Analysis of Improved Performance for a Satellite-to-ground Coherent Optical Communication System with DQPSK Modulation due to Phase Estimation

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***Abstract*—The performance of a satellite-to-ground optical communication system with phase modulation is limited by phase fluctuations induced by atmospheric turbulence. To improve the system performance, one effective way is to use coherent detection. In this paper, a satellite-to-ground coherent optical communication system with differential quadrature phase-shift keying (DQPSK) modulation is studied, and a phase estimation algorithm based on M-th power scheme is used. The simulation results show that the phase noise induced by atmospheric turbulence can be suppressed greatly.**

Keywords- satellite-to-ground optical communication; coherent detection; DQPSK; atmospheric turbulence

I. INTRODUCTION

Compared with the traditional radio frequency wireless communication, free-space optical (FSO) or optical wireless communication has the advantages of super broad bandwidth, lesser terminal volume and weight, low cost and high flexibility, so it has become a significant development direction of satellite-to-ground communications [1,2]. However, when propagating through the air, the optical wave experiences fluctuations in amplitude and phase due to atmospheric turbulence [3], which greatly degrades the performance of satellite-to-ground laser communication system.

Optical coherent detection provides an effective way to counter the influences of atmospheric turbulence, since it needs less optical power to receive each bit and high receiver sensitivity can be achieved. Moreover optical coherent reception also enables the use of multi-level modulation formats, so the system can obtain higher spectral efficiency than traditional direct detection [4]. Multi-level phase modulation signal is more sensitive to the phase noise than intensity modulated signals. In the satellite-to-ground coherent optical communication system, the phase noise is mainly induced by atmospheric turbulence, linewidth of the laser, frequency and initial phase offset and additive noise in the coherent receiver. Especially, the atmospheric turbulence mainly causes random phase fluctuation on the modulated light wave front. So, it is the key for the system design to suppress phase noise and synchronize carrier phase.

With the availability of high-speed digital signal processing, digital phase estimation provides an alternative to recover the carrier phase. The commonly used digital phase estimation method is M-th power phase estimation developed by A. J. Viterbi and A. M. Viterbi in 1983 [5]. It is a feed forward method and has been proven effective in optical fiber communication systems [6]. However, to our best knowledge, this method has not been applied in coherent FSO systems. So, our paper focuses on the validation of the effectiveness of M-th power method in satellite-to-ground coherent optical communication systems with differential quadrature phase-shift keying (DQPSK) modulation.

The paper is organized as follows: in section II, the theoretical model of atmospheric channel is given. The homodyne optical IQ-receiver with the phase estimation algorithm based on M-th power scheme in introduced in section III and the system performance is investigated by simulation in section IV. Finally, some conclusions are drawn in section V.

II. TURBULENT ATMOSPHERE CHANNEL MODEL

A. Lightwave Propagation through the Turbulent Atmoshpere

The propagation of the modulated laser beam in the atmospheric channel is governed by a stochastic Helmholtz equation without consideration of depolarization effects [7]:

$$\partial_z u = \frac{i}{2k}(\partial_x^2 + \partial_y^2)u + ikn_1 u \tag{1}$$

where the complex quantity $u(\mathbf{r})$ is the slowly varying envelope of the scalar electromagnetic field; k is the wave number and $n_1(\mathrm{r}) = n(\mathrm{r}) - \overline{n(\mathrm{r})}$ is the local deviation of the refractive index from its ensemble average. This equation can be resolved using the split-step approach by splitting the propagation distance h into sub-distances $\Delta h = h_i - h_{i-1}$, $h_0=0$, $i=1, 2, \ldots$. For each sub-distance, a phase screen is independently generated to simulate the stochastic phase perturbations occurred in propagation through turbulence from the previous sub-distance. When the beam propagates across the screen, the phase fluctuation is

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induced. With this method, the resolution of Eq. (1) can be described as:

$$u(r,h) \approx \exp\left(\frac{\Delta h}{2}\frac{i}{2k}\left(\partial_x^{\,2}+\partial_y^{\,2}\right)\right)\exp\left(\int_{h-\Delta h}^{h} ikn_1(r,h)dh\right) \times\exp\left(\frac{\Delta h}{2}\frac{i}{2k}\left(\partial_x^{\,2}+\partial_y^{\,2}\right)\right)u(r,h-\Delta h) \tag{2}$$

where k is the wave number.

