# *Investigation on performance of OOK, DPSK, QDPSK in a space laser uplink communication system with the consideration of beam wander*


Mi Li*, Minghui Tang, Bowen Li, Xuping Zhang, Yuejiang Song, Jiachen Yang

Institute of Optical Communication Engineering

Nanjing University

Nanjing 210093, People's Republic of China

*Corresponding author: limihit2008@126.com



***Abstract*—Bit-error rate (BER) performance of on-off keying (OOK), differential phase-shift keying (DPSK), and differential quadrature phase-shift keying (QDPSK) are discussed under effect of beam wander, scintillation, and detector noise in space laser uplink communication system. Actually, DPSK performs better than OOK and QDPSK when the beam wader is considered. DPSK performs approximately 20dB better than OOK and 17dB better than QDPSK in the condition where beam wader is taken into consideration. Besides, optimum divergence angle, transmitter beam radius, zenith angle, receiving aperture are also suggested. The design of the space laser communication system can benefit from this work.**



***Keywords—bit error rate; beam wander; modulation scheme; space optical communication***


## I. INTRODUCTION

Compared with radio frequency communications, ground-to-satellite laser communications have many advantages, such as large bandwidth, low power consumption and compact equipment. However, the performance of laser communication can be severely degraded by atmospheric turbulence [1-4].

In order to overcome this problem, many research groups have studied the intensity scintillation and beam wander which are caused by atmospheric turbulence effects. Especially, beam wander and its induced changes in scintillation are of great significance [5] and have attracted lots of attention recently [6-9]. However, those studies mainly focused on the atmospheric turbulence effects on BER in communication systems [10]. Studies based on specific modulation schemes can be barely seen.

As we know differential phase-shift keying (DPSK) and differential quadrature phase-shift keying (QDPSK) can mitigate the severe effect of atmospheric turbulence [11]. Moreover, QDPSK can also double spectral efficiency by taking advantage of the two signal quadrature of one optical carrier. Many works have been developed to research the application of DPSK and QDPSK in ground optical communication [12-15], but studies based on ground-to-satellite laser link model can be rarely reported.

In this paper, compared with on-off keying (OOK), performances of these two modulation schemes are discussed. Based on weak fluctuation theory, the combined effects of beam wander, intensity scintillation, and detector noise are investigated. In comparison with the condition where beam wander is not taken into account, simulation results considering those all combined effects are given. According to the numerical results, the advantages of DPSK are discussed in contrast with OOK and QDPSK. Optimum divergence angle, transmitter beam radius, zenith angle, receiving aperture based on those three modulation schemes are also further studied, respectively.

## II. THEORY

When it comes to the ground-to-satellite optical communication system, avalanche photo diode (APD) is used to amplify the communication system. Thus, for the receiving terminal, the mean and variation of APD output for '1' bit and '0' bit are [16]

$$m_1 = G \cdot e \cdot \left( K_s\left(I\right) + K_b \right) \tag{1}$$

$$\sigma_1^2 = \left(G \cdot e\right)^2 \cdot F \cdot \left( K_s\left(I\right) + K_b \right) + \sigma_n^2 \tag{2}$$

$$m_0 = G \cdot e \cdot K_b \tag{3}$$

$$\sigma_0^2 = \left(G \cdot e\right)^2 \cdot F \cdot K_b + \sigma_n^2 \tag{4}$$

where $G$ is the gain factor, $e$ is the electron charge, $F$ is the additional noise factor, $\sigma_n^2$ is the thermal noise, $K_b$ is the photon count of background light, $K_s(I)$ is the photon count corresponding to the received pulse intensity of $I$ . $K_s(I)$, $K_b$ and $\sigma_n^2$ can be calculated by [16].

