Experimental demonstration of 110-Gb/s unsynchronized band-multiplexed superchannel coherent optical OFDM/OQAM system

Zhaohui Li,1 Tao Jiang,3 Haibo Li,2 Xuebing Zhang,1 Cai Li,2 Chao Li,2 Rong Hu,2 Ming Luo,2 Xu Zhang,2 Xiao Xiao,2 Qi Yang,2,* and Shaohua Yu2

1 Institute of Photonics Technology, Jinan University, Guangzhou, Guangdong, 510632, China
2 State Key Laboratory of Optical Comm. Technologies and Networks, Wuhan, Hubei, 430074, China
3 Huazhong University of Science and Technology, Wuhan, Hubei, 430074, China
*qyang@wri.com.cn

Abstract: In this paper, we experimentally demonstrate the first 110-Gb/s multi-band superchannel coherent optical orthogonal frequency-division multiplexing based on offset quadrature amplitude modulation (OFDM/OQAM) system. Unlike the conventional orthogonal band-multiplexed OFDM system, no timing or frequency synchronization is required for the OFDM/OQAM system. We further investigate the influence of guard band, and find that very trivial guard band spacing (<20MHz) is required without any sensitivity performance or spectral efficiency degradation. Thus, the newly designed scheme would significantly reduce the implementation constrains for the band-multiplexed superchannel coherent optical OFDM system.

©2013 Optical Society of America

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4080) Modulation.

References and links

1. Introduction

To meet ever-increasing optical demand, the optical system supporting 1-Tb/s and beyond per channel will soon be required. The design of a high speed optical system based on closely spaced band-multiplexed “superchannel” is a promising technique to expand the channel capacity without involving much implementation complexity. Single carrier and orthogonal frequency-division multiplexing (OFDM) are the two complementary approaches to achieve large capacity and long haul transmissions in coherent optical communication [1, 2]. For single-carrier, Nyquist-WDM is a powerful approach to enhance the spectrum efficiency [3, 4]. The spectrum could be easily constructed into a rectangular shape, without introducing significant inter-channel crosstalk. Superchannel could be easily formed with very narrow guard bands between the sub-channels [5]. For O-OFDM, due to its intrinsic merit of the orthogonality, ultra-wide-band of O-OFDM could be ‘seamlessly’ constructed without any guard band using orthogonal band multiplexing (OBM) [6]. However, all the bands have to be timing- and frequency- synchronized in order to avoid inter-symbol interference (ISI) and inter-channel interference (ICI) [7, 8]. It brings huge challenges to the practical implementations for O-OFDM. In order to realize superchannel signal generation and transmission, several key issues need to be addressed: First, the subcarrier spacing within each sub-channel has to be identical. This requires precise sampling frequency alignment of all signal generators. Second, the guard band between the sub-channels has to be set as multiple (integral times) of subcarrier spacing. Frequency-locked optical comb source is commonly used. Third, timing-/symbol- synchronization in the time domain are required to avoid ISI. Any frequency or timing misalignment will introduce great penalties.

In this paper, we employ OFDM based on offset quadrature amplitude modulation (QAM) (OFDM/OQAM), which has lately been widely discussed in wireless communications research, to efficiently release the superchannel implementation constraints. In wireless communications, OFDM/OQAM is presented to eliminate the high out-of-band spectrum leakage in conventional OFDM system. OFDM/OQAM has been considered as one of the candidate technologies in the cognitive radio systems [9, 10]. So far, only a few demonstrations based on single-carrier offset-QAM have been carried out in optical communications [11, 12]. To date, the investigation of OFDM/OQAM in coherent optical communication has only been reported in a simulation study [13]. In this paper, we experimentally demonstrate the first superchannel coherent optical OFDM/OQAM system. By using OFDM/OQAM, the signal with distinguished rectangular spectral shape (side lobe suppression ratio > 35 dB) is efficiently generated, which is 20 dB lower than the conventional OFDM. When applying such technique in unsynchronized band-multiplexed superchannel optical system, very trivial guard band spacing (<20MHz) is required without any sensitivity performance or spectral efficiency degradations. Compared to Nyquist-WDM and CO-OFDM, OFDM/OQAM shows comparable performance, but efficiently enhances the overall spectral efficiency, while greatly releases the implementation constrains.
2. Principle of OFDM/OQAM

