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Transmission and reception of Quad-Carrier QPSK-OFDM signal with blind equalization and overhead-free operation

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Abstract: Quad-Carrier Quadrature Phase Shift Keyed orthogonal frequency division multiplexing (QPSK-OFDM) signal transmission and reception is successfully demonstrated with blind equalization like a 25-ary quadrature amplitude modulation (25-QAM) signal with cascaded multi-modulus algorithm (CMMA) equalization. The phase recovery can be realized with simple Viterbi algorithm and the frequency offset estimation (FOE) should be done with 25-QAM signal before 4-point fast Fourier transform (FFT). 48-Gbit/s Quad-Carrier QPSK-OFDM signal is successfully transmitted over 80-km SMF-28 without penalty.

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1. Introduction

Optical orthogonal frequency division multiplexing (OFDM) has attracted lots of attention due to its high spectral efficiency (SE) and robustness to transmission impairments enabled by digital signal processing (DSP) [1–7]. In traditional coherent OFDM transmission system, the frequency offset estimation (FOE), channel estimation, equalization, and phase recovery are implemented with training sequence (TS) and pilot tones [2–4]. As the TS and pilot tones are critical in the frequency domain equalization scheme, the number of subcarriers in the OFDM modulation/demodulation with Inverse fast Fourier transform/fast Fourier transform (IFFT/FFT) is usually larger than 64 in order to reduce the overhead including pilot tones and TSs and acquire more accurate channel estimation. Unfortunately, an OFDM signal with a large IFFT/FFT size has high peak-to-average power ratio (PAPR) values [8]. The PAPR of OFDM signal can be reduced quickly with a small number of subcarriers, while this will cause a dramatic increase in overhead and the channel estimation based on TSs in frequency domain cannot effectively work. In this paper, we propose an optical OFDM transmission system with only four subcarriers. Compared to two subcarriers OFDM scheme [8], 4-subcarrier OFDM scheme is much more flexible in power allocation and pre-equalization as bandwidth of each subcarrier is smaller. The main difference between our scheme with 4-subcarrier all optical OFDM is the generation and detection. For 4-subcarrier all optical OFDM signal generation we need to generate four frequency-locked subcarriers. The channel spacing between four subcarriers should be equal to the baud rate of each sub-channel in order to make the 4-subcarrier orthogonal. So this generation usually is complicated compared to our scheme. At receiver, after optical to electrical (O/E) conversion, a digital filter is used to separate the 4-subcarrier, and then DSP is applied for each subcarrier [9]. 4-subcarrier OFDM signal shows as a 25-QAM signal in the time domain, and it can be blindly equalized with cascaded multi-modulus algorithm (CMMA) equalization in the time domain [10–13]. With the blind equalization, channel estimation and equalization, FOE, and phase recovery can be implemented without TS and pilot tones. The overhead existing in the traditional optical OFDM transmission system can be completely eliminated in the four subcarriers optical OFDM transmission system with blind equalization.

In this paper, transmission and reception of 48Gbit/s dual-polarization Quad-Carrier quadrature-phase-shift-keying OFDM (QPSK-OFDM) signal is demonstrated. In the off-line DSP, the FOE should be done with 25-QAM signal before 4 subcarriers are separated with FFT. Compared to the traditional OFDM signal with 256 subcarriers, the PAPR of Quad-Carrier QPSK-OFDM signal with blind equalization is decreased dramatically from 14.4 to 6.4 dB at the probability of $1 \times 10^{-4}$. There is no penalty after 80-km single-mode fiber-28 (SMF-28) transmission.

