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Offset-16QAM based Coherent WDM with Multi-carrier Group Detection

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ABSTRACT

Recently, offset-QAM based coherent WDM (CoWDM) has been proposed to build up spectrally-efficient multi-carrier superchannels. Compared with Nyquist wavelength division multiplexing (N-WDM) and orthogonal frequency division multiplexing (OFDM), offset-QAM based CoWDM can relax the stringent transmitter-side requirements for spectrum shaping and achieve significant transmission performance improvement. In order to efficiently utilize the sampling rate of commercially available analog-to-digital converter (ADC) and decrease the receiver-side implementation complexity, multi-carrier group detection scheme is investigated in offset-QAM based CoWDM where multiple carriers are simultaneously detected within single coherent receiver, followed by carrier separation in the digital domain through the 4-point discrete Fourier transform (DFT) method at the baseband. Here, we demonstrate a transmission of five-carrier 100 Gb/s polarization-multiplexed offset-16QAM signal with 12.5 GHz channel spacing. Through 3-carrier group detection, the sampling rate per-carrier is reduced to 1.33 times symbol rate in terms of 50 GS/s ADC and there is only 0.35 dB required OSNR penalty at BER=10⁻³ compared with conventional single channel coherent detection. Meanwhile, good tolerance of coherent receiver analog bandwidth is secured and receiver bandwidth is reduced to 8 GHz. Moreover, 0.5 dB required OSNR penalty at BER=10⁻³ is obtained given 18 GHz ADC bandwidth. Besides, we find that side carriers suffer from severer performance degradation than the central carrier with limited ADC resolution and only 0.08 dB and 0.2 dB required OSNR penalty at BER=10⁻³ are secured with 6 bits ADC resolution for central carrier and side carriers, respectively.

Keywords: Multi-carrier group detection, offset-QAM modulation, Coherent WDM

1. INTRODUCTION

The bandwidth demand of Internet and private line service continues to grow at around 30% to 60% per year, driven by more and more video streaming and proliferation of cloud computing, social media, and mobile data delivery [1]. The increasing bandwidth trend leads to the need of higher-speed fiber optical transmission interfaces and higher spectrum efficiency (SE) technique. The technology options for higher SE transmission are being intensively studied, which comes in two major categories: reducing the channel spacing or increasing the modulation levels. Employing higher-level modulation formats, such as 32-QAM and 64-QAM, is a nature approach for SE improvement. However, it comes at the expense of higher implementation penalty, higher receiver sensitivity requirement, and again reduced optical reach, due to the smaller constellation Euclidean distance. Theoretically, the required optical signal-to-noise ratio (OSNR) of 32-QAM signal is about 3 dB larger than that of 16-QAM and it grows exponentially as the constellation point increase [2]. On the other hand, optically multiplexed multi-carrier systems with channel spacing reducing to symbol rate are currently receiving widespread attention for the purpose of both SE and transmission distance improvement. Thus, two approaches to build up spectrally-efficient superchannels have been intensively studied: orthogonal frequency division multiplexing (OFDM) and Nyquist wavelength division multiplexing (N-WDM) [3]. However, the ideal pulse shaping both for OFDM and N-WDM is challenging to achieve in practice, indicating of inevitable inter-channel interference (ICI) penalty. Moreover, both superchannels require complex transmitter-side (Tx) implementation. Recently, offset-QAM based coherent WDM (CoWDM) has been proposed to relax the stringent transmitter-side requirements of device and shows significant performance improvement over N-WDM and OFDM systems [4,5]. By offsetting the in-phase and quadrature components with half symbol period and controlling the phase difference between individual carriers equal to either $\pi/2$ or $3\pi/2$, the ICI free transmission can be achieved even with severe optical spectrum overlapping between

adjacent carriers. As we know, the overall cost and complexity of superchannels are highly related to the copies of used parallel transceivers. Therefore, given fixed Tx implementation, the detection of more than one carrier is strongly expected for the purpose of efficient utilization of the commercially available analog-to-digital converter (ADC) and decrease of the coherent receiver count. The above ideal of multi-carrier group detection has been investigated in both OFDM and N-WDM superchannel [6,7]. It is desired to extend the ideal of multi-carrier group detection to offset-QAM based CoWDM superchannel.

