & \exp \left[ -\frac{i \phi_r(n)}{2} \cos \left( \frac{\theta_r(n)}{2} \right) \right]
\end{bmatrix}.
\]

The polar angle and the azimuthal angle of the SOP randomly fluctuate on the Poincaré sphere in a bit-by-bit manner through \( \phi_r(n) \) and \( \theta_r(n) \). Parameters \( \phi_r(n) \) and \( \theta_r(n) \) including fluctuations obey the following equations:

\[
\phi_r(n+1) = \phi_r(n) + \Delta \phi_r(n),
\]

\[
\theta_r(n+1) = \theta_r(n) + \Delta \theta_r(n),
\]

where \( \Delta \phi_r(n) \) and \( \Delta \theta_r(n) \) are real-valued Gaussian noises having the variance given as

\[
\sigma^2_{\phi_r} = AT.
\]

The parameter \( A \) with the dimension of \( s^{-1} \) is a constant under a specific condition of the fiber for transmission.

5.2. Determination of discrimination thresholds

In 5.2, we determine the optimum threshold \( S_{th} \) for discriminating \( S_0(n) \) and \( u_{th} \) for discriminating \( u(n) \) through computer simulations. Ignoring the laser phase noise, we assume that \( \delta f = 0 \) in Eq. (14). The fluctuation of the received SOP is also neglected throughout 5.2; then, we assume that \( J = 1 \) in Eq. (15).

Figure 5 shows the simulation result of the probability-density function of the intensity \( S_0(n) \) when \( \text{CNR/pol}=10, 12, \) and \( 14 \) dB. The cases (I) and (II) are clearly separated, and we can decide that both logic levels of the tributaries are low, when the measured intensity \( S_0 \) is smaller than the threshold \( S_{th} = 0.6 \) shown by the solid line. On the other hand, the discrimination ability between (II) and (III) is so poor that the intensity discrimination shown by the broken line cannot be applied to separate (II) and (III).

We can understand the noise distribution shown in Fig. 5 as follows [5]: When we consider that the Gaussian noise originates from amplified spontaneous emission (ASE) of optical pre-amplifiers, the noise distribution in the case (I) is determined from the spontaneous-spontaneous beat-noise process. On the other hand, since the signal-spontaneous beat noise is predominant in the case (II), the probability distribution in the case (II) is broader than that in the case (I). In the case (III), two stochastically independent signal-spontaneous beat noises for orthogonal polarizations are added together; therefore, the variance of the noise in the case (III) is twice as large as that in the case (II).

Figure 6 shows the simulation result on the probability-density function of the inner product \( u(n) \) given by Eq. (5), when \( \text{CNR/pol}=10, 12, \) and \( 14 \) dB. Three peaks clearly appear in this function and we can optimally discriminate (II)(a), (II)(b), and (III) when \( u_{th} = 0.55 \) as shown by solid lines.

5.3. BER performance

In BER calculations, we scramble the SOP of the signal, assuming that the parameter \( A \) in Eq. (23) is \( 10^5 \) [s\(^{-1}\)]. The variance \( \sigma_f(N)^2 \) of \( \phi_r(n) \) and \( \theta_r(n) \) at the \( N \)-th bit is written as

\[
\sigma_f(N)^2 = \sigma_{\phi_r}^2 N = ANT.
\]
Fig. 5. Probability-density function of the intensity of the DP-IM signal. The cases (I) and (II) are discriminated by the solid line; on the other hand, the intensity discrimination shown by the broken line cannot be applied to separate (II) and (III).

Fig. 6. Probability-density function of $u(n)$, which represents the normalized Stokes-vector amplitude along the reference-vector direction. The three cases (II)(a), (II)(b), and (III) are discriminated by solid lines.

Therefore, if we assume the 25-Gbit/s/pol system ($T = 40$ [ps]), the standard deviation is 2 rad in a 40-μs time span for $N = 2^{20}$ bits. This value is much larger than SOP fluctuations observed in real systems [7]. The step-size parameter $\mu$ is set at $1/2^2$ to track the SOP fluctuation most accurately. We also include the effect of the laser linewidth $\delta f$, assuming that $\delta f \cdot T = 1 \times 10^{-3}$, which means $\delta f = 25$ MHz at the bit rate of 25 Gbit/s/pol.

Figure 7 shows the typical convergence property of the error magnitude $\| \epsilon \|$ controlling the reference Stokes vector, where we use the moving average with the span of 21 samples. Within 1,000-sample periods, the SOP tracking process is stabilized; then bit errors are counted after the convergence of the error magnitude.

Figure 8 shows BERs calculated as a function of CNR/pol. The red curve is the BER of each...
Fig. 7. Convergence property of the error magnitude updating the reference Stokes vector. Since the SOP tracking process is stabilized within 1,000-sample periods, bit errors are counted after the convergence of the error magnitude.

polarization tributary of the DP-IM signal demodulated with our proposed method. The black curve represents the BER performance of the single-polarization (SP) IM signal for comparison. In the DP-IM scheme, we find that both of the polarization tributaries have almost the same BER characteristics and the power penalty from the SP-IM scheme is negligible. Thus, the digital polarization-manipulation process does not generate any harmful effect even under very fast SOP fluctuations.

![Graph](image1.png)

Fig. 8. BERs as a function of CNR/pol for the DP-IM signal which is demodulated with our proposed method. The BER curve of the single-polarization signal is also shown for comparison.

The effect from chromatic dispersion of the link is also examined. We include the dispersion value of $\beta_2 L / T^2 = 0.125$, where $\beta_2$ denotes the dispersion parameter and $L$ the fiber length. This value corresponds to a 10-km-long standard single-mode fiber (SMF) at the bit rate of 25 Gbit/s/pol and at the wavelength of 1.55 $\mu$m. Red curves in Fig. 9 show BER characteristics of the proposed DP-IM scheme with and without chromatic dispersion, whereas black curves show those of the SP-IM signal. We find that the dispersion effect is severer in the proposed DP-IM scheme than in the conventional SP-IM scheme; however, the difference in the receiver-sensitivity degradation due to chromatic dispersion is not so significant between the two cases.
6. Conclusions

We have proposed a novel configuration of IM-DD receivers, which enables polarization-division demultiplexing in the digital domain after direct detection. Simulation results show that the power penalty stemming from digital polarization-division demultiplexing is negligibly small even under very fast SOP fluctuations. The proposed method is useful for 100-Gbit/s short-reach optical transmission systems based on the IM-DD scheme, because the bit rate can easily be doubled.

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