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Performance analysis of OOK, BPSK, QPSK modulation schemes in uplink of ground-to-satellite laser communication system under atmospheric fluctuation

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ABSTRACT

Considering the combined effects of the intensity scintillation and the beam wander in the satellite-to-ground laser uplink communication system, the bit error rate (BER) performance of three modulation schemes – on–off keying (OOK), binary phase-shifted keying (BPSK), quadrature phase-shifted keying (QPSK) are investigated. In comparison with the condition in which the atmospheric turbulence is not taken into consideration, conclusions that atmospheric turbulence severely degrades the performance of the system are drawn. Based on the simulation results, the advantages of BPSK are analyzed in contrast with OOK and QPSK. Specially, when transmission power is 4 W, performance of OOK shows 18 dB impairment while performance of QPSK shows 3 dB impairment compared with BPSK under the atmospheric fluctuation. Further compared to QPSK, BPSK owns lower BER and simpler process. Considered the feasibility in communication systems, BPSK should be the most reasonable modulation scheme which can decrease the BER of systems without increasing the transmitter power among these three modulation schemes. Besides, optimum divergence angle, optimum beam radius and appropriate receiver diameter are also analyzed, which is significant in practical applications.

1. Introduction

With outstanding efficiency and capacity, satellite-to-ground laser communication systems are now attracting an increasing number of researches [1–3]. However, for the laser beam propagating across the atmosphere, the turbulence proves to be able to cause deteriorations on the performance of the communication system. Various studies have been done based on the model of the atmospheric fluctuation caused by atmospheric turbulence [4–7]. Generally speaking, the atmospheric fluctuation mainly consists of intensity scintillation and beam wander [8]. Severely affected by beam wander, the distance (r) between the received point and the beam center is closely associated with the mean value and the variance of the intensity scintillation [9,10]. Thus, to obtain more reasonable results, we concentrate on the combined effects of the scintillation and the beam wander.

To mitigate the combined effects, the transmission power is recommended to be increased. This can enhance the performance to some extent, but the power supplied by the satellite is always limited. In order to essentially improve the performance of the communication system, an effective modulation scheme is indispensable.

According to the previous researches, due to its feasibility in both modulation and demodulation, on–off keying (OOK) used to be widely applied. As we known, OOK is a common intensity modulation. Whiles, some frequency modulations and phase modulations own more excellent characteristics. For example, MSK is one of the excellent frequency modulations [11]. However, it is so complicated. Here, we will introduce two simply and excellent phase modulations to satellite-to-ground laser uplink communication system. Compared to OOK, binary phase-shifted keying (BPSK) modulation scheme has improved performance and robustness to different transmission impairments [11,12]. Thus, it is widely accepted as the main modulation schemes in recent years [13–15]. In contrast, the quadrature phase-shifted keying (QPSK) can enhance the spectral efficiency through transmitting the same total bit rate with lower symbol rate [16].

Former studies mainly focus on the degradations caused by atmospheric turbulence in terms of the BER. However, specific researches based on modulation schemes can be rarely seen. In this paper, the performance of OOK is evaluated and the BER of BPSK and QPSK are developed with the consideration of the

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atmospheric fluctuation. Comprehensive conclusions are given through comparing the simulation results. Besides, the optimum divergence angle, the beam radius and receiver diameter at the transmitting terminal are analyzed, which would contribute to the design of the laser communication system.

2. Channel model

As it is mentioned, this paper mainly focuses on the performance of the satellite-to-ground laser uplink communication system, which is primarily influenced by the intensity scintillation and beam wander. Assuming that the laser beam is gauss beam. Based on weak fluctuation theory, the probability density distribution of the received intensity (I) can be expressed as [9]

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

where r is the distance between the received point and the beam center, I stands for the received intensity, $W=\theta L/2$ stands for the radius of the spot, θ stands for the divergence angle and $\sigma_I^2\,(r,L)$ is the variance of the scintillation which can be calculated as [10]

$$\sigma_I^2(r,L)=8.702\mu_2\kappa^{7/6}(H-h_0)^{5/6}\sec^{11/6}(\zeta) + 14.508\mu_1\Lambda^{5/6}\kappa^{7/6}(H-h_0)^{5/6}\sec^{11/6}(\zeta)\left(\frac{r^2}{W^2}\right) \quad (2)$$

where $K=2\pi/\lambda$ is the wave number, λ is the wave length, H is the altitude of the satellite, h_0 is the altitude of the receiving terminal on the ground, ζ is the zenith angle. In (2), parameter μ_1 and μ_2 can be calculated by

