

Performance improvement of all-optical OFDM systems based on combining RZ coding with m-array QAM

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In this paper, we propose a new combination of RZ coding and m-array quadrature amplitude modulation (mQAM) to improve the performance of an all-optical OFDM system. Numerical simulation is used to evaluate the performance of the proposed all-optical OFDM system, which uses coupler-based inverse fast Fourier transform/fast Fourier transform without any nonlinear compensation. The system employs 29 subcarriers where each subcarrier is modulated with a symbol rate of 25Gsymbol/s. The results show that the nonlinear phase noise due to fiber nonlinearity is mitigated when the RZ-4QAM and RZ-16QAM format is employed. At the transmission distance of 550km, the error vector magnitude (EVM) reduces from 12.7% to 10.7% when the RZ-4QAM format is adopted instead of 4QAM. The required optical signal-to-noise ratios (OSNRs) to achieve a BER of 10^{-5} are reduced by about 1.9dB and 5.8dB when adopting the RZ-4QAM and RZ-16QAM all optical OFDM systems, as compared to the 4QAM and 16QAM all-optical OFDM systems.

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1. Introduction

The high bit-rate communication systems have been extensively investigated due to rapid development of internet services. The all-optical orthogonal frequency division multiplexing (OFDM) communication system has been proposed to cater the increasing demand for information transfer [1]. Although, this system succeeds in transmitting data at a high bit rate, it suffers from fiber nonlinearity impairments. Due to these nonlinear effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing, the transmission distance of the optical OFDM systems is limited [2-4]. One of the conventional techniques used for transmitting data over long distance is by employing a multi-span fiber where each span has one optical amplifier [5]. However, the amplifier adds additional noise which interacts with fiber nonlinear effects that causes random nonlinear phase noise [6].

A combination of return to zero (RZ) format with phase modulation formats (such as return to zero differential binary phase shift keying (RZ-DBPSK) or return to zero differential quadrature phase shift keying (RZ-DQPSK) modulation format) is reported to be more tolerant to fiber nonlinear effects in both single channel and WDM transmission systems [7-9]. RZ-DQPSK has also been proposed as an efficient modulation scheme in the presence of SPM and dispersion [10]. It is well-known that non-return to zero (NRZ) format is more adversely affected by nonlinearities whereas RZ format is more

affected by dispersion [11]. In order to increase the spectral efficiency of an optical OFDM system, a high order modulation formats is normally proposed [12]. However, optical OFDM systems that employ m-array Quadrature Amplitude Modulation (mQAM) are greatly affected by fiber nonlinearity due to phase noise that creates a Phase Rotate Term (PRT) on each subcarrier. The PRT leads to the destruction of the orthogonality of subcarriers [13-15]. The nonlinear phase noise is mainly governed by subcarrier power, transmission length, number of amplifiers and number of subcarriers [3].

In this paper, we propose a new combination between RZ coding format and 4QAM and 16QAM modulation formats in all-optical OFDM system for improving the system performance. At transmitter side, the conversion from mQAM to RZ-mQAM formats is optically realized by using a single MZM after mQAM modulator for each subcarrier. The MZM is driven by sinusoidal waveform. At the receiver side, the conversion from RZ-mQAM to mQAM utilizes a delay interferometer (DI) with delay time equal to half symbol period. To keep the time slot for optimum gating at normal frequency, RZ-mQAM is converted to mQAM before the sampling process. The effectiveness of RZ-4QAM and RZ-16QAM in all-optical OFDM systems is successfully demonstrated by numerical simulation. The impact of subcarrier peak power and fiber length on EVM is also studied. Our results reveal that significant improvements on the transmission performance of the all-optical OFDM system are realized by adopting RZ-4QAM and RZ-16QAM.

2. Effect of RZ-mQAM on power of FWM

Due to the high number of subcarriers and low frequency spacing between them, the FWM effect plays a significant role to degrade the performance of all-optical OFDM systems. The power of FWM noise is directly related to the power of subcarriers [16]. Furthermore, the FWM process is phase sensitive and it is strongly depended on the interaction time among the subcarriers. Accordingly, the shape of the modulating signal governs the power of FWM. Therefore, changing the signal envelope can be applied to suppress the impact of FWM on the performance of all-optical OFDM systems.

