Polarization-diversity receiver using remotely delivered local oscillator without optical polarization control

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Abstract: Silicon photonics coherent transceivers have integrated all the necessary optics except the lasers. The laser source has become a major obstacle to further reduce the cost, footprint, power consumption of the coherent transceivers for short-reach optical interconnects. One solution is to utilize remotely delivered local oscillator (LO) from the transmitter, which has the benefits of relaxing the requirements of wavelength stability and laser linewidth and simplifying the digital signal processing (DSP) of carrier/phase recovery. However, a sophisticated adaptive polarization controller (APC) driven by a control loop in the electrical domain with a complicated algorithm is required to dynamically track and compensate for the polarization wandering of the received LO. In this paper, we propose a hybrid single-polarization coherent receiver and Stokes vector receiver (SVR) for polarization-diversity coherent detection without a need of optical polarization control for the remotely delivered LO. With such a scheme, we successfully received a 400-Gb/s dual-polarization constellation-shaped 64-QAM signal over 80-km fibers.

1. Introduction

Intensity modulation and direct detection (IMDD) with low hardware complexity and operational cost is predominant in datacenters nowadays. However, IMDD lacks the critical capability of field recovery to enable multi-dimensional modulation and achieve high spectral-efficiency transmission. Therefore, IMDD is unfavorable to meet the demand of continuous Internet traffic growth in data centers. Benefiting from the capability of full-field recovery, coherent detection captures much attention for achieving ultra-high capacity transmission and providing superior performance [1]. Polarization-multiplexed coherent transmission technique is normally preferred to double the spectral efficiency per wavelength. However, under the same total transmission rate, coherent transceivers have a higher power consumption of DSP than direct-detection counterparts [2]. The cost and footprint of transceivers have also become the main impediments of adopting coherent detection for datacenters. With the development of silicon photonics integration, the integrated circuit of a coherent transceiver contains all the needed optics except the lasers [3,4]. Consequently, the cost and footprint of the coherent transceiver have been significantly decreased. However, coherent detection is mainly deployed in long- or medium- reaches and still considered too costly for short-reach applications due to the laser source. The transmitter and receiver lasers require stringent requirements of wavelength stability and narrow linewidth, generally needing temperature control and thus incurring a large amount of cost, space, and power consumption. Hence, the laser source in the transceiver has become a limiting factor for short-reach optical interconnects.

To address this, LO could be remotely delivered from the transmitter, where the information-bearing signal and a copy of the transmitter laser are transmitted over a pair of parallel fiber.
This is advantageous over self-coherent schemes such as Kramers-Kronig receiver (KKR) [6] and self-coherent Stokes vector receiver (SCOH SVR) [7] where LO is combined with the transmitted signal with a small frequency gap to form a single-sideband signal for KKR and on the orthogonal polarization tributary at the transmitter for SCOH SVR, thus reducing the achievable electrical spectral efficiency and greatly degrading the optical signal-to-noise ratio (OSNR) sensitivity due to the reduced effective signal power. Obviously, the disadvantage of such a scheme is that a separate optical fiber is required for the delivery of LO since the LO has the same wavelength with the information-bearing signal. However, it can fetch more merits. The shared remote LO delivery can be possibly implemented using multi-core fibers, for instance, 8-core fibers [8], where one of the cores can be used for LO delivery and the rest 7 cores for signal transmission. In such a case, the remote LO can be optically amplified then shared among multiple receivers. This is because the transmitter lasers and LO are sharing the same laser source. Compared with the conventional coherent systems, this can be more cost-effective. Additionally, since the transmitted signal and LO share the same laser source, wavelength stability and laser linewidth requirements are greatly relaxed, which allows the usage of un-cooled lasers having large linewidth. As a consequence, the DSP for carrier/phase recovery [9] is greatly simplified. However, one of the great challenges of this scheme is that the polarization states of both signal and remote LO would vary randomly during the transmission due to the time-varying environmental disturbance and the random birefringence distributed along the fiber. Therefore, there would exist a significant power imbalance between the two orthogonal polarizations of LO after the polarization beam splitter (PBS) at some specific polarization states. Consequently, using the conventional polarization-diversity coherent receiver (PDCR) as shown in Fig. 1(a) for the successful reception of a dual-polarization (DP) signal, the state of polarization of the received LO should be well controlled at the receiver side to avoid the polarization fading effect so that the optical power of the received LO can be evenly separated into two orthogonal paths for the effective beating with both polarizations of the DP signal. This commonly requires a sophisticated APC with a control loop in the electrical domain to dynamically track and compensate for the polarization wandering of the received LO [5, 10]. The APC integrated on the board is realized by phase shifters sandwiching couplers which are electrically driven by a polarization tracking algorithm [10]. Proposed most recently, the APC positioned on the LO path has been demonstrated in real time to combat the polarization fluctuations of received LO only up to 300 rad/s with a negligible penalty [11]. To cope with higher-speed polarization rotation scenarios, more advanced APC is required to avoid the high-speed polarization rotation induced performance degradation, which is generally complicated in device design and control algorithm. Therefore, it is desirable to eliminate the usage of the optical polarization controller in remote LO based systems.

