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REGULAR PAPER

Research on transmission performance of multi-input multi-output free space optical communication system channel

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Abstract
Traditional systems are susceptible to noise, atmospheric turbulence and other factors, resulting in large system channel transmission error and outage. Therefore, a new method of analyzing transmission performance of multi-input multi-output free space optical communication system channel with an improved space diversity technology is proposed in this paper in the context of different turbulence environments. In this method, with the Gamma–Gamma distribution model, the atmospheric turbulence process is analyzed and the optical field distribution is transformed into a disturbing function based on multi-scale impact; the differential phase-shift-keyed coherent intensity modulation method is adopted to control the turbulence so that the transmitter and receiver can obtain channel state information; a multi-input multi-output free space optical communication (MIMO-FSO) system is formed by constructing a system model and a multi-input multi-output channel model, and the MIMO-FSO system channel is modulated with the improved maximal ratio combining technology to analyze the transmission performance of MIMO-FSO system channel. Experimental results show that the improved method can reduce bit error rate and outage probability of the free space optical system, which has some advantages over traditional systems.

Keywords Optical communication · Multi-input · Multi-output · Modulation · Transmission

1 Introduction

Optical communication technology is a communication mode adopting light as a medium of communication. Mobile communication technology, communication technology and satellite communication technology are listed as technologies generated in the 1990s, whose emergence and development have brought communication technology into one innovation era [1, 2]. Optical communication technology mainly consists of two categories, namely, wireless optical communication and wired optical communication. Traditional wired optical communication is optical fiber communication technology, which is already a mature technology and has become an important transmission method for wide area networks and regional networks [3]. With the effective promotion of fiber-to-the-home service, some returning cable users need to re-establish indoor communication devices [4]. For the device installation cost and the indoor damage caused by exposed fiber, most users prefer the wireless access mode. Wireless optical communication, also known as free space optical communication (FSO), enables wireless optical communication over a range of distances with an unobstructed line-of-sight path between the transmitter and receiver and sufficient optical transmit power. However, FSO system is susceptible to channel during transmission, resulting in poor transmission performance. For the above problem, in Ref. [5], a free space optical communication Lognormal–Rician channel model is designed. From the aspect of atmospheric channel, how to overcome the phenomenon of light intensity flicker and improve the communication performance of FSO system. The intensity density function (PDF) of the light intensity is usually used to describe the intensity flicker. By estimating the LR channel parameters, various parameter indexes of the atmospheric channel can be obtained, and the communication quality of the atmospheric channel can be grasped in real time. However, the model has a large time overhead during the build process, which will reduce efficiency. In

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Ref. [6], the multi-spectral wavelength division multiplexing visible light communication system is analyzed based on the overlapping of LED spectrum, but LED radiation spectrum will overlap and generate channel crosstalk. In Ref. [7], the bit error rate performance of coherent OFDM free space optical communication (FSO) system is studied and the effect of OFDM mapping and mapping order on bit error rate performance of the system is considered, on which the closed form expression of system symbol error rate is deduced. In practice, the bit error rate performance of the system can be improved by reducing the order of mappings, but it requires a good system, and it results in poor operability. In Ref. [8], that FSO is a kind of line-of-sight bandwidth communication technology is mentioned, which needs a strict and accurate distance between the receiver and transmitter. If there is an obstacle within this distance, the quality of communication will be seriously affected, and the system channel transmission performance will be reduced for the oscillation of equipment due to unavoidable influence of wind force during laser reception and emitting between the two ends. In Ref. [9], domestic scholars put forward the application of adaptive optics technology in experimental form. When it is applied in the wavefront distortion compensation, it can improve the transmission performance of the communication system. However, with this method, the system complexity is increased to a certain extent.