In this paper, we demonstrate a transmission of five-carrier 100 Gb/s polarization-multiplexed offset-16QAM signal with 12.5 GHz channel spacing. Through 3-carrier group detection, the sampling rate per-carrier is reduced to be 1.33 times symbol rate and there is only 0.35 dB required OSNR penalty at $\text{BER}=10^{-3}$ compared with traditional one-by-one detection. Meanwhile, good tolerance of coherent receiver analog bandwidth is secured and a receiver bandwidth of as low as 8 GHz is feasible given 0.5 dB Q-penalty. Moreover, the resistance of ADC analog bandwidth is studied and 0.5 dB required OSNR penalty at $\text{BER}=10^{-3}$ is obtained given 18 GHz bandwidth. Besides, side carriers suffer from severer performance degradation than the central carrier with limited ADC resolution and only 0.08 dB and 0.2 dB required OSNR penalty at $\text{BER}=10^{-3}$ are secured with 6 bits ADC resolution for central carrier and side carriers, respectively.

2. IMPLEMENTATION PRINCIPLE

2.1 ICI free between adjacent carriers in offset-QAM based CoWDM

Fig 1. Principle of offset-QAM based CoWDM.

The principle of offset-QAM based CoWDM is illustrated in Fig 1. The carriers are evenly spaced with channel spacing equal to the symbol rate. At Tx, the complex symbols are written as:

$$x_k(m) = a_k(m) + j \cdot b_k(m) \quad (1)$$

Where $a_k(m)$ and $b_k(m)$ are the real and imaginary parts of the m th symbol in the k th carrier, respectively. Then, the quadrature component is delayed by half of a symbol period with respect to the in-phase component, which forms the modulation of offset-QAM. And additional phase shift is added to each carrier after modulation [8,9]:

$$\Phi_k = k \cdot \pi/2 \quad (2)$$

After combination, the signal can be written as:

$$O(t) = \sum_{k=1}^N \sum_{m=-\infty}^{\infty} [a_k(m)h(t-mT_s) + j \cdot b_k(m)h(t-mT_s-0.5T_s)] \exp[j(\omega_k t + k\pi/2)] \quad (3)$$

Where $h(t)$ is the impulse response of the prototype filter, ω_k is the frequency of k th carrier, T_s is the symbol duration. At the receiver-side (Rx), the received analog signal is demodulated and then fed into the corresponding matched filters. The filtered signal is then sampled with one sample per symbol. The received symbol in the k th carrier is given as:

$$\hat{x}_k(m) = \hat{a}_k(m) + j \cdot \hat{b}_k(m) \quad (4)$$

Where $\hat{a}_k(m)$ and $\hat{b}_k(m)$ are the real and imaginary parts of the m th symbol in the k th carrier, respectively and given as:

$$\hat{a}_k(m) = \int_{-\infty}^{\infty} a_k(m)h(t)h(t)dt + \sum_{n \neq 0} \int_{-\infty}^{\infty} a_k(m+n)h(t)h(t-nT_s)dt$$

$$+ \left\{ \begin{aligned} & \sum_{p \neq k} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} [a_p(m+n)h(t)h(t-nT_s)\cos[(p-k)(2\pi t/T_s + \pi/2)]]dt \\ & - \sum_{p \neq k} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} [b_p(m+n)h(t)h(t-nT_s-0.5T_s)\sin[(p-k)(2\pi t/T_s + \pi/2)]]dt \end{aligned} \right\} \quad (5)$$

$$\hat{b}_k(m) = \int_{-\infty}^{\infty} b_k(m)h(t)h(t)dt + \sum_{n \neq 0} \int_{-\infty}^{\infty} b_k(m+n)h(t)h(t-nT_s)dt$$

$$+ \left\{ \begin{aligned} & \sum_{p \neq k} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} [a_p(m+n)h(t)h(t-nT_s-0.5T_s)\sin[(p-k)(2\pi t/T_s + \pi/2)]]dt \\ & + \sum_{p \neq k} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} [b_p(m+n)h(t)h(t-nT_s)\cos[(p-k)(2\pi t/T_s + \pi/2)]]dt \end{aligned} \right\} \quad (6)$$

