

## Effects of phase fluctuation and intensity scintillation caused by weak atmospheric turbulence to BER employing distributed antenna array

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**Abstract:** In free space optical link systems, atmospheric turbulence is a major limiting factor. Atmospheric turbulence will result in both intensity scintillation and phase fluctuation to the laser beam. This paper is based on MZI-DPSK modulation, considered effects of intensity scintillation and phase noise caused by large-scale and small-scale turbulence to BER, and intensity scintillation is satisfy the inverse Gaussian distribution and phase fluctuation is satisfy the Gaussian distribution. We adopt the distributed antenna array receiver technology, study the performance of bits Error Ratio in free-space optical communication through the atmospheric turbulence, and derive the average BER of antenna array as a function of the phase error considering the inner scale and outer scale effects. In order to improve the BER performance, antenna receiver adopts Maximum Ratio Combining (MRC) technology. The simulation results show that the phase error has a great impact on the error rate, and the inner scale and outer scale has a negligible impact on the error rate. Using antenna reception can reduce the error rate of the system to improve the performance of the communication system and draw the best sub-antennas number of the antenna array receiver.

**Key words:** free space optical communication; weak turbulence; distributed antenna array;

bit error rate(BER); phase error; inner scale and outer scale

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## 自由空间光通信系统中弱大气湍流引起的相位波动和强度闪烁对 DPSK 调制系统的影响

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**摘 要:** 大气湍流是自由空间光通信链路系统的主要限制因素。大气湍流造成光束的强度闪烁和相位起伏。因此, 基于 MZI-DPSK 调制, 考虑大、小湍流尺度引起的强度闪烁和相位噪声对误码率的影响且强度闪烁满足逆高斯分布和相位波动满足高斯分布。利用分布式天线阵接收技术, 研究了大气湍流下自由空间光通信链路的误码率性能, 推导了在内外尺度下, 分布式天线阵接收的误码率关于相位

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误差的函数表达式。为了提高误码率的性能,天线阵接收采用了最大比合并技术。仿真结果得出相位误差对误码率的影响很大;内外尺度对误码率的影响可以忽略不计。采用天线阵接收可以降低系统的误码率,提高通信系统的性能,且得出天线阵接收的最佳子天线个数。

**关键词:** 自由空间光通信; 弱湍流; 分布式天线阵; 误码率; 相位误差; 内外尺度

## 0 Introduction

Free-space optical communication has some high data rate transmission characteristics, for example, cost-effective, no frequency applications, wide bandwidth. In recent years, free-space optical communication has been widespread concern<sup>[1-2]</sup>. However, the performance of free-space optical communication system is severely influenced by atmospheric turbulence. Atmospheric turbulence cause intensity scintillation, beam spread, beam drift and phase fluctuation and so on, seriously affected the communication rate and communication reliability of free-space optical communications<sup>[3]</sup>. In order to overcome the effects of atmospheric turbulence to achieve effective compensation for communication systems, in free space optical communication links, many fading and weakening techniques are proposed. For OOK intensity modulation direct detection free space optical communication system<sup>[4-6]</sup>, the receiving end uses the aperture smoothing effect and space diversity reception technology, can reduce the influence of atmospheric turbulence, OOK modulation implementation is simple and flexible, but it will cause the system error rate<sup>[7]</sup>. Heterodyne detection is a relatively sophisticated detection method, but it can overcome the effects of thermal noise and improve receiver sensitivity and increase transport capacity<sup>[8-9]</sup>.

Anhong Dang etc<sup>[10]</sup> use Maher interferometer DPSK modulation system to study the performance of BER in atmospheric turbulence, this transmit system does not need a partial oscillator and phase locked loop, simplifying system design. Nestor D etc<sup>[11]</sup> respectively use OOK modulation and DPSK modulation to study under the inverse Gaussian channel model the weak turbulence caused the decline of communication links, inverse Gaussian channel model efficiently approximates

logarithmic channel model when variance  $\sigma^2 I$  is less than 0.35, and it's have closed-form expression of the moment-generating function (MGF), and BER expression is simpler than the expression of logarithmic channel model. But they did not consider the effect of phase error on BER.