$$\mu_1=\int_{h_0}^{H}C_n^2(h)\left(1-\frac{h-h_0}{H-h_0}\right)^{5/3}dh \quad (3)$$

$$\mu_2=\mathrm{Re}\int_{h_0}^{H}C_n^2(h)\xi^{5/6}[\Lambda\xi+i(1-\overline{\Theta}\xi)]^{5/6}-C_n^2(h)\Lambda^{5/6}\xi^{5/3}dh \quad (4)$$

in which parameters can be expressed as

$$\xi=1-\frac{h-h_0}{H-h_0},\quad \Lambda=\frac{2L}{\kappa W^2},\quad \overline{\Theta}=\frac{L}{R_r} \quad (5)$$

and R_r represents the phase front radius of curvature. $\langle I(0,L)\rangle$ is the mean value near the beam center, assuming that the beam is gauss beam, thus it can be described as [17]

$$\langle I(0,L)\rangle=\frac{\alpha P_T D_r^2}{2W^2} \quad (6)$$

where α is the energy impairment of the laser beam, D_r is the receiving caliber and P_T is the transmission power of the optical pulse when sending '1'.

In (3) and (4) $C_n^2(h)$ represents the refractive-index structure parameter at the altitude of h. Based on the former studies, one of the most widely accepted model is the Hufnagel–Valley 5/7 model [18,19], in which the parameter can be described as

$$C_n^2(h)=0.0059(v/27)^2(10^{-5}h)^{10}\exp(-h/1000)+2.7\times10^{-16}\exp(-h/1500)+C_0\exp(-h/100) \quad (7)$$

where v is the wind velocity which is transverse to the laser beam with a typical value of 21 m/s and C_0 is the refractive index structure parameter near the ground with a typical value of $1.7\times10^{-14}\,\mathrm{m}^{-2/3}$.

Considering the probability density distribution, it is clear that the variance of the intensity scintillation is seriously influenced by r which is decided by beam wander. The probability density distribution of beam wander obeys the Rayleigh distribution [20] and is calculated by

$$P(r)=\frac{r}{\sigma_r^2}\exp\left(-\frac{r^2}{2\sigma_r^2}\right) \quad (8)$$

where the variance of the beam wander σ_r^2 can be described as [8]

$$\sigma_r^2=2.07\int_{h_0}^{H}C_n^2(z)(L-z)^2W(z)^{-1/3}dz \quad (9)$$

in which the transmission distance is $L=(H-h_0)\sec(\zeta)$ and $W(z)=W_0+\theta z/2$ is the beam radius at z, where W_0 stands for the beam radius at the transmission terminal and θ stands for the divergence angle.

Taking the intensity scintillation and bean wander into account, the combined probability density distribution of the received intensity for uplink can be calculated by [21]

$$P_w(I)=\int_0^\infty P_r(I)P(r)dr=\int_0^\infty\frac{r}{\sigma_r^2}\frac{1}{\sqrt{2\pi\sigma_I^2(r,L)}I}\exp\left(-\frac{r^2}{2\sigma_r^2}\right)\times\exp\left(-\frac{(\ln(I/\langle I(0,L)\rangle)+(2r^2/W^2)+(\sigma_I^2(r,L)/2))^2}{2\sigma_I^2(r,L)}\right) \quad (10)$$

3. Bit error rate of OOK, BPSK, QPSK

3.1. On–off keying

The noise in communication systems is always Gaussian noise in general. Neglecting the combined effects caused by atmospheric fluctuation, the slot-error rate on the receiving terminal of OOK can be calculated by [22]

$$P_{0/1}=\int_{-\infty}^{r}\frac{1}{\sqrt{2\pi}\sigma_1}\exp[-(i-m_1)^2/2\sigma_1^2]di \quad (11)$$

$$P_{1/0}=\int_{r}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_0}\exp[-(i-m_0)^2/2\sigma_0^2]di \quad (12)$$

where $P_{0/1}$ is the probability of receiving '0' while sending '1' and similarly, $P_{1/0}$ is the probability of receiving '1' while sending '0'. r stands for the detection threshold on the receiving terminal. σ_0, σ_1, m_0, and m_1 stand for the mean value and variance of the received intensity while sending '1' bit and '0' bit, respectively. With the use of avalanche photo diode (APD), they can be described as [22]

$$m_0=GeK_b \quad (13)$$

$$\sigma_0^2=(Ge)^2FK_b+\sigma_n^2 \quad (14)$$

$$m_1=Ge(K_s(I)+K_b) \quad (15)$$

$$\sigma_1^2=(Ge)^2F(K_s(I)+K_b)+\sigma_n^2 \quad (16)$$

in which, G is the APD gain factor, e is the electronic charge, I_{dc} is the dark current, T_s is the time duration per slot, F is the additional noise factor, K_s is the photon count corresponding to received pulse intensity I, K_b is the photo count of background light and σ_n^2 is the thermal noise. The last three parameters can be calculated as [22]

$$K_s(I)=\frac{\eta IT_b}{h\upsilon},\quad \sigma_n^2=\frac{2\kappa_c TT_b}{R_L},\quad K_b=\frac{\eta I_b T_b}{h\upsilon} \quad (17)$$