To increase the computational efficiency, we use FFT and inverse FFT in the right side, and convert it into discrete form, we will get:

$$u_l(m,n) = IFFT\left\{FFT\left[\exp\left(i\varphi_{l-1}(m,n)\right)u_{l-1}(m,n)\right]\exp\left(-i\frac{2\pi^2 f_{mn}^{\ 2}}{k}\Delta h\right)\right\} \tag{3}$$

where $\varphi_l(m,n)$ is the simulated random phase screen. It is sampled by M sampling points in the direction of x and y, respectively. So the size of each phase screen $G\times G$. f_{mn} is the spatial frequency, and $f_{mn}=\sqrt{f_m^{\ 2}+f_n^{\ 2}}$, $f_m=1/x_m$, $f_n=1/y_n$, $x_m=mG/M$, $y_n=nG/M$, m, n =-M/2…M/2-1.

B. *Generation of Phase Screens*

The random phase screen $\varphi(m,n)$ can be generated by filtering white Gaussian noise in the wave number domain by the square root of the atmospheric spectrum and then transforming to the spatial domain using the inverse fast Fourier transform [8]:

$$\varphi(m,n) = IFFT\left[h(m,n)\sqrt{F_\varphi(m,n)}\right] \tag{4}$$

Here, $F_\varphi(m,n)$ is the discrete power spectral density of phase over a propagation distance of Δh, and it is decided by the atmospheric spectrum chosen for the study. $h(m,n)$ is a discrete complex standard Gaussian noise process with zero mean and standard deviation of 1, and it is Hermitian, i.e.

$$h(m,n) = h^*(-m,-n) \tag{5}$$

Suppose that the turbulence is isotropic, the modified atmospheric spectrum defined by L.C. Andrews is used in this paper. The spectrum has the form as follows [9]:

$$F_\varphi(\kappa) = 0.490 r_0^{-5/3}\frac{1+1.802(\kappa/\kappa_l)-0.254(\kappa/\kappa_l)^{\frac{7}{6}}}{\exp(\kappa^2/\kappa_l^2)\cdot(\kappa^2+\kappa_0^{\ 2})^{11/6}} \tag{6}$$

where κ is the spatial wave number, $\kappa=2\pi f$, $\kappa_l=2\pi/l_0$, $\kappa_0=2\pi/L_0$. l_0 and L_0 are the inner and outer scale of the atmospheric turbulence, respectively. r_0 is the coherence length of the turbulence named by Fried parameter:

$$r_0 = 0.185\lambda^{5/6}\left[\int_{h}^{h+\Delta h} C_n^2(\xi)d\xi\right]^{-3/5} \tag{7}$$

where $C_n^2(h)$ is the structure constant that describes the strength of the turbulence at a certain altitude h. As the Hufnagel-Valley model described, $C_n^2(h)$ is given as the sum of exponential terms [10]:

$$C_n^2(h) = a_1\left(\frac{V}{27}\right)^2\frac{h}{s_1}\exp\left[-\frac{h}{s_1}\right]+a_2\exp\left[-\frac{h}{s_2}\right]+C_n^2(0)\exp\left[-\frac{h}{s_3}\right] \tag{8}$$

where a_1, a_2, s_1 and s_2 are the parameters which are chosen to simulate different atmospheric cases. h is the altitude (m), V is the rms wind speed (m/s) which controls high-altitude turbulence in the model, $C_n^2(0)$ is the turbulence strength at the ground level (m$^{-2/3}$).

Convert (6) to the discrete form, we will get:

$$F_\varphi(m,n) = 0.023\cdot r_0^{-5/3}\frac{1+3.431\cdot l_0 f_{mn}-0.538\cdot\left(l_0 f_{mn}\right)^{7/6}}{\exp\left(3.626\cdot l_0^{\,2} f_{mn}^{\ 2}\right)\left(f_{mn}^{\ 2}+\frac{1}{L_0^{\,2}}\right)^{11/6}} \tag{9}$$

By substituting (9) into (4), the phase screen can be calculated.

III. COCHERENT OPTICAL IQ-RECEIVER WITH PHASE ESTIMATION METHOD

In our considered satellite-to-ground coherent optical communication system, in the transmitter, the signal is DQPSK modulated, which maps two bits into one symbol. The symbol is Gray coded that only one bit changes when shifts to the adjacent symbol. And this modulation format is well-known in coherent optical fiber communication since it has a higher spectral efficiency and is more effective to combat phase ambiguity. The modulated signal is transmitted over the atmospheric channel. The structure of the coherent optical receiver is described as Fig.1

A. *Coherent Receiver*

The modulated signal is transmitted over the atmospheric channel. The modulated electrical field of the received lightwave can be described as:

$$E_s(r,t) = E_0(r)\exp(j\varphi_{\varepsilon,t}(r))\exp(j\omega_s t+\varphi(t)) \tag{10}$$

where $\omega_s=2\pi f_s$ is the optical frequency and $\varphi(t)$ the modulated phase with a value of ±π/4, ±3π/4. $E_0(r)$ is the envelope of the received signal field, and $\varphi_{\varepsilon,t}(r)$ is phase noise induced by atmospheric turbulence. Here, the optical attenuation and scatter in atmospheric channel that mainly affect the signal amplitude are not considered since the phase modulation is adopted.