**Fig. 1.** Configuration of (a) conventional polarization-diversity coherent receiver using remotely delivered LO with an adaptive polarization controller (APC) and (b) proposed polarization-diversity coherent receiver without any optical polarization control for remote LO. PBS: polarization beam splitter. PSR: polarization splitter/rotator. BPD: balanced photodiode. OC/OS: optical coupler/splitter. SVR: Stokes vector receiver.
In this paper, we propose a novel PDCR structure using remotely delivered LO without optical polarization control, which is a hybrid single-polarization coherent receiver and SVR. To validate the proposed scheme, we carry out 50-Gbaud 64 QAM information transmission with the probabilistic constellation shaping (PCS) technique [12]. In the experiment, the receiver architecture of our proposed PDCR is implemented with discrete optical components for demonstration, which can be manufactured by using compact silicon photonics integration to avoid polarization misalignment in the future. We experimentally demonstrate a 50-Gbaud DP signal yielding a raw source rate of 400 Gb/s over two spans of 80-km single-mode fiber for separate transmission of DP information-bearing signals and remotely delivered LO. This signifies our proposed receiver using remote LO can be a potentially cost-effective solution for inter- and intra-datacenter short-reach communications.

2. Principle of proposed PDCR

To avoid the optical polarization controller in conventional PDCR, we propose a novel PDCR for the recovery of DP signals as shown in Fig. 1(b). It consists of a single-polarization coherent receiver (top $90^\circ$ hybrid followed by 2 balanced photodiodes (BPDs) in Fig. 1(b)) and an SVR, which is distinguished with the conventional PDCR. In the conventional PDCR, a PBS and a polarization splitter/rotator (PSR) are required for the received DP signal and LO, respectively, while in our proposed receiver architecture two 3-dB optical splitters are employed instead. After the two optical splitters, a single-polarization coherent receiver and an SVR are used to retrieve the two orthogonal polarization tributaries, respectively, rather than two ordinary coherent receivers in conventional PDCR. Note that the number of used BPDs is one more than the conventional PDCR since the SVR in our proposed PDCR requires 3 BPDs. Nevertheless, to dynamically track the state of polarization of the received LO, an APC driven by a sophisticated polarization tracking algorithm is required for the conventional PDCR. Hence, the hardware complexity of both systems is envisaged to be comparable.

For explanatory simplicity, we use the polarization coordinate of the received LO as reference for both received DP signals and LO. The electrical field of received DP signal, $E_R$, and LO, $C$ in the received LO polarization coordinate is respectively expressed as

$$E_R = U_p E_f = [X_R, Y_R]$$  \hspace{1cm} (1)

$$C = [1, 0]$$  \hspace{1cm} (2)

where $E_f$ is the output DP signal after the fiber transmission containing a combination of transmitted DP signal $[X_T, Y_T]$, $U_p$ is the coordinate transformation matrix from the polarization coordinate of DP signals to the received LO polarization coordinate. Note that we have used the denotation convention of bold font for vectors and matrices and normal font for scalars. In practice, since the paths of DP signals and LO may not be precisely matched, there exist slow phase drift and residual phase noise between the Jones vectors of the DP signal and the received LO. Consequently, the polarization component, $X_R$, which is parallel with the polarization of received LO, is recovered from the single-polarization coherent receiver given by

$$X_R = E_R \ast C^H$$  \hspace{1cm} (3)

