FSO Link Performance Analysis with Different Modulation Techniques under Atmospheric Turbulence

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***Abstract*— Free space optics (FSO) has achieved prominence in extremely large bandwidth, unlicensed spectrum and low power secure transmission in the field of wireless communication. Despite the advantages, it is deeply impacted due to atmospheric turbulence and fog weather conditions. This paper considers different modulation schemes under the presence of atmospheric turbulence and fog conditions. The desired expression of bit error rate (BER) is obtained by modeling the turbulence as gamma-gamma distributed channel and under this channel condition, 16-PPM has provided better performance than other schemes. BER is considered for the channel performance evaluation. This analysis can help to adopt a modulation technique according to the channel condition.**

Keywords—Free space optics (FSO), atmospheric turbulence, gamma-gamma distribution, Bit error rate (BER), Meijer's G function.

I. INTRODUCTION

FSO has wide range of advantages as extremely high data rate, inherent security and low power consumption. It has unlicensed optical wavelength that allows possible communication for application in order of several kilometers and also has potential to communicate between ground and satellites [1], [2]. FSO uses line of sight communication technology and is popular in several applications. It is categorized in terms of communication range such as inter chip communication, under water communication, inter-city communication, inter satellite communication, visible light communication and wireless body area networks [3], [4]. Due to the property of lower power consumption, FSO systems do not get interfered with other wireless communications links. FSO was developed to fulfill the increasing demand of higher data rate with secure wireless communication over wireless channel. However, this technology is limited to atmospheric turbulence and different weather conditions such as rain, haze, smoke, fog, snow, mist etc. FSO link is deeply degraded with atmospheric turbulence and fog weather conditions. Performance deterioration of the communication link [6] propitiates weather effects in FSO link where spatial diversity technique is employed. The performance of FSO communication systems under the effect of atmospheric turbulence has been analyzed [8]. It investigated the M-ary pulse position modulation (M-PPM) with on-off keying and other modulation schemes in FSO links.

This paper analyzes the performance of FSO link under different modulation schemes such as ON-OFF keying (OOK), BPSK, 16-PSK, 2-PPM, 16-PPM, 4-QAM, 16-QAM under atmospheric and fog conditions.

II. SYSTEM MODEL

This paper considered the FSO communication system in which the data is to be transmitted by using different modulation techniques such as PSK, PPM, QAM, etc. After modulation, signal is transmitted through the atmospheric wireless channel under the weak, moderate and strong atmospheric turbulence condition. It assumes, FSO communication system is highly affected by atmospheric turbulence.

The turbulence over the free space channel is modeled as gamma-gamma distribution in induced fading channel. The channel of FSO communication link is modeled by considering the atmospheric attenuation with channel loss $(\mathrm{h_p})$, due to different fog strength (light fog and moderate fog) and the scintillation $(\mathrm{h_s})$ due to atmospheric turbulence. The relation between the channel loss and scintillation is given as $\mathrm{h} = \mathrm{h_p h_s}$. The channel loss is expressed using Beer Lambert's law as,

$$h_p = e^{-\sigma z} \tag{1}$$

where, z is the propagation length of channel and σ is the attenuation coefficient. To calculate the value of σ, link visibility is a very important parameter and it is meteorological visual range in the turbulent atmospheric channel at which the image contrast reduces to 2% compared to the nearest object. The attenuation due to fog is calculated using Kim model as expressed [12],

$$\sigma = \frac{3.912}{V} \left[\frac{\lambda}{550\,nm}\right]^{-q} \tag{2}$$

where, V is the visibility and q for Kim model is defined as follows.

$$q = \begin{cases} 1.6, & V > 50km \\ 1.3, & 6km \;\; V < 50km \\ 0.16V + 0.34, & 1km < V < 6km \\ V - 0.5, & 0.5km < V < 1km \\ 0, & V < 0.5km \end{cases} \quad (3)$$

Table 1 shows the visibility and attenuation in light and moderate fog conditions. In strong turbulence, dense fog conditions are not considered due to their non-existence [6].

TABLE 1

VISIBLE RANGE AND ATTENUATION COEFFICIENT DUE TO FOG AT 1550 NM WAVELENGTH

Fog strength	Visibility (km)	Attenuation (dB/km)
Light fog	2.0	4.2850
Moderate fog	0.6	25.5160

Atmospheric turbulence due to fluctuation in air mass is modeled by gamma-gamma distributed channel and expressed as[6],[2],

$$f_{h_s}(h_s) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)}\, h_s^{\frac{\alpha+\beta}{2}-1}\, K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_s}\right) \quad (4)$$

where, α and β are the values of spherical wave [6], the distribution shaping parameter $K_{\alpha-\beta}(\cdot)$, represents the modified second order Bessel function, $\Gamma(\cdot)$ denotes the gamma function. α and β can be defined as,

$$\alpha = \left(exp\left[\frac{0.49D_o^2}{\left(1+0.56D_o^{12/5}\right)^{7/6}}\right] - 1\right)^{-1} \quad (5)$$

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

where, $D_o^2 = 0.5C_n^2 k^{7/6} z^{11/6}$, represents the Rytov variance of spherical wave, C_n^2 is the refractive index or strength of turbulence, $k = 2\pi / \lambda$, is the optical wave number [2], and λ is the operating wavelength.

