Research on diversity receive technology for wireless optical communication using PPM in weak turbulence atmosphere channel*

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In order to mitigate atmospheric turbulence, the free space optical (FSO) system model with spatial diversity is analyzed based on intensity detection pulse position modulation (PPM) in the weak turbulence atmosphere. The slot error rate (SER) calculating formula of the system without diversity is derived under pulse position modulation firstly. Then as a benchmark, independent of identical distribution, the average slot error rates of the three linear combining technologies, which are the maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (SelC), are compared. Simulation results show that the performance of system is the best improved by MRC, followed by EGC, and is poor by SelC, but SelC is simpler and more convenient. Spatial diversity is efficient to improve the performance and has strong ability on resistance to atmospheric channel decline. The above scheme is more suitable for optical wireless communication systems.
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Free space optical (FSO) communication links have some distinct advantages over conventional microwave and optical fiber communication systems by virtue of their high carrier frequency that permits large capacity, license-free, enhanced security, high data rate and so on[1-4]. Despite the major advantages of FSO communications, its widespread use is hampered by several challenges in practical deployment. For example, atmospheric particles can cause loss and deflection in light absorption and scattering. Rain, snow and fog can cause the reflection and refraction of light. In addition, a major impairment is the effect of atmospheric turbulence, which is the focus of this paper.

There are many ways to improve the quality of FSO communication systems. On the one hand, we can adopt efficient channel coding modulation technology, such as on-off keying (OOK), pulse position modulation (PPM), differential pulse position modulation (DPPM) and digital pulse interval modulation (DPIM). On the other hand, using spatial diversity to improve the transmission performance of FSO system can be regarded as a good method. Spatial diversity techniques, i.e., the employment of multiple transmit/receive apertures, provide an attractive alternative approach for fading compensation with their inherent redundancy[5]. As a relatively mature technology, multiple-input multiple-output (MIMO) technology is widely used in radio frequency communication system, and many researchers are paying more attention to MIMO technology in the application of FSO communication system.

In view of that the performance of PPM is better than that of others, in this paper, the FSO system models with three different space diversity receive technologies, i.e., the maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (SelC), are analyzed based on intensity detection PPM in the weak turbulence atmosphere. Firstly, the slot error rate (SER) calculating formula of the system without diversity is derived under PPM. Then as a benchmark, the average slot error rates of the three linear combining technologies are compared independent of identical distribution. Simulation results show that the performance of system is the best improved by MRC, which is followed by EGC, and is poor by SelC, but SelC is simpler and more convenient. Spatial diversity is efficient to improve the performance, and it has strong ability on resistance to atmospheric channel decline.

Wireless optical communication systems usually use intensity-modulation/direct detection (IM/DD) system, and light signal after intensity modulation propagating in the atmospheric environment will be mainly affected by atmospheric attenuation and the atmospheric turbulence.

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Atmospheric turbulence occurs as a result of the variation in the refractive index due to the inhomogeneity of temperature and pressure change, and it results in rapid fluctuations at the received signal, i.e., signal fading, which impairs the link performance severely. According to the different turbulent motion states, the atmospheric transmission channel of light can be divided into the weak turbulence channel and the strong turbulent channel.

For outdoor visible optical communication system, considering the average aperture effects, the atmospheric turbulence can be thought of weak turbulence. In weak turbulence atmosphere, one can accurately model the intensity of the optical field using a random variable whose probability density function (PDF) is that of a log-normal random variable. If I denotes the intensity of the received optical field, the PDF of I denoted by $f(I)$ is given by[6]

$$f(I)=\frac{1}{2\sqrt{2\pi}I\sigma_x}\exp\left[-\frac{\left(\ln I/I_0+2\sigma_x^2\right)^2}{8\sigma_x^2}\right], \qquad (1)$$

where I_0 denotes the mean of I, σ_x denotes the atmospheric scintillation index, and generally let σ_x<1 in the condition of weak turbulence.

