Polarization-Insensitive Single Balanced Photodiode Coherent Receiver for Passive Optical Networks

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Abstract *Alamouti polarization-time block coding, combined with heterodyne detection, enables phase-diverse coherent detection using a single balanced photodiode without optical polarization tracking. A 10.7Gb/s OFDM signal is experimentally rotated over the full Poincaré sphere achieving a mean receiver sensitivity of -35.8dBm.*

Introduction

Phase- and polarization-diverse digital coherent receivers are a well-established technology for high capacity long-haul optical communications, and are now under consideration in other areas of optical communications, such as access networks. Coherent receivers enable the use of advanced modulation formats, such as polarization-multiplexed quadrature phase shift keying (PM-QPSK), while permitting the use of digital signal processing (DSP) to compensate transmission impairments. However, in an access network scenario, it is their high receiver sensitivity and frequency selectivity which are of interest[1,2].

In order to make a coherent receiver an attractive prospect for the optical network unit (ONU) in an access network, its optical complexity must be minimized, preferably by limiting the receiver architecture to components which are suitable for monolithic integration and volume production. Monolithically integrated phase-diverse coherent receivers, which combine a 90° optical hybrid, a local oscillator (LO) laser and two balanced photodiodes (BPDs) on a photonic integrated circuit, have been demonstrated. However, to date, such receivers are unsuitable for volume production due to the challenge of polarization beam splitter (PBS) integration, and must be packaged as a discrete optical component[5]. If a coherent receiver is not polarization-diverse, then the LO laser must be polarization aligned with the signal. This requires complexity in the form of feedback loops for endless optical polarization tracking.

Hence, in this paper, we propose a coherent receiver that is immune to polarization rotation without the requirement for polarization-diversity at the receiver. Previously demonstrated polarization-insensitive receivers have either incorporated a PBS in the receiver[3] or incorporated polarization scrambling at the transmitter[4]. The former solution effectively depolarizes the received signal, restricting transmission to pulse amplitude modulation, whereas

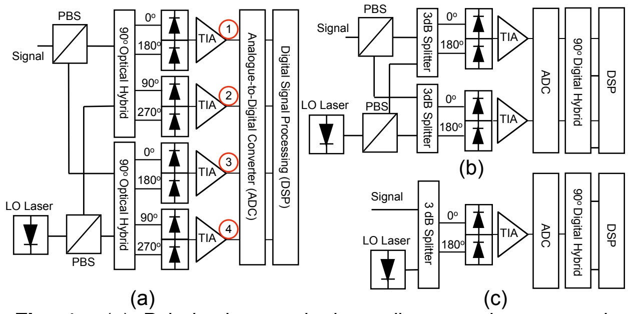

Fig. 1: (a) Polarization- and phase-diverse coherent receiver with (a) intradyne and (b) heterodyne detection. (c) Phase-diverse polarization-agnostic (simplified) coherent receiver enabled by Alamouti PTBC (For a fair comparison, the PBS was included in our experiment but that it is functionally redundant since the coherent detection process only detects one polarization of the signal).

the latter case introduces an intrinsic 6 dB sensitivity penalty versus a dual polarization receiver. By combining a polarization-time block coding (PTBC) scheme with the well-established principle of heterodyne coherent reception, polarization-insensitive detection of the QPSK format is experimentally transmitted over 80 km standard single-mode fiber (SSMF), utilizing only a single balanced photodiode and a LO laser while maintaining receiver frequency selectivity and linearity.

Alamouti Polarization-Time Block Code

In wireless communications, using two-transmit/one receive antenna architecture has been shown possible through a space-time block coding, known as Alamouti coding[6]. This half-rate, orthogonal block coding scheme (two time-slots in two spatial dimensions) replicates the transmitted symbols exactly once, in such a way to enable the recovery of both symbols from a block of transmitted symbols. Drawing an analog between the two polarization modes and the two transmit antennae, referred to as polarization-time block code (PTBC), it has been adapted to optical communications to compensate polarization dependent loss (PDL) in long-haul coherent optical systems using 2×2 multi-input multi-output (MIMO) Orthogonal Frequency Division Multiplexing

(OFDM)[7,8].

Since the Alamouti code can be utilized in a 2×1 multiple-input-single-output (MISO) systems, the polarization- and phase-diverse coherent receiver with intradyne reception can be significantly simplified, as depicted in Fig. 1. The PTBC transformation from a single polarization (SP)-OFDM signal (E_X and E_Y) to an Alamouti-coded dual polarization (DP)-OFDM signal on a single block is given by

$$\begin{bmatrix} E_X \\ E_Y \end{bmatrix} \xrightarrow{\text{Alamouti}} \begin{bmatrix} E_{X_1} & -E^*_{X_2} \\ E_{X_2} & E^*_{X_1} \end{bmatrix}, \qquad (1)$$

where E_{X_1} and E_{X_2} are two consecutive symbols on X-polarization, and * represents the complex conjugate operation.

