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Invited Paper

Investigation of the phase fluctuation effect on the BER performance of DPSK space downlink optical communication system on fluctuation channel

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ABSTRACT

Phase fluctuation effect is an important phenomenon on bit error rate (BER) performance on fluctuation channel in space downlink optical communication system. During research process, both intensity scintillation and phase fluctuation caused by atmospheric turbulence have been considered on fluctuation channel. Through the analysis of simulation results, the influence of phase fluctuation is not sensitive for wavelength and APD gain factor at high data rate. Besides, receiving diameter and divergence angle can be adjusted properly in order to obtain optimal BER performance. This work is helpful to the research of phase fluctuation and the design of practical system.

1. Introduction

With the development of space technique, space optical communication system has attracted much attention because of many extraordinary advantages, such as higher data rate and better ability of anti-electromagnetic interference. Currently, traditional on-off-keying (OOK) modulation has already been widely utilized in space optical communication system and many works have concentrated on the BER performance [1–5]. However, it is agreed by practical experience that OOK scheme on intensity modulation direct detection (IM-DD) in a single channel has several disadvantages.

Particularly, in order to assure the high level of communication quality, the data rate of OOK on IM-DD is hardly over 2.5 Gb/s. However, phase modulation, with better signal-to-noise-ratio (SNR) performance, does not show this deficiency. For the sake of the higher data rate, phase modulation will be an essential modulation mode. And it has been regarded as the next generation applied in satellite laser communication system. Apart from modulation scheme, the atmosphere channel is considered as another significant factor in space optical communication system. Many works have been researched in this area [6–9]. It is proved that the laser beam is inevitably affected by the atmospheric turbulence when it propagates through the atmosphere.

When the optical signal is modulated by OOK scheme, the effect of phase fluctuation is not noticeable for the BER performance. As a result, the current researchers tend to ignore the influence of phase fluctuation [10,11]. However, the effect of phase fluctuation is sensitive for the phase modulation. G. D. Xie deduces the expression of SNR and BER by adding phase fluctuation into traditional Gamma–Gamma atmospheric model [12]. Furthermore, G. D. Xie analyzes the relationship between SNR and BER in various transmission situations and frequency deviations for compensating. However, these works merely provide the basic communication model and lack the discussion about how the phase fluctuation works in practical system. Besides, that model is not suitable for the real optical communication system because the photodiode is utilized [12]. Actually, Avalanche photodiode (APD) is generally used for the sake of amplifying receiving signal in space optical communication system. Thus, the researches in reference [12] cannot satisfy the requirement of current practical system design.

In this paper, we analyze the BER performance under the Kolmogorov turbulence model. During the research process, both intensity scintillation and phase fluctuation caused by atmospheric turbulence have been taken into consideration on fluctuation channel. In order to response to the actual device, the APD is applied in this model. Based on all factors above, the BER expression of DPSK scheme on fluctuation channel is achieved with phase

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fluctuation effect. For practical system parameters, the transmission power and wavelength have been researched versus the BER performance. Some other parameters such as receiving diameters, divergence angle and APD gain factor are also analyzed. As we know, the fluctuation channel becomes more realistic to practical communication channel. And it can depict communication quality more accurately. These analyses can help understand the effect of phase fluctuation on BER performance and improve the design of practical system.

2. Theory model

For the space downlink optical communication system, it is important to understand the transmission process. That schematic diagram is shown in the Fig. 1. As we know, the input signal is modulated on phase modulation with laser diode. During the atmospheric propagation, the signal is affected by intensity scintillation and phase fluctuation caused by atmospheric turbulence. At the receiving terminal, after amplified in the avalanche photodiode, the receiving signal is taken to the demodulation system and the output signal is obtained finally.