Thus, for the signal noise ratio of communication signal for '1' bit and '0' bit are [5]

$$r_1 = m_1^2 / \sigma_1^2 \tag{5}$$

$$r_0 = m_0^2 / \sigma_0^2 \tag{6}$$

For OOK system, considering that the probability of the emission of '1' and the probability of the emission of '0' are the same in general, the BER of OOK is given by [17]

$$BER(I)_{OOK} = \frac{1}{4}erfc(\sqrt{r_1}) + \frac{1}{4}erfc(\sqrt{r_0}) \tag{7}$$

In a PSK system, whether to signify a ‘1’ bit or a ‘0’ bit, the transmitter always emits an optical pulse in a time slot. It is their phase that is used to identify the two signals. DPSK system is the promotion of PSK system. The phase offset between two neighboring symbol signals decides whether to signify a ‘1’ bit or a ‘0’ bit. In a DPSK system, the original code should be converted into the differential code at the very start. What the transmitter emits is the differential code actually. Therefore, a process of converting the differential code into original code must be involved in the receiving end. This converting process produces extra errors and the BER of DPSK is expressed as [18]

$$BER(I)_{2DPSK} = \left(1 - \frac{1}{2}\cdot erfc(\sqrt{r_1})\right)erfc(\sqrt{r_1}), \tag{8}$$

In the demodulation system, the original signal of QDPSK can be regarded as the composition of two orthogonal signals of DPSK. Because the total energy must remain unchanged, the amplitudes of the two orthogonal signals are only the $1/\sqrt{2}$ of the original signal. Consequently, the BER of one orthogonal signal can be expressed as [18]

$$BER(I)_{QDPSK} = 1 - [1 - \frac{1}{2}(1 - \frac{1}{4}erfc(\sqrt{\frac{r_1}{2}}))\cdot erfc(\sqrt{\frac{r_1}{2}})]^2 \tag{9}$$

Speaking of the ground-to-satellite laser uplink communication system, atmospheric turbulence often leads to random changes of refractive index. This then contributes to the intensity scintillation. The probability density function (PDF) of the intensity scintillation can be expressed as [16]

$$P_r(I) = \frac{I}{\sqrt{2\pi\sigma_I^2(r,L)}}\frac{1}{I}\exp\left(-\frac{\left(\ln\frac{I}{\langle I(0,L)\rangle} + \frac{2r^2}{W^2} + \frac{\sigma_I^2(r,L)}{2}\right)^2}{2\sigma_I^2(r,L)}\right) \tag{10}$$

where $\langle I(0,L)\rangle = \partial P_T D_r^2 / 2W^2$ is the mean value of $I$, $P_T$ is the transmitting power, $D_r$ is the receiving aperture and $\partial$ is the dissipation coefficient. $W = \theta L/2$ stands for the beam radius at the receiving plane, $\theta$ stands for the divergence angle, $L = (H - h_0)\sec(\zeta)$ stands for the link distance, $H$ and $h_0$ are the altitude of the satellite and the ground station, respectively. $\zeta$ stands for the zenith angle. $\sigma_I^2(r,L)$ is the variance of the intensity [16].

Furthermore, the mean value and variance of the intensity scintillation are both related to the distance (r) between the receiving point and the beam center. As r is affected by the beam wander directly, the PDF of it is given by [20]

$$p(r) = \frac{r}{\sigma_r^2}\exp(-\frac{r^2}{2\sigma_r^2}) \tag{11}$$

where $\sigma_r^2$ is the variance of $r$, and for uplink, it can be estimated [20].

Thus, taking the intensity scintillation and bean wander into account, PDF based on the combined effects can be expressed as [20]

$$P_w(I) = \int_0^\infty P_I(I)P(r)dr, \tag{12}$$

For OOK, DPSK, QDPSK, time duration of the slot is much smaller than the coherent time of the atmosphere [4]. Based on the method of considering atmospheric turbulence effect [19], the BER of OOK, DPSK, QDPSK for uplink can be expressed as

$$BER_{OOK} = \int_0^{+\infty} BER(I)_{OOK}P_w(I)dI, \tag{13}$$

$$BER_{DPSK} = \int_0^{+\infty} BER(I)_{DPSK}P_W(I)dI, \tag{14}$$

$$BER_{QDPSK} = \int_0^{+\infty} BER(I)_{QDPSK}P_W(I)dI \tag{15}$$

## III. SIMULATIONS

Simulations are based on next parameters: duration time $T_s = 10\text{ns}$, quantum efficienc $\eta = 0.75$, wavelength $\lambda = 800\text{nm}$, background light $I_B$ =10nw/m$^2$, load resistance $R_L$ = 50Ω, temperature $T = 300\text{K}$, height $h_0 = 100\text{m}$, $H$=38000km, noise factor $F = G^{1/2}$, the receiving aperture $D_r$=0.25m, dark current $I_{dc}$ =1nA, amplification $G = 100$, $B_W$=100nm, zenith angle $\xi = 0°$, the typical divergence angle $\theta = 30\mu\text{rad}$.