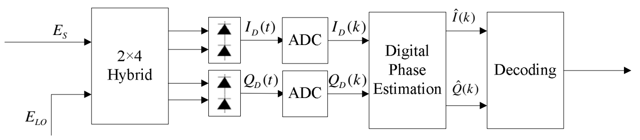


Fig.1. Coherent receiver for the satellite-to-ground optical communication system based on DQPSK modulation.

In Fig.1, the received signal is combined with the light of a local oscillator in a 2×4 hybird. And then the output signals are detected by two balanced photo-detectors. The resulting electrical in-phase and quadrature signals can be calculated by:

$$I_D(t) = R\sqrt{P_{lo}} \cdot \iint_D \left\{ I(r,t)\cos\left[\varphi_\varepsilon(r)\right] + Q(r,t)\sin\left[\varphi_\varepsilon(r)\right] \right\} dr + n_I(t) \quad (11)$$

$$Q_D(t) = R\sqrt{P_{lo}} \cdot \iint_D \left\{ I(r,t)\sin\left[\varphi_\varepsilon(r)\right] + Q(r,t)\cos\left[\varphi_\varepsilon(r)\right] \right\} dr + n_Q(t) \quad (12)$$

where $\varphi_\varepsilon(r)$ is the of total phase offset between the carrier and the oscillator. It is integrative effects of atmospheric turbulence and laser linewidth of the transmitter and the local oscillator. D is the valid detection area. $n_I(t)$ and $n_Q(t)$ represent the shot noise of the two balanced photodiodes. R is the responsivity. P_{lo} is the power of the local oscillator. $I(r,t)$ and $Q(r,t)$ have the form:

$$I(r,t) = E_0(r)\cos(\varphi(t)) \quad (13)$$

$$Q(r,t) = E_0(r)\sin(\varphi(t)) \quad (14)$$

After analog to digital conversion (ADC), the signals, $I_D(k)$ and $Q_D(k)$ are processed with phase estimation algorithm to get the estimation of phase error $\hat{\varphi}_\varepsilon(k)$ for each symbol. Then we can get the estimation of the signals:

$$\hat{I}(k) + j\hat{Q}(k) = \left[I_D(k) + jQ_D(k)\right] \cdot e^{j(-\hat{\varphi}_\varepsilon(k))} \quad (15)$$

B. Phase Estimation Algorithm

In this paper, the M-th power scheme of feed forward phase estimation is used, and the structure of this algorithm is shown in Fig.2. In the scheme, the modulated data are removed by M-th power function $(\ )^M$. The processing unit gets the estimation $\hat{\varphi}_\varepsilon(k)$ of the current symbol by averaging over *Nb* neighbor symbols of which the signal samples are raised to the M-th power. Limited by the speed of digital processing, the number *Nb* should be set large enough so that more symbols can be processed at one time. However, a large *Nb* will lead to high phase estimation error since a same estimation value is obtained from every *Nb* symbols. As a tradeoff of the two factors, *Nb*=8 is used in our simulation shown in section IV. The phase estimation is got with the formula given below:

$$\hat{\varphi}_\varepsilon(k) = \frac{1}{M} \mathrm{Arg}\left\{ \sum_{n=1}^{Nb} \exp\left[jM\varphi_\varepsilon\left((m-1)\cdot Nb + n\right)\right] \right\} - \frac{\pi}{M} \quad (12)$$

where *m* refer to as the *m*-th processing block array.

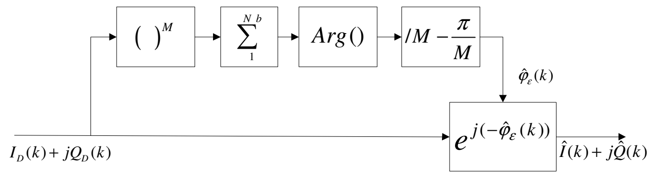


Fig.2. Structure of M-th power phase estimation algorithm

IV. SIMULATION RESULT

We choose two groups of parameters to describe the structure constant $C_n^2(h)$ for two cases. The parameters are shown in Table I.