This paper use the MZI-DPSK modulation heterodox detection system to study under the inverse Gaussian channel model effects of the Intensity Scintillation and phase error caused by atmospheric turbulence on the bit error rate performance of the free space optical communication link. In order to improve the performance of free space optical communication system, distributed antenna array on the receiving end is adopted to receive the maximal ratio combining technology. The second part gives the system model and the inverse Gaussian distribution model under the atmospheric turbulence model and considering the inner scale and outer scale scintillation variance of expression; The third part gives the DPSK modulation system under the inverse Gaussian distribution model of average bit error rate expression; The fourth part is discussion and simulation results; The fifth part draw conclusions.

## 1 System model and the channel model

### 1.1 System model

Figure 1 is a schematic block diagram of an antenna array receiving system, after antenna array that  $n$  sub-antennas composing of receive signal light through the atmospheric turbulence distortion, the signal light is coupled into a single mode optical fiber<sup>[12]</sup>. By the optical fiber phase shifter for dynamic adjustment phase distortion, through erbium-doped fiber amplifier (EDFA) bait for optical zoom, while introducing the spontaneous emission noise (ASE), then through a band-pass filter to filter out the spontaneous emission noise, enter the delay interferometer (MZI), in MZI, the signal light enter two

arms of MZI into two routes, one of the arm increase the delay time of one bit. Assuming the two arms are perfectly matched, in the MZI outlet two adjacent signals into the

strength signal, balanced receivers received optical signal from the two ports of MZI, for photoelectric conversion, and then output the power.

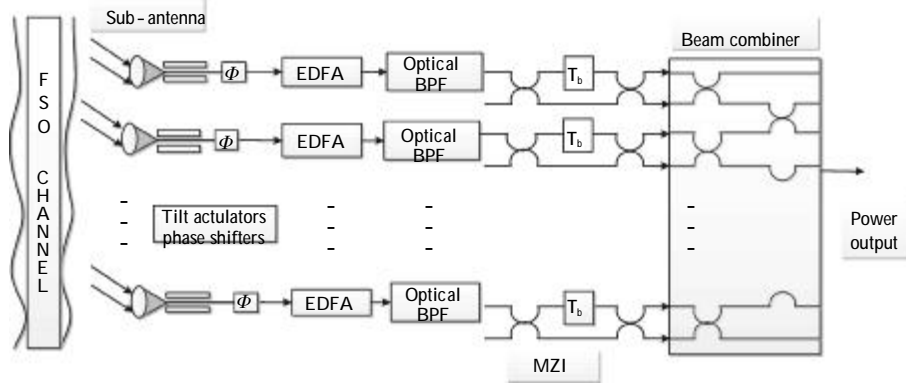


Fig.1 In free space optical communication link antenna receiving DPSK modulation system

1.2 Inverse Gaussian distribution channel model

The inverse Gaussian distribution model is used to describe the performance of the turbulent channel in the free space optical communication. The probability density function(PDF) under Inverse Gaussian channel<sup>[7]</sup>:

$$f_i(I) = \sqrt{\frac{1}{\pi\sigma_i^2 I^3}} \exp\left(-\frac{(I-1)^2}{2\sigma_i^2 I}\right) \quad (1)$$

$\sigma^2 I$  is scintillation variances, regardless of the inner scale and outer scale (namely  $L_0 \approx \infty, I_0 \approx 0$ ) effect<sup>[13]</sup>:

$$\sigma_i^2 = \exp\left[\frac{0.49\sigma_R^2}{(1+0.65d^2+1.11\sigma_R^{12/5})^{7/6}} + \frac{0.51\sigma_R^2(1+0.69\sigma_R^{12/5})^{-5/6}}{(1+0.90d^2+0.62d^2\sigma_R^{12/5})^{5/6}}\right] - 1 \quad (2)$$

