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LETTER

Phase retrieval for coherent detection in short-reach links using self-interference of aggregated optical OFDM subcarriers

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Abstract Low-complexity coherent detection using self-interference of aggregated optical orthogonal frequency division multiplexing (O-OFDM) subcarriers is proposed. Self-interference among the aggregated O-OFDM subcarriers is employed to recover their relative phase relationships through the variation in the obtained power spectra. The differences in a few preselected principal spectral components are successfully demonstrated based on the phase states of four O-OFDM subcarriers modulated via quadrature phase shift keying (QPSK). We experimentally verified self-interference and bit error rate reaches 10^{-3}. The number of bits available in the proposed method increases with the number of subcarriers, gradually approaching that in QPSK beyond OOK.

Keywords: short-reach links, coherent detection, QPSK, O-OFDM, compressed sensing

Classification: Transmission systems and transmission equipment for communications

1. Introduction

Coherent passive optical networks (PONs) are among the prospective advances in access networks required to realize new services offered by the fifth-generation (5G) mobile technology and those beyond 5G [1, 2]. Although low-complexity coherent receivers without the use of a local oscillator, balanced detectors, and digital signal processing (DSP) are expected to reduce costs, they are still actively investigated [3, 4, 5, 6, 7, 8, 9, 10, 11]. At the same time, in short-reach links (within 2 km), such as intra-data center interconnects, the accumulated chromatic dispersion can be very low, eliminating the need for DSP [9, 10]. Nevertheless, balanced detectors still need to be used. As the data volume is large in short-reach links, optical orthogonal frequency division multiplexing (O-OFDM) is an efficient transmission method for next-generation PONs, where a symbol modulated by quadrature amplitude modulation (QAM) is detected at the zero-crossing point to avoid inter-symbol interference with the neighboring O-OFDM subcarriers. In addition to the use of coherent PONs, the aggregation of neighboring O-OFDM subcarriers may be sufficient [12] for satisfying the demand capacity beyond the bandwidth of a single subcarrier; furthermore, batch detection of multiple neighboring O-OFDM subcarriers is effective for such aggregated signals. Except at the zero-crossing point, self-interference occurs among the aggregated O-OFDM subcarriers without a local oscillator, so that the relative phase relationship between the aggregated O-OFDM subcarriers is reflected in the variation in the obtained power spectrum after λ-DeMUX. As the difference in self-interference leads to the difference in the output power spectrum, crosstalk between subcarriers may be used for cross-references to estimate the relative phase relationship of QAM of the aggregated O-OFDM subcarriers without balanced detectors. Although the differences between the output power spectra may be used to detect a signal, the data volume of the obtained power spectrum is too large for real-time detection. At the same time, sparse principal component analysis (SPCA) can provide modified principal components with sparse loadings [13]. Here, SPCA was expected to carefully extract sparse principal spectral components needed to distinguish the relative phase relationship of the QAM of the aggregated O-OFDM subcarriers; thereby reducing the required spectral data and complexity. The principle of low-complexity coherent detection of short-reach links using self-interference of aggregated O-OFDM subcarriers has been previously proposed and ideally verified in simulation [11].

In this paper, we experimentally verified the principle and demonstrate the applicability to real aggregated O-OFDM subcarriers modulated by QPSK. We calculated the available number of bits per subcarriers to confirm the superiority of this method beyond OOK. In addition, BER performance of this method is numerically analyzed and reaches less than 10^{-3} below the FEC limit.

2. Principle of the proposed approach

Figure 1 shows the typical schematic of the proposed low-complexity O-OFDM receiver of short-reach links based on self-interference of the four aggregated O-OFDM subcarriers modulated by QPSK. The spectra of the aggregated O-OFDM subcarriers considerably overlap, and self-interference occurs, as shown in Fig. 2. For example, the power spectrum $S_P(\lambda)$ of the two aggregated O-OFDM subcarriers is given by

$$\begin{aligned} S_p(\lambda) &= |S_1(\lambda) + S_2(\lambda)|^2 \\ &= |S_1(\lambda)|^2 + |S_2(\lambda)|^2 \\ &\quad + |S_1(\lambda)|\,|S_2(\lambda)| \left\{ e^{-i(\phi_1-\phi_2)} + e^{+i(\phi_1-\phi_2)} \right\} \\ &= |S_1(\lambda)|^2 + |S_2(\lambda)|^2 \\ &\quad + 2\,|S_1(\lambda)|\,|S_2(\lambda)| \cos(\phi_1 - \phi_2), \end{aligned} \tag{1}$$