where the superscript $H$ stands for the Hermitian operator. To recover the orthogonal polarization $Y_R$, the SVR is used to function as a polarimeter for tracking the state of polarization of the input signal. In the polarization coordinate where LO is used as reference (see Eqs. (1–2)), the single
input field signal of the SVR is represented as $E_R + C = [X_R + 1, Y_R]$ in Jones space. We assume there is no polarization rotation after the optical splitters in the proposed PDCR. This issue can be avoided by carefully designing the receiver splitters and will be considered in detail in the next section. As the polarization misalignment exists between the single input and the PBS in the SVR, Stokes-space polarization recovery is indispensable to estimate the $3 \times 3$ real-valued polarization rotation matrix and then multiply the received Stokes vector with the inverse of the polarization rotation matrix (more discussion of polarization recovery can be found in the next section). After the Stokes-space polarization recovery, the SVR will produce a complete Stokes vector of $E_R + C$ as

$$S_R = [S_1, S_2, S_3] = [\|X_R + 1\|^2 - |Y_R|^2, 2\text{Re}((X_R + 1)Y_R^*), -2\text{Im}((X_R + 1)Y_R^*)]$$  \hspace{1cm} (4)

where $\text{Re}$ and $\text{Im}$ represent the real and imaginary parts of a complex variable, respectively. Therefore, $(X_R + 1)Y_R^*$ can be retrieved by forming a complex signal of $(S_2 - iS_3)/2$ [7]. Given $X_R$ polarization obtained by the single-polarization coherent receiver, the orthogonal polarization $Y_R$ can be retrieved from

$$Y_R = (S_2 + iS_3)/2(1 + X_R^*)$$  \hspace{1cm} (5)

In particular, $1 + X_R^*$ never crosses zero as the carrier to signal power ratio (CSPR) is set sufficiently high to guarantee superior performance. After the DP field recovery process, both recovered $X_R$ and $Y_R$ contain a combination of the transmitted DP field information $X_T$ and $Y_T$. Then, the conventional $2 \times 2$ MIMO equalization in Jones space is required to perform signal demultiplexing to retrieve transmitted $X_T$ and $Y_T$ [9].

It can be seen that in our proposed PDCR, the polarization fading effect of the received LO does not exist since the optical splitter (rather than polarization splitter) is used for splitting the remotely delivered LO. Furthermore, the Stokes vectors of the fiber output DP signal $E_f$ are unitarily rotated in the Stokes space by a $3 \times 3$ unitary rotation matrix isomorphic to $U_p$ without fading. As a result, our proposed PDCR employs digital unitary transformation in both Stokes and Jones space without a need of optical polarization control for the remote LO and is fundamentally robust against any input state of polarization.

3. Experimental setup

We experimentally demonstrate our proposed DP coherent receiver by a 50-Gbaud DP signal using the setup illustrated in Fig. 2. For the first proof-of-concept demonstration, the laser source with a 100-kHz linewidth at the transmitter is used for the generation of both DP signals and LO. Since the DP signals and LO share the same laser source, the laser source in this experiment could be replaced with an un-cooled distributed feedback (DFB) laser with a large linewidth, which is to be investigated in detail in the future. A 50-Gbaud single-polarization signal is firstly generated by the DSP shown in Fig. 2(i) with 80 GSa/s rate. The constant composition distribution matcher (CCDM) [12] is used to shape the 64-QAM signal with an entropy of 4 bits/symbol. The signal is OFDM-modulated with a DFT size of 512, in which 320 subcarriers are filled with PCS 64-QAM symbols. As the chromatic dispersion (CD) will be post-compensated at the receiver, a 32-point cyclic prefix is inserted to alleviate the complexity of timing and synchronization. After that, the generated OFDM signal is pre-equalized to compensate for the linear frequency response imperfection of the transmitter, and then resampled to 92 GSa/s to fit the sampling speed range of the arbitrary waveform generator (AWG). The DP signals are generated by a polarization emulator, in which one polarization is decorrelated by 1.4-m optical fiber. The optical spectrum of the generated DP signal is shown in Fig. 2(ii). On the LO or optical carrier path, an isolator is inserted at the transmitter side to avoid the strong optical carrier induced backward stimulated Brillouin scattering (SBS) especially for long transmission distance (>40km). A variable optical
attenuator (VOA) on the LO path is used to vary its launch power to be 4 dBm in this experiment. Two spools of 80-km optical fiber are used to be full-duplex fiber or emulate the multi-core fiber for DP signal transmission and remote LO delivery, respectively. After the fiber transmission, two EDFAs are used to compensate for the transmission fiber loss and the insertion loss of the receiver and also control the CSPR for experimental parametric investigation. As there are 7 optical outputs needed at the receiver, to save the required analog-to-digital converter (ADC) ports, two optical switches for the time-multiplexed receiver are employed to perform the gate function with a 4096-ns period and 25% duty. Since the received DP signal and LO in our proposed receiver scheme are based on the same polarization coordinate, the DP signal polarization at the combining points ‘c’ and ‘d’ after the splitting points ‘a’ and ‘b’ should be maintained. For this, standard weakly birefringent fibers should be used. In the typical silica-based single-mode fiber, the birefringence coefficient around the center wavelength of 1550 nm is about $10^{-6}$ [13]. Therefore, the polarization beat length is 1.55m, which means the polarization will have very small changes when the feature of the coupler is much smaller than 1 m. To investigate the impacts of the small polarization changes on the overall system performance, we conduct a simulation and find the signal-to-noise ratio (SNR) penalty is less than 1 dB if the polarization direction of the DP signals relative to the LO changes within ±17°, and this misalignment can be avoided by using compact silicon photonics integration instead of using discrete optical components. In this experiment, the fiber length of the optical paths from the splitting points ‘a’ and ‘b’ to the combing points ‘c’ and ‘d’ are ~0.4 m. These practical optical paths shown in the inset of Fig. 2 are also laid straight to avoid bending induced birefringence. A 3×3 optical coupler (OC) is used to perform the function of 90° optical hybrid in our proposed receiver scheme as shown in Fig. 1(b). Due