2. Principle

The IFFT size during the OFDM modulation is supposed to be $N$ and the time length of one OFDM symbol is $T$. After IFFT, the OFDM signal can be expressed as

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} c_k \exp(j 2 \pi f_k t) \quad (1 \leq t \leq T).$$

(1)

where $k$ is the index of subcarriers, and $f_k = k \Delta f = k/T$ is the frequency of the $k_{th}$ subcarrier. In 4-subcarrier scheme, the $N$ and $T$ of one OFDM symbol are both 4 when only 4-subcarrier is used in OFDM modulation and demodulation, and the expression can be simplified as

$$s(t) = \frac{1}{2} \sum_{j=0}^{3} c_j \exp(j 2 \pi f_j t) = \frac{1}{2} (c_0 + c_2 \exp(j \pi / 4) + c_1 \exp(j \pi / 2) + c_3 \exp(j 3 \pi / 4)) \quad (0 \leq t \leq 3).$$

(2)
where \( c_0, c_1, c_2 \) and \( c_3 \) represent the QPSK symbols modulated onto 4-subcarrier, respectively. After IFFT, the OFDM symbols are generated and one OFDM symbol includes four samples in time domain. Four samples can be expressed as

\[
\begin{align*}
    s(0) &= \frac{1}{2}(c_0 + c_1 + c_2 + c_3), \\
    s(1) &= \frac{1}{2}(c_0 + jc_1 - c_2 - jc_3), \\
    s(2) &= \frac{1}{2}(c_0 - c_1 + c_2 - c_3), \\
    s(3) &= \frac{1}{2}(c_0 - jc_1 + c_2 + jc_3).
\end{align*}
\]  

(3)

Fig. 1. (a) The spectral distribution of the subcarriers in Quad-Carrier QPSK-OFDM signal, and (b) signal conversion between QPSK and 25-QAM.

where \( s(0), s(1), s(2) \) and \( s(3) \) denote the symbols after IFFT. \( s(0) \) in Eq. (3) is obtained by addition of four QPSK symbols, and four 2-level \((-\sqrt{2}/2, \sqrt{2}/2)\) real/imaginary components are combined to get one 5-level \((-\sqrt{2}/2, -\sqrt{2}/2, 0, \sqrt{2}/2, \sqrt{2}/2\) real/imaginary component. The real and imaginary components of other three symbols \( s(1), s(2) \) and \( s(3) \) are also 5-level according to the Eq. (3). After 4-point IFFT, QPSK symbol on four subcarriers in the frequency domain becomes 25-QAM signal in the time domain.

Four subcarriers OFDM signal is generated by 4-point IFFT and the spectral distribution of the subcarriers in Quad-Carrier QPSK-OFDM signal with 12Gbaud rate is shown in Fig. 1(a). Assume \( B \) represents the baud rate of signal on only one subcarrier, and the total bandwidth of Quad-Carrier QPSK-OFDM signal generated in electrical domain is only \( 4B \). The constellations of QPSK and 25-QAM and conversion conditions are shown in Fig. 1(b).

In the dual-polarization Quad-Carrier QPSK-OFDM signal transmission system, DSP algorithms are required to realize de-multiplexing, FOE, channel estimation and phase recovery. In the traditional optical OFDM system, channel estimation and equalization are implemented in the frequency domain with known TSs and pilot tones (i.e., time-interleaved TSs for de-multiplexing, FOE, and channel estimation, and the pilot tones for phase recovery). If the frequency domain equalization based DSP algorithms are applied in the dual-polarization Quad-Carrier QPSK-OFDM signal transmission system, the SE will decrease dramatically as the overhead occupies a large portion of the total data. In order to avoid such overhead, we propose to utilize time domain blind equalization to recover dual-polarization Quad-Carrier QPSK-OFDM signal as a 25-QAM signal. In the blind equalization, the CMMA algorithm is used to implement the polarization de-multiplexing and channel estimation. As for the FOE, 4-th power method is applied to estimate the frequency offset between the signal and the LO. 4-th power method can be performed on either 25-QAM signal before 4-point FFT or QPSK signal after 4-point IFFT, which we will discuss later in this paper. For the phase recovery, Viterbi algorithm is utilized to cancel the phase noise of QPSK signal after 4-point FFT. For the CMMA algorithm, we only select the inner three rings/radii for the error signal calculation to increase equalizer robustness [10, 11], which is the same as CMMA algorithm for 9-QAM signal [12, 13]. We also analyze the PAPR of Quad-Carrier QPSK-OFDM signal and traditional QPSK-OFDM signal. The PAPR performance is evaluated by complementary cumulative distribution function (CCDF). CCDF presents the probability
distribution in which the PAPR of current OFDM symbol is higher than certain threshold. CCDF curves of PAPR for traditional QPSK-OFDM signal with 256 subcarriers and Quad-Carrier QPSK-OFDM signal are shown in Fig. 2. The PAPR of Quad-Carrier QPSK-OFDM signal outperforms the traditional OFDM and there is an 8 dB PAPR improvement at the probability of $1 \times 10^{-4}$.