For transmitting OFDM signal over long fiber link with many optical amplifiers, the power of FWM P_{ijk} that produced by the product of three optical subcarriers with frequencies of ω_i , ω_j , ω_k and optical powers P_i , P_j , P_k can be expressed by [17]:

$$P_{ijk} = \frac{D^2}{9} \gamma^2 L_{eff}^2 P_i P_j P_k \eta \quad (1)$$

where, D is the degeneracy factor which equals to 6 for non-degenerate products and 3 for degenerate products, γ is the nonlinear coefficient, $L_{eff} = (1 - e^{-\alpha L}) / \alpha$ and η is the FWM coefficient, which strongly depends on the relative frequency spacing between the FWM components. Note that η are independent of the OFDM subcarriers' power [17, 18]. For QAM OFDM signal, the power of signals are constant over symbol period ($P_i = P_j = P_k = P$). Then Equation (1) can be re-written as

$$P_{ijk(QAM)} = \frac{D^2}{9} \gamma^2 L_{eff}^2 P^3 \eta \quad (2)$$

It is shown in the equation that the power of FWM can be reduced by reducing the average power of signals. RZ-carving is one of the methods to reduce the average power of the signal. Practically, RZ-mQAM signal is generated by employing one MZM, after mQAM modulator. This MZM is driven by a sinusoidal waveform with frequency equal to the symbol rate. Fig. 1 shows optical fields of four subcarriers that are modulated by RZ-QAM. The optical field of single subcarrier can be written as:

$$u_h = \frac{\sqrt{P}}{2} \left[1 - \cos\left(\frac{2\pi t}{T_s}\right) \right] \quad (3)$$

The average power of RZ-mQAM signal can be expressed as:

$$P_h = \frac{P}{4T_s} \int_0^{T_s} \left[1 - \cos\left(\frac{2\pi t}{T_s}\right) \right]^2 dt = \frac{3}{8} P \quad (4)$$

where $P_h, h \in \{i, j, k\}$ is the power of subcarrier. By substituting Equation (4) into (1), the power of FWM can be written as

$$P_{ijk(RZ-QAM)} = \frac{3D^2}{512} \gamma^2 L_{eff}^2 P^3 \eta \quad (5)$$

By comparing (2) with (5), the power of FWM for RZ-QAM signals is reduced to $(3/8)^3$ of the power of FWM for QAM signal.

3. All-Optical OFDM System Setup

The setup of proposed all-optical OFDM system is shown in Fig. 2. The transmitter side consists of an optical frequency comb generator (OFCG), wavelength selected switch, optical QAM modulator, and an optical beam combiner. The OFCG part utilizes an intensity modulator (IM) and two phase modulators (PMs) driven directly by sinusoidal waveform to generate subcarriers [19]. OFCG is fed by a CW laser source with a frequency of 193.1 THz and linewidth of 100 kHz. The OFCG generates 29 subcarriers with a frequency spacing of $\Delta f = 25$ GHz for keeping the orthogonality among the OFDM subcarriers. Subsequently, a wavelength selection switch splits the subcarriers. Then, the subcarriers are individually modulated with optical mQAM modulators [20, 21]. The mQAM modulator is supplied by two independent branches of pseudo-random binary sequence (PRBS) signals with a length of $2^{11}-1$. For generating mQAM OFDM signal, all modulated subcarriers are directly combined. On the other hand, RZ-mQAM signal can be generated by employing one RZ carver after each modulator. By combining modulated subcarriers, RZ-mQAM OFDM signal is produced. Then, resultant signal is launched into alternate fiber spans. Each fiber span includes standard single mode fiber (SSMF), optical amplifier (OA) and dispersion compensation fiber (DCF). The attenuation is fully compensated by employing optical amplifiers at spans of spacing 55 km, each. The noise figure of each optical amplifier is 6 dB. To maintain the data transmission ability of all-optical OFDM system, the dispersion is optically compensated by the DCF. In each span, the DCF is employed before SSMF so that it fully compensates the dispersion.