Experimental Configuration

The experimental configuration is shown in Fig. 2. An external cavity laser (ECL) at 1550 nm (100 kHz linewidth) was used as an optical source for the integrated dual-polarization (DP) IQ-modulator. Four electrical signals generated by two 12 GSa/s arbitrary waveform generators (AWGs) (effective number of bits (ENOB) of 5-bit and a 6 GHz 3dB bandwidth) were used to drive the DP IQ-modulator.

The DP-OFDM signal was generated offline using a 512-point inverse fast Fourier transform (IFFT). 316 subcarriers were encoded using QPSK symbols of which 10 subcarriers were used as pilot carriers for common phase error (CPE) estimation. Around the DC-component, 18 virtual subcarriers were inserted to enable the frequency offset (FO) correction and RF-aided phase noise compensation (PNC)[9]. For FFT frame synchronization, two highly-correlated OFDM symbols were inserted on X-polarization to utilize Schmidl and Cox algorithm[10]. When the PTBC was applied, the synchronization symbols were also inserted on Y-polarization to mitigate the possible fading on X-polarization. 20 pair-wise training symbols after the synchronization symbols and four pair-wise periodic (every 34 data symbols) training symbols were placed for channel estimation using zero-forcing method[11]. After subcarrier mapping and upsampling with zero padding, the PTBC was applied to the orthogonal polarization states in the time domain, as indicated in Eq. 1. A cyclic prefix (CP) with 30 samples per symbol (5% overhead) was appended as a guard band to compensate chromatic dispersion. For optimised receiver sensitivity performance, the OFDM waveform was clipped such that the peak-average-power ratio (PAPR) was 7 dB. After removing the OFDM overhead, the total net bit rate was chosen to be 10.7 Gb/s, assuming a 7% overhead allowing for a hard decision forward error correction (HD-FEC)

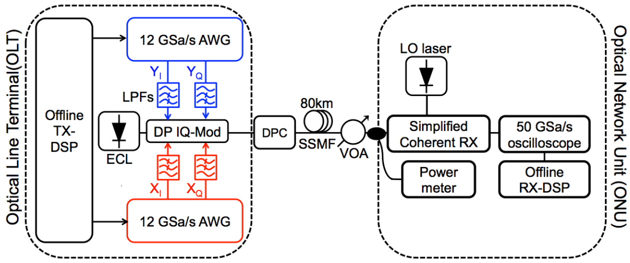

Fig. 2: Experimental configuration.

correcting a bit error ratio (BER) of 3.8×10^{-3} to below 10^{-15}. The optical carrier was added by biasing the modulator, with a carrier-to-signal-power ratio (CSPR) of approximately -11 dB. Note that the carrier was added to both polarization states when PTBC was applied, maintaining the total CSPR $<$-9 dB.

To evaluate the resilience of the Alamouti-coded OFDM signal to polarization rotation, a digitally-operated polarization controller (DPC) was used to rotate the signal over the full Poincaré sphere. Furthermore, to demonstrate a typical optical access link, the signal was transmitted over 80 km of SSMF with an attenuation of 16 dB (0.2 dB/km) and a chromatic dispersion coefficient of 16.8 ps/nm/km at 1550 nm.

The transmitted DP-OFDM signal was initially detected using the intradyne receiver configuration shown in Fig. 1(a) where the DP optical hybrid insertion loss was measured to be 7 dB. In the heterodyne scenario, the SP- and Alamouti-coded OFDM signals were detected by a single balanced photodiode (BPD). For experimental convenience, we achieved this by discarding the signal received by the three unused quadratures (BPDs 2, 3 and 4 shown in Fig. 1(a))[1]. The LO laser wavelength was set to 1550.11 nm, yielding an intermediate frequency (IF) of ~14 GHz. After the signal was digitized using a single analogue-to-digital converter (ADC) (50 GSa/s sample rate, 23 GHz 3 dB bandwidth, 5-bit ENOB at 10 GHz), the received electrical signal was down-converted to obtain I- and Q-baseband signals. After FFT window synchronization, the FO was estimated via peak search utilizing the RF-pilot[9]. Subsequently, PNC was also achieved via RF-pilot using a 5$^{\text{th}}$-order Butterworth LPF with a bandwidth of 500 kHz[9]. Following the CP removal and FFT, the channel estimation for SP- and DP-OFDM signal was achieved using a zero-forcing equalizer (ZFE), whereas the received and transmitted training symbols were first divided into 2 space-time blocks before applying the ZFE in the Alamouti coding case. Finally, 10 data pilots were used to compensate the CPE. The BER was computed by error counting over 2^{18} bits.

