

# Spiral QAM Modulated CO-OFDM System with Increased Tolerance toward Laser Phase Noise

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**Abstract**—To mitigate the phase noise, we propose Spiral QAM in CO-OFDM. Simulation results, based on 40-GS/s CO-OFDM systems, show that 16 Spiral QAM can increase the phase noise tolerance, as compared to square 16 QAM.

**Keywords**—Coherent optical orthogonal frequency-division Multiplexing (CO-OFDM), phase noise, 16 Spiral QAM.

## I. INTRODUCTION

Coherent optical orthogonal frequency-division multiplexing (CO-OFDM) is a promising modulation scheme for high speed optical communications [1]. CO-OFDM brings to optical communication, which is the combination of two powerful techniques, coherent optical detection and OFDM technique [2]. It has been recently proposed to combat fiber chromatic dispersion and polarization-mode dispersion (PMD) [3, 4]. To make use of the available spectrum in optical fibers efficiently, square 16 QAM constellations making a good compromise between spectral efficiency and reach is adopted widely [5]. However, OFDM is prone to phase noise, which will cause both common phase error (CPE) and inter-carrier interference (ICI) [6]. Moreover, square 16 QAM constellations is optimum only for additive white Gaussian noise (AWGN) channels. Phase noise originating from lasers cannot be neglected in optical long-haul links [7]. To realize phase noise suppression, several methods have been proposed, in which CPE is identified and ICI is approximated as an additive Gaussian noise [8, 9]. However, only suppressing CPE is not sufficient for relatively larger laser line width. Moreover, the cost of the CO-OFDM system will be increased as the laser line width become narrower. Estimation and compensation of both CPE and partial ICI in CO-OFDM system were proposed [10, 11]. These schemes use iterative algorithms for joint estimate the data and the phase noise vector. The common drawback of iterative algorithms is that they suffer from large latency and high implementation complexity, which is unsuitable for future real-time CO-OFDM systems. Although those methods can improve the performance of the CO-OFDM system with the influence on the phase noise, there is no consideration about

adopting a new 4 bit/symbol constellations to restrain the phase noise in CO-OFDM.

The Spiral QAM was initially proposed in wireless single carrier communication systems [12]. However, the analysis, focused on phase noise of Gaussian distribution, is not enough for CO-OFDM system with laser noise modeled as Wiener process [13]. In this letter, 16 Spiral QAM modulation format that considers both AWGN and phase noise is introduced into CO-OFDM system for the first time. A detailed comparison between 16 Spiral QAM and square 16 QAM is presented. By means of theory and numerical simulation, it is shown that 16 Spiral QAM for the CO-OFDM system can improve the tolerance to the phase noise effectively. Moreover, the power efficiency and other features of 16 Spiral QAM is close to conversational square 16 QAM.

## II. SPIRAL QAM MODULATED CO-OFDM SYSTEM

### A. Setup of CO-OFDM Systems

Fig. 1 shows the block diagram of 40GS/s coherent optical OFDM system. The OFDM signal is composed by 256 subcarriers from which 192 subcarriers carry data information, 8 are pilot subcarriers used for the maximum-likelihood (ML) phase estimation [9] and 56 subcarriers are guard subcarriers. The length of cyclic prefix for every OFDM symbol is 32. There are 2 training sequence in front of OFDM signal. The first one is used for the frame synchronization [14], and the other is inserted for channel estimation. Because energy loss will increase with longer cyclic prefix and the dispersion impulse response is of finite duration, the finite impulse response (FIR) filter can be used for dispersion compensation [15]. The transmission of signal is composed by 2 training sequence and 48 OFDM signals. The sampling rate of DAC is 40GS/s. In the optical link, the launch power of lasers is assumed to be 0dBm. Then a recirculating loop is considered for transmission purposes. The loop has an 80km standard single mode fiber (SSMF) with a dispersion parameter of 16ps/nm/km and a gain controlled EDFA. The variable OSNR block(in a reference optical bandwidth of 0.1 nm) consist of a variable optical attenuator following the EDFA with 4dB of noise figure, which was used to control the signal power entering the optic-electronic receiver frontend[16]. At the receiver, the coherent detector consists of a local oscillator (LO), a 90°

hybrid, and two balanced detectors. Then the last electrical signal processed by MATLAB.