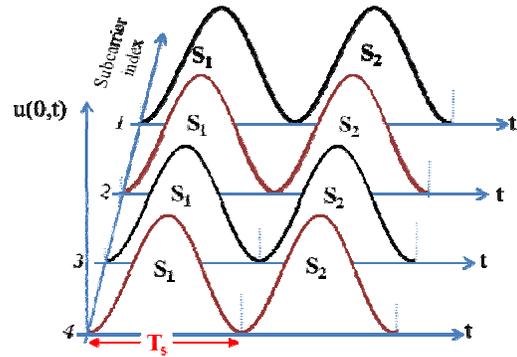


Fig. 1. Optical fields of four subcarriers that modulated by RZ-QAM

All-optical OFDM receiver employs a low-complexity all-optical FFT (OFFT) circuit, which is proposed by [21] and coherent mQAM optical demodulators. The N-order OFFT utilizes N-1 cascaded Mach-Zehnder Interferometer (MZI), electro-absorption modulators (EAMs) and optical filters. Each MZI has one optical time delayer and one optical phase shifter. The main function of the OFFT is to perform serial-to-parallel conversions. For 4 orders OFFT, as shown in Fig.1, the three MZIs are required. The time delay and phase shift of first MZI are adjusted to $T_s/2$ and 0 rad; respectively. The time delay of two other subsequent parallel MZIs is set to $T_s/4$, while the phase shift of upper one is set at 0 rad and phase shift of lower one is $\pi/2$ rad. In case of mQAM OFDM signal, four demultiplexers are employed to split the subcarriers. The resulting signals are sampled by electro-absorption modulators (EAMs). Afterwards, the output of EAM is fed to an optical band pass filter. Then, mQAM demodulators detect the resulted signal and extract the received data.

In all-optical OFDM, the gating is required after the OFFT. By using the RZ pulse, the time slot for optimum gating becomes shorter, making the gating more difficult. To cope with this problem, we have employed four DIs at receiver to convert the received signal into mQAM as shown in Fig. 2. The delay time between the arms of the DI is set at $T_s/2$ so that each symbol can interfere with its delayed replica. This allows the RZ signal to be converted to mQAM signal at the constructive port. To explain the operation of the DI, we assume that the transmitted signal is directly launched to the receiver (back-to-back). Then the optical field of single subcarrier at the constructive port can be described by the following equation;

$$u_r = \frac{\sqrt{P}}{4} \left[1 - \cos\left(\frac{2\pi t}{T_s}\right) \right] + \frac{\sqrt{P}}{4} \left[1 - \cos\left(\frac{2\pi(t - T_s/2)}{T_s}\right) \right] = \frac{\sqrt{P}}{2} \quad (6)$$

From the equation, it is shown that this conversion keeps the time slot for optimum gating at normal frequency since the mQAM signals is recovered before sampling process.

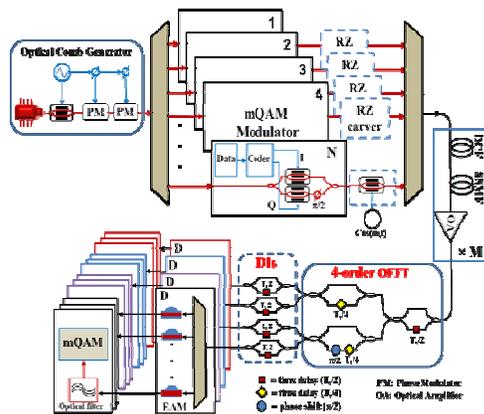


Fig. 2: The setup of proposed system.

4. Results and Discussion

In this section, we examine the effect of employing RZ-4QAM and RZ-16QAM on the transmission performance of all-optical OFDM systems. The system setup in Fig. 2 is numerically simulated by step-split Fourier method using VPITransmissionMaker 9.0. Each subcarrier is modulated at the symbol rate of 25 G Symbol/s. In order to see the phase noise mitigation, EVM due to the impairments of fiber nonlinearity versus the subcarrier power and transmission distance are obtained. Furthermore, bit error rate (BER) is plotted against transmission distance and OSNR for exploring the performance of the system.