When it comes to the atmospheric propagation, the BER performance is affected by intensity scintillation caused by atmospheric turbulence. The probability density function of the intensity I can be expressed as [13]

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

where $\langle I(0, L)\rangle = \alpha P_T D_r^2/2W^2$ is the mean intensify, P_T is the transmission power, D_r is the receiving diameter, α is the energy loss of the link, $W=\theta L/2$ is the radius of beam at the receiving plane, θ is divergence angle, r is the distance deviation between the beam center and receiving point, $L=(H-h_0)\ \sec(\zeta)$ is the length of the laser link, ζ is zenith angle, H and h_0 are heights of the receiver and the emitter, σ_I^2 is the variance and it is [14]

$$\sigma_I^2 = 8.702\mu k^{7/6}(H - h_0)^{5/6}\sec^{11/6}(\zeta) \tag{2}$$

where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, ζ is the zenith angle, and μ can be calculated by [15]

$$\mu = \mathrm{Re}\int_{h_0}^{H} C_n^2(h) \times \left\{\xi^{5/6}\left[\Lambda\xi + i\left(1 - \bar{\Theta}\xi\right)\right]^{5/6} - \Lambda^{5/6}\xi^{5/3}\right\} dh \tag{3}$$

where $\xi = (h - h_0)/(H - h_0)$ is a link parameter, $\Lambda = 2L/(kW^2)$ is a beam parameter $\bar{\Theta} = L/R_r$ and R_r is the curvature radius of the wavelength, and L is the length of laser link, $C_n^2(h)$ is the fricative-index structure parameter at the altitude of h, and the specific parameters are shown from [16].

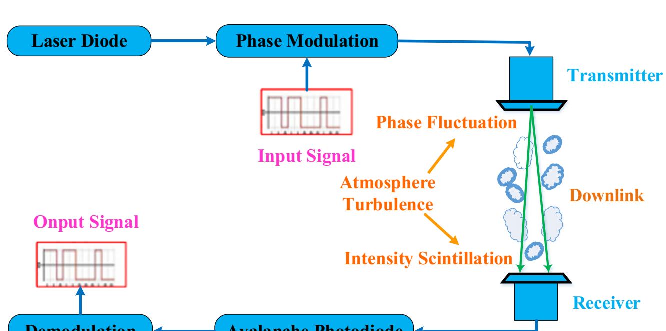

Fig.1. Schematic diagram of space downlink optical communication.

Speaking of phase fluctuation caused by atmospheric turbulence, the distribution phase error is proved to satisfy Gaussian distribution, which is [12]

$$f_g(\Delta\phi) = \frac{1}{\sqrt{2\pi}\sigma_\Phi}\exp^{-\Delta\phi^2/2\sigma^2{}_\Phi} \tag{4}$$

where $\sigma^2{}_\Phi = 2\pi\Delta f_{IF}/f_s$ is the variance of the phase fluctuation, Δf_{IF} is the statistical standard deviation of the received signal frequency, $\Delta\phi$ is the phase deviation on communication process, $f_s = 1/T_s$ is frequency.

In fact, the distance of transmission is far and signal will be affected by atmospheric turbulence. Thus, the avalanche photodiode (APD) is necessary to be applied to amplify the signal. The current from the detector and variance of noise $\sigma_1{}^2$ can be expressed as [17]

$$a_1 = G{\cdot}e{\cdot}\left(K_s(I) + K_b\right) + I_{dc}T_s \tag{5}$$

$$\sigma_1^2 = (G{\cdot}e)^2{\cdot}F{\cdot}\left(K_s(I) + K_b\right) + \sigma_T^2 \tag{6}$$

