Simplified Self-coherent System Enabled by Alamouti Coding and Digital Subcarrier Multiplexing Technology

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Abstract In this paper, a simplified self-coherent system achieved by Alamouti coding and digital subcarrier multiplexing technology is proposed. The transmission of 50Gbaud 4-subcarrier 16QAM signal over 40km single mode fiber is experimentally demonstrated. ©2023 The Author(s)

Introduction
To support the development of the digital economy, the demand for transmission capacity of data center interconnects (DCIs) increases rapidly. The next-generation Ethernet links are aiming at 800GbE or even 1.6TbE. Although intensity modulation and direct detection (IM/DD) is the mainstream for short-reach optical interconnect due to its low cost and low complexity, meeting such high data rate requirements is still a considerable challenge.

Coherent reception has the ability to achieve larger capacity benefiting from its high linearity, high receiver sensitivity, and high spectral efficiency. However, the fatal barriers to the deployment of conventional coherent systems in DCIs are the implementation cost, power consumption, and complex system architecture. To promote the introduction of coherent technology into short-reach optical interconnects, self-coherent technology realized by using the separate optical fiber for remote local oscillator (LO) delivery to share the same laser source for the transceivers is considered as an attractive approach [1]. Thus, the frequency offset (FO) and phase noise (PN) compensation operations can be saved at the receiver side digital signal processing (Rx DSP), which is able to reduce the complexity of Rx DSP [2]. Due to the polarization rotation of the remote LO, the received signal will suffer from power fading. Thus, an automatic polarization controller (APC) is inevitable for the remote LO to track the polarization state [3]. In this paper, Alamouti polarization-time block coding is adopted to overcome the power fading issue as the coded signal can achieve polarization insensitivity [4, 5], thereby avoiding the use of APC. And the coherent receiver can also be simplified to a structure that only requires a 3dB coupler, a 90° Hybrid, and two balanced photodiodes (BPDs), which simplifies the receiver significantly. In addition, chromatic dispersion compensation (CDC) is also a significant overhead in Rx DSP. Fortunately, digital subcarrier multiplexing (DSCM), which divides a high baud rate single carrier into several low baud rate subcarriers without spectrum overlap shows the potential to simplify the CDC procedure [6].

In this paper, a simplified self-coherent system enabled by Alamouti coding and DSCM technology is proposed for simplification both in system architecture and Rx DSP. And the transmission performance of 50Gbaud 4-subcarrier 16QAM (4SC-16QAM) DSCM signal over 40km single mode fiber (SMF) is investigated. The experimental results show that, apart from no need for FO and PN compensation in Rx DSP, the damage caused by CD can also be settled by increasing two taps in the subsequent equalizer in the absence of frequency domain CDC.

Alamouti Coding
The operation principle of Alamouti coding is depicted in Fig. 1(a). The key idea is to send the same information during two symbol duration, which is interleaved between two polarizations. As shown in Fig. 1(a), the transmitted symbol sequences on X- and Y-polarization are denoted as $E_x = \{s_1, -s_2, s_3, -s_4, \cdots \}$ and $E_y = \{s_2, s_1^*, s_4, s_3^*, \cdots \}$, where * represents the conjugate operation. And considering the channel transmission matrix $H = \begin{bmatrix} h_{xx} & h_{xy} \\ h_{yx} & h_{yy} \end{bmatrix}$, the received signal of one polarization of Fig. 1(b) can be expressed as:

$$s'_x = h_{xx}s_1 + h_{xy}s_2$$
$$s'_{x2} = -h_{xx}s_2^* + h_{yy}s_1^* \quad (1)$$

According to Eq. (1), the transmitted signal can be recovered by detecting only one polarization regardless of any polarization rotation. Thus, there is no need for APC in a self-coherent system adopting Alamouti coding, and
the receiver architecture can be simplified due to the advantage of polarization insensitivity.

**Experimental Setup**

Figure 1 gives the experimental setup of the proposed simplified self-coherent system and the operation principle of Alamouti coding. Figure 1 gives the experimental setup of the proposed simplified self-coherent system and the operation principle of Alamouti coding.