Probability density function (pdf) of the channel $f_h(h)$ can be represented as follows.

$$f_h(h) = \left|\frac{d}{dh}\left(\frac{h}{h_p}\right)\right| f_{h_s}\left(\frac{h}{h_p}\right) \quad (7)$$

The above Bessel function can be formulated in terms of Meijer-G function [7] as follows.

$$k_v(z) = \frac{1}{2}\, G_{0,2}^{2,0}\left[\frac{z^2}{4}\left|\begin{matrix} - \\ \frac{v}{2}, \frac{-v}{2}\end{matrix}\right.\right] \quad (8)$$

Gamma-gamma distributed channel can be expressed using Meijer-G as follows.

$$f_{h_s}(h_s) = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)}\, h_s^{\frac{\alpha+\beta}{2}-1}\, G_{0,2}^{2,0}\left(\alpha\beta h_s\left|\begin{matrix} - \\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}\end{matrix}\right.\right) \quad (9)$$

Now, the probability density function of the atmospheric turbulence channel is given as follows.

$$f_h(h) = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)}\, \frac{h^{\frac{\alpha+\beta}{2}-1}}{h_p^{\frac{\alpha+\beta}{2}}}\, G_{0,2}^{2,0}\left(\alpha\beta\frac{h}{h_p}\left|\begin{matrix} - \\ \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}\end{matrix}\right.\right) \quad (10)$$

III. BER ANALYSIS FOR DIFFERENT MODULATION SCHEMES

BER is the average of the conditional error probability, $P_e(h)$, over the *pdf*, of the atmospheric turbulence channel, $f_h(h)$, which is mentioned below [4] [6],

$$BER = \int_0^\infty P_e(h)\, f_h(h)\, dh \quad (11)$$

$P_e(h)$ can be used for different modulation techniques to calculate the BER of the system, those modulation techniques are explained below.

A. ON-OFF modulation scheme

The $P_e(h)$ for ON-OFF keying is expressed in terms of complimentary error function as [6],

$$P_e(h) = \frac{1}{2}\, erfc\left(\sqrt{\frac{SNR(h)}{2}}\right) \quad (12)$$

where, the instantaneous value of received SNR is given by γh^2, γ is the mean electrical output SNR. The above Eq. 12 can be expressed using Meijer-G as follows.

$$P_e(h) = \frac{1}{2\sqrt{\pi}}\, G_{1,2}^{2,0}\left(\frac{\gamma h^2}{2}\left|\begin{matrix} 1 \\ 0, \frac{1}{2}\end{matrix}\right.\right) \quad (13)$$

Now, Eq. 13 and Eq. 10 are substituted in Eq. 11 to obtain the corresponding BER expressed as,

$$BER = Qo\, G_{5,2}^{2,4}\left(\frac{8\gamma h_p^2}{(\alpha\beta)^2}\left|\begin{matrix} \frac{1-\alpha}{2}, 1-\frac{\alpha}{2}, \frac{1-\beta}{2}, 1-\frac{\beta}{2}, 1 \\ 0, \frac{1}{2}\end{matrix}\right.\right) \quad (14)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

B. Binary phase shift keying (BPSK) modulation scheme

$P_e(h)$ of BPSK modulation technique is expressed using Meijer-G [5].

$$P_e(h) = \frac{1}{2\sqrt{\pi}} G_{1,2}^{2,0}\left(\gamma h^2 \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (15)$$

Now, the BER can be expressed as,

$$BER = Qo\, G_{5,2}^{2,4}\left(\frac{16\,\gamma h_p^2}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (16)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

C. 16-PSK modulation scheme

The $P_e(h)$ of 16-PSK can be expressed in terms of Meijer-G as [11] follows.

$$P_e(h) = \frac{1}{4\sqrt{\pi}} G_{1,2}^{2,0}\left(\frac{8\,\gamma h^2}{50} \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (17)$$

Now, the corresponding BER can be expressed as,

$$BER = \frac{Qo}{2}\, G_{5,2}^{2,4}\left(\frac{64\,\gamma h_p^2}{25\,(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (18)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

D. 4-QAM modulation scheme

The $P_e(h)$ for 4-QAM modulation technique is expressed using Meijer-G as [10] follows.

$$P_e(h) = \frac{3}{2\sqrt{\pi}} G_{1,2}^{2,0}\left(\gamma h^2 \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (19)$$