Thus, the signal-to-noise ratio by APD can be calculated as

$$r_1 = \frac{\left[G{\cdot}e{\cdot}\left(K_s(I) + K_b\right) + I_{dc}T\right]^2}{2\left[(G{\cdot}e)^2{\cdot}F{\cdot}\left(K_s(I) + K_b\right) + \sigma_T^2\right]} \tag{7}$$

where G is the photomultiplier gain factor, and F is the additional noise factor, $\sigma_T^2 = 2\kappa_c TT_s/R_L$ is the thermal noise, $K_b = \eta I_b T_s/h\upsilon$ is the photon count of the background light, η is quantum efficiency, h is the Planck constant, υ is the frequency of the signal light, i is the receiving current, T is the temperature, T_s is bit time, R_L is load resistance, and $I_b = \pi D_r{}^2 I_B/4$ is the background light in the optical communication system, K_s is the photon count corresponding to the receiving intensity I, which is [18]

$$K_s = \eta I T_s/h\upsilon \tag{8}$$

For a DPSK scheme, the BER with only consideration of intensity scintillation with the effect of the detector noise is [18]

$$\mathrm{BER}_1 = \frac{1}{2}\left[1 - erf\left(\frac{\left[G{\cdot}e{\cdot}\left(K_s(I) + K_b\right) + I_{dc}T_s\right]}{\sqrt{2\left[(G{\cdot}e)^2{\cdot}F{\cdot}\left(K_s(I) + K_b\right) + \sigma_T^2\right]}}\right)^2\right] \tag{9}$$

When effect of phase fluctuation is considered in fluctuation channel, BER will get more complicated. Speaking of the parameter K_s, it is necessary to analyze its relationship with receiving current i from signal. As we know, photon count K_s is microscopic quantity and the current i is macroscopic quantity. We can find the relationship between K_s and i by the charge conservation. To be more specific, K_s is photon count corresponding to the receiving intensity i, and $K_s e$ means the number of electric charge receiving from APD during time of T_s. On the other hand, iT_s means the same meaning by the definition of the current. Thus, there exists an important equal

$$K_s e = iT_s \tag{10}$$

where e is the electron charge, i is receiving current from signal, T_s is the optical pulse time.

By substituted Eq. (8) into Eq. (10), i is expressed as

$$i = e\eta I/h\upsilon \tag{11}$$

On the other hand, when it comes to the DPSK scheme, the signals are delayed by 1 bit to generate the differentially encoded data sequences. Thus, the difference of phase is expressed by [18]

$$H_0: \phi_2 - \phi_1 = 0$$
$$H_1: \phi_2 - \phi_1 = \pm\pi \tag{12}$$

where ϕ_1 is the phase modulated for carrier wave, ϕ_2 is the modulated phase for next code element. H_0 means the '0' is transmitted, and H_1 means '1' is transmitted.

When the signals enter the demodulation process, the final signal is expressed as

$$s_1(t) = E\cos(w_c t + \phi_1)\cdot E\cos(w_c t + \phi_2 + \Delta\phi) \tag{13}$$

where E is amplitude for signal, w_c is radiation frequency, $\Delta\phi$ is the phase error on communication process.

When the signal passes the LPF, part of the signal of higher frequency is filtered. Thus, the signal can be expressed as

$$s_2(t) = \frac{1}{2}E^2\cos(\phi_2 - \phi_1 + \Delta\phi) \tag{14}$$

Eq. (14) is also shown as

$$s_2(t) = \frac{1}{2}E^2(\cos(\phi_2 - \phi_1)\cos(\Delta\phi) - \sin(\phi_2 - \phi_1)\sin(\Delta\phi)) \tag{15}$$

As $\sin(\phi_2 - \phi_1) = 0$ from Eq. (12), we simplify the equation above and it is

$$s_2(t) = \frac{1}{2}E^2\cos(\Delta\phi)\cos(\phi_2 - \phi_1) \tag{16}$$

In reality, $\cos(\phi_2 - \phi_1)$ only affects the polarity of signal and does not change the absolute value of the signal. During the later calculus of overall BER, the variation of ergodic is classified discussed, so it can be ignored in the former theoretical calculus. As the signal expression shows the additive phase parameter, which is $\cos(\Delta\phi)$, the receiving current i will be obtained the corresponding part in detector. Thus, it means that the phase effect can be illustrated by adding $\Delta\phi$ in the signal equation. Consequently, the earlier format of receiving current in Eq. (11) is given by

$$i = e\eta I/(h\upsilon)\cos(\Delta\phi) \tag{17}$$

By substitute from Eqs. (10) and (17) to Eq. (8), the photon count K_s on fluctuation channel considering both intensity scintillation and phase fluctuation is

$$K_s = \eta I T_s\cos(\Delta\phi)/h\upsilon \tag{18}$$

Take this K_s to variances of noise and current from the detector, and can be shown as

$$a_2 = G\cdot e\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + I_{dc}T_s \tag{19}$$

$$\sigma_2^2 = (G\cdot e)^2\cdot F\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + \sigma_T^2 \tag{20}$$

