MDPSK based Non-Equalization OFDM for Coherent Free-Space Optical Communication

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***Abstract*—In this letter, we apply a non-equalization orthogonal frequency-division multiplexing (NE-OFDM) technique in optical turbulence channel for coherent free-space optical (FSO) systems, utilizing multilevel differential phase-shift-keying (MDPSK). We adopt the modified Rician distribution as the optical turbulence channel for coherent FSO systems, where both amplitude fading and phase distortion are taken into consideration. The differential encoding process of MDPSK based NE-OFDM can be performed either in the frequency domain (FD) or in the time domain (TD). Our simulation results show that NE-OFDM using FD-MDPSK achieves nearly the same bit-error-rate (BER) performance as that using TD-MDPSK, but with a relatively lower hardware complexity and a higher spectral efficiency. It is also revealed that FD-MDPSK based NE-OFDM attains a comparable BER performance to the conventional OFDM with pilot tones or training sequences assisted channel estimation and equalization. Hence, FD-MDPSK based NE-OFDM is promising for coherent FSO communication.**

***Index Terms*—Non-equalization orthogonal frequency-division multiplexing (NE-OFDM), multilevel differential phase shift keying (MDPSK), free-space optics (FSO), coherent detection.**

I. INTRODUCTION

ORTHOGONAL frequency division multiplexing (OFDM) is a promising technology that has been widely studied in optical fiber communication [1]. OFDM has also been used in free-space optical (FSO) communication, thanks to its inherent advantages: 1) high spectral and power efficiency [2]-[4], 2) low cost and efficient implementation [2], 3) strong immunity to burst errors caused by the atmospheric turbulence [4], and 4) high tolerance against deep fading in the turbulent channel [5]. Although OFDM has its disadvantages such as sensitivity to phase noise and high peak-to-average power ratio (PAPR), we can fully exploit its advantages and minimize its disadvantages for FSO channels with a careful design [3]. Coherent detection is another interesting technique for FSO channels since it can greatly increase receiver sensitivity [6]. Therefore, OFDM with coherent detection reveals significant potential for future FSO communication. In a coherent FSO system, optical OFDM signal propagates over the turbulence channel, where signal amplitude fluctuates due to the scintillation effect while signal phase changes due to the aberration effect and laser phase noise [7]. So far, several statistical models have been developed for the atmospheric turbulence channel, such as log-normal and Gamma-Gamma distributions. However, these models can only describe the amplitude fluctuation [7]. The modified Rician distribution proposed by Belmonte and Kahn, which describes the turbulence channel with both log-normal scintillation and Gaussian aberration [8], can be adopted as the channel model for FSO systems with coherent detection.

In OFDM based coherent FSO systems where multilevel phase shift keying (MPSK) or multilevel quadrature amplitude modulation (MQAM) are used, additional pilot tones or training sequences must be utilized for channel estimation and equalization, so as to compensate the amplitude and phase variations caused by the turbulence channel and the laser phase noise. As a result, the system complexity is increased while the spectral efficiency is reduced. In contrast, owing to its strong tolerance to amplitude fading and phase distortion, multilevel differential PSK (MDPSK) is very promising for OFDM based coherent FSO systems, which can minimize the disadvantage of OFDM (sensitive to phase noise) and also guarantee a good system performance without performing equalization. MDPSK based OFDM has been studied in electrical Rayleigh channels where only amplitude fading was considered [9]. However, to the best of our knowledge, it has not yet been introduced in the optical turbulence channel for coherent FSO communication.