In addition, the probability of sending '1' and '0' are usually the same. Therefore, substituting (13)–(16) into (11) and (12), the bit error rate (BER) of OOK can be expressed as

$$BER(I)=\frac{1}{2}\int_r^\infty\frac{1}{\sqrt{2\pi}\sigma_0}\exp\left[-\frac{(i-m_0)^2}{2\sigma_0^2}\right]di$$

$$+\frac{1}{2}\int_{-\infty}^{r}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i-m_1)^2}{2\sigma_1^2}\right]di \tag{18}$$

Apparently, BER of OOK is decided by the receiving intensity which is directly influenced by the intensity scintillation in the uplink. After taking detector noise into account, the BER of the whole system can be expressed as

$$BER_r=\int_0^{\infty}BER(I)P_r(I)dI \tag{19}$$

According to the above discussion, since beam wander induces changes in intensity scintillation, it must be taken into consideration. Based on the above research about the combined effects in (10), we can gain the final BER, described as

$$BER=\int_0^{\infty}BER(I)P_w(I)dI \tag{20}$$

3.2. Binary phase-shift keying

When talking about the BPSK, it has essential differences with the OOK. Primarily, different bits are encoded in particular signals with various phase in BPSK. Comparatively speaking, BPSK performs better than OOK in terms of the capacity and efficiency [11].

As for BPSK, there are two specific phase 0 and π standing for '1' and '0', respectively. Former studies mainly investigate the performance with the consideration of the simple channel noise. In the satellite-to-ground laser communication system, taking the atmospheric fluctuation and the detector noise of APD into consideration, BER of BPSK should be revised. As we known, the slot-error rate in BPSK can be described as [23]

$$P_{0/1\_BPSK}=\int_{-\infty}^{r}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i-m_1)^2}{2\sigma_1^2}\right]di \tag{21}$$

$$P_{1/0\_BPSK}=\int_{r}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i+m_1)^2}{2\sigma_1^2}\right]di \tag{22}$$

Then, we can draw the final BER of BPSK with the consideration of the detector noise only.

$$BER_{BPSK\_0}(I)=\frac{1}{2}\int_{r}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i+m_1)^2}{2\sigma_1^2}\right]di+\frac{1}{2}\int_{-\infty}^{r}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i-m_1)^2}{2\sigma_1^2}\right]di \tag{23}$$

Based on the above results, when considering the intensity scintillation only, the BER of BPSK can be expressed as

$$BER_{BPSK\_1}=\int_0^{\infty}BER_{BPSK\_0}(I)P_r(I)dI \tag{24}$$

When taking the combined effects into account, the BER of BPSK can be expressed as

$$BER_{BPSK\_2}=\int_0^{\infty}BER_{BPSK\_0}(I)P_w(I)dI \tag{25}$$

3.3. Quadrature phase-shift keying

Different from the BPSK, the QPSK transmit signals in four particular phase, which can further enhance the spectral efficiency. As the consequence of the four kinds of phase which have $\pi/2$ phase offset between two neighboring phase, QPSK can be regarded as the composition of two orthogonal signals of BPSK.

Since each of them has half of the original received intensity, the mean value of received intensity should be $m_1/\sqrt{2}$ and the variance remains ${\sigma_1}^2$. Therefore, the BER for each BPSK can be described as

$$BER_{BPSK1}(I)=\frac{1}{2}\int_{r}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i+m_1/\sqrt{2})^2}{2\sigma_1^2}\right]di+\frac{1}{2}\int_{-\infty}^{r}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{(i-m_1/\sqrt{2})^2}{2\sigma_1^2}\right]di \tag{26}$$