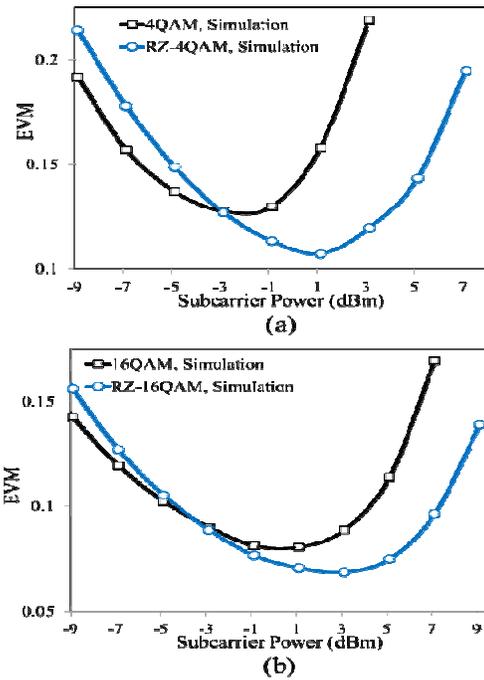


Fig. 3: Effect of combination RZ with mQAM in all optical OFDM systems on the Error Vector Magnitude (EVM), a) RZ-4QAM and 4QAM b) RZ-16QAM and 16QAM

In order to show the effect of combining RZ with 4QAM and 16QAM in all optical OFDM systems on the EVM, we first vary the subcarrier power and measure the EVM. The magnitude of EVM is mainly depends on the phase noise of SPM, XPM, and FWM. Fig. 3 (a) depicts EVM as a function of the subcarrier power for both RZ-4QAM and 4QAM all-optical OFDM. The fiber length and the subcarriers number are fixed at 550 km and 29, respectively. Generally, EVM for RZ-4QAM and 4QAM modulation formats is initially decreased with rising subcarrier power since the phase noise due to the interaction of ASE noise being dominant at low powers. However, when subcarrier power increases beyond 1 dBm and -3dBm for RZ-QAM and QAM, respectively, EVM is increased due to the interaction of XPM and FWM with ASE noise become dominant at higher powers. For

RZ-4QAM, the minimum EVM of 0.107 can be achieved while, for 4QAM signal, the minimum EVM of 0.127 can be obtained. Similarly, by comparing with 16QAM format, RZ-16QAM has less EVM. Referring to Fig. 3 (b), at fiber length of 165km, minimum EVMs are occurred at subcarrier powers of 3dBm and -1dBm for RZ-16QAM and 16QAM, respectively. This phenomenon due to the phase noise depends on subcarriers power and the interaction time among subcarriers. At a certain number of subcarriers and symbol rate, QAM signal has lower peak power than RZ-mQAM signal, but RZ-mQAM signal has shorter interaction time than QAM signal.

Fig. 4 (a) shows the EVM versus the transmission distance for 9 and 29 subcarriers. For each transmission distance, the corresponding subcarrier power that gives minimum EVM is adopted. Referring to Fig. 6 (a), RZ-4QAM modulation format is superior to the traditional 4QAM format along transmission distance for both subcarriers numbers. In addition, the proposed system performance is highly improved with 9 subcarriers where it is able to transmit the data over 3300km fiber length, representing a 62% increase compared to the 4QAM OFDM system.