In this letter, for the first time, we apply MDPSK based non-equalization OFDM (NE-OFDM) in the optical turbulence channel and evaluate its performance over the modified Rician distribution for coherent FSO communication. Both amplitude fading from scintillation and phase distortion from aberration and laser phase noise are taken into consideration in this work. Due to the frequency non-selective and time slow-varying (on the order of millisecond [6]) nature of the turbulence channel, MDPSK based NE-OFDM can be differentially encoded either in the frequency domain (FD) or in the time domain (TD). We investigate the hardware complexity and spectral efficiency of FD-MDPSK and TD-MDPSK based NE-OFDM and then evaluate their bit-error-rate (BER) performances. We further compare the overall performance of FD-MDPSK based NE-OFDM and MPSK/MQAM based equalized OFDM to verify the feasibility and advantages of applying MDPSK based NE-OFDM in future coherent FSO communication systems.

II. SYSTEM MODEL

The schematic of coherent FSO system using MDPSK based

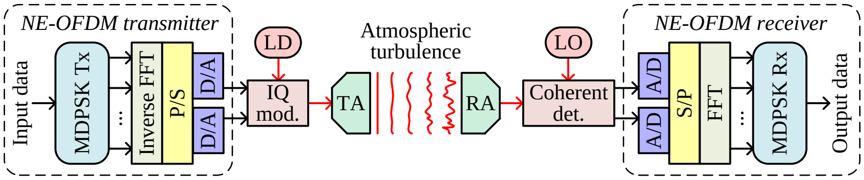

Fig. 1. Schematic of a coherent FSO system using MDPSK based NE-OFDM (FFT: fast Fourier transform, LD: laser diode, TA: transmit aperture, RA: receive aperture, LO: local oscillator, mod.: modulation, det.: detection, Tx: transmitter, Rx: receiver).

NE-OFDM is shown in Fig. 1. The system mainly consists of three parts: 1) a CO-OFDM transmitter, 2) the atmospheric turbulence channel, and 3) a CO-OFDM receiver.

A. *CO-OFDM transmitter*

As shown in Fig. 1, the electrical OFDM signal is generated in the NE-OFDM transmitter. The input serial data are firstly mapped into complex coefficients in the MDPSK Tx. After performing inverse fast Fourier transform (IFFT), the obtained parallel and discrete signal is converted into a serial and analog signal by parallel-to-serial conversion and digital-to-analog conversion. The generated electrical OFDM signal with N subcarriers in the k^{th} symbol period can be expressed as

$$s_k(t) = \sum_{n=1}^{N} x_{k,n} \exp\left(j\frac{2\pi nt}{T}\right) \tag{1}$$

where $x_{k,n}$ donates the complex coefficient on the n^{th} subcarrier in the k^{th} symbol. n and k are frequency (subcarrier) index and time (symbol) index, respectively. The complex coefficient $x_{k,n}$ is generated in the MDPSK Tx. The differential encoding process of MDPSK based NE-OFDM can be performed either in the FD or in the TD, which will be discussed in Section III. Then the electrical OFDM signal is modulated onto the optical carrier in an optical I/Q modulator. After that, the obtained optical OFDM signal is launched into the turbulence channel through a transmit aperture (TA).

B. *Atmospheric turbulence channel*

Here, we adopt the modified Rician distribution to model the turbulence channel for coherent FSO system [8]. In this model, both amplitude fading and phase distortion caused by the atmospheric turbulence are considered. The effective fading coefficient can be defined as $\alpha = \alpha_r + j\alpha_i$ where α_r and α_i are the real and imaginary parts, respectively. It is shown in [8] that both α_r and α_i follow Gaussian distribution and their corresponding means and variances are given by

$$\overline{\alpha}_r = \exp[-(\sigma_\chi^2 + \sigma_\varphi^2)/2] \tag{2a}$$

$$\overline{\alpha}_i = 0 \tag{2b}$$

$$\sigma_r^2 = [1 + \exp(-2\sigma_\varphi^2) - 2\exp(-\sigma_\chi^2 - \sigma_\varphi^2)]/(2N) \tag{2c}$$