Because of the two orthogonal signals, the comprehensive BER of QPSK, with the consideration of intensity scintillation only, can be calculated as

$$BER_{QPSK0}=1-[1-BER_{BPSK1}]^2 \tag{27}$$

$$BER_{QPSK1}=\int_0^{\infty}BER_{QPSK0}(I)P_r(I)dI \tag{28}$$

While, taking the combined effects into account, the BER of QPSK can be expressed as

$$BER_{QPSK2}=\int_0^{\infty}BER_{QPSK0}(I)P_w(I)dI \tag{29}$$

4. Simulation results

Simulation results are based on the following parameters: the altitude of the satellite and the ground station $H=36,000$ km and $h_0=100$ m, wave length $\lambda=800$ nm, the received aperture $D_r=0.25$ m, zenith angle $\zeta=0^{\circ}$, the divergence angle $\theta=30$ μrad, the quantum efficiency $\eta=0.75$, APD gain factor $G=100$, additional noise factor $F=G^{0.5}$, the time duration per slot $T_s=10$ ns, spectral density $I_B=10\ \mathrm{nW}/m^2$, the dark current $I_{dc}=1$ nA, the load resistance $R_L=50\,\Omega$, current temperature $T=300$ K. To simplify the simulation, the energy loss is neglected for uplink.

Considering intensity scintillation only, the variation of BER as a function of transmitting power in various modulation schemes is shown in Fig. 1. In order to simplify the system, r is assumed to be 0. The simulation indicates that with the increase of transmitting power, the BER show a consistent decrease. Compared with BPSK, the BER of QPSK is about 3 dB higher and for OOK, it is 24 dB higher when the transmission power is 4 W. Thus, following conclusions can be obtained

(a) BPSK and QPSK display a much better performance than OOK.
(b) Although the variation tendency of BPSK and QPSK are approximately the same, BER of BPSK is about 3 dB lower.

In addition, the modulation system of BPSK is much simpler than QPSK while being utilized in practical applications. Therefore, although QPSK can provide better spectral efficiency, BPSK should

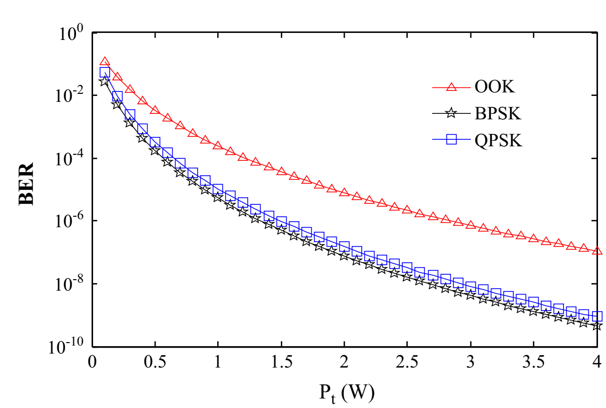

Fig. 1. BERs as functions of transmitting power P_t.

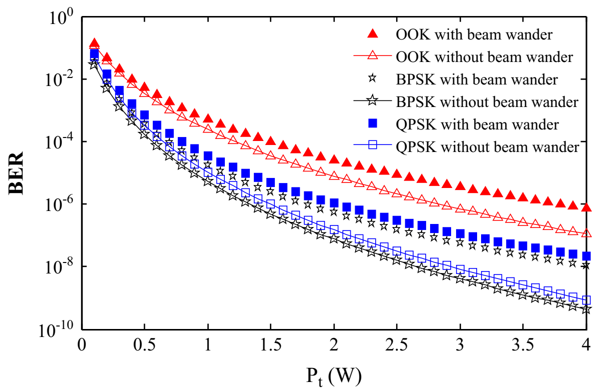

Fig. 2. BERs as functions of transmitting power P_t in various cases.

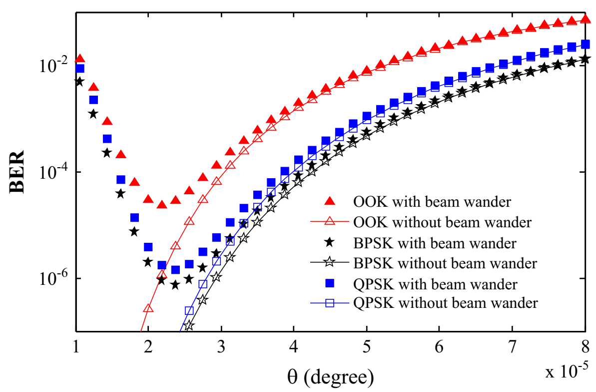

Fig. 3. BERs as functions of divergence angle in various cases.