![CCDF curves of PAPR for traditional QPSK-OFDM signal with 256 subcarriers and Quad-Carrier QPSK-OFDM signal](image)

Fig. 2. The CCDFs of the traditional QPSK-OFDM signal with 256 subcarriers and Quad-Carrier QPSK-OFDM signal.

### 3. Experimental setup

Figure 3 shows the experimental setup of Quad-Carrier QPSK-OFDM signal transmission system. At the transmitter, an external cavity laser (ECL) at 1549.48 nm with less than 100-kHz linewidth and maximum output power of 14.5 dBm is modulated by I/Q modulator driven by an electrical baseband OFDM signal. The OFDM signal is generated offline by MATLAB and then uploaded into an arbitrary waveform generator (AWG) with a 12-GSa/s sample rate. In this paper, the Quad-Carrier QPSK-OFDM signal is without additional CP and TS and the signal is equalized with CMMA blind equalization method. For optical OFDM modulation, two parallel Mach-Zehnder modulators (MZMs) in I/Q modulator are both biased at the null point and the phase difference between the upper and lower branches of I/Q modulator is controlled at $\pi/2$. The polarization multiplexing is realized by a polarization multiplexer, comprising a polarization-maintaining optical coupler (OC) to halve the signal into two branches, an optical delay line (DL) to remove the correlation between X-polarization and Y-polarization by providing a 150 symbols delay, an optical attenuator to balance the power of two branches and a polarization beam combiner (PBC) to recombine the signal. The generated signal is boosted via an erbium doped fiber amplifier (EDFA) before launched into 80 km SMF-28. The output signal is then injected into the integrated coherent receiver to implement optical to electrical detection. After integrated coherent receiver, the signal is captured by the real-time oscilloscope with 50 GSa/s sample rate. The resolution of DAC in the AWG and ADC in real-time oscilloscope is 10 and 8 bits, respectively.

The optical eye diagram of Quad-Carrier QPSK-OFDM signal is inserted as inset (a) in Fig. 3. The optical spectra before and after 80-km SMF-28 transmission with 0.1-nm resolution are shown in Fig. 3(b) and there is no optical signal to noise ratio (OSNR)
degradation observed after 80-km SMF-28 transmission. The DSP for receiver offline processing of the Quad-Carrier QPSK-OFDM signal is shown in Fig. 3(c). At the receiver, the 25-QAM Quad-Carrier QPSK-OFDM signal can be equalized with CMMA method without additional overhead compared to traditional OFDM signal with frequency domain equalization. After optical link, four signal components are first captured by the real-time oscilloscope with 50GSa/s sample rate. Secondly, a T/2-spaced time-domain finite-impulse-response (FIR) filter is firstly used for chromatic dispersion (CD) compensation, where the filter coefficients are calculated from the known fiber CD transfer function using the frequency-domain truncation method. Thirdly, the CMMA is used to retrieve the modulus of the polarization-division-multiplexed 25-QAM signal and realize polarization de-multiplexing. The subsequent step is to realize the FOE, and here we have to claim the position of FOE is flexible and it can also be done after 4-point FFT. After these procedures, 4-point FFT is applied to convert the 25-QAM signal in time domain into QPSK signal in frequency domain and then the bit-error ratio (BER) can also be obtained with the BER counting after QPSK signal phase recovery. As blind equalization is applied for Quad-Carrier QPSK-OFDM signal, there is no overhead and the capacity is 48Gbit/s. In this experiment, the BER is counted over $10 \times 10^6$ bits (10 data sets, and each set contains $10^6$ bits). The optical spectra of different sub-carriers are shown in Fig. 3(d) with 0.01 nm resolution, and it can be seen that the distribution of sub-carriers in optical domain is the same as that in the electrical domain demonstrated in Fig. 1(a).