Thus the signal-to-noise ratio by APD is calculated as

$$r_2 = \frac{\left[G\cdot e\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + I_{dc}T_s\right]^2}{2\left[(G\cdot e)^2\cdot F\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + \sigma_T^2\right]} \tag{21}$$

For a DPSK scheme, the BER with consideration of intensity scintillation and phase fluctuation under the effect of the detector noise is

$$\mathrm{BER}_2 = \frac{1}{2}\left[1 - erf\left(\frac{G\cdot e\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + I_{dc}T_s}{\sqrt{2\left[(G\cdot e)^2\cdot F\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + \sigma_T^2\right]}}\right)^2\right] \tag{22}$$

Besides the noise of detector at receiving terminal, the effect of atmosphere should also be emphasized. When the signal is transmitting across the atmosphere, the signal is inevitably affected by surrounding influence. It plays a great part in the performance of BER. With consideration of the atmospheric turbulence and noise from detector, the actual BER should be the ensemble average of the BER at all values of I. According to the processing model for atmospheric effect from [11], the final BER considered only the intensity scintillation should be

$$\mathrm{BER}_{r1} = \int_0^{+\infty}\mathrm{BER}_1 P_r(I)\,dI \tag{23}$$

However, if taking the effect of phase fluctuation into consideration, $\Delta\phi$ and I should be contained both in BER. Based on the specific method of expression [12], the BER is shown as

$$\mathrm{BER}_{r2} = \int_{-\infty}^{+\infty}\int_0^{\infty}\mathrm{BER}_2 P_r f_g(\Delta\phi)\,dI\,d\Delta\phi \tag{24}$$

It should be noted that the intensity scintillation and phase fluctuation effects are totally independent with each other. The light intensity will change irregularly and the phase turns to be random during transmission. These two factors have their own distribution respectively. Besides, compared with high rate of optical signal (Mb/s or Gb/s), atmospheric turbulence effect varies more slowly. Thus, we can make double integral for original BER with probability density function of intensity scintillation and phase fluctuation. This double integral can be seen as the ergodic process, which can show BER performances at all the random changes of light intensity and phase fluctuation.

By substituting Eq. (9) to Eq. (23), the BER can be shown as

$$\mathrm{BER}_{r1} = \int_0^{+\infty}\frac{1}{2}\left[1 - erf\left(\frac{(G\cdot e\cdot(K_s(I) + K_b) + I_{dc}T_s)}{\sqrt{2\left((G\cdot e)^2\cdot F\cdot(K_s(I) + K_b) + \sigma_T^2\right)}}\right)^2\right]P_r(I)\,dI \tag{25}$$

If phase fluctuation and intensity scintillation have been all considered, we can take from Eqs. (22)–(24). As the phase fluctuation not only lessens the amplitude of the current from the detector, but also changes the polarity of the current, so the ergodic process must be considered, which should be