to the high insertion loss of the time-multiplexed receiver, the SVR in this experiment requires an extra stage of an optical amplifier (OA) (note that this high loss is not due to the receiver architecture, rather from the two optical switches due to the insufficient number of high-speed ADC ports). The 7 optical outputs (including three outputs of 3×3 OC and four outputs of the SVR) are detected by only 2 single-ended photodiodes then sampled by 80-GSa/s time-domain oscilloscope. The receiver DSP is shown in Fig. 2(iii). As the polarization, which is parallel with the polarization of received LO, is directly recovered by the single-polarization coherent receiver, there is no need to perform polarization recovery for the single-polarization coherent receiver. Compared with the conventional APC-based PDCR, our proposed PDCR requires one more stage of DSP: polarization recovery in Stokes space. To perform the polarization recovery for SVR, the approach of analog polarization identification (API) [14] can be used to align the polarization orientation in Stokes space since the constant strong carrier on one polarization of the single input of the SVR results in an asymmetric signal distribution in Stokes space. The API can be achieved in the analog domain without clock recovery and any clock synchronization [14]. Therefore, the computational cost of the polarization recovery for SVR is expected to be small if not negligible. Note that the excessive number of OAs in the experiment for the receiver are required just for our lab demonstration. In practice, only one OA is needed at the receiver for LO to be shared among multiple signals when the transmitters share the same laser source.

4. Experimental results

Figure 3 shows the received signal polarization in Stokes space illustrating the process of the polarization recovery (PR) in Stokes space. The principle of the PR is as follows: after combining the received DP signals and remote LO using optical coupler before the SVR, the strong carrier is lumped into the $X_R$ polarization of the DP signals as described in section 2 to enhance the performance of $Y_R$ polarization via the polarization beating in SVR. As a result of the constant strong carrier, the normalized time-averaged Stokes vector $\langle S \rangle$ of the combined signal $E_R + C$ is $[1, 0, 0]$ [15], which coincides with the orientation of $S_1$ axis. Therefore, the time average of the received Stokes vector should coincide with the orientation of $S_1$ axis. Figure 3(a) shows the received signal distribution of the SVR in the Poincare sphere. Due to the strong carrier on $X_R$ polarization, the spatial distribution of received Stokes vector is biased towards one hemisphere. The time average of the received Stokes vector indicates the orientation of the signal distribution. To perform the PR in Stokes space, a three-dimensional real-valued unitary rotation matrix is used to align the time average of the received Stokes vector $\langle S \rangle$ to $[1, 0, 0]$ as shown in Fig. 3(b).

Fig. 3. Received signal distribution of SVR in Stokes space: (a) before polarization recovery (PR) and (b) after PR. H/V: horizontal/vertical polarization orientation in Stokes space; subscript R: received. $\langle S \rangle$: time-average of received Stokes vector.
where the rotation within the $S_2 - S_3$ plane orthogonal to the $S_1$ axis is arbitrary and produces a phase uncertainty in the recovered $Y_R$ polarization. The constant phase uncertainty can be readily eliminated either by the subsequent carrier phase recovery stage or channel equalization.