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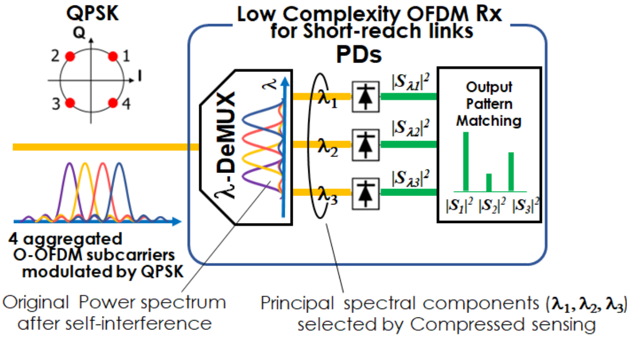

Fig. 1 Schematic of the proposed low-complexity O-OFDM receiver for short-reach links using compressed sensing and self-interference of the aggregated O-OFDM subcarriers.

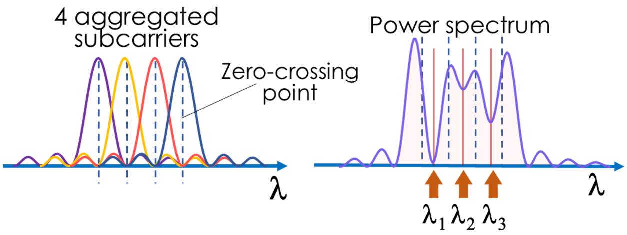

Fig. 2 Four aggregated O-OFDM subcarriers and the power spectrum after their interferences which depends on a set of the phase states of the four subcarriers. Three spectral lines show the spectral components preselected using SPCA; these were used for direct detection.

where $S_1(\lambda)$, $S_2(\lambda)$, ϕ_1, and ϕ_2 are the spectra of the two subcarriers and their phases, respectively. According to Equation (1), the shape of the power spectrum depends on phase states (ϕ_1 and ϕ_2); thus, the differences may be used for phase retrieval in direct coherent detection without a local oscillator and balanced detectors. We used SPCA [13] to reduce the data volume of the power spectrum of the four aggregated O-OFDM subcarriers after λ-DeMUX. The preselected principal spectral components were automatically extracted, and the number of required photodetectors was reduced to less than the number of O-OFDM subcarriers. In Figs. 1 and 2, we assume that three principal spectral components: λ_1, λ_2, and λ_3, are preselected with the assistance of SPCA. The output signal powers $|S_{\lambda 1}|^2$, $|S_{\lambda 2}|^2$, and $|S_{\lambda 3}|^2$ are strongly affected by the modulated QPSK states of the four O-OFDM subcarriers. The output pattern set of $|S_{\lambda 1}|^2$, $|S_{\lambda 2}|^2$, and $|S_{\lambda 3}|^2$ enables distinguishing between the modulated states using simple pattern matching without the use of a local oscillator and balanced detectors.

3. Experimental verification of the proposed principle

3.1 Self-interference of aggregated O-OFDM subcarriers modulated by QPSK

We experimentally verified the self-interference of the four aggregated O-OFDM subcarriers modulated by QPSK. Figure 3 illustrates the setup used for the verification of self-interference of the four O-OFDM subcarriers. The O-OFDM signal for phase recovery is transmitted from the O-OFDM signal synthesizer using a wavelength-selective switcher. On the transmitter side, the O-OFDM signal consists of four repeating 50 MHz O-OFDM subcarriers, with

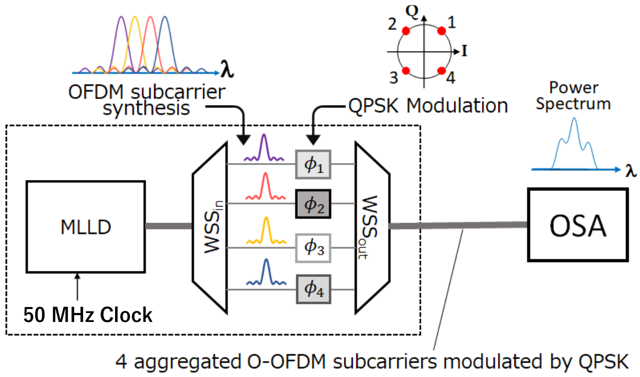

Fig. 3 Setup used for the verification of self-interference of the four aggregated O-OFDM subcarriers modulated by QPSK.