$$\begin{aligned}\mathrm{BER}_{r2} = &\sum_{n=-\infty}^{\infty}\int_{2n\pi-\frac{\pi}{2}}^{2n\pi+\frac{\pi}{2}}\int_0^{\infty}\frac{1}{2}\left[1 - erf\left(\frac{G\cdot e\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + I_{dc}T_s}{\sqrt{2\left[(G\cdot e)^2\cdot F\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + \sigma_T^2\right]}}\right)^2\right]\cdot f_g(\Delta\phi)P_r(I)\,dI\,d\Delta\phi\\ &+\sum_{n=-\infty}^{\infty}\int_{2n\pi-\frac{3\pi}{2}}^{2n\pi-\frac{\pi}{2}}\int_0^{\infty}\frac{1}{2}\left[1 - erf\left(\frac{G\cdot e\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + I_{dc}T_s}{\sqrt{2\left[(G\cdot e)^2\cdot F\cdot\left(\eta I T_s\cos(\Delta\phi)/h\upsilon + K_b\right) + \sigma_T^2\right]}}\right)^2\right]\cdot f_g(\Delta\phi)P_r(I)\,dI\,d\Delta\phi\end{aligned} \tag{26}$$

From the equation of BER above, the phase fluctuation effect on space downlink optical communication system under atmospheric turbulence can be further analyzed by numerical method.

3. Numerical results and analysis

Numerical results are based on the following parameters, which refer to Ref. [9] and our optical communication system: zenith angle $\zeta = 0°$, the divergence angle $\theta = 30\ \mu$rad, wavelength $\lambda = 850$ nm, the altitude of the ground station $h_0 = 100$ m, the altitude of the satellite $H = 36{,}000$ km, quantum efficiency of APD

$\eta = 0.75$, load resistance $R_L = 50\ \Omega$, additional noise factor $F = G^{0.5}$, photomultiplier gain factor $G = 100$, the receiving aperture $D_r = 0.4$ m, temperature $T = 300$ K, the dark current $I_{dc} = 1$ nA, the time duration per slot $T_s = 10$ ns, spectral density $I_b = 10$ nW/m^2, the energy loss $\alpha = 1$, P_T is 1 W, atmospheric refractive index $C_n^2 = 10^{-16}$ m$^{-2/3}$.

Fig. 2 shows the BER performance versus transmission power at different data rates on fluctuation channel. With the increase of transmission power, BER performances at different data rates show the stable decrease. When the effect of phase fluctuation is considered, the BER performance on fluctuation channel will increase to some extent. To be more specific, it produces 13 dB, 6 dB, and 0.4 dB deterioration for BER at different data rates (100 Mb/s, 200 Mb/s, 2.5 Gb/s respectively) when the transmission power is at 1 W. It also indicates that with consideration of phase fluctuation, it produces more BER increase on fluctuation channel at data rate of 100 M than in data rate of 2.5 Gb/s. It means that the effect of phase fluctuation on BER performance in the low data rate (100 Mb/s) is larger than BER performance in the high data rate (2.5 Gb/s).

Apart from transmission power, another important parameter in space optical communication system named wavelength is also valuable to be explicated on fluctuation channel. In Fig. 3, BER performances versus wavelength are shown at different data rates on fluctuation channel. When the wavelength increases from 100 nm to 1600 nm, the BER in all different circumstances have the stable decrease. It can be seen that the difference of BER performance at same data rate becomes obvious when the wavelength is over 250 nm. In addition, when the wavelength is 400 nm, 800 nm, 1310 nm, 1550 nm, the BER is about 3 dB, 13 dB, 28 dB and 34 dB higher on fluctuation channel with consideration of phase fluctuation at the data rate of 100 M. But when data rate is 2.5 Gb/s, it produces little height for BER on fluctuation channel with increasing of wavelength. It indicates that the influence of phase fluctuation becomes more obvious for wavelength at lower data rate. However, the phase fluctuation effect is not sensitive to wavelength at high data rate. It means that designers do not need to think about the impression of the wavelength if the data rate of the detector is high such as 2.5 Gb/s.