$$\sigma_i^2 = [1 - \exp(-2\sigma_\varphi^2)]/(2N). \tag{2d}$$

In (2a-2d), σ_χ^2 and σ_φ^2 represent the variances of amplitude fluctuation and phase variation, respectively. N is the number of statistically independent cells in the receiver aperture which is given by $N = \{1.09(r_0/D)^2\,\Gamma[6/5, 1.08(D/r_0)^{5/3}]\}^{-1}$ where D is the aperture diameter, r_0 is the wavefront coherence diameter and $\Gamma(\cdot,\cdot)$ is the lower incomplete Gamma function. The log-normal amplitude variance σ_χ^2 is often described as a scintillation index (SI) $\sigma_\beta^2 = \exp(4\sigma_\chi^2) - 1$. Considering active modal compensation of phase distortion, the Gaussian phase variance after modal compensation can be expressed as $\sigma_\varphi^2 = C_J (D/r_0)^{5/3}$, where C_J is determined by the number (J) of Zernike terms which are corrected by the active modal compensation. Therefore, the intensity fading I induced by optical atmospheric turbulence can be statistically described as [8]

$$f(I) = \frac{1+K}{\overline{I}} \exp\left[-\frac{K\overline{I} + (1+K)I}{\overline{I}}\right] I_0\left[2\sqrt{\frac{(1+K)KI}{\overline{I}}}\right] \tag{3}$$

where $I_0(\cdot)$ is the first-kind modified Bessel function of order zero, $\overline{I}$ is the mean of the intensity fading and K is reciprocal of the contrast parameter. $\overline{I}$ and K can be computed by

$$\overline{I} = \overline{\alpha}_r^2 + \sigma_r^2 + \sigma_i^2 \tag{4}$$

$$\frac{1}{K} = \frac{\overline{\alpha}_r^2 + \sigma_r^2 + \sigma_i^2}{[\overline{\alpha}_r^4 + 2\overline{\alpha}_r^2(\sigma_i^2 - \sigma_r^2) - (\sigma_i^2 - \sigma_r^2)^2]^{1/2}} - 1. \tag{5}$$

C. *CO-OFDM receiver*

After propagating through atmospheric turbulence channel, optical OFDM signal is captured by a receive aperture (RA). In the coherent detector, the received optical OFDM signal is mixed with the local oscillator (LO) laser and converted to the electrical OFDM signal which is then demodulated in the NE-OFDM receiver. Heterodyne detection is used in the coherent detector and thus the total photocurrent is

$$i(t) = i_{\text{DC}} + i_{\text{AC}}(t) + n(t) \tag{6}$$

where i_{DC}, $i_{\text{AC}}(t)$ and $n(t)$ represent the DC term, the AC term and the zero-mean additive white Gaussian noise (AWGN), respectively. The DC term can be neglected since it will be eliminated in the FFT and the AC term can be obtained as

$$i_{\text{AC}}(t) = 2R\sqrt{I\,P_0(t)P_{\text{LO}}}\exp\{[\omega_{\text{IF}}t + \Phi + \varphi(t) + \psi(t)]\} \tag{7}$$

where R is the responsibility of the photo detector and I is the intensity fading coefficient which follows the modified Rician distribution as in (3). $P_0(t)$ is the received optical power without atmospheric turbulence and P_{LO} is the optical power of LO laser. $\omega_{\text{IF}} = \omega_0 - \omega_{\text{LO}}$ is the intermediate frequency with ω_0 and ω_{LO} being the angular frequencies of the optical carrier and the LO

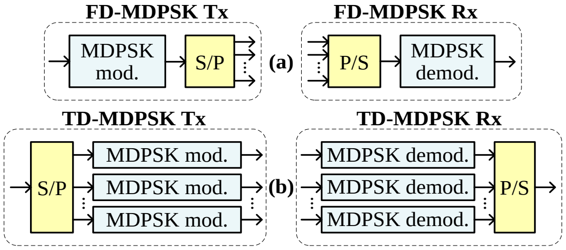

Fig. 2. Block diagrams of MDPSK transmitters and receivers in (a) frequency domain and (b) time domain.