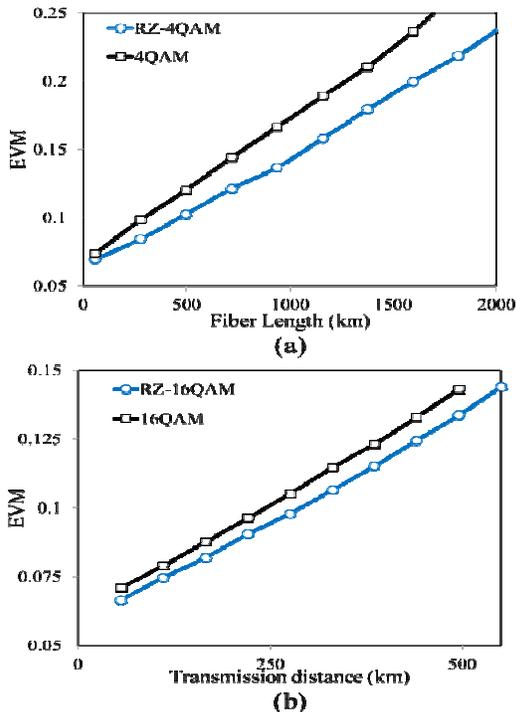


Fig. 4: EVM versus fiber length, a) RZ-4QAM versus 4QAM
b) RZ-16QAM versus 16QAM

Figs. 5 (a) and (b) show the constellation diagrams of the 4QAM and RZ-4QAM OFDM signals, respectively. The ideal constellation is plotted by red square. Both diagrams are simulated for the transmission distance of 550km and 29 subcarriers. It is shown that the RZ-4QAM

signals produces a clearer constellation diagram compared to that of the conventional 4QAM one. We observe the similar trend for 16QAM and RZ-16QAM as shown in Figs. 5(c) and (d), respectively for the same number of subcarriers and transmission distance of 150 km.

In optical OFDM transmissions, the phase noise is related to the subcarriers number since the interaction between subcarriers depends on their number such as XPM and FWM. For that reason, we numerically investigated and compared the proposed all-optical OFDM system performance at various subcarriers number. Fig. 6 depicts the relation between BER and the transmission distance for 9 and 29 subcarriers. For each transmission distance, the corresponding subcarrier power that gives minimum EVM is adopted. Referring to Fig. 6 (a), RZ-4QAM modulation format is superior to the traditional 4QAM format along transmission distance for both subcarriers numbers. In addition, the proposed system performance is highly improved with 9 subcarriers where it is able to transmit the data over 3300km fiber length, representing a 62% increase compared to the 4QAM OFDM system.

The higher-order modulation formats such 16QAM require more OSNR to overcome the phase noise. Accordingly, the transmission distances are substantially reduced when employing 16QAM or the RZ-16QAM format in all-optical OFDM signal as shown in Fig. 6 (b). As expected, at BER of 1×10^{-5} and 29 subcarriers, the transmission distance is increased from 55 km with 16QAM to 220 km with RZ-16QAM. Furthermore, with 9 subcarriers and at same BER, the transmission distance is expanded to 275 km, representing a 150% increase compared to the 16QAM OFDM system. However, both 16QAM and RZ-16QAM OFDM systems performances are limited by laser phase noise. Generally, in coherent communication systems, the laser phase noise plays significant role in the degradation of system performance [22]. Therefore, BER floor is apparent in the Fig. 6 (b).

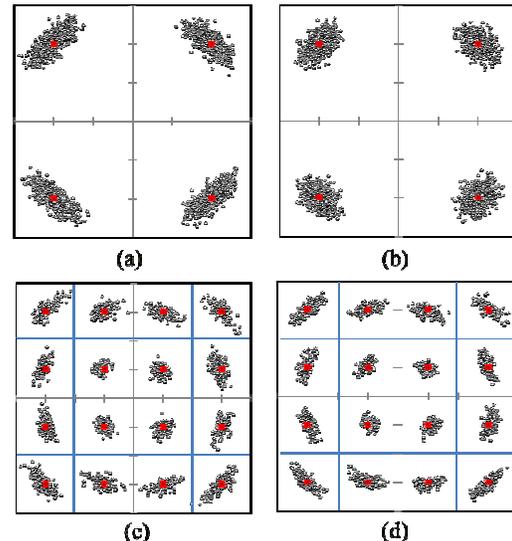


Fig. 5: The constellation diagrams of (a) 4QAM, (b) RZ-4QAM, (c) 16QAM, (d) RZ-16QAM.

Finally, the receiver sensitivity for both RZ-mQAM and mQAM are investigated and compared. Fig. 7 (a) illustrates BER versus OSNR, which indicates the receive sensitivity for both RZ-4QAM and 4QAM all-optical OFDM systems. The result is obtained at a symbol rate of 25 Gsymbol/s and transmission distance of 1500 km for both 9 and 29 subcarriers. It can be seen that RZ-4QAM all-optical OFDM system has a better BER performance. The required OSNR to obtain a BER= 1×10^{-5} is reduced by 1.9 dB for both 9 and 29 subcarriers. Referring to Fig. 7 (b), the performance of all-optical OFDM system is also improved by employing the RZ-16QAM format, as compared with 16QAM format. The required OSNRs to obtain a BER= 1×10^{-5} are reduced by 5.8dB for both number of subcarriers.