Fig. 4 Experimental results of power spectrum variations as a result of self-interference of the four aggregated O-OFDM subcarriers modulated by QPSK.

subcarrier spacing of 40 GHz. Each O-OFDM subcarrier is individually phase-modulated in QPSK format. The power spectrum of the four aggregated O-OFDM signals is measured using an optical spectrum analyzer. Figure 4 shows the power spectra for different QPSK-modulated signals, and the phase states of the four subcarriers are expressed as vectors in the component form. Herein, the self-interference of the aggregated O-OFDM subcarriers does not change in the case of rotationally symmetric phase modulation in QPSK because the relative phase differences between subcarriers of the rotationally symmetric modulation patterns are the same. Subsequently, we verified the principle for 36 non-rotationally symmetric modulation patterns of the four aggregated O-OFDM subcarriers modulated by QPSK. As shown in Fig. 4, each spectrum has a different shape depending on the phase state.

3.2 Phase retrieval for coherent detection using SPCA of a set of self-interference power spectra

SPCA was used to identify a few spectral components as the principal spectral components of a set of self-interference power spectra that can distinguish the relative phase relationship of the QPSK of the aggregated O-OFDM subcarriers.

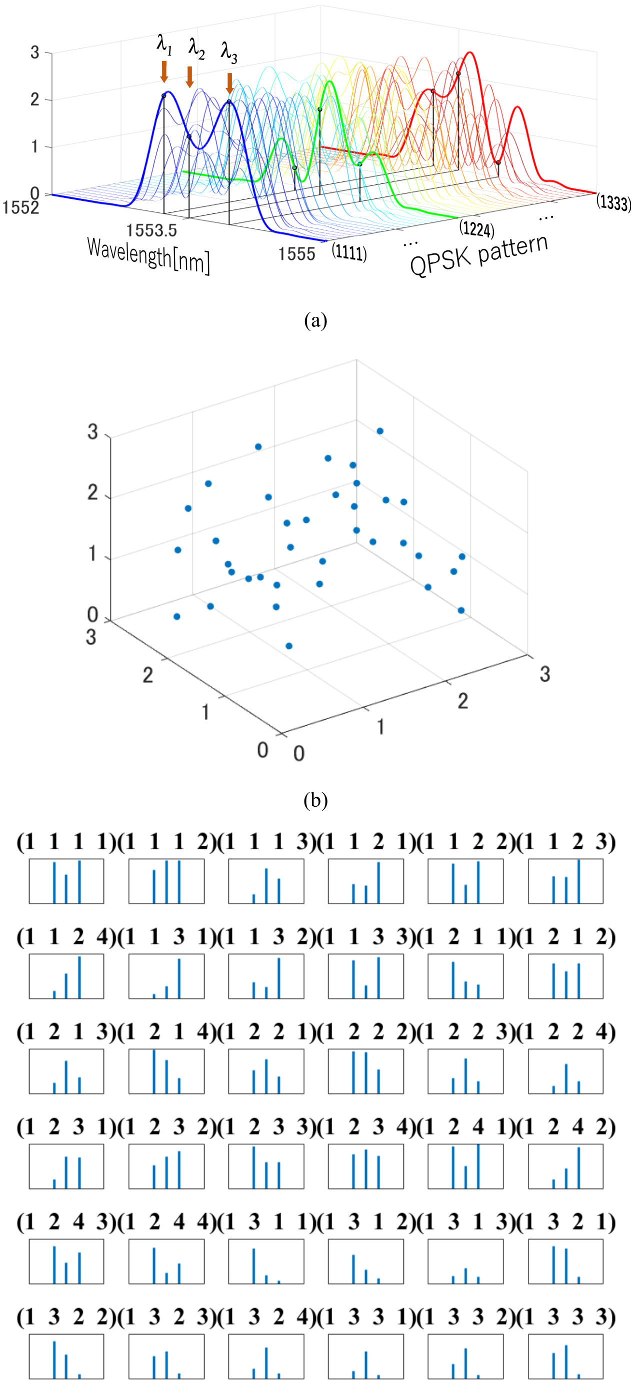

Fig. 5 Analyzed results using compressed sensing:(a) the results of selecting the principal spectral components from the overlayed available 36 power spectra with three components selected, (b) the mapped 36 different QPSK modulated signals in the 3D space of the three principal spectral components, and (c) the extracted three principal spectral components from the experimental results.

Figure 5(a) shows the experimental results for the principal spectral components from the overlayed available 36 power spectra with three components selected. It shows that three photodetectors (PDs) can describe the four aggregated O-OFDM subcarriers modulated by QPSK, and the number of devices is less than that in an on–off keying (OOK) receiver for the four O-OFDM subcarriers. Figure 5(b) shows the 36 different QPSK-modulated signals in the 3D space of the three principal spectral components, indicating that all 36 signals can be successfully recognized using the three principal spectral components without overlapping. Figure 5(c) shows the principal spectral components extracted from the experimental results for different QPSK-modulated signals shown in Fig. 4.