When it comes to parameters related to the receiver terminal, some other properties will be researched to analyze the quality of propagation system. Fig. 4 shows the BER versus receiving diameter at different data rates on fluctuation channel. With the receiver diameter increase, the BER at three different data rates on fluctuation channel show the stable decrease. When the effect of phase fluctuation is considered on fluctuation channel, the BER is

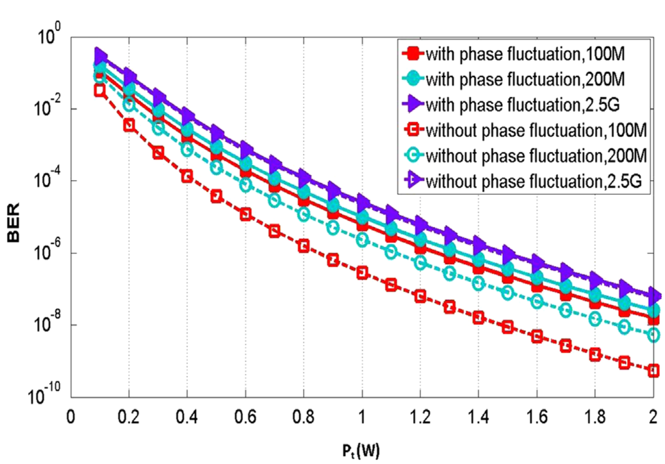

Fig. 2. BER versus transmitting power with and without phase fluctuation at different data rates.

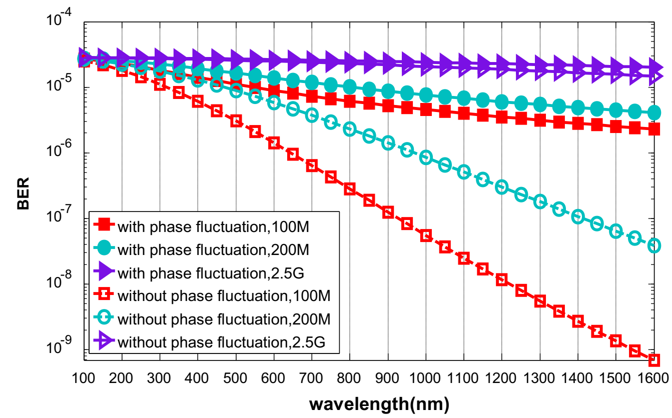

Fig. 3. BER versus wavelength with and without phase fluctuation at different data rates.

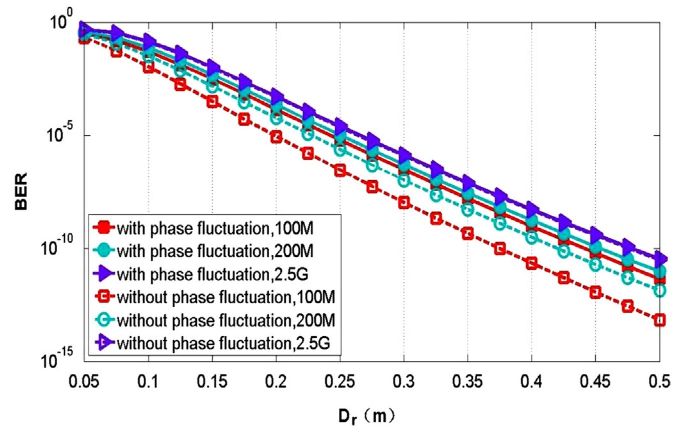

Fig. 4. BER versus receiving diameter with and without phase fluctuation at different data rates.

about 9 dB higher, 6 dB higher and 0.5 dB higher at different data rates (100 Mb/s, 200 Mb/s, 2.5 Gb/s) when the receiving diameter is merely 0.25 m. Actually, enlarging the receiving diameter will definitely enhance the cost of terminal in ground. The increase of receiving diameter is limited by these factors. As a result, the choice of reasonable parameter plays great part in improving the performance of communication system.