Fig.3 shows the C_n^2 as a function of height h. It can be seen that the turbulence is negligible when the altitude is above 12 km. So the total simulation distance is set as L=12 km.

TABLE I. PARAMETERS FOR DIFFERENT TURBULENCE CASES

	Case I	**Case II**
a_1	1.5×10^{-23}	5.94×10^{-23}
a_2	1.5×10^{-16}	2.7×10^{-16}
s_1	1000m	1000 m
s_2	1500m	1500 m
s_3	100m	100 m
V	27 m/s	21 m/s
$C_n^2(0)$	1.5×10^{-15} m$^{-2/3}$	1.7×10^{-14} m$^{-2/3}$

To simulate the turbulent channel in the satellite-to-ground coherent optical communication system, the modified atmospheric spectrum is used with the inner and outer scale of l_0=0.01m and L_0=10m. The size of phase screen is G=2m sampled by 256×256. The sub-distance is set as Δh=200m. In the transmitter, a pseudo-random binary sequence (PRBS) with a length of 2^{13}-1 is modulated to generate the DQPSK modulated signals with a bit rate of 500Mb/s. The modulated Gaussian beam has a waist radius of w_0=0.08m and the wavelength is 1550nm. The received optical power is -15dBm and the power of the local oscillator laser is 0dBm.

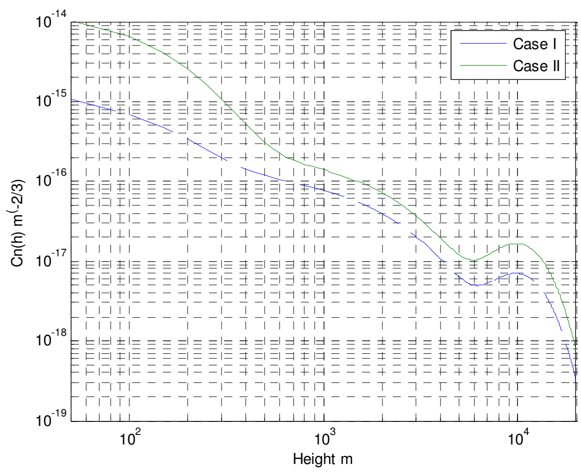


Fig.3. Cn2 versus height for strong and weak turbulence cases

Fig.4. shows the beam intensity for different cases. It is clear that the intensity fluctuation, i.e. scintillation, is induced by atmospheric turbulence. This fluctuation can also be observed from the normalized optical field of the received DQPSK signals as shown in Fig.5. In the constellation diagram each point represents the amplitude and phase of a DQPSK bit

sampling at the center of the bit period. It can be seen that strong turbulence induces phase fluctuations in a larger range, and the phase noise can be greatly suppressed with the phase estimation algorithm based on M-th power scheme in both the two cases.

In order to further evaluate the system performance improvements due to the phase estimation algorithm, we investigate the system performance with different SNRs in the receiver, and a BER evaluation method based on differential phase Q is introduced. This method is proposed in [11] and its effectiveness has been proved experimentally. The parameter of differential phase Q is defined as

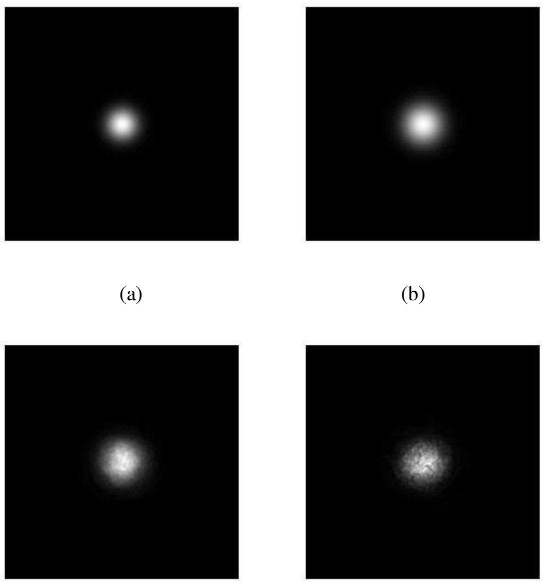
$$Q_{\varphi_\varepsilon}^{(I,Q)} = \pi \Big/ [2(\sigma_{\varphi_{\varepsilon,0}}^{(I,Q)} + \sigma_{\varphi_{\varepsilon,1}}^{(I,Q)})] \qquad (16)$$