Fig.1 shows the typical MIMO-FSO system. We consider an FSO link with M transmit apertures and N receive apertures. We assume the high signal-to-noise ratio (SNR) regime where we can use Gaussian noise model. Assuming OOK, the received signal at the nth receive aperture can be expressed as[7]

$$R_n=T\eta\sum_{m=1}^{M}x_{nm}+\rho_n, n=1,\cdots,N , \qquad (2)$$

where $T\in(0,1)$ is the transmitted information bit, η is the optical-to-electrical conversion coefficient, ρ_n is the additive white Gaussian noise (AWGN) with zero mean and variance of $\sigma_s^2=N_0/2$, and x_{nm} denotes the irradiance from the mth transmitter to the nth receiver. The receiving photocurrent of photoelectric detector is given as

$$I=A\frac{He}{hf}P_r=\eta P_r , \qquad (3)$$

where A is the gain coefficient of the photoelectric detector, H and f denote the light wave frequency and quantum efficiency, respectively, e and h denote the electronic charge and Planck's constant, respectively, and $P_r=x_{nm}\cdot A_r$, where P_r is the average optical power and A_r is the receive antenna area.

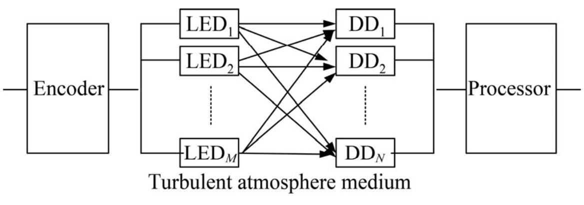


Fig.1 Schematic diagram of typical MIMO-FSO link system model

We present the SER expressions for FSO links with spatial diversity. Firstly, we study the SER performance of a single-input single-output (SISO) FSO link which is used as a benchmark for spatial diversity systems under consideration. The FSO system is considered over a discrete-time ergotic channel with AWGN model with zero mean and variance of σ^2. We assume binary input, continuous output and IM/DD with PPM. Then the slot error rate under the condition of the received light intensity x is given as[8-10]

$$P_e(x)=\frac{1+erf\left[(b-\sqrt{P})/\sqrt{2\sigma^2}\right]+(2^m-1)\left[1-erf(b/\sqrt{2\sigma^2})\right]}{2^{m+1}} , \qquad (4)$$

where $b=\frac{2\sigma^2\ln(2^m-1)+P}{2\sqrt{P}}$ is the decision threshold, and $P=Ax$ is the average optical power of the received signal, which depends on the received light intensity x and the detector's area A. In addition, because of the photoelectric detection current of $i=\eta P=\eta Ax$, the electrical signal average power can be expressed as $P=i^2R=\eta^2A^2Rx^2$. The electrical signal to noise ratio (SNR) is defined as $\mu=\frac{P}{2\sigma^2}=\frac{\eta^2A^2Rx^2}{2\sigma^2}=\eta^2A^2R\frac{x^2}{2\sigma^2}$. Let A=1 and η^2A^2R=1, the average electrical SNR is expressed as $\mu=\frac{x^2}{2\sigma^2}$, and we know that $erfc(x)=1-erf(x)$, so Eq.(4) can be simplified as

$$P_e(x)=\frac{2-erfc(c)+(2^m-1)erfc(d)}{2^{m+1}} , \qquad (5)$$

where $c=\ln(2^m-1)\sqrt{\frac{x}{4\mu}}-\sqrt{\frac{\mu}{4x}}$, and $d=\ln(2^m-1)\sqrt{\frac{x}{4\mu}}+\sqrt{\frac{\mu}{4x}}$.

So, under the condition of weak turbulence channel, the average SER expression for SISO-PPM system can be expressed as[11]

$$P_e=\int_0^\infty f(x)\times P_e(x)\mathrm{d}x=$$

$$\int_0^\infty\frac{1}{2\sqrt{2\pi}x\sigma_1}\exp\left[-\frac{(\ln\frac{x}{x_0}+2\sigma_1^2)^2}{8\sigma_1^2}\right]\times$$

$$\frac{2-erfc(c)+(2^m-1)erfc(d)}{2^{m+1}}\mathrm{d}x . \qquad (6)$$

Then we focus our attention on FSO links with spatial diversity. Considering an FSO system with N receive antennas and one transmit antenna, we can use a variety of linear combining technologies, including MRC, EGC and SelC, to merge different signals on the receive antennas.