To solve the above problems, a new method of analyzing transmission performance of MIMO-FSO system channel with an improved space diversity technology is proposed. In this method, with the Gamma–Gamma distribution model, the atmospheric turbulence process is analyzed and the optical field distribution is transformed into a disturbing function based on multi-scale impact. The differential phase-shift-keyed coherent intensity modulation method is adopted to control the turbulence so that the transmitter and receiver can obtain the channel state information. A MIMO-FSO system is formed by constructing a system model and a multi-input multi-output channel model, and the system channel is modulated with improved maximal ratio combining technology to analyze the transmission performance of MIMO-FSO system channel.

2 Construction of channel model of MIMO-FSO system

MIMO-FSO system is susceptible to atmospheric environment during signal transmission, resulting in the randomness of transmission channel, which reduces the transmission performance. Gas molecules and aerosol plasmas in the atmosphere interfere with the FSO system and the transmission performance of the system through the action of light absorption and reflection, etc. [10]. As the transmission medium of optical communication, atmospheric turbulence has become the main factor that affects the transmission performance of MIMO-FSO system channel. MIMO-FSO system is constructed as shown in Fig. 1.

For the FSO system, atmospheric turbulence mainly changes randomly according to the local atmospheric environment, affecting the channel performance of the FSO system [11].When light passes the atmosphere, under the influence of atmospheric turbulence, the signal phase and amplitude change randomly, resulting in shake of light intensity of the receiver, which affects the communication effect. The shake index SI is expressed as follows [12]:

$$|Z| = \sqrt{I_{\mathrm{OSR}} + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}, \tag{1}$$

where I_{OSR} is the optical strain response coefficient value, the intensity of the received signal is expressed by f; the

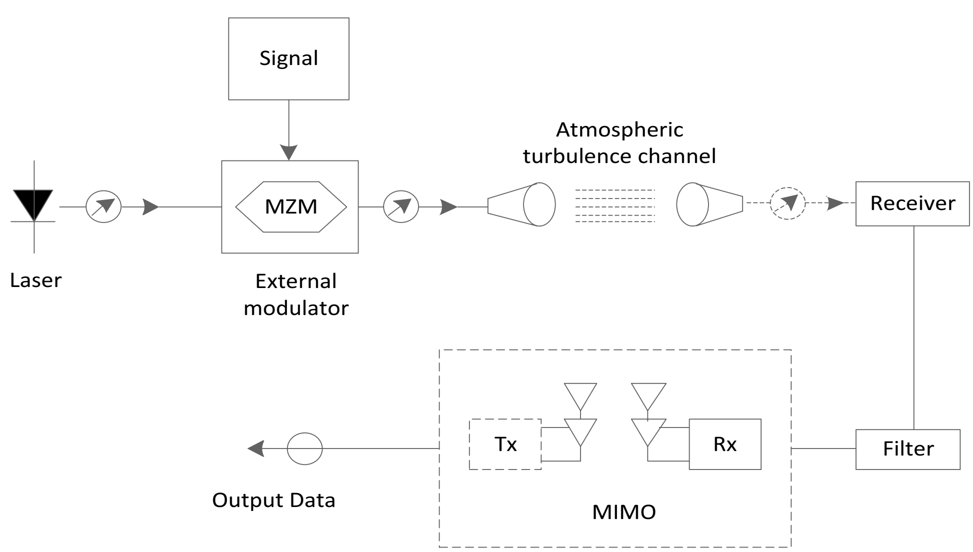

Fig. 1 Schematic diagram of MIMO-FSO system

calculated expected value is expressed by C; R represents the damping coefficient and L represents the optical transmission distance. In the FSO system, the diversity technology can be adopted to alleviate the influence of fading channel and the noise on system communication performance and solve the problem of attenuation of multipath channel transmission signal. The multi-input multi-output (MIMO) technology in the space diversity technology is adopted, and it is described that M transmit antennas are used at the transmitter and N receive antennas are used at the receiver. That is to say, it is a multi-aperture transmitter multi-aperture receiving method [13]. With the differential phase-shift-keyed coherent intensity modulation mode, channels are distributed independently, and there is additive white Gaussian noise. The nth detector acquires the signal y_n, which is expressed as follows:

$$y_n = h_{mn}Rx + |Z|, \tag{2}$$

where the state of the mth channel sent to the nth receiving link is expressed by h_{mn}; the photoelectric conversion efficiency is expressed by R; the communication signal is expressed by x and $x \in \{0, 2P_t\}$; P_t represents the average transmit power; variance is the zero-mean of σ_n^2; the white Gaussian noise is expressed by n_n. For the link sending from the mth transmitting aperture to the nth receive aperture, the signal-to-noise ratio of the link received signal is described as:

$$\gamma_{mn} = \frac{2P_t^2R^2h_{mn}^2y_n}{\sigma_n^2}. \tag{3}$$

If only the atmospheric attenuation effect and atmospheric turbulence are taken into account, the state of FSO system channel h_{mn} can be expressed as the product of two attenuation factors, and then:

$$h_{mn} = h_1h_a, \tag{4}$$

where the loss due to atmospheric attenuation effect is expressed by h_1; the random light intensity attenuation due to atmospheric turbulence is expressed by h_a. Controlled by weather condition, the atmospheric attenuation effect will lead to loss, which should follow the Lambert–Beer rule, and then:

$$h_1(z) = \exp(-\sigma z), \tag{5}$$

where the atmospheric loss due to signal transmission at a distance is expressed by $h_1(z)$; attenuation coefficient is expressed by σ. Usually, the atmospheric loss is a constant.

Due to the scintillation effect of atmospheric turbulence, optical signals generated during wireless optical communication will attenuate during this process [14]. The Gamma–Gamma distribution statistical model is adopted to describe the FSO system channel. With this model, interference factors within a certain range can be described, respectively. Based on the impact scale, the light field distribution is converted to disturbing function. Large turbulent eddies and small turbulent eddies meet the Gamma distribution. In the model, the probability density function of received light intensity is described as [15]:

$$f_{h_a}(h_a) = \frac{2(\alpha\beta)^{(\alpha-\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{(\alpha-\beta)/2-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_a}\right), \tag{6}$$

where the modified Bessel function taking a as order is expressed by $K_a(\cdot)$; the intensities of large turbulent eddies and small turbulent eddies are expressed by α and β respectively; the Gamma function is expressed by $\Gamma(\cdot)$. α and βcan be described as follows, respectively [14]:

$$\alpha = \left[\exp\left(\frac{0.49\chi^2}{\left(1+0.19d^2+0.58\chi^{12/5}\right)^{7/6}}\right)-1\right]^{-1}, \tag{7}$$

$$\beta = \left[\exp\left(\frac{0.52\chi^2\left(1+0.68\chi^{12/5}\right)^{-5/6}}{\left(1+0.92d^2+0.63\chi^{12/5}\right)^{5/6}}\right)-1\right]^{-1}. \tag{8}$$

h_1 represents a fixed constant and h_a represents a random variable. Under the influence of atmospheric attenuation and turbulence, the joint channel state is $h_{mn} = h_1h_a$ and the channel model expression of the MIMO-FSO system is obtained as follows:

$$M = \left|\frac{d}{dh_{mn}}\left(\frac{h_{mn}}{h_1}\right)\right| f_{h_a}(h_a). \tag{9}$$

The channel model of MIMO-FSO communication model is susceptible to h_a, so the constructed signal model is prone to instability. The higher the h_a, $f_{h_a}(h_a)$ is lower and the channel model is susceptible to the intensities of large turbulent eddies and small turbulent eddies; on the contrary, the smaller the h_a, $f_{h_a}(h_a)$ is larger and the channel model is not susceptible to the intensities of large turbulent eddies and small turbulent eddies, and is more steady.