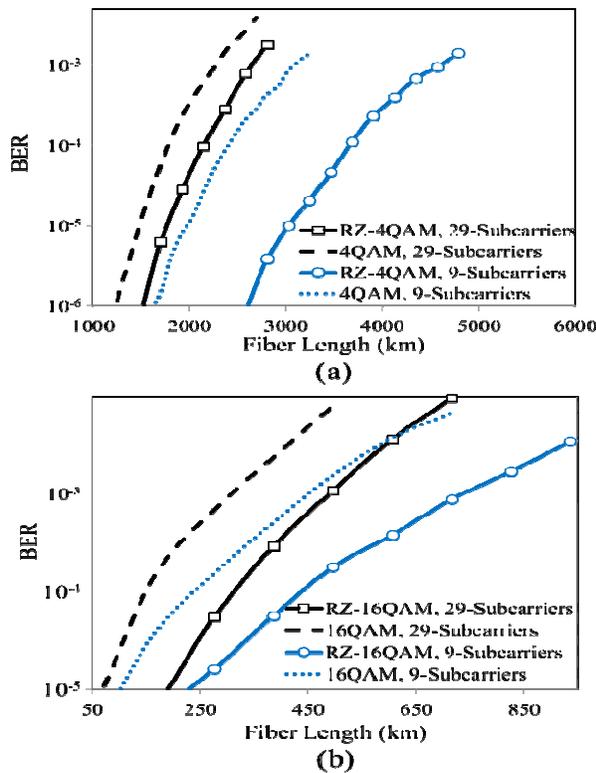


Fig. 6: Bit rate error versus transmission distance at symbol rate of 25GSymbol/s for a) 4QAM and RZ-4QAM, b) 16QAM and RZ-16QAM

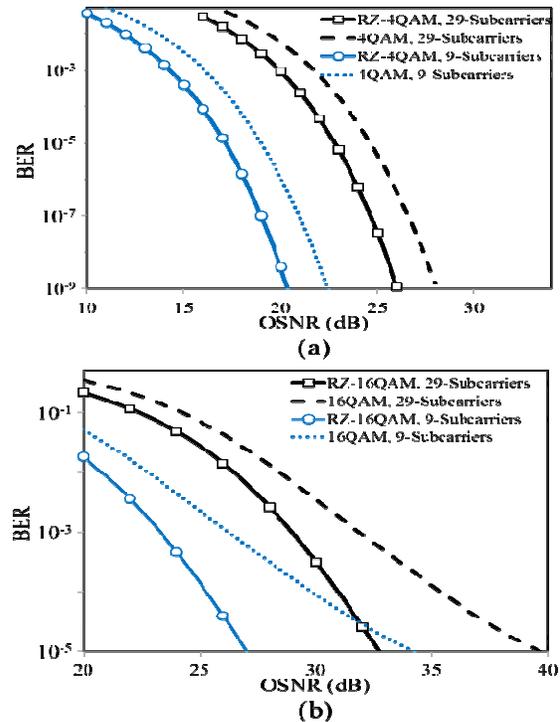


Fig. 7: Performance comparison of All-optical OFDM that employ: a) RZ-4QAM and 4QAM, b) RZ-16QAM and 16QAM.

5. Conclusion

A new and efficient RZ-4QAM and RZ-16QAM modulation formats are proposed for improving the performance of an all-optical OFDM system. The performances of the proposed systems are compared to that of a conventional all-optical OFDM using 4QAM and 16QAM. Our results show that the performance of the proposed system is significantly better than that of the conventional ones since the effects of fiber nonlinearities have been successfully mitigated. It is observed that the required power for getting minimum EVM increases when RZ-4QAM and RZ-16QAM formats are employed. Furthermore, the required OSNRs to achieve a BER of 10^{-5} are reduced by about 1.9 dB and 5.8dB when RZ-4QAM and RZ-16QAM are adopted in all optical OFDM systems, as compared to that of the conventional OFDM systems with 4QAM and 16QAM.

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