where $\sigma_{\varphi\varepsilon,0}$ and $\sigma_{\varphi\varepsilon,1}$ are the standard deviations of $\sigma_{\varphi\varepsilon}$ for the '0' and '1' bit rails. The distribution of the differential phase for each bit can be seen as a superposition of two Gaussian distributions with positive (P) and negative (N) means and different standard deviations. Therefore, two differential phase Q are obtained. Thus, the BER of the I and Q components is computed,

$$BER^{(I,Q)} = \frac{1}{4}[erfc(Q_{\varphi_{\varepsilon,P}}^{(I,Q)} \Big/ \sqrt{2} + erfc(Q_{\varphi_{\varepsilon,N}}^{(I,Q)} \Big/ \sqrt{2})] \qquad (17)$$

where *erfc(x)* is complementary error function. The system BER can be calculated as:

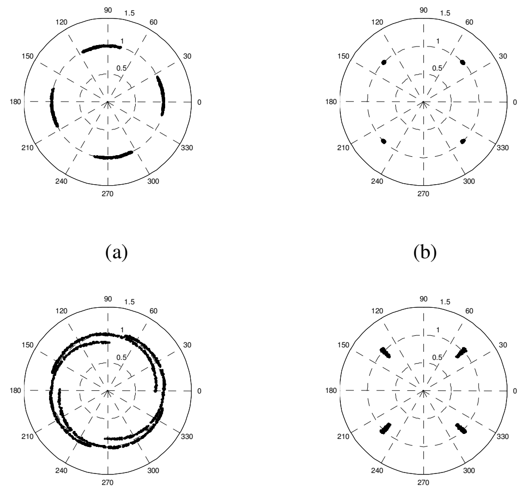
$$BER = \frac{1}{2}[1-(1-BER^{(I)})(1-BER^{(Q)})] \qquad (18)$$



(a) (b) (c) (d)

Fig.4. Beam intensity for different cases. (a) before propagation (b) zero turbulence (c) case I (d) case II.

Based on the method described above, the BER performance of the system is plotted as a function of SNR in the receiver with different linewidth and *Nb*=8 for the turbulence of Case I when with or without phase estimation. It is obvious that the system performance is degraded seriously due to strong turbulence even with a linewidth of 1kHz, and the phase estimation algorithm can greatly improved the system performance under the same condition. When the linewidth of the laser in the transmitter and the local oscillator is increased to 100kHz, the improvement can also be observed, a BER performance of 10^{-8} can be obtained even when SNR=10dB.



(a) (b) (c) (d)

Fig.5. Normalized constellation diagram of DQPSK signal with laser linewidth 1kHz for the transmitter and the local oscillator, the noise in the receiver is SNR=20dB and *Nb*=8. (a) and (b) with the turbulence of Case I, (a) without phase estimation and (b) with phase estimation. (c) and (d) with turbulence of Case II, (c) without phase estimation and (d) with phase estimation.

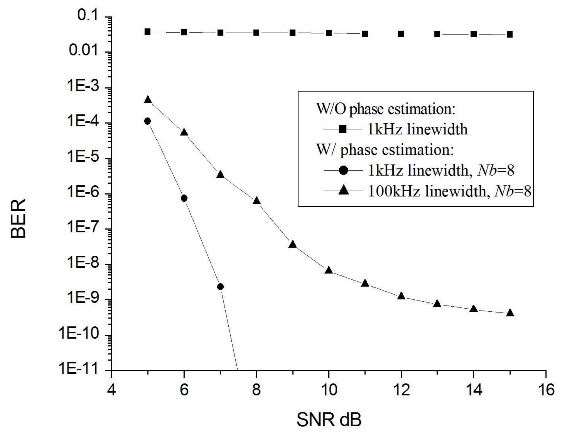


Fig.6. BER versus SNR in the receiver with different linewidth and *Nb*=8 for the turbulence of Case I,when with or without phase estimation.

V. CONCLUSION AND FURTHER WORK

In the paper, the phase estimation algorithm based on M-th power scheme is used in a satellite-to-ground coherent optical communication system with DQPSK modulation, and the system performance improvements due to this algorithm is investigated by simulation. The results show that the phase noise induced by atmospheric turbulence can be suppressed greatly. It is found that the BER of the system can be keep to the order of 10^{-8} with SNR=10dB in the case of strong turbulence even when the linewidth of the laser in the transmitter and the local oscillator is 100kHz.

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