Considering the inner scale and outer scale effect, scintillation variances<sup>[11]</sup>:

$$\sigma_i^2 = \exp\left[\sigma_{\ln x}^2(D, I_0) - \sigma_{\ln x}^2(D, L_0) + \frac{0.51\sigma_{PL}^2(1+0.69\sigma_{PL}^{12/5})^{-5/6}}{(1+0.90d^2(\sigma_R/\sigma_{PL})^{12/5}+0.62d^2\sigma_R^{12/5})}\right] - 1 \quad (3)$$

$0 \leq \sigma_R^2 \leq \infty$

In an expression,  $\sigma_R^2$  is the Rytov variance,  $\sigma_R^2 = 1.23C_n^2 k^{7/6} L^{11/6}$ ,  $d = \sqrt{kD^2/4L}$  is the ratio of Round hole radius and the Fresnel zone,  $\sigma_{\ln x}^2(D, I_0)$ ,  $\sigma_{\ln x}^2(D, L_0)$  respectively are the inner scale and outer scale of the logarithmic amplitude variance. Under weak turbulence,  $\sigma_{PL}^2$  is the plane wave scintillation index based on the atmospheric spectral modification. In free -space optical communication systems of the antenna array receiving, we define the sum S of N independent of the same inverse

Gaussian distribution of signal light auxiliary illumination:

$$S = \sum_{i=1}^N I_i \quad (4)$$

In the expression,  $I_i$  is the value of probability density function (PDF) under inverse Gaussian channel in the formula(1), the probability density function formula of the N sub antenna reception of Inverse Gauss distribution:

$$f_i(I) = \sqrt{\frac{1}{2\pi\sigma_i^2 I^3}} \exp\left(-\frac{(I-1)^2}{2\sigma_i^2 I}\right) \quad (5)$$

1.3 Influence of atmospheric turbulence on the phase noise

Phase noise caused by atmospheric turbulence can be as a statistical standard deviation of the relative received signal frequency  $\Delta f$ , then the phase error<sup>[14-15]</sup>:

$$\Delta\phi(t) = \int_t^{t+T_b} 2\pi f(t) dt \quad (6)$$

$T_b$  is the interval of two consecutive detection time. Based on perturbation theory<sup>[11]</sup>, phase noise is satisfied the Gaussian distribution, then the distribution of  $\Delta\phi$ :

$$f_g(\Delta\phi) = \frac{1}{\sqrt{2\pi}\sigma_\phi} e^{-\frac{\Delta\phi^2}{2\sigma_\phi^2}} \quad (7)$$

$f_g(\Delta\phi)$  is the probability density function of  $\Delta\phi$ ,  $\sigma_\phi^2$  is the phase noise variance, defined as follows:

$$\sigma_\phi^2 = \frac{2\pi\Delta f}{f_s} \quad (8)$$

In the expression,  $f_s = \frac{1}{T_b}$  is the signal rate.

## 2 BER analysis

Assuming that the thermal noise was limited, random phase noise is as the duration of the bit, then in T free - space optical communication systems, the DPSK modulation error rate<sup>[16]</sup>:

$$p(e | I, \Delta\phi) = \frac{1}{2} \exp(-\bar{\gamma} I |\cos(\Delta\phi)|) \quad (9)$$

In the expression, the average SNR  $\bar{\gamma}$ :

$$\bar{\gamma} = \frac{RA^2}{2q} \quad (10)$$

In the expression, R is the sensitivity of the photoelectric detector, A is modulation amplitude, q is the elementary charge of electricity. erfc (·) is the complementary error function, then the average error rate  $P_e$ <sup>[10]</sup>:

$$P_e = \int_0^\infty \int_{-\infty}^\infty p(e | I, \Delta\phi) f(I) f_g(\Delta\phi) dI d\Delta\phi = \int_{-\infty}^\infty M(\bar{\gamma}, \Delta\phi) f_g(\Delta\phi) d\Delta\phi \quad (11)$$

In the expression, M ( $\bar{\gamma}, \Delta\phi$ ) is the moment generating function<sup>[11]</sup>:

$$M(\bar{\gamma}, \Delta\phi) = \int_0^\infty p(e | I, \Delta\phi) f(I) dI = \exp\left(\frac{1}{\sigma_i^2} (1 - \sqrt{1 + 2\sigma_i^2 \bar{\gamma} |\cos(\Delta\phi)|})\right) \quad (12)$$