laser, respectively. The desired phase information is Φ and the phase variation induced by aberration in the turbulence channel is $\varphi(t)$ with the variance of $\sigma_\varphi{}^2$. $\psi(t)$ represents the phase fluctuation caused by laser phase noise from both transmitter laser and LO laser. Laser phase noise can be generally modeled as a zero-mean Gaussian process with a variance $\sigma_\psi{}^2 = 2\pi\beta t$, where β represents the combined linewidth of transmitter and receiver lasers [10].

III. PRINCIPLE OF MDPSK BASED NE-OFDM

Fig. 2 shows the block diagrams of two different types of MDPSK transmitters and receivers. For FD-MDPSK, as shown in Fig. 2(a), serial input binary bits are sequentially encoded in the MDPSK modulator. After the serial-to-parallel conversion, N consecutive MDPSK data are in parallel, which are the inputs of the N-point IFFT. Therefore, all the data are differentially encoded in the FD and only a single MDPSK modulator is required at the transmitter. In the receiver, a parallel-to-serial converter is used to convert the received parallel data into serial and then a single MDPSK demodulator is used to recover the transmitted data. For the case of TD-MDPSK, as shown in Fig. 2(b), serial input binary bits pass through a serial-to-parallel converter and then N MDPSK modulators are utilized to differentially encode the parallel input data in the TD. Since each subcarrier is assigned with a MDPSK modulator, N parallel modulators are used in the transmitter. The receiver also needs N MDPSK demodulators to simultaneously decode the data. Compared with TD-MDPSK which needs N pairs of modulators/demodulators in the transceiver, FD-MDPSK only requires one pair of modulator/demodulator operating at a faster speed. Thus, the hardware complexity of FD-MDPSK is expected to be lower than that of TD-MDPSK [9].

Since the coherence time of the turbulence channel is on the order of millisecond, we can assume that one OFDM block consists of K symbols each has the same amplitude fading and the same phase rotation, when the block period is smaller than the coherence time [6]-[8]. The block design of FD-MDPSK based NE-OFDM is illustrated in Fig. 3(a). The first data (x_1) in the OFDM block serves as a phase reference, so x_1 does not carry any practical information. The FD-MDPSK data on the n^{th} subcarrier in the k^{th} symbol is determined not only by the current input data but also by the data on the n-1$^{\text{th}}$ subcarrier in the same symbol. Therefore, FD-MDPSK data on the n^{th} subcarrier in the k^{th} symbol can be expressed as

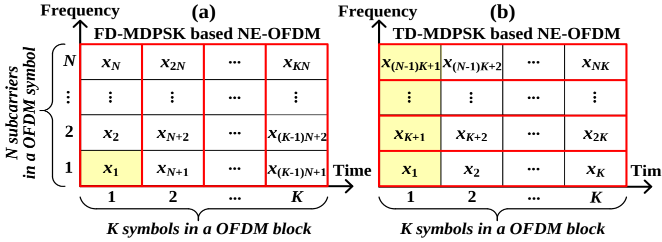

Fig. 3. Block design of MDPSK based NE-OFDM in (a) frequency domain and (b) time domain.

$$x^{\mathrm{FD}}_{(k-1)\times N+n} = x_{(k-1)\times N+n-1}\exp[\,j\theta_{(k-1)\times N+n}] \tag{8}$$