After the polarization recovery, the field recovery (FR) for the received DP signal is implemented by using Eqs. (3–5) in section 2. Figure 4(a) shows the electrical spectrum of $S_2 - iS_3$ at various DSP stages and the retrieved $Y_R$ polarization from $S_2 - iS_3$. After the polarization recovery, the effective power level of $S_2 - iS_3$ is reduced due to the applied polarization rotation induced power reallocation between Stokes parameters. Since the recovered $Y_R$ polarization contains both transmitted DP signal tributaries, the spectrum of the retrieved $Y_R$ polarization has periodic interference induced by the optical delay in the polarization emulator. Compared to the spectrum of $S_2 - iS_3$ after polarization recovery, the total power of the retrieved $Y_R$ polarization drops due to high CSPR.

![Graphs and charts showing spectral comparison and performance metrics](image)

**Fig. 4.** (a) Spectra comparison of $S_2 - iS_3$ before/after polarization recovery (PR) and the retrieved $Y_R$ polarization after field recovery (FR). (b) Achieved SNR under different CSPR at back-to-back (BtB) and 80 km. (c) Generalized mutual information (GMI) of the 50-Gbaud DP signal under various OSNR at 9- and 13-dB carrier to signal power ratio (CSPR). (d) Corresponding normalized GMI (NGMI) as a function of OSNR.

To identify the optimal operation parameter in this experiment, we measure the optimum CSPR at both BtB and 80-km transmission and use the SNR as a metric for comparison which is shown in Fig. 4(b). Since high CSPR could enhance the system performance but sacrifices the effective signal power, the optimum CSPR appears at 9 and 13 dB. The SNR dip at the CSPR of 10 dB is due to the imperfection of the single-polarization coherent receiver and Stokes receiver in the experiment.
To reliably predict the post-FEC performance, we quantify the system performance by generalized mutual information (GMI) and normalized GMI (NGMI) for bit-metric decoding, which are a practical estimation of the achievable information rate [16] and an accurate prediction of post-FEC performance from measured pre-FEC data [17], respectively. Figure 4(c) shows the calculated GMI for both back-to-back (BtB) and 80-km transmission at 9- and 13-dB CSPR. All GMI curves saturate to one level because the time-multiplexed receiver is quite lossy and limits the overall system performance. The inset shows the recovered PCS 64-QAM at 9-dB CSPR after 80-km transmission. The corresponding NGMI is also presented in Fig. 4(d). We assume a practical 19.02% FEC overhead using spatially coupled low-density parity-check (SC-LDPC) code and the required NGMI threshold is 0.8798 [18]. At 9-dB CSPR, the required OSNR is 21 dB for both BtB and 80 km. It indicates the ASE noise from EDFA added on the LO has an insignificant impact on the overall system performance after 80-km fiber transmission. At 13-dB CSPR, the OSNR requirement is 21 dB for BtB and 22 dB for 80 km transmission. The OSNR sensitivity is decreased by 1 dB after 80-km transmission because high CSPR results in high noise power from the optical amplifier on LO. The raw data-rate in this experiment is 400 Gb/s. Excluding the FEC overhead, the net rate is 323 Gb/s.

5. Conclusion

We demonstrate a hybrid single-polarization coherent receiver and SVR performed as a novel PDCR using remotely delivered LO without optical polarization control. Our proposed PDCR employs digital unitary transformation in both Stokes and Jones space and is fundamentally robust against any input state of polarization of the remote LO. A raw information rate of 400 Gb/s (net rate 323 Gb/s) DP signal after 80-km transmission verifies the robustness of our proposed receiver scheme to combat the polarization wandering of received LO. Such a PDCR scheme using remotely delivered LO without optical polarization control could be a promising solution for short-reach optical interconnects in saving the cost, space, and power consumption of the coherent transceivers.

Funding

Australian Research Council (ARC) under Discovery Projects (DP150101864) and (DP190103724); National Natural Science Foundation of China (61671053).

Disclosures

The authors declare no conflicts of interest.

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Author/s:
Ji, H; Zhou, X; Sun, C; Shieh, W

Title:
Polarization-diversity receiver using remotely delivered local oscillator without optical polarization control.

Date:
2020-07-20

Citation:

Persistent Link:
http://hdl.handle.net/11343/242054

File Description:
Published version