



A polarization-division multiplexing SSB-OFDM system with beat interference cancellation receivers

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ABSTRACT

In this paper, we have proposed a polarization-division multiplexing (PDM) single-sideband optical orthogonal frequency division multiplexing (SSB-OFDM) scheme with signal-signal beat interference cancellation receivers with balanced detection (ICRBD). This system can double channel capacity and improve spectrum efficiency (SE) with the reduced guard band (GB) due to the PDM. Multiple input multiple output (MIMO) technique is used to solve polarization mode dispersion (PMD) associated with channel estimation and equalization. By simulation, we demonstrate the efficacy of the proposed technique for a 2×40 Gbit/s 16-QAM SSB-PDM-OFDM system according to the error vector magnitude (EVM) and the constellation diagrams.

1. Introduction

Recently, orthogonal frequency division multiplexing (OFDM) technology has been widely used in optical fiber communication system because of its robustness against the inter-symbol interference (ISI) caused by chromatic dispersion (CD) [1–4]. Moreover, optical OFDM (OOFDM) technology combining with the quadrature amplitude modulation (QAM) can improve spectrum efficiency greatly [5,6]. At present, the research on direct-detection OOFDM (DDO-OFDM) in the optical OFDM system is deepening and has gained many achievements. Moreover, in our previous studies, a signal-signal beat interference cancellation receiver with balanced detection (ICRBD) was proposed to achieve signal-signal beating interference (SSBI) cancellation, and substantially the guard band (GB) is reduced in single polarization DD-OFDM system [7–9]. For further enhancing the channel capacity and spectral efficiency, we combine polarization division multiplexing (PDM) and ICRBD.

The polarization division multiplexing (PDM) technology, utilizing the polarization dimension of light wave to transmit two independently modulated signals with orthogonal states-of-polarization (SOPs) at the same wavelength, can double the channel capacity and spectrum efficiency of the optical communication system. However, PDM causes some issues including the polarization mode dispersion (PMD) and input signal nonorthogonal, which leads to the crosstalk, and polarization dependent loss, and seriously reduces system performance.

Researches have been done to eliminate the effect caused by PMD. In Ref. [10–13], two signals with different polarization states are mounted

on two carriers with different central frequencies to avoid the crosstalk. Because the two signals are not in the same frequency band, the PMD can be avoided. In [14], the authors have proposed the polarization insensitive converted signal resulted from four-wave mixing (FWM) based on a semiconductor optical amplifier (SOA). The system can get rid of PMD by using a PDM emulator that one symbol delay exists between the two polarizations. In [15], by placing two orthogonal-polarization signals of different modulation formats to different center frequencies, a PDM-DMT-SSB system with a signal photodetector (PD) is purposed to achieve polarization demultiplexing. Even though the two signals are very easy to separate with optical filtering, the scheme needs the bandwidth equal to the total bandwidth of two polarization signals. In the above studies, these methods sacrifice spectral efficiency (SE) to a certain extent. For suppressing the effect induced by chromatic dispersion (CD) and PMD, Fang et al. have proposed time-domain least square (TDLS) channel estimation method for PDM CO-OFDM/OQAM systems in [16–18]. In [19], Zhang et al. have proposed polarization multiplexed band interleaving (PMBI) of optical multiband OFDM (MB-OFDM) technology, achieving zero-guard-band and zero-PMD transmission by placing two signals with orthogonal state of polarization on interleaving sub-bands. Multi-input-multi-output (MIMO) technique can be considered as a promising solution to compensate the polarization mode dispersion (PMD). In [20], a PDM-QPSK method employing MIMO-based crosstalk transmission compensation is purposed to reduce the nonlinear penalty, which uses three special patterns of signal configuration by using MIMO processing to achieve crosstalk compensation. Some PDM-CO-OFDM schemes with