As we know that, there are two atmospheric effects in ground-to-satellite laser uplink communication system. They are intensity scintillation and beam wander. The differences between $P_r(I)$ and $P_w(I)$ indicates that BER would witness a significant rise when taking beam wander into account. BER in those two conditions are shown in Fig.1. It turns out that the previous prediction is right. Beam wander produces about 13dB impairment in DPSK system when the laser power is 4 Watts. However, whether beam wander is taken into accounted or not, the BER performance of DPSK is always the best. While for OOK, it is always the worst. In fact, when taking beam wader into consideration, DPSK performs approximately 20dB better than OOK with the laser power being 4 Watts. It can also be evaluated that in this same condition DPSK also performs roughly 17dB better than QDPSK. That means beam wander degrades the performance of OOK, DPSK, QDPSK, but does not change the particular sequence based on BER. Because of the always best performance, DPSK can be the best choice.

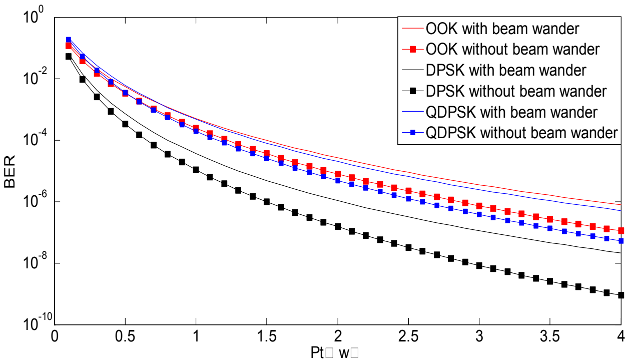


Fig.1.BER of OOK, DPSK, QDPSK with or without the consideration of beam wander

As it is defined, BER of the three modulation schemes are closely associated with receiving aperture $D_r$, zenith angle $\zeta$, divergence angle $\theta$, and transmitter beam radius $W_0$. In order to enhance the performance of the communication system, optimum $D_r$, $\zeta$, $\theta$ and $W_0$ must be discussed.

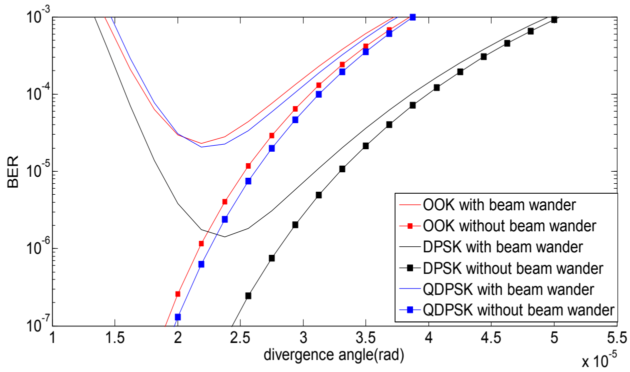


Fig.2.The variation of BER as a function of $\theta$

The variation of BER as a function of divergence angle $\theta$ is illustrated in Fig.2. It is evident that when neglecting beam wander, BER of all modulation schemes rise with the increase of $\theta$, while there are optimum divergences for all those modulation schemes when considering beam wander. As the optimum divergence of DPSK is larger than OOK and QDPSK, it can be easier to obtain in practical application. In this aspect, DPSK is the best choice.

The variation of BER as a function of receiving aperture $D_r$ is shown in Fig.3. It convinces that beam wander degrades the performance of the communication system again. Although with the increasing of $D_r$, whether beam wander is taken into account or not, BER decrease, the performance of DPSK is always the best while OOK is always the worst. Since for DPSK, to gain the same BER, it needs the smallest $D_r$ which is often limited in practical application, it is the best choice in this aspect.

