Performance Analysis for BPSK, DPSK and OOK-Based FSO System in Atmospheric Turbulence Conditions

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***Abstract* — Free Space Optical communication (FSO) has received much attention in recent years. However, the optical signal will be severely affected by atmospheric attenuation when transmitted under atmosphere channel. In this paper, performance of average BER and average channel capacity for FSO system based on three modulation schemes such as On-Off keying (OOK), Binary Phase Shift Keying (BPSK), Differential Phase Shift Keying (DPSK) with effect of atmosphere turbulence are investigated. Novel closed-form expressions of average BER and average channel capacity for various modulation techniques are derived by employing the hyper-geometric functions substitution method. Numerical simulation results for BER (Bit Error Ratio) and channel capacity are analyzed. The results show that the BER performance for BPSK modulation is better compared with others, and the average channel capacity for BPSK modulation is best for FSO system under atmospheric turbulence channel.**

Keywords-Modulation; Bit error rate; Atmosphere turbulence; Hyper-geometric functions

I. INTRODUCTION

Free space optical communication (FSO) because of its high transmission rate, high bandwidth and strong anti-interference characteristics has much attention, it became a striking alternative for the last-mile problem and well established for inter satellite and deep-space communication systems. FSO is one of techniques that use of light as a carrier transmitting information in the space and the transmission rate in excess of 1Gbps (Gigabit-per-seconds) is achievable. Besides a higher data rate, the smaller terminal size and load weight, data-secure, which makes it a promising method to meet the growing issue of next generation broadband network established. Therefore, FSO technique will has extensive application prospects. However, performance of FSO system will be deteriorated by various interference when the laser beam carried information propagating across the atmospheric channel. Generally speaking, varying atmospheric conditions such as, rain, clouds, fog and the effect of atmospheric turbulence including atmospheric absorption, scattering of gas molecules and aerosol particles have a detrimental impact on FSO links performance.

In order to mitigate the effect of atmospheric turbulence, United States, Japan, Europe and other countries have carried out a large number of laser atmospheric propagation experiments and researches. Different methods have proposed, such as large aperture receiver technology ,multiple input multiple output (MIMO) system, partial diversity technology, coherent optical communication, adaptive optics technology, coded modulation technology, etc. Heba Yuksel developed a series of theoretical and experimental studies that using a large aperture receiving technology to immune the turbulence in FSO system and relationship between pore size and pore size of smoothing effect and turbulence intensity has verified. The diversity combining technique has studied by Belmonte Aniccto etc. Ivan B. Djordjcvic have made LDPC (Low Density Parity Check Code) coding technology for FSO system and found that performance has effectively improved. Although the above method can enhance performance to some extent, but it has not greater progress because of its limitations for non-adaptive and atmospheric turbulence disturbances in real time [1-5].In order to improved the performance of FSO, an effective scheme is indispensable. Jennifer Roberts set up an adaptive optics test platform to test the performance of FSO system, results show the gain will increased 2~4dB with adaptive optics correction[6].Although, adaptive optics technology for FSO has a good compensation, it is difficult to realize. Recently, many scholars have found that coherent optical communication technology can be effectively degraded atmospheric turbulence and it is easier to achieve [7-9]. Usually, IM/DD (Intensity Modulation/Direct Detection) methods used to FSO be widely applied. OOK format is relative simple but performance of anti-noise is not superior. Another modulation/detection method for FSO system is phase modulation. Homodyne BPSK uses coherent detection and it needs an optical phase-locked loop in receiver when demodulation, thus, it is difficult to realized. In addition, DPSK modulation is worth noting, it is a promising modulation scheme. According to previous works, FSO channel are described as three major statistical models, log-normal distributed model, K- distributed model and Gamma-Gamma model. It was found that log-normal model and K- distributed model is generally used for weak and heavy turbulence conditions respectively. Gamma-Gamma distribution model is proposed as a tractable mathematical model for both weak and strong turbulence and the probability density functions(pdf) of which is independent Gamma distribution, it provides a good fit to experimental results[10-12].