That the expression (12) and (7) was substituted into the expression (11) can draw a conclusion. Using DPSK modulation, considering the influence of the phase noise, the average error rate the of the free - space optical communication system:

$$P_e = \frac{1}{\sqrt{2\pi} \sigma_\phi} \int_{-\infty}^\infty \exp\left(\frac{1}{\sigma_i^2} \times (1 - \sqrt{1 + 2\sigma_i^2 \bar{\gamma} |\cos(\Delta\phi)|})\right) e^{-\frac{\Delta\phi^2}{2\sigma_\phi^2}} d\Delta\phi \quad (13)$$

Space diversity reception technology can effectively reduce the effects of atmospheric scintillation<sup>[17]</sup>, the fading of signals that different receiving antenna received are mutually independent, the instantaneous SNR using the maximum ratio combining technology<sup>[11]</sup>:

$$\bar{\gamma}_N = \bar{\gamma} \sum_{i=1}^N I_i \quad (14)$$

So using DPSK modulation, and the inverse Gaussian distribution and MRC combining technique, the average error rate of the free space optical communications system:

$$P_e = \frac{1}{\sqrt{2\pi} \sigma_\phi} \int_{-\infty}^\infty \exp\left(\frac{N}{\sigma_i^2} \times (1 - \sqrt{1 + 2\sigma_i^2 \bar{\gamma} |\cos(\Delta\phi)|})\right) e^{-\frac{\Delta\phi^2}{2\sigma_\phi^2}} d\Delta\phi \quad (15)$$

## 3 Results and discussions

Some constants the following simulation have some constants, for example, wavelength  $\lambda = 1\ 550\ \text{nm}$ , the propagation distance  $L = 1\ \text{km}$ , the sub - antennas diameter  $D = 5\ \text{cm}$ .

Figure2 is Average Bit Error Rate(BER) as a function of SNR for different value of  $\Delta f$  without considering the inner scale, outer scale ( $L_0 \approx \infty, l_0 \approx 0$ ), and Rytov variance  $\sigma_R^2 = 0.36$ , and the sub - antennas diameter  $D = 5\ \text{cm}$ , and the number of the sub - antennas  $n = 4$  (The selection of the number is based on the product of Flight Strata that Light Point launched<sup>[18]</sup>), at the transmission rate of 1 GHz. The figure shows, the received signal frequency increases, the bit error rate increases. When  $\Delta f > 100\ \text{MHz}$ , the error rate little change with the increase of  $\Delta f$  the error rate of  $\Delta f = 3\ 000\ \text{MHz}$  and the error rate of  $\Delta f = 200\ \text{MHz}$  are almost coincide. When  $\Delta f > 200\ \text{MHz}$ , namely the phase error variance  $\sigma_\phi^2 > 2\pi/5$ , the error rate does not change with increasing of  $\Delta f$ .

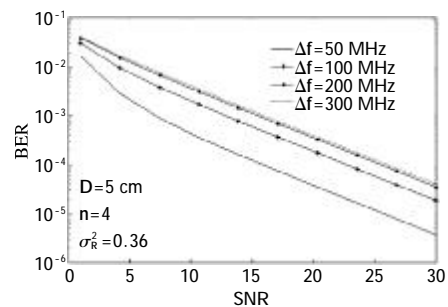


Fig.2 Average Bit Error Rate(BER) as a function of SNR for different value of at the transmission rate of 1 GHz