Fig. 5 indicates the performance of BER versus divergence angle at different data rates on fluctuation channel. When the divergence angle increases from 20 μrad to 50 μrad, the BER on fluctuation channel shows the stable increase. It means that the larger divergence angle will decrease communication quality. It can be explained that received power from detector will be diminished with the increase of divergence angle. In addition, when the divergence angle is changing from 25 μrad to 50 μrad, the BER produce about 40 dB higher on fluctuation channel at the data rate of 2.5 Gb/s. However, with consideration of the effect of phase fluctuation, the raise of BER does change a little on fluctuation channel at the data rate of 2.5 Gb/s when the divergence angle increases from 5 μrad to 50 μrad. To be more specific, it produces about 0.4 dB on fluctuation channel at the data rate of 2.5 Gb/s. It is noted that the effect of phase fluctuation is not sensitive to variations of divergence angle at high data rate, although the communication quality can be deteriorated. Larger divergence angle will reduce the difficulty of communication system design and improve stability of propagation process.

Moreover, gain factor is another important parameter to discuss in the space optical communication system. Fig. 6 shows the BER versus APD gain factor at different data rates on fluctuation

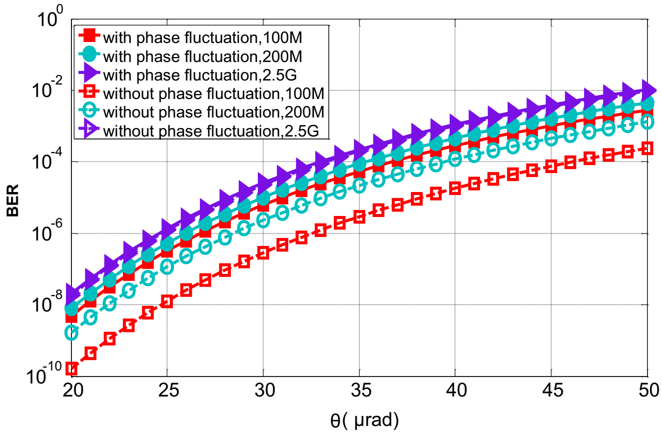

Fig. 5. BER versus divergence angle with and without phase fluctuation at different data rates.

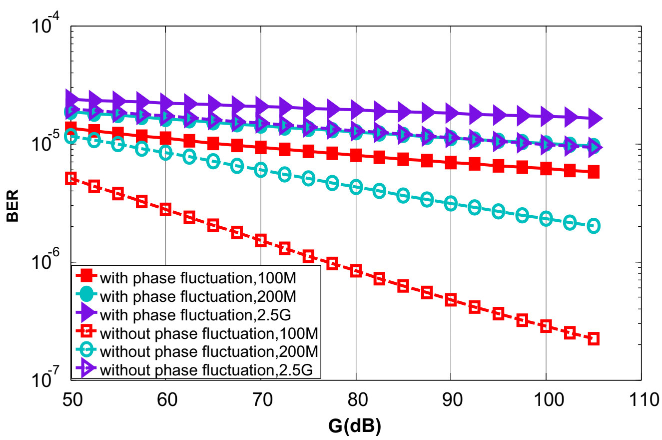

Fig. 6. BER versus APD gain factor with and without phase fluctuation at different data rates.

channel. When the APD gain factor increases from 50 to 110, the BER of different data rates have the gradual decrease. From the figure, when the APD gain factor is enlarging from 70 to 100, three real lines show that the BER on fluctuation channel decease only 1.7 dB, 1.4 dB, 0.8 dB at the data rate of 100 Mb/s, 200 Mb/s, 2.5 Gb/s respectively. However, three dotted lines show that performances of BER decease obviously with the increasing of APD gain factor when phase fluctuation is considered. This will be helpful to the choice of APD gain factor in the practical system.

4. Conclusion

The bit error rate (BER) performance of space downlink optical communication system is analyzed with consideration of both intensity scintillation and phase fluctuation on fluctuation channel. Through analysis mentioned above, the communication quality is deteriorated by the effect of phase fluctuation. At high data rate, BER performance does not change obviously as to the wavelength and APD gain factor. Specifically, the phase effect on BER is little, but becomes sensitive especially at low data rate such as 100 Mb/s. When it comes to the receiving diameter and divergence angle, we can adjust them properly so as to take better BER performance. These conclusions can help keep greater communication on fluctuation channel and improve design of practical system.