3 Analysis of transmission performance of system channel

Based on the determination of stability of FSO system channel with the construction of channel model of MIMO-FSO system, the optimum combining technology is adopted and the bit error rate is taken as analysis standard to analyze the transmission performance of system channel. The optimum combining technology, also known as maximal ratio combining (MRC) technology, enables N non-correlated decomposition signals from different paths [16, 17] to configure gain coefficients for optical communication signals after gain variable amplifier processing, and to select the basis weight parameters to achieve the same phase weight combination. The sum of signal-to-noise ratio of each diversity branch is the total signal-to-noise ratio for the output of the technology, and then:

$$R_{\text{SN-MRC}} = \sum_{i=1}^{N} R_{\text{SN-}i}/N = \frac{\bar{\gamma}}{N}\sum_{i=1}^{N} h_i, \tag{10}$$

where the signal-to-noise ratio for the output of the ith branch is expressed by $R_{\text{SN-}i}$.

Since the MRC weight system is proportional to the received light intensity, average input error rate of the FSO system through the atmosphere [18] can be expressed as:

$$\begin{aligned} P_{\text{MINO-MRC}} &= \int_0^{\infty} f_{h_n}(h_n) \times \frac{1}{2}\text{erfc}\left(\sqrt{\sum_{i=1}^{N} R_{\text{SN-MRC}}} \times \frac{1}{\sqrt{2N}}\right) dh_n \\ &= \int_0^{\infty} f_{h_n}(h_n) \times Q\left(\sqrt{\sum_{i=1}^{N} R_{\text{SN-MRC}}} \times \frac{1}{\sqrt{N}}\right) dh_n, \end{aligned} \tag{11}$$

where Q is an integral function.

Set the number of transmit antennas for the FSO system as M and the number of receive antennas as N. If the attenuation property of each receiving antenna is independent, make the distance between receiving antennas exceed the atmospheric coherence length [19]. For FSO systems, regulation is done after linear merger, and the average output bit error rate of FSO system channel is

$$P_{MN} = \int_0^{\infty} f_h(h) \times \frac{1}{2}\text{erfc}\left[\frac{\sqrt{\bar{\gamma}}}{\sqrt{2MN}}\sqrt{\sum_{n=1}^{N}\left(\sum_{m=1}^{M} h_{mn}\right)}\right] \text{d}h, \tag{12}$$

where the length is MN; the vector h forms the channel state; the probability distribution function is expressed by $f_h(h)$; the average signal-to-noise ratio is expressed by $\bar{\gamma}$. Here, the paper introduces the Meijer G-function: $G_{4,3}^{2,3} \times \prod_{m=1}^{M} \prod_{n=1}^{N} \frac{\delta^2}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)}$; by simplifying the Meijer G-function, the average transmission bit error rate of MIMO-FSO system is described as:

$$\begin{aligned} P_{\text{MINO}} &= \prod_{m=1}^{M} \prod_{n=1}^{N} \frac{\delta_{mn}^2}{2\sqrt{\pi}\Gamma(\alpha_{mn})\Gamma(\beta_{mn})} \\ &\times G_{4,3}^{2,3}\left[\frac{\bar{\gamma}A_{0mn}h_{1mn}}{2\alpha_{mn}\beta_{mn}M^2N^2}\middle| \begin{matrix} 1-\delta_{mn}^2, 1-\alpha_{mn}, 1-\beta_{mn}, 1 \\ 0, \frac{1}{2}, -\delta_{mn}^2 \end{matrix}\right], \end{aligned} \tag{13}$$

where A is the area of receiving antenna. At the receiver, the diversity technology can be adopted to reduce the negative effects of large and small atmospheric turbulences on FSO systems and improve the signal-to-noise ratio. The core idea of this technology is to effectively combine multiple fading signals at the receiver. It is of great importance to select an appropriate combing diversity technology. The bit error rate is affected by outage probability. The higher the outage probability, the higher the possibility of bit errors is and the bit error rate is higher. Therefore, it is necessary to analyze the phenomenon of outage in the FSO system channel transmission. The outage probability is an important index to measure the performance of communication system. In a short time, the probability for the signal-to-noise ratio of system is lower than that of threshold at the receiver $R_{\text{SN-th}}$. Assuming that the channel performance meets the given sensitivity of threshold, the outage probability of FSO system channel transmission is