Figure 3 is the diagram with the plane wave scintillation variance and  $\sigma_R$  under the different scale when the sub-antennas aperture respectively are  $D=5$  cm and  $D=10$  cm. The figure shows, when  $\sigma_R < 0.1$ , scintillation variance does not change with the change of the inner scale and outer scale and sub-antenna aperture. When  $0.1 < \sigma_R$  and  $\sigma_R < 0.2$ , scintillation variance does not change with the change of the inner scale and outer scale, but changes with the different caliber. When  $0.2 < \sigma_R$  and  $\sigma_R < 1$  and  $D=5$  cm, the intensity variance of  $I_0 \approx 1$  mm is less than the  $I_0 \approx 4.6$  mm, and the gap changes with the increase of  $\sigma_R$ , but far less than the scintillation variance that does not consider the inner scale and outer scale ( $L_0 \approx \infty, I_0 \approx 0$ ). When the inner scale and outer scale is the same, effect of the outer scale of  $L_0 \approx \infty$  and  $L_0=1$  m on the scintillation variance is very small. When  $D=10$  cm, the scintillation variance is far less than the scintillation variance of  $D=5$  cm, and the effects of the inner scale and outer scale on the scintillation variance is very small.

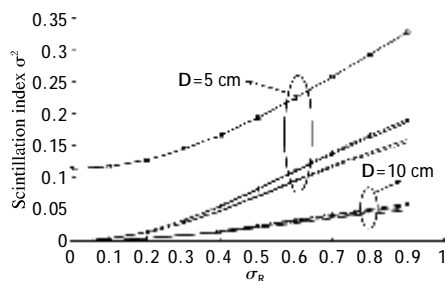


Fig.3 Plane wave scintillation index as a function of  $\sigma_R$  for different the inside and outside scale

Figure 4 is the Average Bit Error Rate (BER) as a function of SNR for the different number of sub-antenna  $n$ , when the received signal frequency  $\Delta f=100$  MHz, the sub-antennas aperture is 5 cm and  $\sigma_\phi^2=0.36$ , the inner scale and outer scale respectively are  $I_0=1$  mm,  $L_0=1$  m and  $I_0=4.6$  mm,  $L_0=1$  m. The figure shows, when the sub-antenna  $n=1$  and the scale  $L_0=1$  m, there is little difference between A and B the error rate of inner scale  $I_0=1$  mm and inner scale  $I_0=4.6$  mm. When the sub-antenna  $n=3, 4, 5$ , the inner scale and outer scale has no effect on the bit error rate.

The bit error rate is decreased with increasing the

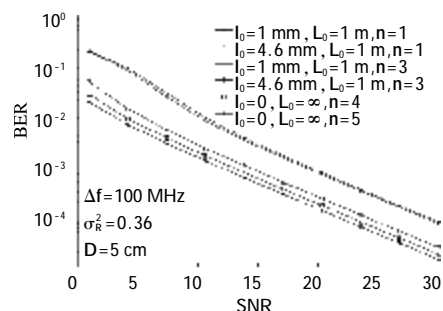


Fig.4 Average Bit Error Rate(BER) as a function of SNR for different value of different scale and the number of sub-antenna

number of sub-antenna, and the decreasing trend get smaller. It shows, whether it is a single antenna or antenna reception, effects of the inner scale and outer scale on the bit error rate is very small, for simplicity, when we calculate the bit error rate, the inner scale and outer scale can be ignored, using antenna reception can reduce the error rate of the system, considering the complexity of devices and the difficulty of making devices, the number of antenna that less is more, then exist the best receiving sub-antennas number.

## 4 Conclusion

In a free space optical communication system, the phase fluctuation and intensity scintillation caused by atmospheric turbulence reduces the receiving performance of the free space optical communication receiving end. This paper is based on MZI-DPSK modulation, in the inverse Gauss distribution for the atmospheric turbulence channel model, we study that the effect of phase noise and intensity scintillation caused by the inner scale and outer scale turbulence on BER, we derive the bit error rate expressions about inner scale and outer scale and phase noise under single antenna reception and space diversity reception with maximal ratio combining technique. The simulation results show, the effects of the inner scale and outer scale turbulence to scintillation variance gradually increase with the increases of Rytov variance, and consideration of the inner scale and outer scale. The scintillation variance far less than that does not consider the inside and outside scale. The inner scale and outer

scale almost haven't effects on the bit error rate in receiving systems. Using the antenna array receiver, it can reduce the bit error rate of system and have the best receiver sub-antennas number. Effect of the different phase noise on bit error rate is great, but it almost has no effect on the bit error rate when the phase noise variance greater than  $0.4\pi$ .

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