Acknowledgments

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References

[1] L. Yang, X.Q. Gao, M.S. Alouini, Performance analysis of relay-assisted all-optical FSO networks over strong atmospheric turbulence channels with pointing errors, J. Light. Technol. 32 (23) (2014) 4011–4018.
[2] Y.C. Chi, G.R. Lin, Self optical pulsation based RZ-BPSK and reused RZ-OOK bidirectional oc-768 transmission, J. Light. Technol. 32 (20) (2014) 3728–3734.
[3] L. Yang, M.O. Hasna, X.Q. Gao, Asymptotic BER analysis of FSO with multiple receive apertures over M-distributed turbulence channels with pointing errors, Opt. Express 22 (15) (2014) 18238–18245.
[4] S.T. Le, K.J. Blow, V.K. Mezentsev, S.K. Turitsyn, Bit error rate estimation methods for QPSK co-OFDM transmission, J. Light. Technol. 32 (17) (2014) 2951–2959.
[5] P. Wang, L. Zhang, L.X. Guo, F. Fang, T. Shang, R.R. Wang, Y.T. Yang, Average BER of subcarrier intensity modulated free space optical systems over the exponentiated Weibull fading channels, Opt. Express 22 (17) (2014) 20828–20841.
[6] J. Ma, Y.J. Jiang, L.Y. Tan, S.Y. Yu, W.H. Du, Influence of beam wander on bit-error rate in a ground-to-satellite laser uplink communication system, Opt. Lett. 32 (22) (2008) 2611–2613.
[7] T. Chiba, Spot dancing of the laser beam propagated through the turbulent atmosphere, Appl. Opt. 10 (11) (1971) 2456–2461.
[8] L.C. Andrews, R.L. Phillips, C.Y. Hopen, M.A. Al-Habash, Theory of optical scintillation, J. Opt. Soc. Am. 16 (18) (1974) 1417–1429.
[9] M. Jing, Y.J. Jiang, S.Y. Yu, L.Y. Tan, W.H. Du, Packet error rate analysis of OOK, DPIM and PPM modulation schemes for ground-to-satellite optical communications, Opt. Commun. 283 (2010) 237–242.
[10] J.C. Ding, M. Li, M.H. Tang, Yan Li. and J.Y. Song, BER performance of MSK in ground-to-satellite uplink optical communication under the influence of atmospheric turbulence and detector noise, Opt. Lett. 38 (18) (2013) 3488–3491.
[11] A. Garcia-Zambrana, C. Castillo-Vazquez, B. Castillo-Vazquez, Rate-adaptive FSO links over atmospheric turbulence channels by jointly using repetition coding and silence periods, Opt. Exp. 18 (24) (2010) 25422–25440.
[12] Xie, G.D., Dang, A.H., Guo, H., 2011. Effects of atmosphere dominated phase fluctuation and intensity scintillation to DPSK system. In: Proceedings of the IEEE International Conference on Communication ICC.
[13] L. Andrews, R. Phillips, C. Hopen, Laser Beam Scintillation with Applications, SPIE Press, New York, 2001.
[14] M. Toyoshima, T. Jono, K. Nakagawa, A. Yamamoto, Optimum divergence angle of a Gaussian beam wave in the presence of random jitter in free-space laser communication systems, J. Opt. Soc. Am. 19 (3) (2002) 567–571.
[15] L.C. Andrews, R.L. Phillips, P.T. Yu, Optical scintillations and fade statistics for a satellite- communication system, Appl. Opt. 34 (33) (1995) 7742–7751.
[16] D.L. Hutt, Modeling and measurement of atmospheric optical turbulence over land, Opt. Express 38 (8) (1999) 1288–1295.
[17] J. Jay Jones, Modern Communication Principle with Application to Digital Signaling, McGraw Hill, New York, 1967.
[18] Gagliardi, R.M., Karp, S., 1998. Optical Telecommunications. New York, Publishing House of Electronics Industry.