Optical Layer Modulation Format Conversion in OFDM-Based Flexible Optical Networks

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***Abstract*—In this letter, we proposes and experimentally demonstrates an optical layer modulation format conversion technique from quadrature phase shift keying (QPSK) to 16 quadrature amplitude modulation (QAM) in orthogonal frequency division multiplexing (OFDM)-based flexible optical wavelength division multiplex (WDM) networks. The 16-QAM-OFDM signal is generated by direct detection after the superposition of two QPSK-OFDM optical signals with different optical powers and wavelengths. The optical power ratio 2:1 of two QPSK-OFDM signals can be realized by adjusting the power of two coupled optical signal in switching nodes. The tolerance to symbol delay and power deviation of two QPSK-OFDM signals is also experimentally evaluated.**

Keywords-orthogonal frequency division multiplexing; modulation format conversion; direct detection; flexible optical networks

I. INTRODUCTION

In a flexible optical WDM (FWDM) network, the fixed channel grid restrictions are removed and non-uniform and dynamic allocation of spectrum are allowed, leading to higher spectral efficiency compared to conventional fixed grid networks. A suitable technology for implementing FDWM networks is OFDM, which provides the ability to separate a single channel into multiple closely-allocated subcarriers with finer granularity and has better resistance to chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. The capacity of FWDM networks is usually limited by wavelength congestion at network nodes and system management requirements for network reconfiguration on link failure. Using wavelength converters and modulation format converters it is found that such restrictions can be relaxed by providing for more flexible spectrum allocation, thus allowing for evolution of the network. In the past, numbers of researches had demonstrated various conversion schemes in single carrier systems. Return to zero (RZ) could be converted to non-return to zero (NRZ) by using four-wave mixing (FWM) and dispersion in a delay-asymmetric nonlinear loop mirror [2]. Optical conversions techniques for M-ary PSK signals based on highly nonlinear fiber [3] or semiconductor optical amplifier [4] have also been proposed. The conversion from on–off keying (OOK) to binary phase-shift keying (RZ-BPSK) has been demonstrated utilizing cross-phase modulation (XPM) in a passive AlGaAs waveguide [5]. M-ary QAM signal generation schemes employing nonlinear optical loop mirror or highly nonlinear fiber have been also been realized in [6, 7]. However, to our knowledge, optical layer format converters from QSPK to 16 QAM in OFDM-based system have not been reported.

In this paper, for the first time, we propose and experimentally demonstrate an optical layer QPSK to 16 QAM format conversion technique in OFDM-based switching networks. Symbol delay of two converted signals is not allowed in single carrier system [8]. While to OFDM signal, the orthogonality of the converted OFDM signal is maintained for the use of cyclic prefix (CP). The symbol delay of two OFDM signals introduces special rotation of constellation, which could be recovered by training symbols. Finally, to verify the correctness of the principle, two 5 Gbaud QPSK-OFDM signal after 40-km standard single-mode fibers (SSMF) transmission are converted to 16-QAM-OFDM signal, and the converted signal is successfully transferred another 40-km SSMF. The system performance under symbol delay and the tolerance to power deviation of two QPSK-OFDM signals are evaluated in the following experiment. The results show that there is only 0.6 dB power penalty caused by the impact of symbol delay. Compared with symbol delay, the system performance is more robust to power deviation.

II. PRINCIPLE

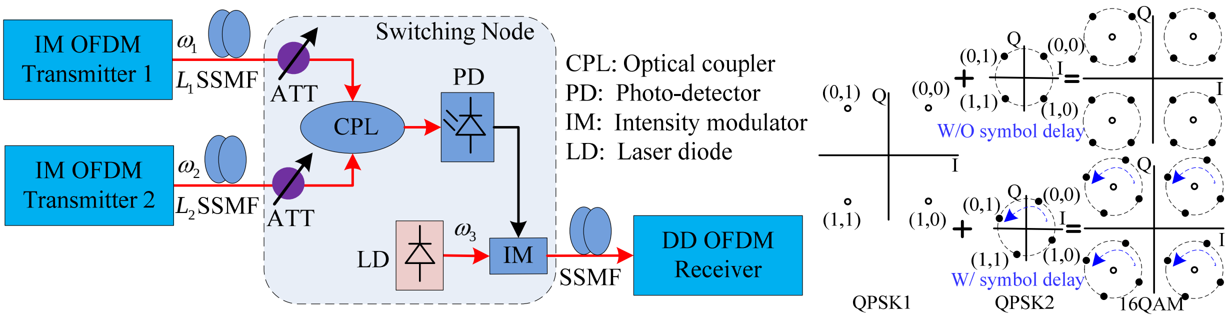
Figure I (a) shows the configuration of the proposed modulation format converter. The two OFDM transmitters use a conventional intensity modulation scheme [9]. The output double-sideband (DSB) optical signals of two transmitters can be written as