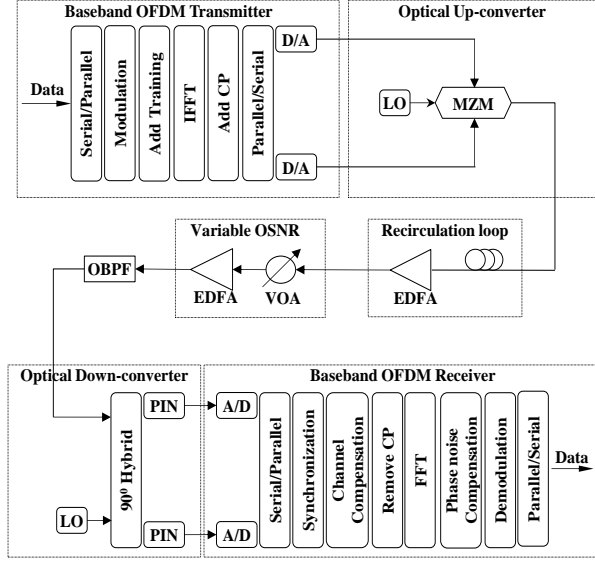


Figure 1. Block diagram of the CO-OFDM system setup.

### B. 16 Spiral QAM

In 16 QAM modulations, one symbol represents four bits. We can map the binary sequence as the corresponding 16 QAM constellation as long as the mapping rule is known. Based on [12], the constellation of 16 Spiral QAM can be obtained. Usually, gray mapping is used in combination with the conventional 16 QAM [17], which the first two bits are used for the generation of in-phase component (I) and the last two are used for the generation of quadrature component (Q), the generated symbol is  $I + jQ$ . However, gray mapping is unavailable for the unique constellation structure of Spiral QAM. The appropriate symbol mapping rule for 16 Spiral QAM is shown in Fig.2. In order to understand the advantage of Spiral QAM, we concentrate on analyzing the structural features of 16 Spiral QAM.

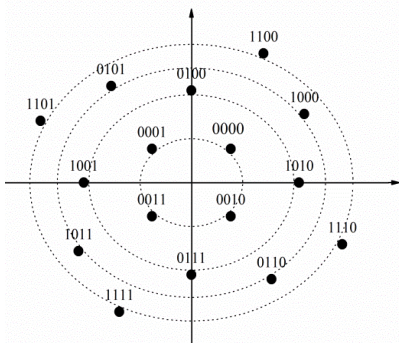


Figure 2. Symbol mapping for 16 Spiral QAM.

In the outskirts of the IQ-plane, the next symbol locations of Spiral QAM are determined by not only the minimum

angular distance but also the minimum Euclidean distance between adjacent symbols. In order to resist the phase noise, 16 Spiral QAM sets a larger minimum angular distance than square 16 QAM. The performance of the constellations is evaluated by the method using the constellation points [18]. Assuming that the average power of Gaussian noise is  $2N_0$  and all the signals in the set share the equal probability of transmitting. The theoretical average symbol error rate based on constellation in the presence of phase noise can be expressed as [18]

$$\left\{ \begin{aligned} Pe &\approx \frac{1}{N} \sum_T \sum_{R \neq T} \frac{1}{A\sqrt{2\pi}} e^{-\frac{A^2}{2}} \\ A &= \frac{(S_R - S_T) \left[ S_R + S_T (1 - 2e^{j\varphi}) \right]}{2\sqrt{N_0} \|S_R - S_T\|} \end{aligned} \right. \quad (1)$$

Where  $S_R$  and  $S_T$  are the transmitted and the received signal, respectively.  $R$  and  $T$  represent the constellation of the corresponding transmitted and the received signal, respectively.  $N$  is the total number of the constellation points.  $A$  is a variable to simplify the expression. " $\bullet$ " represents dot product. " $\|$ " represents the amplitude of a complex number.  $\varphi$  is the phase noise.