3. Experimental results

![Fig. 4. Constellations in different stages of DSP: (a) FOE after 4-point FFT, and (b) FOE before 4-point FFT.](image)

Figure 4 shows the constellations of Quad-Carrier QPSK-OFDM signal with OSNR of 20dB in different stages of the offline DSP, which is described in detail in section 3. In Fig. 4(a), the FOE is done after 4-point FFT in the receiver offline DSP. While in Fig. 4(b), FOE is completed before 4-point FFT. Compared to the constellations after phase recovery in Fig. 4(a), those in Fig. 4(b) are converged much better, which means the FOE should be done with 25-QAM signal before 4-point FFT. As FFT causes the spread of noise induced by frequency offset [6], it should be better to finish the FOE before the FFT in the time domain.

![Fig. 5. Measured BER of Quad-Carrier QPSK-OFDM signal versus OSNR.](image)

Figure 5 shows the measured BER of Quad-Carrier QPSK-OFDM signal versus OSNR. There is nearly no OSNR penalty observed after 80-km SMF-28 transmission. The BER for
the 48-Gbit/s dual polarization Quad-Carrier QPSK-OFDM signal is less than the pre-forward-error-correction (7% overhead) threshold of $3.8 \times 10^{-3}$ when the OSNR is higher than 10 dB after 80-km SMF-28 transmission. The constellations of dual polarization Quad-Carrier QPSK-OFDM signal after phase recovery with OSNR of 17dB after 80-km SMF-28 transmission are shown in the inset of Fig. 5.

In the back-to-back (BTB) case, we adjust the receiver bandwidth via changing the bandwidth of the real-time oscilloscope to determine the minimum bandwidth for the 48-Gbit/s Quad-Carrier QPSK-OFDM signal transmission. Figure 6 shows measured BER versus receiver bandwidth. Compared to the situation when the receiver bandwidth is larger than 6GHz, there is less than 0.3 dB OSNR penalty when the bandwidth of the receiver is set to 6 GHz according to the relationship between OSNR and BER in Fig. 5. The electrical spectra of the obtained signal with different receiver bandwidth are inserted as insets (i)-(v) in Fig. 6.

The receiver bandwidth of real-time oscilloscope can be only changed by integral interval, and it has been found that the signal cannot be recovered with 5-GHz receiver bandwidth in the experiment. The OSNR penalty and BER versus receiver bandwidth when the bandwidth is set between 5 and 6GHz are measured and shown in Fig. 7. The fractional change of the receiver bandwidth is virtually realized via offline low pass filter (LPF), and during this virtual realization the frequency offset of two lasers in the experiment should be close to 0. The received sample for the test is the data obtained with 10GHz bandwidth receiver. The signal cannot be recovered if the bandwidth of receiver is smaller than 5.2GHz, because in this case some useful spectral components are filtered out due to the inadequate bandwidth. There is 3-dB OSNR penalty when the bandwidth of the LPF is only 5.2GHz and the BER is $1.02 \times 10^{-2}$.

4. Conclusions

In this paper, Quad-Carrier QPSK-OFDM signal transmission and reception is successfully demonstrated with blind equalization without any overhead. The phase recovery can be
implemented with simple Viterbi algorithm and the FOE should be done before 4 subcarriers are separated with FFT. Using these techniques, we successfully generate and transmit 48-Gbit/s Quad-Carrier QPSK-OFDM signal over 80-km SMF-28 without penalty.

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