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MIMO technique have been experimentally demonstrated in [21–24]. In [21–23], these papers discuss MIMO processing in the receiver for polarization demultiplexing, using training symbols to estimate the channel transfer matrix. In [24], PDM is used in the CO-OFDM-FDM (frequency division multiplexing) system to improve the spectrum efficiency to 3.33 bit/s/Hz and channel capacity of 1.21 Tb/s in each channel, and MIMO processing is used for polarization demultiplexing. However, the CO-OFDM system needs complex receivers and high cost hardware. There are some researches about performance optimization of CO-PDM-OFDM system such as phase noise estimation, ONSR monitoring and IQ Mismatch Estimation [25–29]. In [30,31], a DD-PDM-OFDM system is proposed combining both PDM and MIMO signal processing in the receiver. In [32], channel equalization is used with a 2×2 channel matrix, which is continuously updated by the periodically inserted training symbols, equivalent to MIMO processing. In [33], the paper has proposed a PDM-QPSK-OFDM system with a 2×2 MIMO in the receiver, and the SE reaches 3.41 bit/s/Hz. However, a sufficient GB between the optical carrier and OOFDM signal is always required to avoid the SSBI in the DD-SSB-OOFDM system, which increases the bandwidth requirements.

In the recent published paper [34–38], the SSB-DD systems with Kramers–Kronig receiver have been proposed to achieve SSBI compensation. Without any frequency guard-band between the optical carrier and the SSB signal, the digital signal processing (DSP)-based receiver linearization techniques have been experimentally demonstrated to achieved beyond 100 Gb/s/channel transmission. However, the digital signal processing (DSP)-based receiver is at the expense of a significant increase in DSP complexity, which means the scheme requires increasing huge computational burden. What is more, this scheme only uses a polarization direction of the single mode fiber, which means the channel capacity can still be expanded. In [7–9], we have proposed the ICRBD, which consists of an optical inter-leaver (IL), a 2×2 three-decibel optical coupler (OC) and two photodetectors (PDs), to cancel the SSBI with the reduced GB. The SE and the receiver sensitivity are improved greatly with relatively simple electronic devices and structure combinations. PDM technology can be introduced into the DD-SSB-OOFDM system for further improving the channel capacity. The PDM-OFDM system can double the SE and channel capacity. However, PMD along the fiber link needs to be considered since it causes the random rotation of polarization directions of the optical signals.

In this paper, a PDM-OOFDM system is proposed, where MIMO signal processing is used to PDM DD-SSB-OOFDM system with the ICRBD to deal with the PMD of the single-mode fiber transmission link. In the scheme, two training symbols of the two polarization-orthogonal signals are used for channel matrix estimation. A DSP module implementing MIMO in the receiver makes polarization demultiplexing feasible to equalize efficiently PMD and CD. Then, a 16-QAM SSB-PDM-OOFDM transmission link is built on the simulation platform with each channel rate of 40 Gb/s, and the constellation diagram and the error vector magnitude (EVM) are obtained. According to effective metrics including SE, GB and capacity, the performance of optical communication system is improved. Compared with the previous SSB-OFDM system with the ICRBD, this paper introduces the polarization-division multiplexing (PDM) technique for doubling channel capacity and improving spectrum efficiency (SE) further with the reduced guard band (GB). At the same time, a low complexity structure of MIMO algorithm and SSBI cancellation receiver is used to deal with the polarization mode dispersion (PMD) and SSBI without additional optical filters. Moreover, we use a simple combination of two training sequences, and the scheme about orthogonal combination of short training sequences is proposed to achieve frequency offset estimation and PMD estimation at the same time, which can also be used to channel equalization.

This rest of the paper is organized as follows: In Section 2, we describe the principle of the PDM-MIMO technology for the demultiplexing in DD-SSB-OFDM link. In Section 3, the simulation link of our proposed PDM-OOFDM system with the ICRBD is built and run. Then simulation results are analyzed. Finally, we summarize this paper in Section 4.