Therefore, this paper focus on performance of FSO system based on three modulation such as, OOK, DPSK and homodyne BPSK modulation. The BER performance and average channel capacity for three modulations have analyzed under Gamma-Gamma channel with atmospheric turbulence conditions. And the closed-form expression has derived by hyper-geometric functions substitution method to simplify analysis. Simulation is carried out based on the expressions achieved and performance analysis is discussed, simulation results show that BPSK scheme is suitable for FSO.

II. CHANNEL MODEL AND SYSTEM MODEL

A. Channel model

The most common optical transmission caused by atmospheric turbulence effect is light intensity fluctuation (light flashing).Because of Lognormal model is closely described low turbulence strengths, and the slow flashing condition of large-scale and small-scale turbulence effects will effectively described by Gamma-gamma model. Therefore, the Gamma-gamma model is chosen in this paper for its model parameters most suitable for the actual parameters of the channel, and the moderate-to-strong turbulent fading is appropriately modelled by the (normalized) Gamma-Gamma distribution. The PDF of beam intensity for I using Gamma-Gamma model, which can be expressed as [13][14]

$$f(\mathrm{I}) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\frac{\alpha+\beta}{2}-1)} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \quad (1)$$

where, I is the received optical irradiance, and I>0.$\Gamma(\cdot)$is the standard Gamma function, Kv is the vth -order modified Bessel function of the second kind, α and β are the scintillation parameters that denotes the effective number of large-scale and small-scale eddies of the scattering process in the atmosphere. Assuming the plane wave propagation and the inside scale is zero. According to the atmospheric environment, the parameters α and β defined as

$$\alpha = (\exp[\frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{12/5})^{7/6}}]-1)^{-1} \quad (2)$$

$$\beta = (\exp[\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{12/5})^{5/6}}]-1)^{-1}$$

In Eq.2, σ_R^2 is Rytov variance, the mathematical model is obtained as

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (3)$$

where, k denotes optical wave number, $k = 2\pi/\lambda$,λ is wavelength, and L is the transmission length between the transmitter and receiver, C_n^2 is the refractive index structure parameter determining turbulence strength and varies from $10^{-13}m^{-2/3}$ for strong turbulence to $10^{-17}m^{-2/3}$ for weak turbulence. According to the H-V model, its expression is given by

$$C_n^2 = 8.2\times10^{-16} W^2 (h/10)^{10} \exp(-h) + 2.7\times10^{-16} \exp(h/10) + A\exp(h/0.1) \quad (4)$$

In Eq.4,A is the constant for ground level structure and it is the experience value for C_n^2 which is closed to ground($m^{-2/3}$),W is the wind speed (m/s) under vertical path for 5~20km,h is altitude(m).The typical values of A and W is $1.7\times10^{-14}m^{-2/3}$ and 21m/s.

B. System model

An typical FSO system is consisted of transmitter, atmospheric channel and receiver. The transmitted data are modulated by various modulation technique such as, OOK, BPSK and DPSK. The modulated signal is transmitted through telescope into atmospheric turbulence channel. Assuming the channel to be memoryless, stationary, ergodic with additive white Gaussian noise (AWGN). When the transmitted signal propagated in atmospheric channel, it will scattered due to path loss, turbulent atmosphere and pointing errors. At receiving end, receiving signal can be expressed as[15]

$$y = x\eta I + n \quad (5)$$

where, y is the received signal that suffers from a fluctuation in signal intensity due to atmospheric turbulence and additive noise, ηI denotes the instantaneous beam intensity, I is receiver irradiance and η is the effective photo-electric conversion ratio, x is the transmitted signal, n is the additive white Gaussian noise with zero mean and variance is $\sigma_N^2 = N_0/2$,and I is assumed that $I = I_a I_l I_p$, where I_l is the path loss and it is a constant, I_a is the attenuation owing to atmospheric turbulence and I_p is the attenuation owing to pointing errors. In this paper, the atmospheric turbulence is considered only.