$$E_1 = e^{j\omega_1 t}\left(1+\sum_{n=1}^{N} v_{1,n}\cos\left(n\omega t+\theta_{1,n}\right)\right) \tag{1}$$

and

$$E_2 = e^{j\omega_2 t}\left(1+\sum_{n=1}^{N} v_{2,n}\cos\left(n\omega t+\theta_{2,n}\right)\right) \tag{2}$$

where ω_1 and ω_2 are the angular frequency of optical carriers, N is the subcarrier number, $v_{1,n}$, $v_{2,n}$ and $\theta_{1,n}$, $\theta_{2,n}$ are the amplitudes and phases of the n^{th} subcarrier, and the second-



(a) (b)

FIGURE I. (a)PRINCIPLE OF MODULATION FORMAT CONVERSION IN OFDM-BASED SWITCHING NODE. (b) THE 16 QAM CONSTELLATION CAN BE REPRESENTED AS THE COMBINATION OF TWO QPSK CONSTELLATIONS WITH AND WITHOUT SYMBOL DELAY.

and higher-order terms after power series expansion are disregarded [9]. After transmission with the distance of L_1 and L_2, the group-velocity dispersion parameter of β_2 and no fiber loss, then the optical signals become

$$E_{1,CD} = e^{j\omega_1 t}\left(1+\sum_{n=1}^{N} v_{1,n} e^{j\left(n^2\theta_{1,D}\right)} \cos\left(n\omega t+\theta_{1,n}\right)\right) \tag{3}$$

and

$$E_{2,CD} = e^{j\omega_2 t}\left(1+\sum_{n=1}^{N} v_{2,n} e^{j\left(n^2\theta_{2,D}\right)} \cos\left(n\omega t+\theta_{2,n}\right)\right) \tag{4}$$

where $\theta_{1,D} = \beta_2 L_1 \omega^2 / 2$, and $\theta_{2,D} = \beta_2 L_2 \omega^2 / 2$. The two optical signals at switching node are coupled and direct detected, then the received signal can be expressed as

$$\begin{aligned} R &= \left|E_{1,CD}\right|^2 + \left|E_{2,CD}\right|^2 \\ &= \sum_{n=1}^{N} v_{1,n} \cos\left(n^2\theta_{1,D}\right)\cos\left(n\omega t+\theta_{1,n}\right) \\ &\quad + \sum_{n=1}^{N} v_{2,n} \cos\left(n^2\theta_{2,D}\right)\cos\left(n\omega t+\theta_{2,n}+n\theta_\tau\right) \\ &= \sum_{n=1}^{N} \left|r_n\right| \cos\left(n\omega t+\theta_n\right) \end{aligned} \tag{5}$$

where $n\theta_\tau$ represents the phase of symbol delay relative to $E_{1,CD}$, $r_n = v_{1,n}\cos\left(n^2\theta_{1,D}\right)e^{j\theta_{1,n}} + v_{2,n}\cos\left(n^2\theta_{2,D}\right)e^{j\left(\theta_{2,n}+n\theta_\tau\right)}$ and θ_n is the compound angle of r_n. $\cos\left(n^2\theta_{1,D}\right)$ and $\cos\left(n^2\theta_{2,D}\right)$ are the conventional formula of power fading [10]. The influence of power fading in short distance (< 40 km) applications could be ignored [11], so $\cos\left(n^2\theta_{1,D}\right) \cong \cos\left(n^2\theta_{2,D}\right) \cong 1$.

To explain the principle of the converter, in Figure I (b), the 16 QAM constellations could be represented as the combination of two QPSK constellations. In order to achieve the constellation of 16 QAM signal, the amplitude of QPSK1 should be double that of QPSK2, $v_{1,n} : v_{2,n} = 2:1$. Each point of the original constellation is obtained as the product of a point from the first constellation (QPSK1) and a point from the second constellation (QPSK2). That is to say 16 QAM is generated by the superposition of these two QPSK signals. An ideal 16 QAM constellation will be produced when the two QPSK-OFDM signals are perfectly synchronized, the constellation of top-right corner shown in Figure I (b). However, in the actual network, signals from different transmitters are difficult to achieve absolute symbol synchronization, which is caused by the phase noise of clock recovery circuit [13] and symbol timing error. So a special rotation of 16 QAM constellation is happened, the constellation of bottom right corner shown in Figure I (b). For each subcarrier, the ideal rotated 16 QAM constellation could be obtained by using training symbols. The demodulation of data subcarrier is realized by the calculation and comparison of the minimum Euclidean distance between the ideal rotated constellation and the signal after equalization.