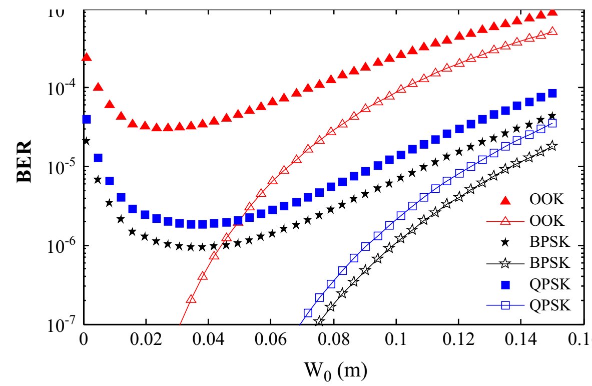

Fig. 4. BERs as functions of beam radius in various cases.

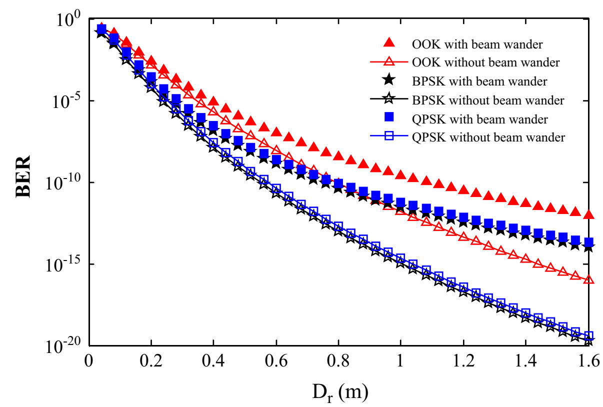

Fig. 5. BERs as functions of receiver diameter D_r in various cases.

be the most effective alternative among these three modulation schemes.

In Fig. 2, the performance of three modulation schemes affected by combined effects are illustrated according to (20), (27), and (31). Just as the previous prediction, when considering the combined effects, BER of all these three modulation schemes display a distinct raise in BER. Specifically, it produces an 8 dB, 14 dB and 14 dB deterioration for OOK, BPSK and QPSK, respectively, when the transmission power is 4 W. Consequently, we can draw the conclusion that the performances of three modulation schemes are dramatically aggravated by beam wander.

Based on the comparison among OOK, BPSK and QPSK, it is obvious that the BER of BPSK is consistently lower than that of OOK and QPSK. Specially, compared with BPSK, BER of OOK is 18 dB higher and for QPSK, it is 3 dB higher when the transmission power is 4 W. Consequently, combining with its feasibility, BPSK is more effective than OOK and QPSK whether or not the beam wander is taken into consideration.

Fig. 3 indicates the variation of the BER as a function of divergence angle in various modulation schemes. And Fig. 4 shows the variation of the BER as a function of beam radius in various modulation schemes. Approximately the same results can be drawn. When neglecting beam wander, with the divergence angle and the beam radius increasing, the BER of three modulations see a stable increase. Apparently, there exists optimum divergence angle and beam radius when the combined effects are considered. Except for that, receiver diameter is another important parameter for the ground-to-satellite laser communication systems. And the BERs as functions of receiver diameter in various cases are shown in Fig. 5. It is clear that with the receiver diameter increasing, the BER of three modulations see a stable decrease. In addition, apparently with the consideration of beam wander, the BER of three modulation formats shows a considerable increase.

According to Figs. 3–5, it is clear that BPSK and QPSK perform much better than OOK. Further taking the optimum divergence angle, optimum beam radius and appropriate receiver diameter into consideration, BPSK and QPSK is much more practical. In addition, compared to QPSK, BPSK owns lower BER and simpler process. Thus, BPSK should be the most reasonable modulation scheme which can decrease the BER of systems without increasing the transmitter power among these three modulation schemes in practical satellite-to-ground laser communication systems design.

5. Conclusions

With the consideration of atmospheric fluctuation and detector noise, performance of OOK, BPSK and QPSK are discussed in terms of the BER. Compared with OOK, BPSK and QPSK show a much lower BER under the same situation. When considering combined effects caused by atmospheric fluctuation, all of them see a distinct increase. In addition, there exists the optimum divergence angle and beam radius in three modulation schemes. In conclusion, the consideration of the combined effects caused by the atmospheric turbulence is of great significance. Besides, as can be seen clearly from the simulation results, BER of OOK shows 18 dB impairment and BER of QPSK shows 3 dB impairment compared with BPSK under the atmospheric fluctuation when transmission power is 4 W. Therefore, BPSK and QPSK show a more outstanding performance than OOK. Compared with QPSK, BER of BPSK is 3 dB lower. Furthermore, considering the simpler process of BPSK modulation and demodulation, BPSK is more practical than QPSK. Consequently, although QPSK can provide better spectral efficiency, BPSK should be recognized as the most reasonable modulation scheme which can decrease the BER of systems without increasing the transmitter power among these three modulation schemes in practical satellite-to-ground laser communication systems design.

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