Now, based on Eq. 19 and Eq. 10 the modified expression for BER can be expressed as,

$$BER = 3\,Qo\, G_{5,2}^{2,4}\left(\frac{16\,\gamma h_p^2}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (20)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

E. 16-QAM modulation scheme

$P_e(h)$ for 4-QAM modulation technique can be expressed using Meijer-G as [10] follows.

$$P_e(h) = \frac{15}{8\sqrt{\pi}} G_{1,2}^{2,0}\left(\gamma h^2 \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (21)$$

Now, BER can be represented as,

$$BER = \frac{15\,Qo}{4}\, G_{5,2}^{2,4}\left(\frac{16\,\gamma h_p^2}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (22)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

F. 2-PPM modulation scheme

The $P_e(h)$ of 2-PPM modulation technique can be expressed using Meijer-G as [9] follows.

$$P_e(h) = \frac{1}{2\sqrt{\pi}} G_{1,2}^{2,0}\left(\frac{\gamma h^2}{8} \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (23)$$

Now, the modified expression of BER can be expressed as,

$$BER = Qo\, G_{5,2}^{2,4}\left(\frac{2\,\gamma h_p^2}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (24)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

G. 16-PPM modulation scheme

The $P_e(h)$ of 16-PPM modulation technique can be expressed using Meijer-G as [9] follows.

$$P_e(h) = \frac{1}{2\sqrt{\pi}} G_{1,2}^{2,0}\left(4\,\gamma h^2 \middle| \begin{matrix} 1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (25)$$

Now, the corresponding BER can be represented as,

$$BER = Qo\, G_{5,2}^{2,4}\left(\frac{64\,\gamma h_p^2}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{1-\alpha}{2},1-\frac{\alpha}{2},\frac{1-\beta}{2},1-\frac{\beta}{2},1 \\ 0,\frac{1}{2} \end{matrix}\right) \quad (26)$$

where, $Qo = 2^{\alpha+\beta}/8\,\pi^{3/2}\,\Gamma(\alpha)\,\Gamma(\beta)$.

IV. SIMULATION AND RESULTS

Performance analysis of different modulation formats under different channel conditions is simulated using MATLAB. Table 2 shows the parameters considered for simulation [7].

TABLE 2

PARAMETERS CONSIDERED FOR SIMULATION

PARAMETER	VALUES
λ	1550 nm
z	3.5 km
C_n^2 (weak)	$8.4 \times 10^{-15}\ m^{-2/3}$
C_n^2 (moderate)	$1.7 \times 10^{-14}\ m^{-2/3}$
C_n^2 (strong)	$5 \times 10^{-14}\ m^{-2/3}$

Fig. 1 represents the performance of FSO link under weak turbulence and light fog condition. Fig. 2 and 3 represents the performance of different modulation formats under moderate and strong turbulence with light fog.

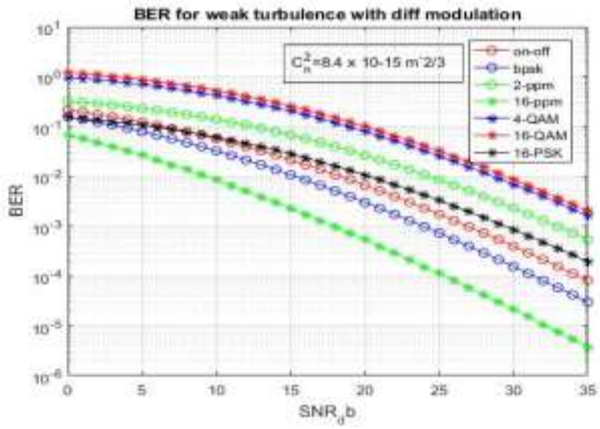

Fig.1. BER under weak turbulence and light fog for different modulation schemes

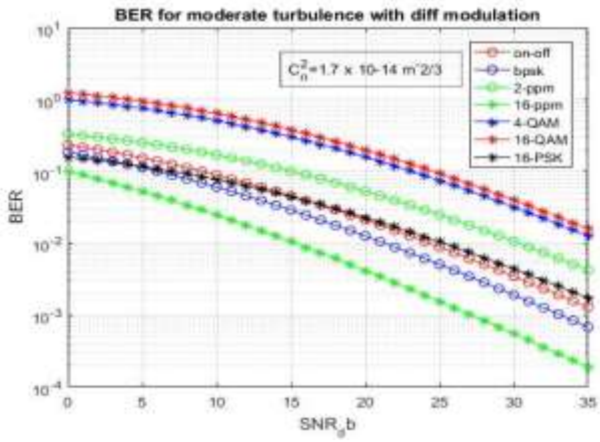

Fig.2. BER for moderate turbulence with light fog condition for different modulation scheme.