![Experimental setup of the proposed simplified self-coherent system and the operation principle of Alamouti coding.](image)

The 50Gbaud 4SC-16QAM DSCM signal is generated offline in MATLAB. At the transmitter side DSP, the pseudo-random binary sequence (PRBS) is mapped into two sets of 16QAM symbols for X- and Y-polarization respectively, and each polarization contains 4 subcarriers. Then, Alamouti encoding is executed between the two polarizations for each subcarrier to avoid power fading induced by polarization rotation. Afterward, the coded signals are shaped by a root-raised-cosine (RRC) filter with a roll-off factor of 0.1. And then the 4 subcarriers are multiplexed to obtain the DSCM signal. Finally, the DSCM signal is resampled to 64GSa/s to match the sampling rate of the Keysight M8195 arbitrary waveform generator (AWG). And the outputs from AWG are then amplified and loaded into the DP-IQM. Before fiber transmission, the optical signal is boosted by an EDFA.

After 40km SMF transmission, another EDFA is utilized to amplify the transmitted signal at the receiver side. Since the proposed simplified self-coherent system is polarization insensitive, only a 3-dB coupler, a 90° Hybrid, and two BPDs are utilized. And the APC is also avoidable for the remote optical carrier. The detected signal is captured by a Lecory oscilloscope operating at 80GSa/s with cut-off bandwidth of 36GHz. As for Rx DSP, resample, Gram-Schmidt orthogonalization procedure (GSOP), RRC filter, CDC, synchronization, Alamouti decoding, and equalization are carried out in order. Finally, the bit error rate (BER) is counted.

**Experimental Results and Discussion**

First, we investigate the BER performance of 50Gbaud 4SC-16QAM DSCM signal based on the proposed simplified self-coherent system in optical back-to-back (OBTB) transmission. The measured BER versus different optical signal-to-noise ratios (OSNRs) is given in Fig. 2. And the performance is compared to that of 50Gbaud 16QAM signal with single subcarrier. The optical spectrums of 50Gbaud 4SC-16QAM and 1SC-16QAM signals are given in Fig. 1(c). As shown in Fig. 2, the BER curves of the signal with single subcarrier and 4 subcarriers almost overlap. And the required OSNR is about 25dB at the hard decision forward error correction (HD-FEC) threshold of 3.8e-3.

The transmission performance over 40km SMF is also investigated. Fig. 3(a) gives the...
measured BER of 50Gbaud 4SC-16QAM DSCM signal under different launch power. According to the experimental results, increasing the launch power can bring performance improvement when the launch power is lower than 5dBm. However, further increasing the input power will lead to performance degradation due to fiber nonlinearity. And the optimal launch power is about 5dBm here. Then, the CD tolerance of the DSCM signal is discussed. Fig. 3(b) compares the BER performance of 50Gbaud 4SC-16QAM DSCM signal with and without frequency domain CDC by varying the tap length of the equalizer. The experimental results show that about 9 taps are required to achieve the best performance when CD compensation is implemented. While 11 taps are required for the case without CDC. It indicates that the procedure of CDC realized in the frequency domain can be saved but only increases 2-tap longer of the following equalizer, which operates in a much low complexity manner. Additionally, the transmission performance of 50Gbaud 16QAM signal with and without CDC is also investigated for comparison, and the results are shown in Fig. 3(c). It can be seen that the required tap length of the equalizer is longer than that of the 50Gbaud 4SC-16QAM DSCM signal, especially without CDC. The required tap length is about 35 after CDC in this case. However, as for the signal without CDC, increasing the tap length of the equalizer is also unable to compensate for the penalty induced by CD. According to the experimental results, the proposed method is provided with a characteristic of low complexity not only in the structure but also in DSP flow.

Conclusions
In this paper, the transmission of 200 Gbit/s 4SC-16QAM DSCM signal over 40km SMF without frequency domain CDC is experimentally achieved based on the proposed simplified self-coherent system. Benefits from the Alamouti coding between two polarizations, the receiver becomes insensitive to polarization. Thus, the APC is needless without power fading, and only a 3dBi coupler, a 90° Hybrid and two BPDs are required, which reduces the complexity of the receiver significantly. Since the LO comes from the same laser at the transmitter side in this self-coherent system, the FO and PN compensation is no longer needed in the Rx DSP. Besides, according to the experimental results, the damage caused by CD can be addressed by increasing two taps in the equalizer. As a result, the proposed simplified self-coherent system provides the possibility for the application of coherent technology in next-generation optical interconnects.

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