$$P_{\text{out}} = P_r(R_{\text{SN}} - R_{\text{SN-th}}) = F_{\gamma}(R_{\text{SN-th}}), \tag{14}$$

where the probability of occurrence is expressed by P_r; the distribution function of instantaneous signal-to-noise ratio is expressed by $F_{\gamma}(R_{\text{SN-th}})$. With the MIMO technology, the strong anti-interference ability requirements of FSO system can be met, and the influence of large and small atmospheric turbulences on the system communication can be reduced effectively. The Meijer G-function is adopted to converse the above formula, and the channel transmission of the FSO system is obtained and described as follows:

$$f_{h_{mn}}(h_{mn}) = \frac{(\alpha\beta)^{(\alpha+\beta)/2} h_{mn}^{(\alpha+\beta)/2-1} P_{\text{out}}}{h_1^{(\alpha+\beta)/2-1}(P_{\text{MINO}} + P_{\text{MN}})} \times G_{0.3}^{3.0}\left[\frac{\alpha\beta}{h_1}h_{mn}\middle| \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}\right]. \tag{15}$$

In summary, transmission performance of FSO system channel is susceptible to h_{mn} except for h_a. While the intensities of large turbulent eddies and small turbulent eddies α andβ can interfere h_{mn}. Therefore, the intensities of large turbulent eddies and small turbulent eddies α and β are the key factors of influencing the transmission performance of FSO system channel.

4 Simulation experiment and data analysis

To verify the effectiveness and feasibility of the improved FSO system, this paper take the OptiX OSN 7500 system of Huawei optical transmission equipment as an example, the numerical simulation method is used to study the effects of atmospheric turbulence effect and atmospheric attenuation effect on the transmission performance of FSO system. To reduce the influence of large and small atmospheric turbulences on the anti-interference capability of FSO system, MRC technology mentioned in this paper is adopted to form a modulator to modulate the FSO system, and MINO-FSO system formed by this technology, the performance analysis

Table 1 Data on visibility and attenuation coefficient of different weather conditions

Weather condition	Visibility (km)	Attenuation coefficient (dB/km)
Sunny	61.5	0.0598
Rainy	25.4	0.2413
Haze	8.1	0.8462
Dense fog	2.2	5.2146

Table 2 Data on varying atmospheric turbulence intensity parameters

Turbulence	χ^2	α	β
Weak	0.3	11.9	9.8
Middle	1.5	4.12	1.84
Strong	3.4	4.31	1.43

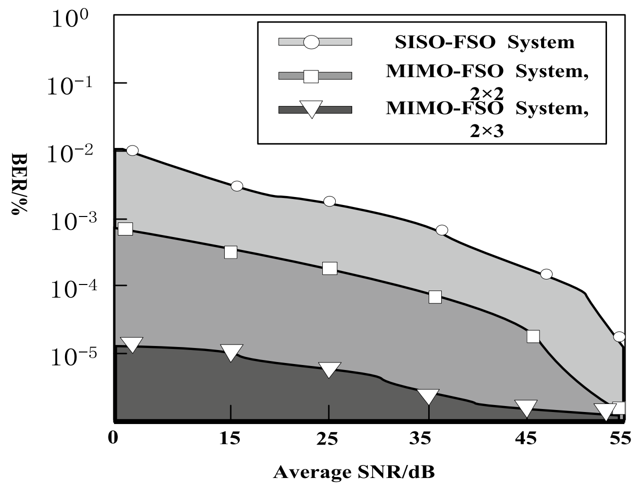

Fig. 2 Comparison of bit error rate of different communication systems in clear weather conditions

