Atmospheric phase fluctuation effect on communication quality in space uplink optical communciation

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Abstract. The BER performance with consideration of phase fluctuation effect in space optical communication is investigated. When the phase fluctuation effect is considered, BER definitely increase which leads to the worse communication quality. Based on numerical simulation, BER is sensitive to the higher level of zenith angle. There exists the optimal point of divergence angle in practical system and this point turns to be lower if phase fluctuation effect is considered. After we analyze different BER performance in different wavelengths, we can know that 1550nm of wavelength is always the better choice for great communication quality. The work is beneficial for increasing the communication quality and designing the practical communication system.

Introduction

Nowadays, space optical communication has attracted much attention with many extraordinary advantages [1-5]. For digital optical communication, the digital information is modulated in carrier wave and then it will be transmitted. As we know, the phase modulation is widely applied with better bit error rate (BER) performance [6].

Speaking of the process of space optical communication, the signal is usually affected by atmospheric turbulence [7-9]. For the uplink system, the signal is transmitted from the ground to the satellite. The atmospheric turbulence will lead to the intensity scintillation and beam wander effect for the signal. The intensity scintillation will make the received light intensity change irregularly and beam wander will make the receiver point randomly move. Besides, there also exists phase fluctuation effect on signal [10]. For phase fluctuation, it can affect the phase information in carrier wave which will decrease the performance of demodulation. Thus, it is necessary to research effect of phase fluctuation effect on BER performance.

In this paper, we analyze the BER performance of binary phase shift keying (BPSK) with consideration of three atmospheric turbulence effects. Intensity scintillation, beam wander and phase fluctuation effects are all considered in research process. To further research the performance of practical system, we simulate all functions in different wavelengths (800nm, 1060nm, 1550nm). The BER as the function of transmission power and phase frequency are analyzed. The transmission diameter, divergence angle and zenith angle are also analyzed respectively. These analyses are beneficial for increasing transmission quality and enhancing the design of practical system.

Theory

The space optical uplink communication system has transmission system, receiver system. The whole process is shown in Fig.1.

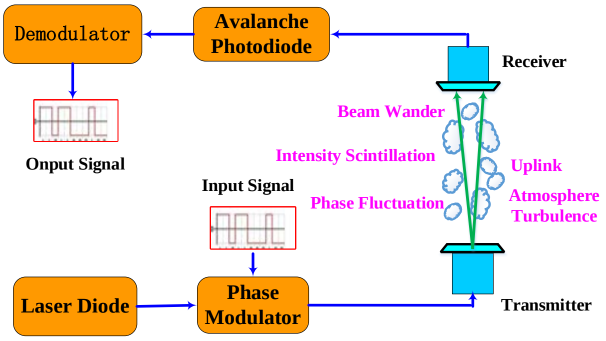

Fig.1 the diagram of process of communication

As we know, all modulation scheme has original BER without considering other factors. If the atmospheric turbulence is not taken into account, the BER performance of BPSK scheme is [11]

$$BER_1 = 1/2 \cdot erfc(\sqrt{SNR_1}). \tag{1}$$

where SNR_1 is the signal noise rate. For space optical communication, the avalanche photodiode(APD) is applied to amplify the received weak signal. The signal noise rate is [12]

$$SNR_1 = a_1^{\ 2} / 2\sigma_1^{\ 2}. \tag{2}$$

where a_1 is the current from the detector and the variance of noise $\sigma^2{}_1$ can be expressed as [13]

$$a_1 = G \cdot e \cdot \left(K_s\left(I\right) + K_b\right) + I_{dc} T_s. \tag{3}$$

$$\sigma_1^2 = \left(G \cdot e\right)^2 \cdot F \cdot \left(K_s\left(I\right) + K_b\right) + \sigma_T^2. \tag{4}$$

where e is electron quantity, G is gain factor, K_b is the photon count of the background light, T_s is bit time, K_s is the photon count, $\sigma_T^2 = 2\kappa_c T T_s / R_L$ is thermal noise, T is the temperature, k_c is Boltzmann constant, R_L is load resistance [13].

When it comes to atmospheric turbulence, phase fluctuation should be considered firstly. The distribution of phase fluctuation satisfies Gaussian distribution, which is [10]

$$f_g(\Delta\phi) = \frac{1}{\sqrt{2\pi\sigma_\Phi}} \exp^{-\Delta\phi^2/2\sigma^2{}_\Phi}. \tag{5}$$

where $\sigma^2{}_\emptyset$ is the phase fluctuation variance, $\Delta\emptyset$ is the phase deviation.