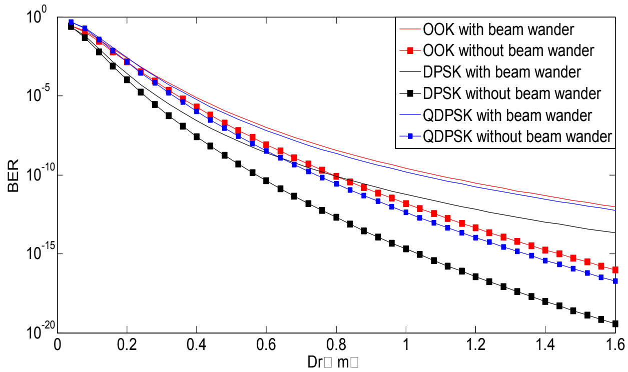


Fig.3.The variation of BER as a function of $D_r$

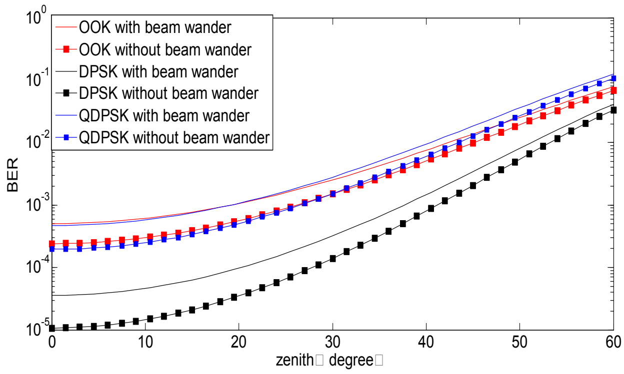


Fig.4.The variation of BER as a function of $\zeta$

The variation of BER as a function of zenith angle $\zeta$ is shown in Fig.4. As it is described, with the increment of $\zeta$, BER performance rise and the DPSK scheme shows the best BER performance. However, when neglecting beam wander, it is approximately at the position of $\zeta$ equals 28 degree that BER of QDPSK surpasses OOK, making itself the worst. In contrast, if beam wander is taken into account, it is at the position where $\zeta$ is about 20°that BER performance of QDPSK surpass OOK.

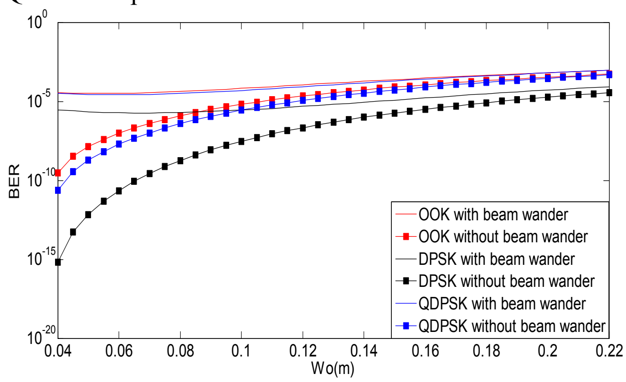


Fig.5. The variation of BER as a function of $W_0$

The variation of BER as a function of transmitter beam radius $W_0$ is illustrated in Fig.5. When neglecting beam wander, BER of the three modulation schemes grow with the increase of $W_0$. However, with the consideration of beam wander, the optimum $W_0$ of those modulation schemes all focus on roughly 6.5cm. As the optimum $W_0$ of DPSK is in the widest range and is the easiest to gain, DPSK is the best choice.

## IV. CONCLUSION

In conclusion, beam wander caused by atmospheric turbulence increases the BER of all these three modulation schemes. Specifically, beam wander produces about 13dB impairment in DPSK system when laser power is 4 Watts. Whether beam wander is considered or not, OOK always performs worst, while DPSK always performs the best. In fact, DPSK performs approximately 20dB better than OOK in the condition where beam wader is taken into consideration and the laser power is 4 Watts. In this same condition, DPSK also performs roughly 17dB better than QDPSK, though QDPSK can double spectral efficiency. Besides, the optimum divergence $\theta$ of DPSK is largest, the optimum beam radius $w_0$ of DPSK is in the widest range and to gain the same BER, DPSK needs the smallest receiving aperture $D_r$, these all make DPSK the most easy implemented modulation scheme. Since DPSK also has the best BER performance, it can be the best modulation scheme to be chosen. This work is useful for the design of the ground-to-satellite laser uplink communication system.

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