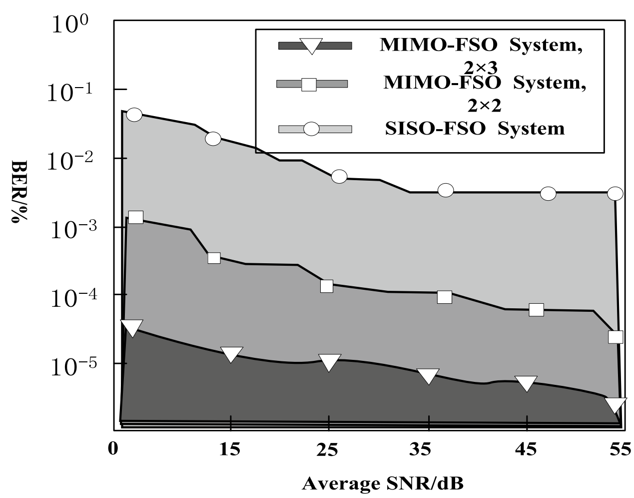

Fig. 3 Comparison of bit error rate of different communication systems in heavy fog conditions

of the single-input single-output optical communication (SISO-FSO) system and the MINO-FSO system was carried out with the error rate and the outage probability as the test indicators.

4.1 Experiment 1

To simulate the actual situation, assuming that the wavelength $\lambda = 1600$ nm and the transmission distance $L = 1100$ m, to ensure that the channel is independent, the distance between each receiving aperture needs to be greater than the coherent length $\sqrt{\lambda L} \approx 4.0$ cm. Data concerning signal attenuation coefficients under different weather conditions and the corresponding variation parameters under different atmospheric turbulence conditions are given, which are shown in Tables 1 and 2 in detail.

Based on different weather conditions, the clear weather and dense foggy weather are focused on in this experiment. The numbers of transmitting antennas and receiving antennas in a single-input single-output system are $M = 1$ and $N = 1$, respectively. The numbers of transmitting antennas and receiving antennas in a multi-input multi-output system are $M = 2.2$, $N = 2.3$, respectively. The relationship about bit error rate between the two systems is analyzed. The specific system output bit error rates are shown in Figs. 2 and 3.

Under different weather conditions, the effect of clear weather and heavy fog weather on FSO system is simulated. MRC technology is adopted to form a single-input single-output system and a multi-input multi-output system to compare the output bit error rate of the SISO-FSO system with transmit antenna $M = 1$ and receive antenna $N = 1$ and that of MIMO-FSO system with transmit antenna $M = 2.2$ and receive antenna $N = 2.3$. Figure 2 shows that under clear weather conditions, the influence of atmospheric attenuation effect and turbulence effect is small. Therefore, the overall output bit error rate of SISO-FSO system and MIMO-FSO system is relatively low. However, the bit error rate of SISO-FSO system is obviously higher than that of MIMO-FSO system with transmit antenna $M = 2.2$ and receive antenna $N = 2.3$. The curve in Fig. 3 shows that under bad weather conditions as shown in Fig. 3, the output bit error rate of SISO-FSO system has been very high, which shows a clear upward trend when being compared with that in clear weather conditions.

Compared with the bit error rate of multi-input multi-output system, the output error rate of FSO system is low when the diversity technology is adopted, which reaches 10^{-9} at the lowest and achieves a certain degree of improvement when being compared with that provided by traditional systems. It can be seen from the above two figures that the FSO system using the diversity technology is less affected by the degree of atmospheric attenuation and the performance is superior.

4.2 Experiment 2

The outage probability increases with the increase of turbulence intensity regardless of the atmospheric turbulence degree. In case of strong turbulence, the outage probability is low; in case of weak turbulence, the outage probability is high. Statistics is carried out to the data on outage probabilities of SISO-FSO system and MINO-FSO system under the influence of weak turbulence and strong turbulent conditions in rainy, respectively. The numbers of transmitting antennas and receiving antennas of the single-input single-output system are set to be $M=1$, $N=1$, respectively; the numbers of transmitting antennas and receiving antennas of the multi-input multi-output system are set to be $M=2.2$ and $N=2.3$. 100 simulation experiments are carried out on the simulation platform to compare the difference of outage probability between the two systems. The statistical graph containing the outage probabilities of the two FSO systems is shown in Fig. 4.