[1] N.B. For the heterodyne DP-OFDM receiver, this corresponds to discarding the input from BPDs 2 and 4.

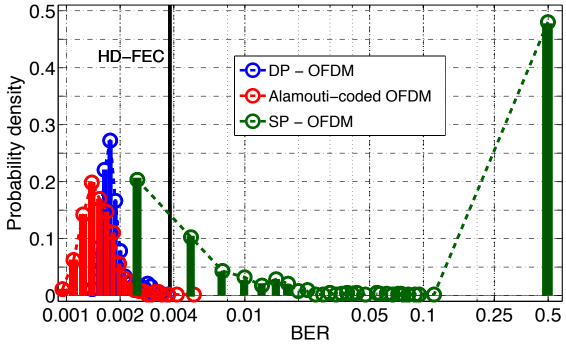

Fig. 3: The probability densities versus BER.

Results and Discussions

The back-to-back and transmission results presented in this section were obtained using the experimental configuration shown in Fig. 2. To assess the SP-, DP- and Alamouti-coded OFDM signals' tolerance to polarization rotation, 625 equally-spaced polarization states over the Poincaré sphere were measured and the achieved BERs are plotted in Fig. 3. The DP-OFDM signal achieved an average BER of 1.8×10^{-3} at a receiver sensitivity of -35.5 dBm. The Alamouti-coded OFDM signal also successfully achieved an average BER of 1.6×10^{-3} at a receiver sensitivity of -34.9 dBm in 99.7% of the measurements. In contrast, 50% of the received SP-OFDM signals failed to achieve a BER below the FEC threshold using the single BPD, as expected.

Following this, maintaining the polarization orthogonality, the receiver sensitivity of SP- and Alamouti-coded OFDM signals at a bit rate of 10.7 Gb/s and, the DP-OFDM signal at a bit rate of 21.4 Gb/s, were found to be -39.4, -35.8 and, -36.4 dB, respectively, at the HD-FEC threshold, as shown in Fig. 4. During the receiver sensitivity measurements, LO power was fixed to 2.5 dBm at the photodiode in all cases. An additional penalty of 3.6 dB for the Alamouti-coded OFDM signal, compared to the SP-OFDM signal, was observed due to sending a redundant data on Y-polarization and using a higher CPSR value for the PNC. However, SP-OFDM signal fails to operate using the proposed simplified coherent receiver, whereas the Alamouti-coded OFDM signal has exhibited excellent resilience to polarization rotation, and thus, it can be reliably detected by the simplified coherent receiver. This also implies that the receiver sensitivity of the Alamouti-coded OFDM signal can be improved by 7 dB if the loss of 10.5 dB due to the PBS and 90° optical hybrid are omitted (assuming a 3.5 dB insertion loss for a nominally 3dB coupler used in the simplified coherent receiver). Finally, the Alamouti-coded OFDM signal was transmitted over a SSMF of 80 km with no additional penalty at a launch power of -1 dBm, achieving a power budget of -35.8 dB, or -42.8 dB when the excess receiver insertion loss is

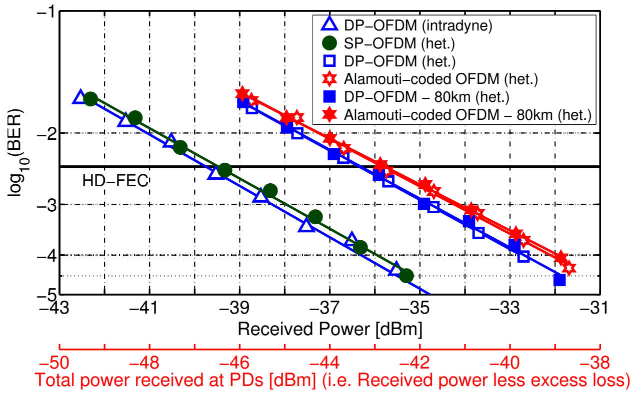

Fig. 4: BER vs. receiver sensitivity. Using the simplified receiver, enabled by the Alamouti coding, the received power at the photodiodes is 7dB higher due to the loss of PBS and 90° optical hybrid.

calibrated from the measurement, as shown in Fig. 4.

Conclusions

We experimentally demonstrated how the optical complexity of coherent receivers can be significantly reduced using a combination of PTBC and heterodyne detection. The coding scheme enables a DP signal (two transmit diversity) to be received using a single balanced photodiode, independent of the phase or amplitude modulation scheme employed. Crucially, this enables a coherent ONU with no additional optical components versus a direct detection ONU. The technique was verified by rotating the signal over the full Poincaré sphere, observing only 0.6 dB degradation in receiver sensitivity.

Acknowledgements

This work was supported by EPSRC UNLOC EP/J017582/1 and FP7 project ASTRON. S.J.S. thanks the RAEng/Leverhulme Trust for funding his fellowship.

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