The principle of OFDM/OQAM is illustrated in Fig. 1. The subcarriers are evenly spaced, \( \Delta f = \frac{1}{T} \), where \( T \) is the symbol period. The system can resist ISI and ICI by taking the merit of the orthogonality between subcarrier and the perfect reconstruction (PR) condition of the prototype filter [14]. At the transmitter the complex symbols are

\[
x_k(n) = s_k^I(n) + j s_k^Q(n),
\]

where \( s_k^I(n) \) and \( s_k^Q(n) \) are the real and imaginary parts of the \( n \)th symbol in the \( k \)th subcarrier. Then, the quadrature component is delayed by half of a symbol period /2 with respect to the in-phase component, which forms the modulation of offset QAM.

\[
x_k(n) = \sum_{n=-\infty}^{\infty} X_k(n) e^{j 2\pi n T/2} = \sum_{n=0}^{N-1} X_k(n) e^{j 2\pi n T/2},
\]

where \( h(t) \) is the impulse response of the prototype filter, and \( \phi = \frac{2\pi}{T} + \frac{\pi}{2} \). When the OFDM/OQAM baseband is formed, it is then up-converted to a wireless or optical channel.

At the receiver, the analog signal \( r(t) \) is demodulated and then fed into the corresponding matched filters. The filtered signal is then sampled at rate of \( 1/T \). The output symbol on \( k \)th subcarrier is given as

\[
r_k(n) = s_k^I(n) + j s_k^Q(n),
\]

where \( s_k^I(n) \) and \( s_k^Q(n) \) are the real and imaginary parts of the \( n \)th received symbol on the \( k \)th subcarrier, respectively. From [15], we have

\[
s_k^I(n) = \sum_{s=-\infty}^{\infty} \sum_{k'=-\infty}^{\infty} h(nT-t) \sum_{s'=-\infty}^{\infty} \sum_{k''=-\infty}^{\infty} h(nT-t) \cos[(k'-k)\phi_t] s_k^I(s) s_{k'}^I(s') + s_k^Q(s) s_{k'}^Q(s') dt,
\]

and
\[
\hat{s}^0_i(n) = \sum_{n=0}^{N-1} \sum_{k'=-\infty}^{\infty} \int h(nT-t+T/2) \times \left[ s_i'(n) h(t-n'T) \sin[(k'-k)\varphi_i] \right] dt.
\]

If the filter response \( h(t) \) is real and even (i.e., \( h(t) = h(-t) \)), and meets the PR condition, which is given in the following equations, then the received signal can be recovered.

\[
\int_{-\infty}^{\infty} h(t-n'T) h(nT-t) \cos[(k'-k)\varphi_i] dt = \delta(k'-k,n'-n),
\]

(6)

\[
\int_{-\infty}^{\infty} h(t-n'T-T/2) h(nT-t) \sin[(k'-k)\varphi_i] dt = 0,
\]

(7)

\[
\int_{-\infty}^{\infty} h(t-n'T) h(nT-t+T/2) \sin[(k'-k)\varphi_i] dt = 0,
\]

(8)

\[
\int_{-\infty}^{\infty} h(t-n'T-T/2) h(nT-t+T/2) \cos[(k'-k)\varphi_i] dt = \delta(k'-k,n'-n).
\]

(9)

The prototype filter \( h(t) \) is designed to not only contribute great stopband attenuation, but also compensate the optical channel dispersion [16]. Note that, the direct implementation of OFDM/OQAM system depicted in Fig. 1 would be very costly. However, it can be realized by an efficient FFT/IFFT-based implementation [17], which has also been used in our demonstrations.

Without loss of generality, we assume that \( h(t) \) is a square-root raised cosine filter (roll-off factor in the simulation for Fig. 2 is 0.5). The rectangular time response used in conventional OFDM is also shown in Fig. 2(a) for comparison. The frequency domain response clearly shows that the side bands of OFDM/OQAM are significantly suppressed. Figure 2(b) shows two spectra of conventional OFDM and OFDM/OQAM. As shown in the Fig. 2(b), the side lobe suppression ratio of OFDM/OQAM system is much higher (>35dB) than the conventional OFDM (~15dB).