Figure 4 shows that based on the statistics of outage probabilities in strong atmospheric turbulence and weak atmospheric turbulence, in 100 simulation experiments, when the MIMO-FSO system is adopted under strong atmospheric turbulence, the outage rate in 2×2 region reaches 75% and that in 2×3 region reaches 15%; The lowest outage probability of the MIMO-FSO system with the diversity technology is 3%, which is lower than that of MIMO-FSO system in 2×2 region by 72% and lower than that of MIMO-FSO system in 2×3 region by 12%. In case of weak atmospheric turbulence, the outage rate in 2×2 region reaches 60% and that in 2×3 region reaches 13%; the lowest outage probability of the MIMO-FSO system with the diversity technology is 2%, which is lower than that of MIMO-FSO system in 2×2 region by 58% and lower than that of MIMO-FSO system in 2×3 region by 11%.

Therefore, after MRC technology in diversity technology is adopted to modulate the FSO system, the system can effectively resist the influence of turbulence on its performance, so it has certain advantages.

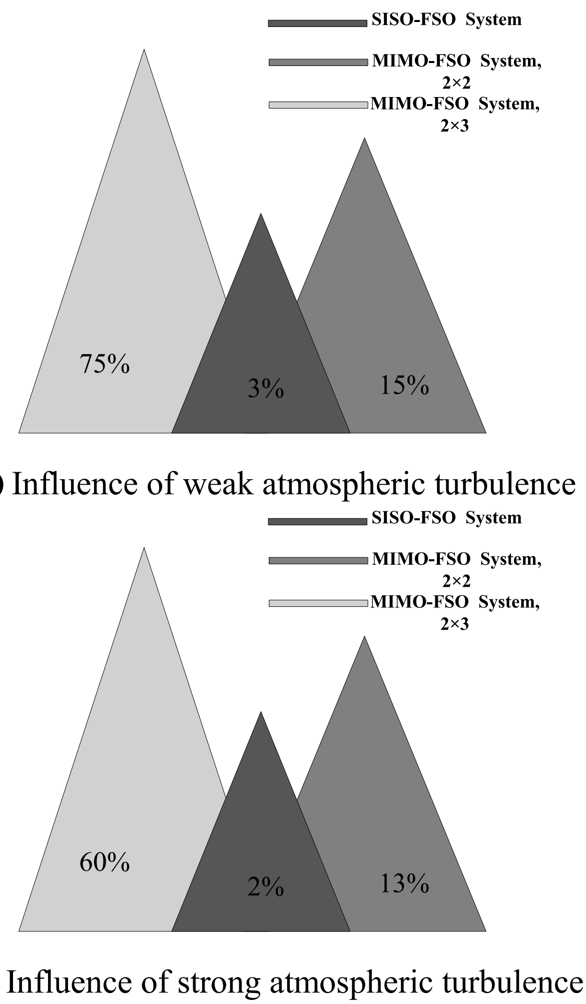

Fig. 4 Statistics of outage probability in two kinds of FSO system

5 Conclusion

1. A channel transmission performance analysis method based on improved space diversity technology for MIMO-FSO system is proposed. The Gamma–Gamma distribution model is used to analyze the atmospheric turbulence process and convert the light field distribution into an interference function. Differential phase-shift keying coherence intensity modulation is used. The method controls the turbulence, so that the transmitter and the receiver obtain the channel state information, constructs the MIMO-FSO system, and uses the improved maximum ratio combining modulation MIMO-FSO system channel to analyze the transmission performance of the MIMO-FSO system channel, and achieves the channel transmission interference reduction purpose.
2. In comparison of transmission performance of MIMO-FSO system channel in different regions, the bit error rate and outage rate are both improved, which enables more stable transmission.
3. For SISO-FSO system, the transmission performance under the condition of large interference factors is mainly studied and the correlation between the light intensity and the transmission performance of the communication channel needs to be further studied.

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