The first, second, and third terms of Eq. (2,3) represent the signal, inter-symbol interference (ISI), and ICI, respectively. If the impulse response $h(t)$ is real and even, then we can get the following equations:

$$\int_{-\infty}^{\infty} [a_p(m+n)h(t)h(t-nT_s)\cos[(p-k)(2\pi t/T_s + \pi/2)]]dt = 0, \quad p-k=2l+1 \quad (l \in \mathbb{Z}) \quad (7)$$

$$\int_{-\infty}^{\infty} [b_p(m+n)h(t)h(t-nT_s)\cos[(p-k)(2\pi t/T_s + \pi/2)]]dt = 0, \quad p-k=2l+1 \quad (l \in \mathbb{Z}) \quad (8)$$

$$\int_{-\infty}^{\infty} [a_p(m+n)h(t)h(t-nT_s-0.5T_s)\sin[(p-k)(2\pi t/T_s + \pi/2)]]dt = 0, \quad p-k=2l+1 \quad (l \in \mathbb{Z}) \quad (9)$$

$$\int_{-\infty}^{\infty} [b_p(m+n)h(t)h(t-nT_s-0.5T_s)\sin[(p-k)(2\pi t/T_s + \pi/2)]]dt = 0, \quad p-k=2l+1 \quad (l \in \mathbb{Z}) \quad (10)$$

From Eq. (7-10), we can see that the ICI term of Eq. (2) and (3) is zero considering $p-k=2l+1 \quad (l \in \mathbb{Z})$, namely the ICI from adjacent carriers is free in offset-QAM based CoWDM system.

2.2 Multi-carrier group detection

Fig 2. Illustration of multi-carrier group detection.

The concept of the multi-carrier group detection is illustrated in Fig 2. In order to make full use of ADC sampling rate and reduce Tx implementation complexity, it is desired to detect multiple carriers simultaneously by properly tuning the central wavelength of the local oscillator (LO) and employing a proper detection window bandwidth. For instance, if a 3-carrier group detection scheme is applied, the LO wavelength is aligned with the central carrier and Rx analog bandwidth are sufficient to capture all the 3 carriers. On the other hand, the sampling rate per carrier is reduced to be 1/3 times of ADC sampling rate by simultaneously detecting 3 carriers.

3. SIMULATION SETUP SCHEMATICS

As shown in Fig 3, the multi-carrier source is obtained from an optical comb generator (OCG) with channel spacing of 12.5 GHz. The linewidth of each carrier from OCG is 10 kHz. The signal data trains consist of 12.5 Gbit/s $2^{17}-1$ pseudo-random binary sequences (PRBS) and differential coding is used to solve the phase ambiguity problem. These logic data trains are used to generate 4-level electrical signals and the quadrature signal is delayed by $T_s/2$ with respect to the in-phase signal. Then, 5 carriers are, respectively, introduced to 5 parallel modulators driven by these electrical signals. Polarization multiplexing is achieved through the addition of a delay of 180 symbols between two polarization tributaries. After polarization multiplexing, the modulated 5 carriers are phase shifted by $\Phi_k = (k-3)\pi/2 \quad k=1 \dots 5$. Then, each carrier is filtered by a 4th-order Gaussian optical filter, whose response is available in commercial products, in order to shape the optical spectrum. After spectrum shaping, all the carriers are launched into the 12×80 km EDFA-only SSMF link with launched optical power controlled by a variable optical attenuator (VOA). At Rx, amplified spontaneous emission (ASE) noise loading is firstly used to adjust the optical signal-to-noise-ratio (OSNR) for the back-to-back (B2B) measurement. Then, one 0.8 nm optical band-pass filter is used to suppress the ASE noise before coherent detection. The coherent optical receiver front-end is assumed perfect. After coherent detection, four 5th electrical Bessel

low-pass filters (Bessel-LPF) are applied to emulate the bandwidth constraint of receiver front-end. After Bessel-LPF, four anti-aliasing filters (AAF) with 6th super-Gaussian profile are also used to emulate the analog bandwidth restriction of 50 GS/s ADC front-end, which indicates 4 samples per symbol considering 12.5 Gbaud symbol rate.

Fig 3. System configuration and offline DSP for offset-16QAM based coherent WDM with 3-carrier group detection.

Offline digital signal processing (DSP) is firstly started with chromatic dispersion (CD) compensation by using a frequency-domain equalization approach. Then, carrier separation is conducted by 4-point Discrete-Fourier-Transform (DFT) at baseband [7]. Three identical DSP flows are next performed in parallel for the three carriers under investigation. A butterfly T/4 spaced finite impulse response (FIR) filters with only 1 tap is adapted to implement the constant modulus algorithm (CMA) for the purpose of polarization de-multiplexing, which is followed by frequency offset compensation (FOC) using the fast Fourier transform (FFT) method. Then, the adaptive equalization is performed by four butterfly 25-tap T/4 spaced FIR filters using modified least-mean-square algorithm (M-LMS) for the sequences after FOC [10]. The carrier phase recovery (CPR) is based on blind phase search (BPS) algorithm with 64 test angles. After CPR, ISI equalizers are applied to each polarization to compensate residual ISI induced by optical or electrical filtering in the link.