where $k=1, 2, \cdots, K$ and $n=2, \cdots, N$. $x_{(k-1)\times N+n-1}$ is the data on the n-1$^{\text{th}}$ subcarrier in the same k^{th} symbol and $\theta_{(k-1)\times N+n}$ is the phase change determined by the current serial input data $d_{(k-1)\times N+n}$. $d_{(k-1)\times N+n}$ is generated from $\log_2 M$ consecutive input serial bits with Gray coding. The first data in the k^{th} symbol, i.e., $x_{(k-1)\times N+1}$, except x_1, is determined by the current input data $d_{(k-1)\times N+1}$ and $x_{(k-1)\times N}$ which is the data on the N^{th} subcarrier of the k-1$^{\text{th}}$ symbol. Fig. 3(b) shows the block design of TD-MDPSK based NE-OFDM, where N data (x_1, $x_{K+1}, \cdots$, $x_{(N-1)K+1}$) in the first symbol in the OFDM block are used as phase references. The TD-MDPSK data on the n^{th} subcarrier in the k^{th} symbol is determined both by the current serial input data and the data in the k-1$^{\text{th}}$ symbol on the same subcarrier. Thus, the TD-MDPSK data on the n^{th} subcarrier in the k^{th} symbol can be described as

$$x^{\mathrm{TD}}_{(n-1)\times K+k} = x_{(n-1)\times K+k-1}\exp[\,j\Theta_{(n-1)\times K+k}] \tag{9}$$

where $k=2, \cdots, K$ and $n=1, 2, \cdots, N$. $x_{(n-1)\times K+k-1}$ is the data on the n^{th} subcarrier in the k-1$^{\text{th}}$ symbol and $\Theta_{(n-1)\times K+k}$ is the current phase change determined by the parallel input data $d_{(n-1)\times K+k}$, which is obtained by parallelizing the serial Gray encoded input data. It can be seen from Fig. 3 that TD-MDPSK based NE-OFDM uses much more reference data than FD-MDPSK based NE-OFDM, especially when N is relatively large. Hence, NE-OFDM using FD-MDPSK has a relatively higher spectral efficiency than that using TD-MDPSK.

IV. PERFORMANCE OF COHERENT FSO SYSTEM USING MDPSK BASED NE-OFDM

In this section, we evaluate the performance of coherent FSO system employing MDPSK based NE-OFDM by Monte Carlo simulation. In the simulation, we consider a 10 Gbaud/s OFDM

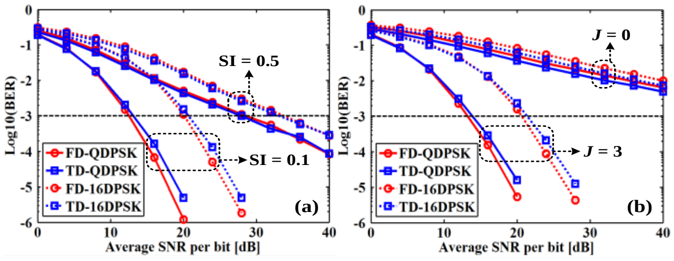

Fig. 4. BER performance of NE-OFDM using FD-MDPSK and TD-MDPSK: (a) J=4 with different SI values and (b) SI=0.1 with different J values.

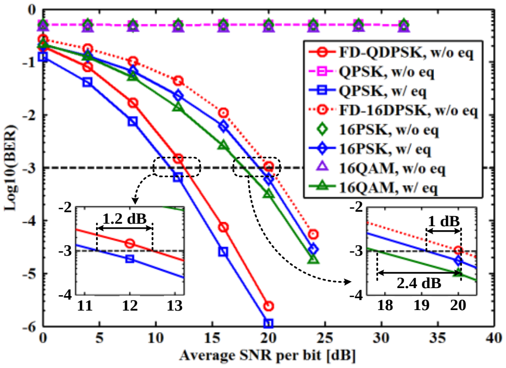

Fig. 5. BER performance comparison between FD-MDPSK based NE-OFDM and equalized OFDM using MPSK and MQAM for SI=0.1 and *J*=6 (w/: with; w/o: without; eq: equalization).