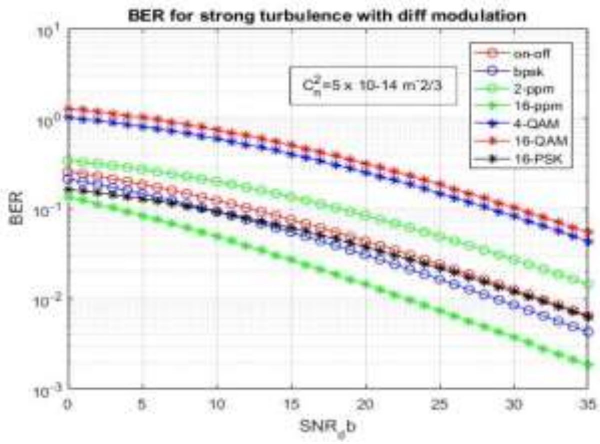

Fig.3 BER for strong turbulence with light fog condition for different modulation scheme

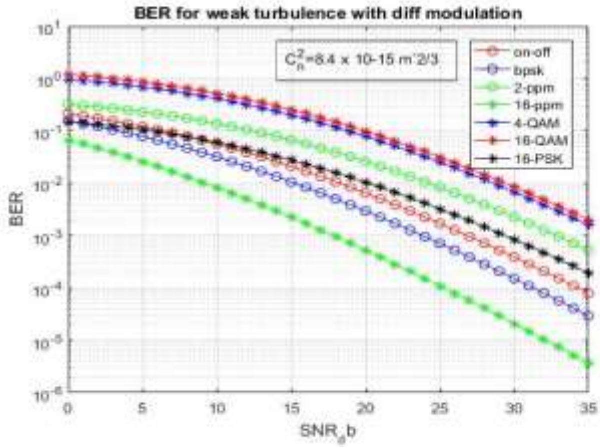

Fig.4. BER for weak turbulence with moderate fog condition for different modulation scheme

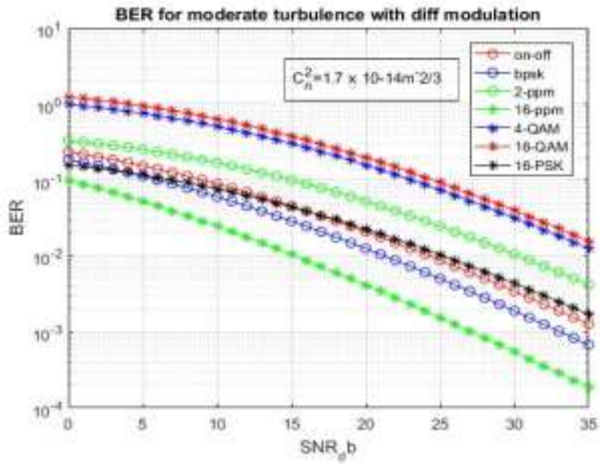

Fig.5. BER for moderate turbulence with moderate fog condition for different modulation scheme

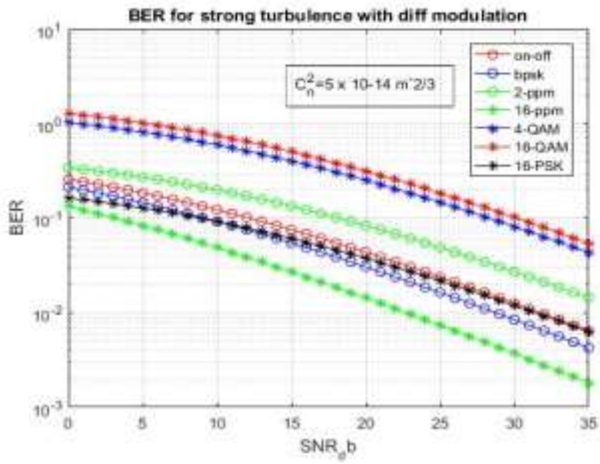

Fig.6. BER for strong turbulence with moderate fog condition for different modulation scheme

Fig. 4, 5 and 6 represents the performance analysis of different modulation techniques under weak turbulence, moderate turbulence and strong turbulence with moderate fog conditions. It can be observed that 16-PPM has the least effect and is more susceptible to the channel conditions compared to 2-PPM, BPSK, 16-PSK, QAM and ON-OFF Keying.

V. CONCLUSION

Performance analysis of FSO link under different channel condition with various modulation schemes is analyzed. 16-PPM forms more tolerant to turbulence channel and fog conditions. This analysis mechanism can help to adopt a modulation technique for different channel conditions. The analysis also conclude that for both weak and moderate fog conditions the BER reduces as the turbulence strength goes from strong to weak. It is also found that the BER increases with the M value in M-PSK, M-QAM, but in the case of M-PPM the BER decreases as M value increases.

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