4. RESULTS AND DISCUSSION

4.1 Effect of filtering

Firstly, we examine the restriction of optical Gauss filter bandwidth and Bessel-LPF bandwidth under back-to-back (B2B) measurement, given fixed ADC analog bandwidth of 20 GHz. The mean Q-factor is calculated based on the average BER of outside carriers (carrier 2, 4) due to the fact that the limited-bandwidth of Bessel-LPF mainly destroys the two outside carriers by losing high frequency component during 3-carrier group detection. The contour plot is shown in Fig 4, considering 18.5 dB OSNR for 0.1 nm noise bandwidth. As we can see, a Bessel-LPF bandwidth of as low as 8 GHz can be tolerated within 0.5 dB Q-penalty. In addition, narrower Gaussian optical filter bandwidth will lead to serious ISI while broader Gaussian optical filter bandwidth will results in spectral overlaps between the targeted carrier and carriers more than one carrier distance, bringing ICI. As a result, both broader and narrower Gaussian optical filter bandwidth lead to performance penalty given fixed Bessel-LPF bandwidth. In particular, the optimal Bessel-LPF bandwidth of 13 GHz and the optimal Gaussian optical filter bandwidth of 15 GHz can be obtained. Then, the effect of ADC analog bandwidth is studied by sweep AAF bandwidth from 17GHz to 22 GHz, given Bessel-LPF bandwidth of 13 GHz and Gaussian optical filter bandwidth of 15 GHz. As we can see from Fig 5, similar performance is observed when the AAF bandwidth is broader than 19 GHz. When the AAF bandwidth further decreases, performance degradation is obtained. In particular, 0.5 dB required OSNR penalty at $\text{BER}=10^{-3}$ is secured given 18GHz AAF bandwidth. The inset in Fig 5 shows the measured frequency response of AAF with a fast roll-off characteristic and the received signal spectrum after Bessel-LPF.

Fig 4. Q-factor contour plot for outside carriers.

Fig 5. Required OSNR vs AAF bandwidth for outside carriers.

4.2 Performance sensitivity

The B2B performance is obtained in Fig 6, considering optical Gauss filter bandwidth of 15 GHz, Bessel-LPF bandwidth of 13 GHz and AAF bandwidth of 20 GHz. As we can see, similar performance is obtained between central carrier and outside carriers either with 3-carrier detection or one-by-one detection. Moreover, there is only an additional OSNR penalty of 0.35 dB, 0.95 dB with group detection compared with the case with one-by-one detection and theoretical limit, respectively. The inset in Fig 6 shows the constellation of the side carriers before BER counting with group detection and one-by-one detection, given 20 dB OSNR. Then, the achieved Q-factor after 960 km SSMF transmission is calculated as a function of launched optical power per carrier. As we can see from Fig 7, the allowed input optical power per carrier range beyond $\text{BER}=10^{-3}$ is from -8.4 dBm to -2.7 dBm for both outside carriers and central carrier with group detection.

Fig 6. B2B performance.

Fig 7. Performance after 960 km SSMF transmission.

4.3 Effect of ADC resolution

It is well known that quantizing noise will inevitably introduced into the system during ADC operation with finite resolution. Therefore, the effect of the DAC resolution on system performance is investigated, as shown in Fig 8. As we can see that, the system performance keeps almost constant with ADC resolution varying from 10 to 6 bits. Specifically, only 0.08 dB and 0.2 dB required OSNR penalty at $\text{BER}=10^{-3}$ are secured with 6 bits ADC resolution for central carrier and side carriers, respectively. If the ADC resolution decreases below 6 bits, both central channel and side channels suffer large performance degradation. On the other hand, side carriers suffer from severer performance degradation than the central carrier.

Fig 8. Required OSNR vs ADC resolution.

5. CONCLUSION

3-carrier group detection is investigated for offset-16QAM based CoWDM, resulting in reduced sampling rate per carrier of 1.33 times symbol rate in terms of 50 GS/s ADC. Compared with traditional one-by-one coherent detection, there is only 0.35 dB required OSNR penalty at $\text{BER}=10^{-3}$. Moreover, coherent receiver bandwidth can be tolerated to 8GHz and ADC bandwidth of 18 GHz is feasible given 0.5 dB required OSNR penalty at $\text{BER}=10^{-3}$. Furthermore, only 0.08 dB and 0.2 dB required OSNR penalty at $\text{BER}=10^{-3}$ are secured with 6 bits ADC resolution for central carrier and side carriers, respectively.

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