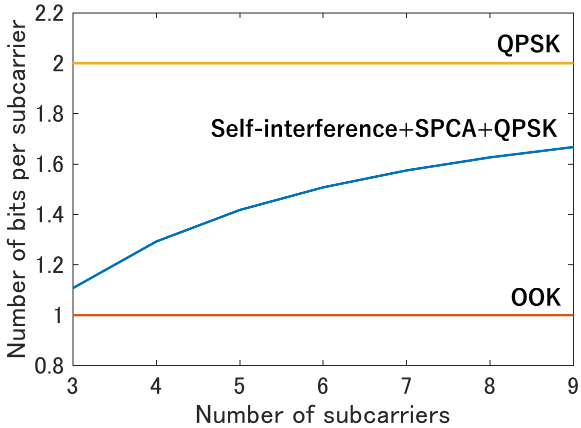

Fig. 6 Comparison with conventional methods on the available number of bits per subcarrier.

3.3 Number of bits per subcarrier when using the proposed phase retrieval method

The efficiency of the proposed method was compared with those of conventional methods for the available number of bits per subcarrier. When the number of subcarriers is N, the number of available patterns in the conventional QPSK method is 4^N. At the same time, as the proposed method cannot distinguish between rotationally and linearly symmetric patterns, the number of available patterns in the proposed method is no greater than $4^{N-2} \times 2 + 2^{N-2}$. Thus, the number of bits per subcarrier in the proposed method is $\log_2 \left(4^{N-2} \times 2 + 2^{N-2}\right) / N$. For example, the interference waveforms of the (1 2 3 1) and (1 4 3 1) phase states are identical.

Figure 6 compares the available numbers of bits per subcarrier in the proposed and conventional methods. In particular, the available numbers of bits in OOK and QPSK are shown. As the number of subcarriers increases, the available number of bits in the proposed method increases, approaching that in QPSK. This suggests that the proposed method ensures coherent detection, even if the local oscillator and balanced detectors are removed from the coherent receiver.

3.4 Phase retrieval for coherent detection using compressed sensing of a set of self-interference power spectra

The BER performance of the proposed phase retrieval method was numerically analyzed using the experimental power spectra phase modulated by QPSK, taking into account the shot noise and thermal noise. We set the number of subcarriers, the repetitive frequency of each subcarrier, and the subcarrier spacing to 4, 50 MHz, and 40 GHz, respectively. Using direct detection with three PDs and analog-to-digital converters, a set of outputs at the selected principal spectral components in the spectrum was used to identify QPSK modulation patterns. We generated a long

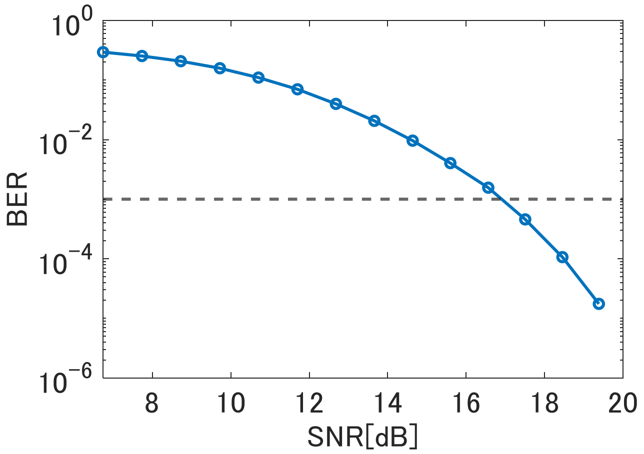

Fig. 7 BER performance of the proposed phase retrieval method.

sequence of the sets of four randomly modulated QPSK subcarriers and used it as an input to the proposed receiver, with a controlled amount of noise distortion added to the input signal. The receiver demodulated the signal using the detected principal component pattern, producing a sequence of recovered received signals. Finally, we compared the four received randomly modulated QPSK subcarriers to the original input and calculated the errors. The comparison was performed through pattern matching using the difference between the original and distorted principal component patterns; the original pattern with the smallest difference from the detected pattern was adopted as the received signal. Figure 7 shows the simulation results, indicating that the SNR is approximately 17 dB at −9 dBm input light intensity, and the code error rate is below the FEC limit of 10^{-3} BER.

4. Conclusion

We experimentally verified our proposed phase retrieval method using real self-interference of aggregated O-OFDM subcarriers modulated by QPSK. The differences in the power spectrum because of self-interference among the aggregated O-OFDM subcarriers enable the identification of their relative phase relationships. SPCA can narrow down the data to a few necessary spectral components to identify the relative phase relationship of QPSK in the aggregated O-OFDM subcarriers and simultaneously reduce the number of necessary devices to less than that of a conventional OOK receiver for four O-OFDM subcarriers.

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