2. Principle of the proposed PDM-OOFDM link

Fig. 1 shows the proposed channel transmission link with PDM-MIMO-OFDM. In the transmitter, two different baseband OFDM signals T_X and T_Y are generated by OFDM modulation. Then, with an I/Q modulator driven by the RF local oscillator, each baseband OFDM signal is up-converted to an intermediate frequency to create a variable GB. On the other hand, the light wave is generated from a continuous-wave (CW) laser diode (LD), which can be expressed as $E_{LD}(t) = E_c \exp(j2\pi f_c t)$ [8]. Then, a polarization beam splitter (PBS) divides the light wave into two polarization-orthogonal optical carriers with vertical state of polarization (SOP) and equal optical power, as shown in Fig. 1(a). Next, via an optical Mach–Zehnder modulator (MZM) in the vestigial OCs pattern for optimizing the optical carrier and sideband ratio, two generated radio-frequency-OFDM (RF-OFDM) signals are modulated on the two polarization-orthogonal optical carriers at the center frequency f_c . Since the dc bias is a little deviated from the null point, the vestigial optical carrier exists, and its amplitude depends on the deviation of the DC bias from the null point. Then, a polarization beam combiner (PBC) is used to combine two polarization-orthogonal DSB-OOFDM signals. After that, an optical band-pass filter (OBPF) is used to suppress one sideband to generate the SSB-OOFDM signals, as shown in Fig. 1(b). The SSB-OFDM signals in the transmitter can be expressed as

$$\begin{aligned} \overline{s(t)} &= \frac{E_c}{\sqrt{2}} e^{j2\pi f_c t} + E_s \sum_{i=-\infty}^{i=\infty} \left[\sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} \overline{c_{ni}} \prod(t-iT) \exp[j2\pi(f_c + f_{RF} + f_n)t] \right] \\ \overline{s(t)} &= \begin{bmatrix} s_x \\ s_y \end{bmatrix} \quad \overline{c_{ni}} = \begin{bmatrix} c_{ni}^x \\ c_{ni}^y \end{bmatrix} \\ \prod(t) &= \begin{cases} 1, & 0 < t \leq T \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (1)$$

where N is the number of subcarriers, $-N/2 \leq n < N/2$; $(s_x \ s_y)^T$ are the transmitted signals modulated on the polarization-orthogonal two optical carriers; c_{ni} is the complex signal carried by the n th subcarrier in the i th OFDM symbol; V_{RF} and f_{RF} are the voltage amplitude and the frequency of RF signal, respectively; $\prod(t)$ is the pulse shaping function; T is the OFDM symbol duration; $f_n = n/T$ is the frequency of the n th subcarrier of the baseband OFDM signal. The bandwidth of the baseband OFDM signal is $W_S = N/T$ and the GB of the RF OFDM signal is $W_G = f_{RF} - W_S/2$.

The generated PDM-SSB-OOFDM signal is injected into the single-mode fiber (SMF) for transmission, where the transmission function including PMD can be expressed as channel matrix H_{fiber} . At the receiver, a PBS is used to orthogonally split the received PDM-SSB-OOFDM optical signal into two optical components, X' - and Y' -polarization signal components. Then, the ICRBDs are used to convert the two optical signals back to the electrical ones with the SSBI elimination [7,8]. In the ICRBD, the optical IL is used to separate the optical carrier and the OOFDM signal from each branch. The following 2×2 three-decibel OC is used to couple with the optical carrier and the OOFDM signal with equal power but with relative phase shifts of 90° and -90° for the two branches. Then, the two combined signals from the OC are fed to the BPD including two PDs. Fig. 2 shows the principle of the ICRBD [7,8].

Since the DC and SSBI components in the photocurrents are in-phase for the two PDs while the RF OFDM signals have antiphase, the former is canceled out and the latter is doubled after the differential circuits with coherent addition, as shown in Fig. 1(c)–(h) and Fig. 2. Designed as the proposed link, the OOFDM signal and its optical carrier come from the same laser with linear polarization and are transmitted over the same optical path, so they are always rotated synchronously and keep parallel polarizations [9]. Furthermore, the frequency offset and phase offset of the optical carriers and OOFDM sidebands are synchronous and can be canceled by beating each other, which can reduce the requirement for

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