Based on the research [10], the phase fluctuation ia added to APD. Thus, for BPSK scheme, the BER with consideration of phase fluctuation is [14]

$$BER_2 = 1/2 \cdot erfc(\sqrt{SNR_2}). \tag{6}$$

where SNR_2 is the signal noise rate. It can be shown as [14]

$$SNR_2 = a_2^{\ 2} / 2\sigma_2^{\ 2}. \tag{7}$$

where they can be shown as

$$a_2 = G \cdot e \cdot \left(K_s\left(I\right)\cos(\Delta\phi) + K_b\right) + I_{dc} T_s. \tag{8}$$

$$\sigma_2^2 = \left(G \cdot e\right)^2 \cdot F \cdot \left(K_s\left(I\right)\cos(\Delta\phi) + K_b\right) + \sigma_T^2. \tag{9}$$

Besides phase fluctuation, the intensity of communication signal is also affected. Intensity scintillation effect and beam wander are both caused by atmospheric turbulence. Intensity scintillation can make light intensity change randomly, and beam wander can lead to the movement of the center of received light spot. Speaking of atmospheric turbulence effect, it will lead to the intensity scintillation in space optical communication system. The probability density function (PDF) of receiving light can be shown as [3]

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

where $\langle I(0,L)\rangle=\alpha P_T D_r^2/2W^2$ is the mean intensify, D_r is the receiving diameter, P_T is the transmission power, $W=\theta L/2$ is the radius of beam at the receiving plane, α is the energy loss of the link, r is the distance deviation between the beam center and receiving point, θ is divergence angle, $L=(H-h)\sec(\zeta)$ is the length of the laser link, ζ is zenith angle, H and h_0 are heights of the receiver and the emitter, $\sigma_I^2(z,L)$ is the variance [3].

The probability density function (PDF) of distance deviation caused by beam center follows Rayleigh distribution, which is expressed by [3]

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

where r is size of the beam, $\sigma^2{}_r$ is variation of beam wander and parameters are given in [3].

Therefore, combining with intensity scintillation and beam wander, the PDF of receiving intensity under the influence of both scintillation and beam wander should be [3]

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

Therefore, BER considered only the intensity scintillation and beam wander can be

$$BER=\int_0^\infty BER_1 P_w dI. \tag{13}$$

However, with consideration of phase fluctuation effect, the BER is shown as

$$BER=\int_{-\infty}^{+\infty}\int_0^\infty BER_2 P_w f_g(\Delta\phi)dId\Delta\phi.$$

(14)

Numerical Simulations

Simulation parameters are as following: zenith angle ζ = 0°, the divergence angle θ= 30μrad, wavelength λ = 850nm, the altitude of the ground station h_0 =100m, the altitude of the satellite H = 36,000km, quantum efficiency of APD $\eta=0.75$, load resistance R_L = 50Ω, additional noise factor F = $G^{0.5}$, photomultiplier gain factor G =100, the receiving aperture D_r = 0.4m, temperature T = 300K, the dark current I_{dc} =1nA, the time duration per slot T_s=10ns, spectral density I_b=10nW/m^2, the energy loss $\alpha=1$, P_T is 1W， atmospheric refractive index $C_n^2=10^{-16}m^{-2/3}$.

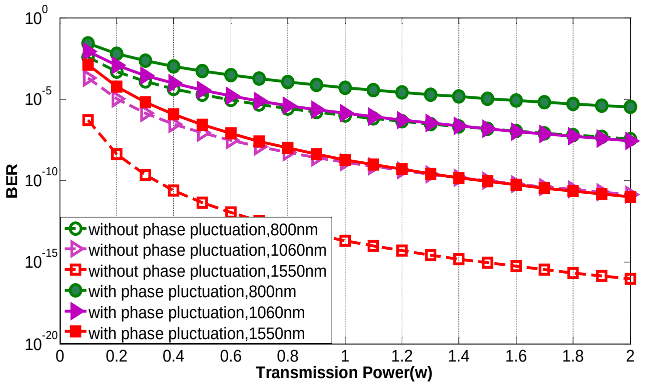

Fig.2 BER versus transmission power with and without phase fluctuation effect

In Fig.2, the BER performance as the function of transmission power with and without phase fluctuation effect are shown. As the transmission power is growing from 0W to 2W, the BER in different wavelengths gradually decrease. Besides, when we take phase fluctuation effect into consideration, BER definitely increase. Specifically, if the transmission power is 1W, BER increase about 48dB, 31dB, and 16dB in different wavelengths (1550nm, 1060nm, 800nm respectively). We can also see that BER performance in wavelength of 1550nm is better than the other two. As these three wavelengths are all widely applied in practical system, we can predict that the wavelength of 1550nm could be a better opportunity for enhancing communication quality.