MRC technique is the optimum combiner for independent AWGN channels in which the signals from all channels are added together. And the gain of each channel is proportional to the average power and inversely proportional to the mean noise power in that channel, so different proportionality constants are used for different channels. The average SNR of MRC is equal to the sum of SNRs of all channels. As a result, even if any channel signal is poor, it is likely for MRC to merge and achieve a demodulation signal which meets the requirement of system transmission.

It is well known that the weighted factor of each channel is proportional to the receiving light power. In order to compare its performance with SISO-FSO system, it must be ensured that the sum of areas of N receive apertures is the same as the area of the receive aperture of the SISO link. Assuming that the receive aperture area is a constant of A, the average receive area of each photoelectric detector is A/N, and the average receiving light power is $P=Ax/N$. We also assume that the light intensity distribution of the channels between transmitter and receiver is independently and identically distributed. Using the related calculation method of conditional probability function, we can deduce that $I_N=\eta P_N=\eta Ax/N$, and the average SNR of the input of demodulator can be expressed as[12]

$$\mu_{\mathrm{MRC}}=\sum_{n=1}^{N}\mu_n=\frac{1}{2N^2\sigma^2}\left(\sum_{n=1}^{N}x_n^2\right) , \tag{7}$$

where μ_n is the average SNR of each channel. So the average SER expression for FSO system using MRC technique can be expressed as

$$P_{\mathrm{e(MRC)}}=\left(\int_0^\infty f_{x_n}(x_n)\times P_{\mathrm{e(MRC)}}(x_n)\mathrm{d}x_n\right)^N=$$
$$\left\{\int_0^\infty\frac{1}{2\sqrt{2\pi}x_n\sigma_1}\exp\left[-\frac{\left(\ln\frac{x_n}{x_0}+2\sigma_1^2\right)^2}{8\sigma_1^2}\right]\times\right.$$
$$\left.\frac{2-erfc(c_1)+\left(2^m-1\right)erfc(d_1)}{2^{m+1}}\mathrm{d}x_n\right\}^N , \tag{8}$$

where $c_1=\ln(2^m-1)\sqrt{\frac{x_n}{4\mu_{\mathrm{MRC}}}}-\sqrt{\frac{\mu_{\mathrm{MRC}}}{4x_n}}$, and $d_1=\ln(2^m-1)\times\sqrt{\frac{x_n}{4\mu_{\mathrm{MRC}}}}+\sqrt{\frac{\mu_{\mathrm{MRC}}}{4x_n}}$.

EGC technique is of a practical interest because it not only provides performance comparable to that of the optimal MRC technique but also is with greater simplicity. We don't need to know the average SNR of each channel, but should know the amplitude of each one. In EGC technique, the outputs of the different branches are co-phased and equally weighted, then they are summed to give resultant output, and the weighted factor is constant. As a result, the average SNR of the input of demodulator can be expressed as[13]

$$\mu_{\mathrm{EGC}}=\frac{1}{2N^2\sigma^2}\left(\sum_{n=1}^{N}x_n\right)^2 . \tag{9}$$

Therefore, the average SER expression for FSO system using EGC technique can be expressed as

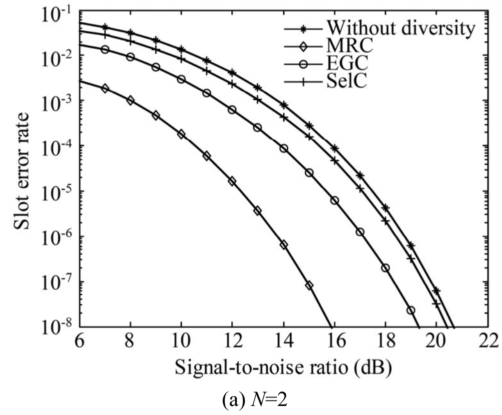
$$P_{\mathrm{e(EGC)}}=\left[\int_0^\infty f_{x_n}(x_n)\times P_{\mathrm{e(EGC)}}(x_n)\mathrm{d}x_n\right]^N=$$
$$\left\{\int_0^\infty\frac{1}{2\sqrt{2\pi}x_n\sigma_1}\exp\left[-\frac{\left(\ln\frac{x_n}{x_0}+2\sigma_1^2\right)^2}{8\sigma_1^2}\right]\times\right.$$
$$\left.\frac{2-erfc(c_2)+\left(2^m-1\right)erfc(d_2)}{2^{m+1}}\mathrm{d}x_n\right\}^N , \tag{10}$$

where $c_2=\ln(2^m-1)\sqrt{\frac{x_n}{4\mu_{\mathrm{EGC}}}}-\sqrt{\frac{\mu_{\mathrm{EGC}}}{4x_n}}$, and $d_2=\ln(2^m-1)\times\sqrt{\frac{x_n}{4\mu_{\mathrm{EGC}}}}+\sqrt{\frac{\mu_{\mathrm{EGC}}}{4x_n}}$.