signal with 256 subcarriers over the modified Rician channel. A BER of 10^{-3} is set as the benchmark since forward error correction (FEC) code can be used to correct transmission errors. Fig. 4(a) shows the BER performance of NE-OFDM using FD-MDPSK and TD-MDPSK for two different SI values (0.1 and 0.5) where the number of compensated modes is fixed at *J*=4. As shown in Fig. 4(a), higher average signal-to-noise ratios (SNRs) per bit are required for both FD-MDPSK and TD-MDPSK when SI increases from 0.1 to 0.5, as a higher SI indicates a stronger channel fading caused by scintillation. Fig. 4(b) gives the BER performance for the cases of *J*=0 (no phase compensation) and *J*=3 (three modes are compensated), when the SI is fixed at 0.1. Compared with the case of *J*=0, significant BER improvements are obtained when only three modes are compensated. For NE-OFDM using QDPSK and 16DPSK in TD, the average values of SNR per bit for attaining the BER benchmark are about 13 dB and 21 dB, respectively. The BER performance of NE-OFDM using QDPSK and 16DPSK in FD is almost the same as that in TD. It can be concluded from Figs. 4(a) and (b) that both FD-MDPSK based NE-OFDM and TD-MDPSK based NE-OFDM have comparable BER performance. Considering its lower complexity and higher spectral efficiency as discussed in Section III, FD-MDPSK based NE-OFDM is a better choice for coherent FSO systems.

We have also carried out the BER performance comparison between FD-MDPSK based NE-OFDM and equalized OFDM using MPSK and MQAM. The results are shown in Fig. 5, where SI is fixed at 0.1 and *J* is set at 6. In the simulation, for equalized OFDM, eight pilot subcarriers among the total 256 subcarriers are used for the channel estimation and equalization [10]. For the case of M=4, an SNR penalty of 1.2 dB is observed for FD-QDPSK based NE-OFDM, compared with equalized OFDM using QPSK. For the case of M=16, FD-16DPSK based NE-OFDM has SNR penalties of about 1 dB and 2.4 dB, respectively, compared with equalized OFDM using 16PSK and 16QAM. It also can be seen that MPSK or MQAM based OFDM can hardly work without equalization. Fig. 6 shows the corresponding constellation diagrams. Clearly, the constellation diagrams of QPSK or 16QAM based OFDM are severely destroyed by scintillation, aberration and laser phase noise. In contrast, the constellations of QDPSK based NE-OFDM show a great robustness to all these distortions.

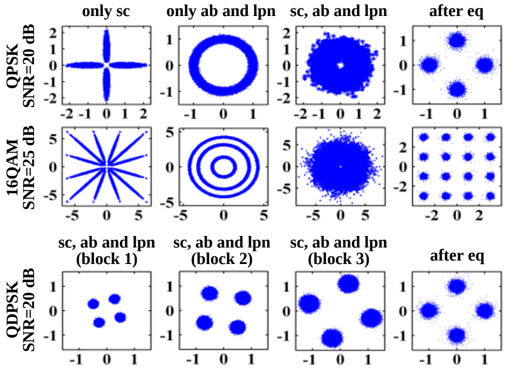

Fig. 6. Constellation diagrams of QPSK/16QAM based OFDM and QDPSK based NE-OFDM for SI=0.1 and *J*=6 (sc: scintillation; ab: aberration; lpn: laser phase noise).

V. CONCLUSION

We have evaluated the performance of coherent FSO system using MDPSK based NE-OFDM over the modified Rician channel, where both amplitude fading and phase distortion are considered. Simulation results have revealed that NE-OFDM using FD-MDPSK has a relatively lower hardware complexity and a higher spectral efficiency than that using TD-MDPSK, while achieving almost the same BER performance. It has been further verified that FD-MDPSK based NE-OFDM attains a comparable BER performance to the equalized OFDM using MPSK or MQAM, but has a strong robustness to phase noise and thus does not require any pilot tones or training sequences for equalization. In conclusion, FD-MDPSK based NE-OFDM is promising for future coherent FSO communication.

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