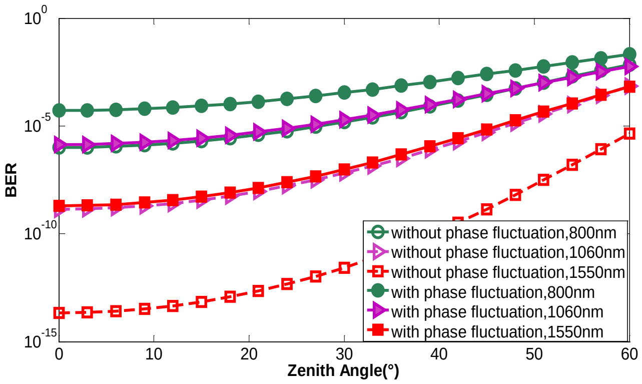

Fig.3 BER versus zenith angle for with and without phase fluctuation effect

In Fig.3, the relationship between BER and zenith angle is shown. With the zenith angle increasing from 0 degree to 60 degree, BER gradually increase. It is easy to explain because higher zenith angle leads to longer transmission distance. And it can make the optical signal propagate longer time in atmospheric turbulence. When the zenith angle increases up to 10 degree, BER has fast increasing. We can see that BER performance is more sensitive to higher value of zenith angle. When the phase fluctuation effect is considered, BER definitely increase, especially in lower zenith angle. During the design of practical communication system, we must carefully choose the value of zenith angle.

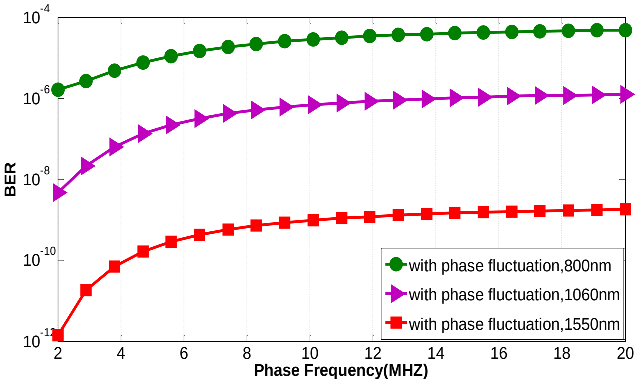

Fig.4 BER versus phase frequency with and without phase fluctuation effect

Fig.4 shows the BER as a function of phase frequency with and without phase fluctuation effect. We can see that BER in wavelength of 1550nm has the minimum value, which also shows the superiority of 1550nm wavelength. Besides, when the phase frequency is lower than 6MHz, BER in different wavelengths increase obviously. BER increase about 19dB, 14dB, 9dB with phase frequency increasing from 2MHz to 6MHz in the wavelength of 800nm, 1060nm and 1550nm respectively. When the phase frequency is larger than 6MHz, BER keep almost the same value and hardly increase. It indicates that BER is sensitive to lower phase frequency with consideration of phase fluctuation effect.

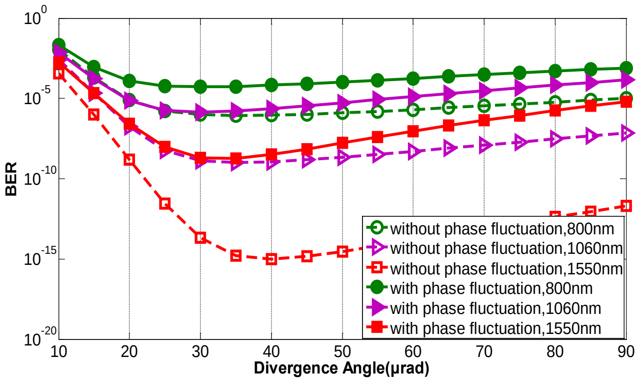

Fig.5 BER versus divergence angle with and without phase fluctuation effect

Fig.5 shows the BER versus divergence angle with and without phase fluctuation effect. It is easy to see that there has the optimal point of divergence angle with the best BER performance. Without consideration of phase fluctuation effect, the best divergence angles are about 41μrad, 36μrad, 31μrad in wavelength of 1550nm, 1060nm, and 800nm respectively. However, when the phase fluctuation effect is considered, the optical point od divergence angle turns to be lower. The optimal angles become to be 29μrad, 26μrad, and 24μradfor wavelengths of 1550nm, 1060nm, and 800nm respectively. This work can help us design the divergence angle for better BER performance.

Summary

In conclusion, the BER performance with consideration of phase fluctuation effect in space optical communication is investigated. When the phase fluctuation effect is considered, BER definitely increase which leads to the worse communication quality. Based on numerical simulation, BER is sensitive to the higher level of zenith angle. There exists the optimal point of divergence angle in practical system and this point turns to be lower if phase fluctuation effect is considered. After we analyze different BER performance in different wavelengths, we can know that 1550nm of wavelength is always the better choice for great communication quality. The work is beneficial for increasing the communication quality and designing the practical communication system.

Acknowledgements

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