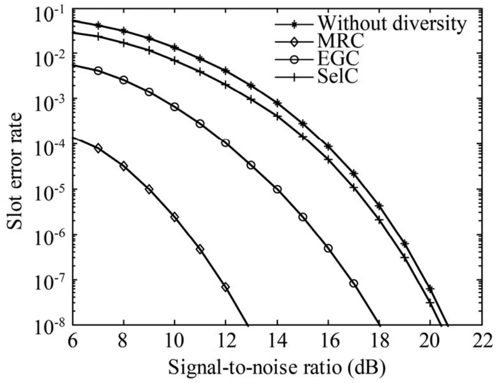
SelC technique is the simplest and the most convenient one among the three linear combining approaches mentioned above. With selection diversity, the receiver selects the antenna with the highest received signal power and ignores the observations from the other antennas, so the ability on resistance to atmospheric channel decline is not satisfied. As a result, the average SNR of the input of demodulator can be expressed as

$$\mu_{\mathrm{SC}}=\max\left\{\mu_1,\mu_2,\cdots,\mu_N\right\} . \tag{11}$$

According to Eqs.(6)–(11), we present numerical results for the average SER performance of FSO links with three different diversity receive technologies for various numbers of receive apertures and correlation values. With the modulation order of m=4 and the atmospheric scintillation index of σ_1=0.3, Fig.2 illustrates the SER performance of the FSO links with the number of receive apertures of N=2 and 3 over a weak turbulence channel, respectively.



(a) N=2



(b) N=3

Fig.2 SERs of FSO links using different diversity receive technologies with *N*=2 and 3

It can be seen from Fig.2 that for any kind of technique, the average SER decreases when the SNR increases. Using spatial diversity is efficient to improve the performance, and it has strong ability on resistance to atmospheric channel decline. And the performance of system is the best improved by MRC, followed by EGC, and is poor by SelC. It shows that the SNR of SIMO-FSO system adopting EGC technique can be decreased by about 2 dB than that of SISO-FSO system without diversity at $SER=10^{-4}$ when N=2, while that of FSO system adopting MRC can be decreased by about 5 dB.

Fig.3 shows the average SER performance of EGC with different numbers of the receive antennas. It is clearly illustrated that the performance is improved significantly with the increase of the number of receive

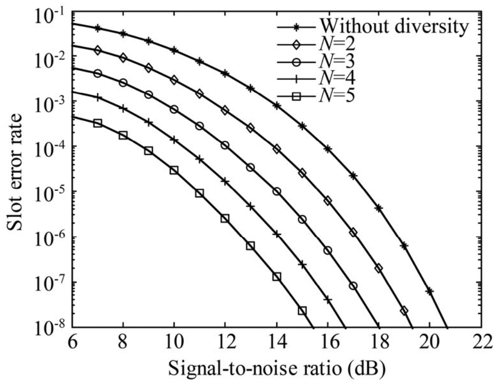


Fig.3 SERs of FSO links using EGC with different numbers of the receive antennas

apertures. And the performance of the system using EGC is better obviously than that of the one without diversity. It shows that the SNR of FSO system adopting EGC technique can be decreased by about 2 dB, 4 dB, 5.5 dB and 6.5 dB when N=2, 3, 4 and 5, respectively.

In this paper, we investigate the SER performance of FSO links in weak turbulence atmospheric channels with spatial diversity. Simulation results show that the performance of system is the best improved by MRC, followed by EGC, and is poor by SelC, but SelC is simpler and more convenient. Our results demonstrate that FSO links with receive diversity have better performance and strong ability on resistance to atmospheric channel decline. The above scheme is more suitable for optical wireless communication systems.

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