Fig. 2. (a) time and frequency domain impulse response; (b) frequency spectra for conventional OFDM and OFDM/OQAM.
3. Experiments and discussions

We conduct three experiments with different transmitter configurations to evaluate the OFDM/OQAM performance in the coherent optical communication. In the first experiment, a simple back-to-back measurement is carried out to compare the bit error rate (BER) versus optical signal noise ratio (OSNR) sensitivity performance of OFDM/OQAM with the conventional CO-OFDM. The setup is shown in Fig. 3. The external cavity laser (ECL, 1550 nm) with line-width less than 100 kHz is firstly split into two polarization branches by a polarization beam splitter (PBS). Each branch is modulated by an individual optical I/Q modulator. Two arbitrary waveform generators (AWGs) running at 10GS/s sample rate are used to produce the dual polarization radio frequency (RF) signals. The FFT size is 256, in which 166 subcarriers are loaded with OFDM/OQAM signal. The center two subcarriers are unloaded to avoid the DC influence. 4 subcarriers are selected as the pilots to estimate the phase noise. For the channel estimation, we design training symbols in a manner of [A A] and [A -A] on the two polarizations, where 'A' denotes an independent OFDM/OQAM symbol. In this experiment, 10 training symbols (TSs) are periodically inserted in the front of each OFDM frame, which contains 500 payload symbols. It is worth noting that, no cyclic prefix (CP) is used in OFDM/OQAM scheme. The ISI and ICI are combated by specially designing the prototype filter [16]. Thus, the data rate of OFDM/OQAM on each polarization is 12.25 Gb/s for 4QAM loading case, and 24.50 Gb/s for 16QAM case. For the purpose of comparison, the conventional CO-OFDM is tested under the same configuration, but with the CP length of 1/32 FFT size per OFDM symbol. Thus, the date rate of CO-OFDM is 11.88 Gb/s on each polarization with 4QAM loading. Considering the data rate of all the TSs, pilots, and CP, the raw line rates for both OFDM/OQAM and CO-OFDM are the same of 12.81 Gb/s. A typical integrated coherent receiver is used to detect signals of both polarizations, which are then fed into a Tektronix oscillator scope operating at 50 GS/s. Off-line digital signal processing (DSP) is done with MATLAB program. The main DSP procedures are shown in the insert. Most of the procedures are similar to conventional OFDM, but OFDM/OQAM requires an additional process of the digital filtering with function of $h(t)$ before the FFT operation.

Fig. 3. Experimental setup of back-to-back measurement for polarization-division multiplexed OFDM/OQAM system.
The BER versus OSNR performance is first measured at back-to-back, as shown in Fig. 4. To achieve a BER of 1x10⁻³, the required OSNR is 5.3 dB for both single-polarization OFDM-4QAM and OFDM/OQAM-4QAM. This suggests that OFDM/OQAM gives the same BER-OSNR sensitivity performance as the conventional OFDM. The required OSNR for polarization-diversity multiplexed (PDM) OFDM/OQAM-4QAM (line rate of ~25.62 Gb/s) is 8.8 dB. Compared to single-polarization scheme, 3 dB difference is caused by the increased data rate, while another 0.5 dB is mainly due to the implementation errors. The required OSNR for single polarization OFDM/OQAM-16QAM scheme is 13.7 dB. The insets show the recovered 4QAM and 16QAM constellations.

Fig. 4. BER versus OSNR measurement for OFDM/OQAM and the conventional OFDM schemes at back-to-back.

Then, we experimentally evaluate the guard band influence of OFDM/OQAM in a timing-/frequency-unsynchronized multi-band system. Only single polarization is utilized due to lacks of enough generator equipments, but without losing generality. This experiment is also carried out at back-to-back. The data loading parameters are the same as the first experiment. The experimental setup is shown in Fig. 5. Three bands are assumed here. Band2 is generated from the upper path, which is driven by an I/Q optical modulator and an AWG running at 10GS/s. In the lower path, an intensity modulator is first used to generate two optical carriers (carrier 1 and 3), while suppress the center carrier. The two carriers are then fed into another IQ modulator driven by an AWG running at 12GS/s. By doing so, the center band (band2) is completely independent from the two adjacent bands (band1 and band3) in both time and frequency domain. The guard band spacing could be easily adjusted by changing the driven frequency for the intensity modulator.