III. PERFORMANCE ANALYSIS OF FSO SYSTEM

A. Average BER without atmosphere turbulence

Assuming direct intensity modulation direct detection is used in FSO system, The BER for OOK modulation can be expressed as

$$p_{e,ook} = \frac{1}{2} erfc\left(\frac{1}{2}\sqrt{SNR}\right) = Q(\frac{\eta I}{\sqrt{2N_0}}) \quad (6)$$

After detection, the instantaneous electrical SNR is define as $\gamma = \frac{\eta^2 I^2}{N_0}$. And it related to the complementary error function erfc (·) as $erfc(x) = 2Q(\sqrt{2}x)$. If heterodyne synchronization BPSK format is used for FSO system, total BER for BPSK as Eq.7.By the same, the conditional BER for DPSK can be expressed as [16]

$$p_{e,BPSK} = \frac{1}{2} erfc\left(\sqrt{SNR}\right)$$

$$p_{e,DPSK} = \frac{1}{2} erfc\left(\frac{\sqrt{SNR}}{\sqrt{2}}\right) \quad (7)$$

In Eq.7,it denotes conditional BER for coherent detection BPSK and DPSK without turbulence. The homodyne receiver is used for FSO system based on BPSK modulation, and delay receiving structure for coherent DPSK. From theoretical analysis above, it is obvious that under same SNR (Signal Noise Ratio), the BER performance for BPSK is the best compared with other modulation schemes and OOK format is the worst.

B. Average BER with atmosphere turbulence

The performance degrade due to turbulence and pointing errors. In this work, we do not consider pointing errors, so that we have I=Ia. Random fluctuation of light intensity is obeyed with Gamma-Gamma distribution. The instantaneous electrical SNR of received signal and average SNR for OOK modulation are defined as [17-20]

$$SNR = \frac{(\eta I)^2}{N_0} \quad \mu = \frac{\eta^2 E[I]^2}{N_0} \quad (8)$$

In Eq.8,E[I] denotes the mathematical expectation which corresponds to the average SNR with E[I]=1. μ is the average SNR. Therefore, the probability of average BER for OOK under Gamma-Gamma channel can be obtained by using the following integral calculate as

$$P_{e,OOK} = \int_0^\infty f(I)[\frac{1}{2}\mathrm{erfc}(\frac{\eta I}{2\sqrt{N_0}})]dI = \int_0^\infty f(I)[\frac{1}{2}\mathrm{erfc}(\frac{\eta I}{2\sqrt{N_0}})]dI \quad (9)$$

By using Eq. (1) in (9),the average BER for OOK format can be calculated

$$P_{e,OOK} = \int_0^\infty \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\frac{\alpha+\beta}{2}-1)} \times K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \times [\frac{1}{2}\mathrm{erfc}(\frac{\eta I}{2\sqrt{N_0}})]dI \quad (10)$$

To simplified the above integral, we express the $K_v(\cdot)$ and $\mathrm{erfc}(\cdot)$ in terms of the Meijer-G function. Which can be written as[21]

$$erfc(\sqrt{x}) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left[x \,\middle|\, \begin{matrix} 1 \\ 0, \frac{1}{2} \end{matrix}\right]$$

$$K_v(x) = \frac{1}{2} G_{0,2}^{2,0}\left[\frac{x^2}{4} \,\middle|\, \begin{matrix} - \\ \frac{v}{2}, -\frac{v}{2} \end{matrix}\right] \quad (11)$$

In order to further simplified Eq.(10),the operational characteristic of Meijer-G function is used. Therefore, a closed-form of average BER for OOK format can be expressed as

$$P_{e,ook} = \frac{2^{\alpha+\beta-3}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)} \times G_{5,2}^{2,4}\left[(\frac{2}{\alpha\beta})^2 \mu \,\middle|\, \begin{matrix} \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2}, 1 \\ 0, \frac{1}{2} \end{matrix}\right] \quad (12)$$