And in order to calculate SNR, we need normalized the average power of the constellation. The new constellation points  $C_n$  is given by

$$C_n = \frac{S_n}{\sqrt{\frac{\sum_{k=1}^N \|S_k\|^2}{N}}} \quad k = 1, 2, 3, \dots, N \quad (2)$$

Here  $S_n$  are the original constellation points.

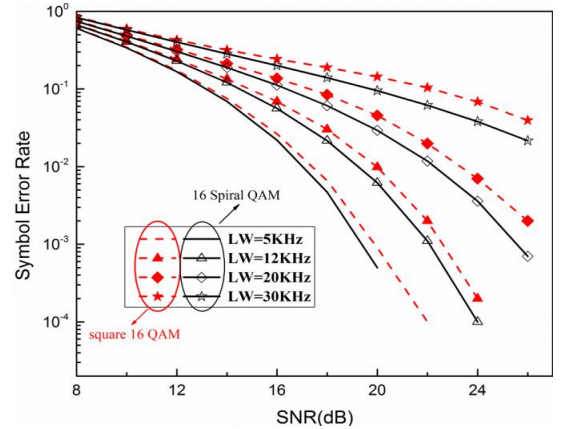


Figure 3. SER curves of 16 Spiral QAM and the conventional 16 QAM for various values of phase error modeled as Wiener process in theory.

We can get the relationship between symbol error rate and SNR in the presence of phase noise through (1), which is shown in Fig. 3. Furthermore, from theoretical results depicted in Fig. 3, we notice that 16 Spiral QAM achieve a

performance similar to square 16 QAM as the SNR increased. To achieve  $SER=10^{-3}$ , square 16 QAM requires a 0.6 dB higher SNR when line width is 12 kHz. And the superiority of 16 Spiral QAM will be more obvious while the line width become larger. The detail analysis will be drawn in the next Section.

### III. SIMULATION RESULTS AND ANALYSIS

We first consider a back-to-back system with a laser of various line widths, which two different modulated signals are used in the transmitter. We assume that the line width of transmitter and LO lasers are the same.

The performance of Symbol Error Rate (SER) against the OSNR of received square 16 QAM and 16 Spiral QAM modulated OFDM signal is simulated for laser line width of 5 kHz, 12 kHz, 20 kHz and 30 kHz, respectively, as shown in Fig. 4.

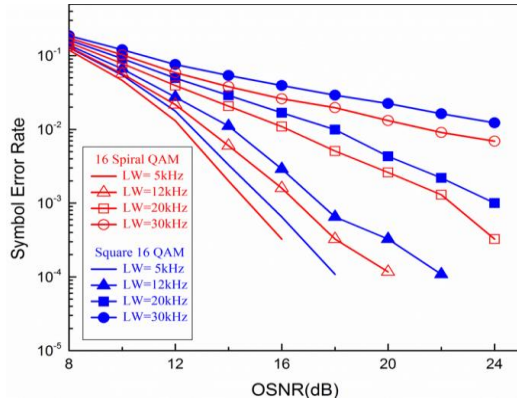


Figure 4. SER versus OSNR for various line widths in back-to-back case.