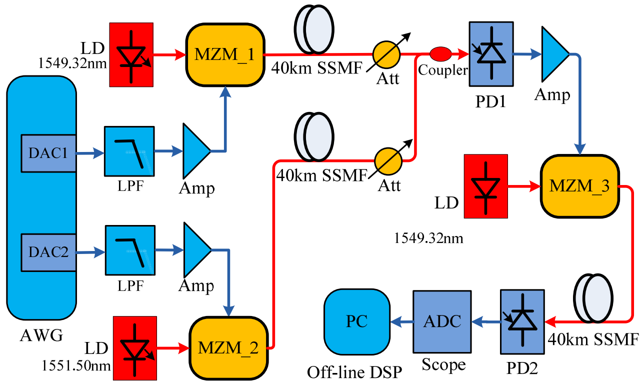


FIGURE II. EXPERIMENTAL SETUP OF QPSK TO 16 QAM FORMAT CONVERSION IN DIRECT DETECTION OFDM SYSTEM.

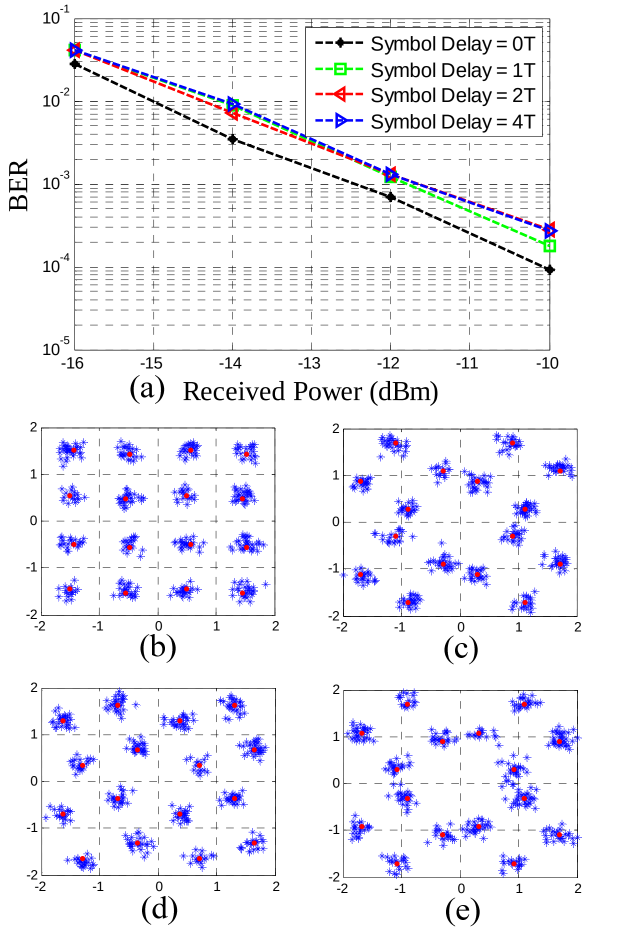


FIGURE III. (a)BER VERSUS THE RECEIVED POWER OF PD2 AT DIFFERENT SYMBOL DELAY. THE CONSTELLATION AFTER EQUALIZATION AT SUBCARRIER NUMBER OF (b) N=1, (c) N=25, (d) N=50, AND (e) N=100.

III. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is shown in Figure II. Two channel baseband electrical OFDM signals are generated by an arbitrary waveform generator (AWG, Tektronix® AWG7122) using the MATLAB® program. The sampling rate and digital to analog converter (DAC) resolution of AWG are 12 GSample/s and 8 bits, respectively. The OFDM signal contains 107 subcarriers of QPSK format to occupy 5-GHz bandwidth with an inverse fast Fourier transform (IFFT) size of 256, yielding a total raw data rate of 10 Gbps for each channel. CP of 1/8 is used. A low pass filter (LPF) with 3-dB bandwidth of 5.5 GHz is inserted after AWG to prevent high-frequency residual images. The electrical signal after microwave amplifier is used to drive a single drive Mach-Zehnder modulator (MZM), which is biased at its quadrature point to generate an optical DSB signal. The optical powers after 40-km SSMF transmission and without the use of erbium doped fiber amplifier (EDFA) are adjusted by two optical attenuators. 16 QAM signal could be obtained after optical-electrical (O/E) conversion of the coupled optical signal. The

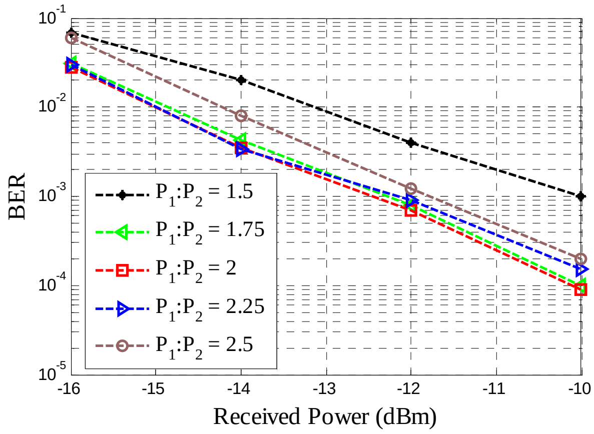


FIGURE IV. BER VERSUS THE RECEIVED POWER WITH DIFFERENT POWER DEVIATION.

16 QAM-OFDM electrical signal after the third microwave amplifier is used to drive the third MZM with the same configuration as the first two. The launch powers and optical modulation index (OMI) of the three transmitters are all set to be 6 dBm and 0.25. The received electrical signal after another 40-km SSMF transmission and O/E conversion is captured by a LeCroy® digital oscilloscope (WaveMaster813ZI-A) with 40-GSample/s sampling rate and 8-bit resolution. The received signal is processed off-line by MATLAB® digital signal processing (DSP) program. The OFDM signal after direct detection will suffer from subcarrier-to-subcarrier intermixing interference (SSII) [9], [11, 12], which will reduce the accuracy of channel estimation and the reconstruction of ideal rotated constellation. Specially designed training symbols with subcarrier interleaving [14] and lower peak to average power ratio (PAPR) are used to protect the training symbols from being affected by SSII.

To give an analysis of the influence of symbol delay on system performance, the two QPSK-OFDM signals at B2B are pre-emphasis [15] before IFFT to get a flat signal-to-noise ratio (SNR) curves for all subcarriers. The amplitude ratio of two QPSK signals is fixed to $v_{1,n}:v_{2,n}=2:1$ and the received power of the PD1 is fixed to -3 dBm. Bit error rate (BER) versus the received power at different symbol delay after 80-km SSMF transmission are shown in Figure III (a). Compared with zero symbol delay case, there are only 0.6 dB power penalty at BER of 1×10^{-3} (the FEC limit) with symbol delay = 1 T, 2 T and 4 T, where T= $1/12\times10^{9}$ (seconds) is the sampling interval of DAC. The SNR of each subcarrier has not changed for different symbol delay cases at the same received power. The reason of power penalty is that special rotation of 16 QAM constellation decreases the Euclidean distance. The constellations of data symbols and training symbols, after equalization, with received power of -3 dBm and symbol delay of 1 T, at different subcarrier number of n=1, 25, 50 and 100 are shown by blue points and red points in Figure III (b-e). The corresponding SNR of data symbols are 20.31 dB, 20.25 dB, 20.10 dB, and 18.90 dB. The decline of signal quality at higher frequency subcarrier is attributed to the power fading and SSII [9], [11, 12].

Figure IV shows the BER versus the received power of PD2 after 80-km SSMF transmission with different power deviation of two QPSK-OFDM optical signals. The symbol delay of two coupled optical signal is set to be zero by adjusting the time delay of AWG output signal and the received power of PD1 is fixed to -3 dBm. The three curves with power ratio of P_1:P_2 = 1.75, 2, and 2.25 are overlapped. Moreover, compared with symbol delay of two QPSK signals, the system performance is more robust to power deviation of two coupled optical signals.

IV. CONCLUSIONS

In this paper, we propose and experimentally demonstrate a QPSK signal to 16 QAM format conversion method in direct detection optical OFDM FWDM networks. The feasibility of the proposed method is confirmed by experiments. The impacts of symbol delay and power deviation of the two coupled optical signals on system performance are evaluated.

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