Likewise, the closed form of average BER expression for BPSK format is given by

$$P_{e,BPSK} = \frac{1}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} \times G_{3,2}^{2,2}\left[\frac{\bar{\gamma}}{\alpha\beta} \,\middle|\, \begin{matrix} 1-\beta, 1-\alpha, 1 \\ 0, \frac{1}{2} \end{matrix}\right] \quad (13)$$

In Eq.(13), SNR for BPSK modulation is $\bar{\gamma} = \frac{\eta D}{2qB}$.However, average SNR for heterodyne DPSK format is $\delta = \frac{\eta DT}{hv}$.Where, η is the detector responsivity, q is electronic charge, B is the noise equivalent bandwidth of the PD,D is the detector area in m^2 ,T is the DPSK symbol duration in seconds ,h is Planck's constant, v is frequency of received optical signal. The closed form expression for average BER expression of DPSK format is given by

$$p_{e,DPSK} = \frac{1}{2\sqrt{\pi}\Gamma(\alpha)\Gamma(\beta)} \times G_{3,2}^{2,2}\left[\frac{\delta}{2\alpha\beta} \,\middle|\, \begin{matrix} 1-\beta, 1-\alpha, 1 \\ 0, \frac{1}{2} \end{matrix}\right] \quad (14)$$

C. Average Channel capacity with atmosphere turbulence

The average channel capacity (ergodic capacity) is also an important parameter to estimate FSO communication link. It is a quantitative measurement of the limiting data transmission rate that can be achieved through a non-deterministic fading channel with a minimum probability of error. For OOK modulation based FSO channel it can be estimated using mathematical analogy as follows [22][23]

$$< C >= \int_0^\infty B \times \log_2(1 + SNR(I)) f(I) dI \quad (15)$$

Where,<C> is expectation and B is bandwidth of transmitted signal, SNR(I) is SNR for OOK modulation. Making Eq.(1) and Eq.(8) in Eq.(15),with identity transformation $\log_2(x) \equiv \ln(x)/\ln 2$ .By expressing $K_v(\cdot)$ as Meijer-G function and $\ln(1+x) = G_{2,2}^{1,2}\left[x \,\middle|\, \begin{matrix} 1,1 \\ 1,0 \end{matrix}\right]$ respectively into the (14),(15)can be simplified to (16)

$$< C >_{OOK} = \frac{B 2^{\alpha+\beta-2}}{\pi \ln 2\Gamma(\alpha)\Gamma(\beta)} \times G_{6,2}^{1,6}\left[\frac{16}{(\alpha\beta)^2}\mu \,\middle|\, \begin{matrix} 1, 1, \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, \frac{1-\beta}{2}, \frac{2-\beta}{2} \\ 1, 0 \end{matrix}\right] \quad (16)$$

By the same, the average channel capacity of FSO system for BPSK and DPSK modulation can be expressed respectively as below

$$< C >_{BPSK} = \int_0^\infty B \times \log_2(1 + \frac{\eta DI}{2qB}) f_I(I) dI$$

$$< C >_{DPSK} = \int_0^\infty B \times \log_2(1 + \frac{\eta DT}{hv} I) f_I(I) dI \quad (17)$$

The further derivation follows by expressing the logarithmic function and the channel model of Eq.(15) as Meijer G function is simplified to obtain a closed-form mathematical expression for channel capacity expressed as below

$$< C >_{BPSK} = \frac{B}{\ln 2\Gamma(\alpha)\Gamma(\beta)} G_{4,2}^{1,4}\left[\frac{\bar{\gamma}}{\alpha\beta} \,\middle|\, \begin{matrix} 1, 1, 1-\beta, 1-\alpha \\ 1, 0 \end{matrix}\right]$$

$$< C >_{DPSK} = \frac{B}{\ln 2\Gamma(\alpha)\Gamma(\beta)} \times G_{4,2}^{1,4}\left[\frac{\delta}{\alpha\beta} \,\middle|\, \begin{matrix} 1, 1, 1-\beta, 1-\alpha \\ 1, 0 \end{matrix}\right] \quad (18)$$