As in term of line width, the results are the same with the theoretical results as shown in Fig. 3. Because of the same Euclidean distance between each constellation point, two different QAM modulations show comparable performance with the narrow line width. As the line width became larger, the performance of the square 16 QAM degrades more considerably than 16 Spiral QAM. To achieve  $SER=10^{-3}$  with 12 kHz line width, the required OSNR value for 16 Spiral QAM modulated OFDM is about 16.7dB, and for square 16 QAM modulated OFDM is 17.5dB. When the line width is 20 kHz, the required OSNR for a SER of  $10^{-3}$  is 22.3dB and 24dB for 16 Spiral QAM and square 16 QAM, respectively. Therefore, the OSNR improvement is increased to 1.7dB. To achieve  $SER=10^{-2}$ , square 16 QAM requires about a 2dB higher OSNR than 16 Spiral QAM when the line width increased to 30 kHz. This is due to the fact that 16 Spiral QAM possesses 4 amplitude rings, each carrying 4 points with an  $90^\circ$  angular distance between two adjacent points in the same radius, while square 16 QAM is made up of 3 amplitude rings and the minimum angular distance is  $37^\circ$  in the middle ring. The angular distance determines the performance of the constellation against the phase noise.

Then the phase noise tolerance was considered in case of back-to-back and after 800 km transmission. The maximum-

likelihood (ML) phase estimation [9] is used to mitigate partial phase noise with the laser line width larger than 200 kHz. Considering the advantage on phase noise, no matter which case 16 Spiral QAM will perform better. As depicted in the Fig. 5, the proposed 16 QAM clearly outperforms square 16 QAM over the whole studied laser phase noise line width region from 200 to 2000 kHz with a fixed OSNR of 22dB. Because ML phase estimation works effectively to the laser with a line width less than 1 MHz [9], the performance of 16 Spiral QAM is near to square 16 QAM with line width less than 1MHz. Furthermore, 16 Spiral QAM is still useful to residual phase noise after ML phase estimation with larger laser line width.

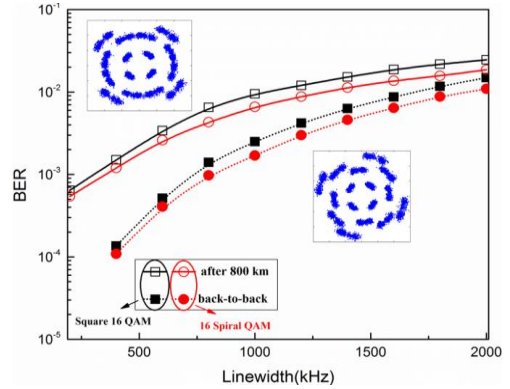


Figure 5. Simulated BER as a function of line width with fixed received OSNR of 22 dB in case of back-to-back and after 800km transmission.

As the ASE noise decrease OSNR of the system, the tolerance towards line width becomes lower after 800 km transmission, comparing the back-to-back case. However, 16 Spiral QAM still improve noise tolerance of CO-OFDM than square 16 QAM after 800 km transmission, as well as in back-to-back case. For the CO-OFDM system of 800-km transmission, a benefit of about 100 kHz is possible for the maximum line width. The close Euclidean distance of two QAM modulation scheme guarantee that their performance against the additive noise is close. Moreover, 16 Spiral QAM make full use of the same power with square 16 QAM by the rational constellations arrangement. Obviously, 16 Spiral QAM exceeds square 16 QAM in the presence of phase noise without degrading the performance towards ASE noise tolerance, namely the advantage on phase noise of 16 Spiral QAM is very stable compared to square 16 QAM.

### IV. SUMMARY

In this paper, we have proposed 16 Spiral QAM encoded coherent optical OFDM for the first time. Although the laser phase noise is a stochastic Wiener processes unlike the Gaussian noise, the constellation of 16 Spiral QAM is still optimized. Due to the angular distance between two adjacent points of 16 Spiral QAM is larger than Square 16 QAM, and the performance of two different QAM is discussed theoretically, the phase noise tolerance of 16 Spiral QAM with CO-OFDM is enhanced. After mixed in ASE noise through the fiber transmission, the advantage on

phase noise of 16 Spiral QAM is similar to back-to-back case. In addition, some methods such as the minimum distance detection, dispersion compensation and maximum-likelihood phase estimation can be used for 16 Spiral QAM like the conventional 16 QAM.

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