Fig. 5. Experimental setup for unsynchronized multi-band OFDM/OQAM at back-to-back.

The received spectra of three bands are shown in Fig. 6. The wavelengths of the transmitter laser and local oscillator are set to 1550 nm. To de-multiplex three band signals, the band2 is selected by using a rectangular digital filter. The bandwidth of that digital filter is...
slightly wider than the bandwidth of band2. We choose the half of the subcarrier spacing \( \Delta f / 2 \) (10 GHz/256/2 = ~19.5 MHz) as the step size. According to [8], the Q-factor of the right edge subcarrier of band2 is tested to investigate the influence from the adjacent band. We first load OFDM/OQAM for all the three bands. As shown in Fig. 7, the Q-factor for OFDM/OQAM scheme stays at level of ~19 dB for all the indexes, which suggested that no influence from other band is introduced. Then we change the modulation format to conventional OFDM. Because timing and frequency are unsynchronized for the adjacent OFDM bands, the Q-factor significantly drops when decreasing the guard band. The penalty at the spacing of \( \Delta f / 2 \) is as high as 8 dB. Thus, it apparently shows that the channel crosstalk could be efficiently overcome for unsynchronized multi-band system by using OFDM/OQAM. This would greatly reduce the implementation complexities. Currently the commercial ECLs could be easily locked within ten of megahertz. With a small guard band between the sub-channels, we can even use multiple laser sources to form the superchannel without considering the frequency or timing alignment issues. Thus, taking the consideration of the cost and implementation complexities, OFDM/OQAM would be a promising solution for the optical superchannel design.

Finally, we evaluate the BER sensitivity of OFDM/OQAM in the superchannel configuration at back to back, as shown in Fig. 8. Two stages of optical comb generator are used to produce 9 optical carriers. The ECL (1550 nm) is firstly fed into a phase modulator, which is driven by RF sine wave of ~19.5 GHz. Three tones are selected and reshaped by wavelength selective switch (WSS). An intensity modulator (driven at ~6.5 GHz) is followed to triple the input into nine tones. Finally, those tones are fed into an I/Q modulator driven by an AWG at 10GS/s. the OFDM/OQAM data loading is the same as described in the first
experiment. The data rate for the superchannel is 12.25x9 = 110.25 Gb/s. The configuration of the receiver end is the same as previous two experiments.

![Experimental setup](image)

Fig. 8. The experimental setup for 110Gb/s OFDM/OQAM superchannel transmission.

Figure 9 shows the averaged BER performance of the 9 sub-bands as a function of OSNR at back-to-back. The guard band frequency is set as 39 MHz, which equals to only one subcarrier spacing. The required OSNR is 15 dB for the BER of 1x10^{-3}. Compared to the single-band performance, the implementation error is only ~0.15 dB. Thus, it proves that our OFDM/OQAM modulation can be used in unsynchronized superchannel without any penalties.

![BER vs OSNR](image)

Fig. 9. BER versus OSNR for 110.25 Gb/s OFDM/OQAM superchannel at back-to-back.

**Conclusion**

In this paper, we experimentally demonstrated the first coherent optical OFDM/OQAM superchannel system. By using OFDM/OQAM, the signal with distinguished rectangular spectral shape (side lobe suppression ratio > 35 dB) could be efficiently generated, which is 20 dB lower than conventional OFDM. When applying such technique in unsynchronized band multiplexed superchannel system, very trivial guard band spacing (<20MHz) was required without any performance degradations. A 9-band 110-Gb/s superchannel OFDM/OQAM system was shown with comparable performance as the conventional OFDM, but with much reduced implementation complexities. Our demonstrations showed that OFDM/OQAM would be a promising alternative to OFDM to be used in high capacity transmission, re-configurable optical access and networks.

**Acknowledgments**

This work is supported by the National Basic Research (973) Program of China (2010CB328300), and 863 Program of China (2012AA011302).