IV. Numerical Simulation and Analysis

In order to verified performance, simulations of FSO system employing OOK,BPSK and DPSK modulation with the turbulent channel have developed under Matlab platform based on the previous numerical analysis. The parameters needed are displayed as follows, laser wavelength is 1.55 ,optical power is 10mW,modulation bandwidth is 100MHz, photo detector responsivity is 0.5A/W, active ares is 1mm2,transmission distance L is 1km.Fig.1 illustrate the average BER performance versus SNR for different modulation formats without turbulence.

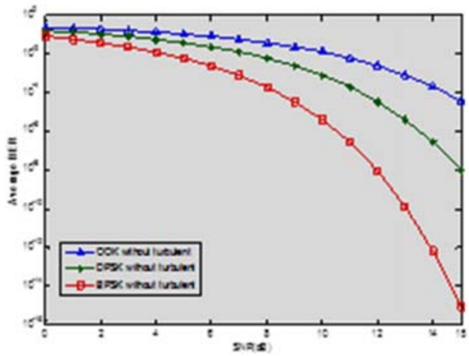
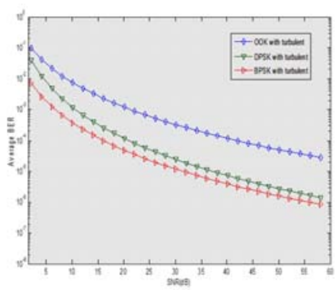
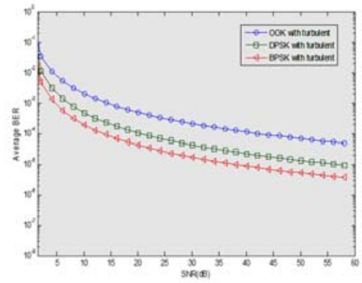


Figure 1.Average BER VS SNR without turbulent

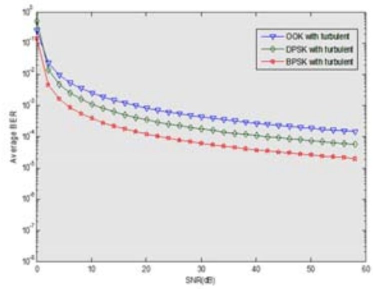
As it shown in Fig.1,we can see that with the SNR increased the average BER is decreased. Among three modulation formats, the average BER of BPSK is consistently lower than that of OOK and DPSK scheme. When the average BER is 10-4,the SNR for BPSK modulation is 7.82dB,and 11.6dB for DPSK,14.5dB for OOK type. It is obvious that the BPSK format is 3.78dB better than DPSK format, and DPSK format is 2.9dB better than OOK modulation types. Hence, BPSK modulation type has preferable BER performance. Neglecting impact of pointing errors, the three typical turbulence conditions has chosen, strong turbulence scale($\sigma_R^2 = 2.0$), moderate scale turbulence($\sigma_R^2 = 1$) and weak turbulent scale($\sigma_R^2 = 0.3$).The figures of average BER performance versus SNR under different turbulent are demonstrated in Fig.2.



(a) $\sigma_R^2 = 0.3$



(b) $\sigma_R^2 = 1$



(c) $\sigma_R^2 = 2.0$

Figure 2. Average BER vs SNR with turbulent for different turbulent condition

From Fig.2,the following conclusions can be obtained.(1)With the turbulent increased the average BER performance suffers a dramatic degradation. Especially, the BER performance for FSO system based on three modulation schemes are severely aggravated under strong turbulence.(2)Under strong turbulence condition, when the average BER is 10-3,the SNR for BPSK modulation is 8.72dB,for DPSK and OOK format is 13.6dB and 19.1dB respectively. It is clearly depicted that the average BER performance for BPSK modulation is significantly better than others. That is ,it can degrade turbulence effectively. (3) Consequently, BPSK is more effective than OOK and DPSK whether or not the turbulent is taken into consideration. The simulation parameters remain unchanged, the channel capacity in terms of bandwidth of FSO system under atmospheric turbulence channel for various modulation techniques are shown in Fig.3.

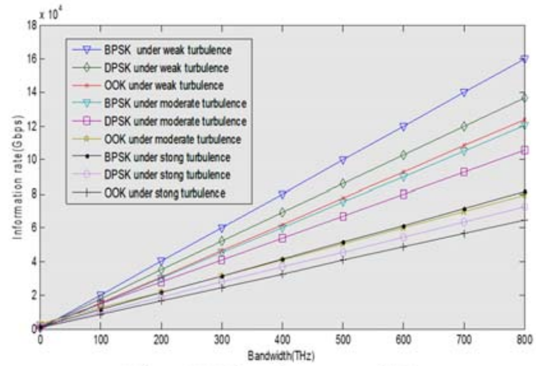


Figure 3. Information rate vs SNR

From Fig.3,it is inferred that the information rate will influenced by the turbulent condition ,and the information rate increases along with the bandwidth. It is observed that BPSK provides higher channel capacity for various turbulence. The relationship between channel capacity and average SNR for BPSK scheme under various atmospheric turbulence channel as shown in Fig.4.The curve between the channel capacity and average SNR under strong atmospheric turbulence condition for the three modulations is shown in Fig.5.

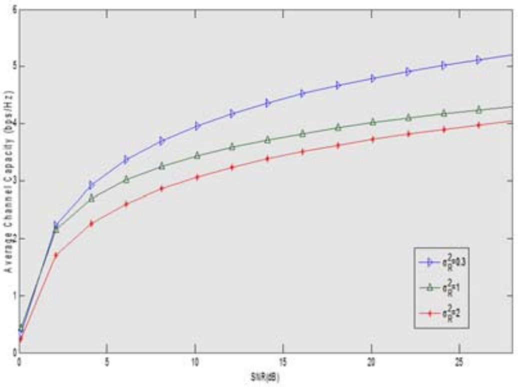


Figure 4. Channel capacity vs SNR

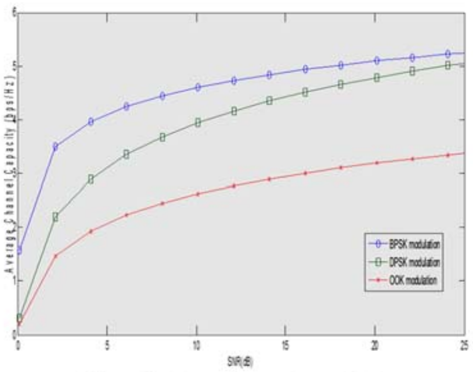


Figure 5. Channel capacity vs SNR

Fig.4 indicates that while the turbulence increases the channel capacity decreases to some extent.

But, the channel capacity will improved with SNR increased. Relationship between channel capacity and SNR for three modulations under strong turbulence condition is shown in Fig.5.It is clear that performance of channel capacity for BPSK is better compared with OOK and DPSK. When the SNR is 10dB, the channel capacity for BPSK is 4.5, and 3.8 for DPSK scheme, 2.4 for OOK scheme. Specially, BPSK format has better effect for resisting the turbulence.

V. CONCLUSIONS

With the consideration of atmospheric turbulence, performance of OOK, BPSK and DPSK are discussed in terms of average BER and channel capacity. In order to simplified analysis, the hyper-geometric function is used and the novel closed-form expressions have derived. The channel capacity and BER of FSO system using various modulation formats under different turbulent conditions were simulated and compared. It is inferred that the BPSK not only perform a more outstanding BER performance than OOK and DPSK schemes but also it offers high channel capacity compared with other modulations. Therefore, BPSK modulation should be the most reasonable scheme for FSO system which can effectively decrease turbulence.

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