BER performance analysis of a non-Hermitian coherent optical OFDM FSO system with polarization diversity using various atmospheric turbulent channel models

M. Shariful Islam[1,2] · S. P. Majumder[1]

Abstract

In this research article, we investigate the impact of different atmospheric turbulence along with polarization crosstalk on the bit error rate (BER) performance of a non-Hermitian orthogonal frequency division modulated (OFDM) free-space optical (FSO) system with polarization diversity. Analysis is carried out for a non-Hermitian coherent optical OFDM followed by differential quadrature phase shift keying FSO system with polarization diversity in presence of atmospheric turbulence for all weather conditions. We considered Log-normal, Gamma-Gamma and Negative exponential turbulence fading model for weak, medium and strong atmospheric turbulent channel respectively and for cross polarization induced crosstalk, the random misalignment angle is Maxwellian distributed. The system average BER is calculated by averaging the conditional BER over the probability density function of the channel irradiance along with Maxwellian distributed random misalignment angle. Results are evaluated in terms of BER, power penalty due to polarization crosstalk along with atmospheric turbulence and receiver sensitivity due to OFDM. Results show that the system suffers almost 7.5, 11 and 16 dB power penalty due to polarization crosstalk along with weak, medium and strong turbulence respectively at a constant BER of 10^{-12} when the system link length is 3000 m. It is clearly observed that, almost 19, 16 and 10 dB receiver sensitivity is achieved when number of subcarriers increase into 512 for weak, medium and strong turbulence conditions, respectively at a constant BER of 10^{-12}.

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1 Introduction

Free-space optical communication system is a prominent technology for the future broadband optical networks because of its huge bandwidth capacity, required no license, high data rate, easy to deployment, simple hardware architecture, low cost and full duplex communication (Wang et al. 2014; Vincent 2006; Chinta et al. 2009; Chao et al. 2021). Nowadays, high speed FSO communication system is considered for inter satellite data transmission link where pointing error due to misalignment causes severe performance degradation (Singh et al. 2022; Ebrahim et al. 2022). The user demand of high data rate for live streaming, video conferencing, high-speed internet, exponential growth of mobile data traffic etc. is increasing day by day (Singh and Malhotra 2020a, 2020b, 2021). So, FSO communication can be considered to meet up the user's increased data rate demand. But, there is a problem in FSO communication system which is adverse weather condition simply known as atmospheric turbulence. The atmospheric turbulence causes the amplitude fading and phase distortion in the received light wave which actually increases the bit error rate severely (Antonio 2007; Zhu and Kahn 2002; Zhang et al. 2019; Sunilkumar et al. 2019). Different turbulence fading models are already developed for different atmospheric turbulence regimes. For weak turbulence, the fading model is well known Log-normal model (Stephen et al. 2005), for medium to strong turbulence the model is Gamma-Gamma (Singh and Malhotra 2021; Bekkali et al. 2010) and for very high turbulence the model is Negative exponential model (Wilson et al. 2005).

For FSO communication systems, orthogonal frequency division modulation (OFDM) is considered as multiple subcarrier modulation and it is a very key technology against frequency selective fading channel (Barua and Majumder 2018; Cvijetic et al. 2008; Shariful and Majumder 2019; Bukola et al. 2019). It enhance the FSO system capacity and flexibility without increasing the complexity and cost of the system (Singh and Malhotra 2020c). The spectrum efficiency and channel capacity of high speed FSO systems improves by using higher order modulation scheme such as polarization division multiplexed 16 quadrature amplitude modulation (PDM-16 QAM) (Arun et al. 2021). Polarization diversity also improves system performance but there is a possibility of crosstalk due to cross polarization (Grosinger 2008; Xie et al. 2011; Zhang et al. 2018; Ruhin and Choyon 2021; Zhang and Dang 2017). To account induced cross polarization crosstalk we considered Maxwellian Distribution (Winter et al. 2009; Islam and Majumder 2007; Glauco et al. 2013).

In Shariful and Majumder (2020), the performance of a non-Hermitian OFDM based DQPSK FSO system with polarization diversity over strong turbulence was reported. In this research article, we compare the same system BER performance proposed in Shariful and Majumder (2020), but considering different atmospheric turbulent conditions by using different turbulence fading models.

2 System model

Block diagram of our proposed non-Hermitian OFDM based DQPSK FSO system considering polarization diversity is given in Fig. 1. The OFDM modulated complex data is put into a Real Imaginary separator. The separated real and imaginary data is then fed into two different DQPSK modulators to perform DQPSK modulation. A laser light wave is spillited into horizontal and vertical light signal and then these two light signals are used
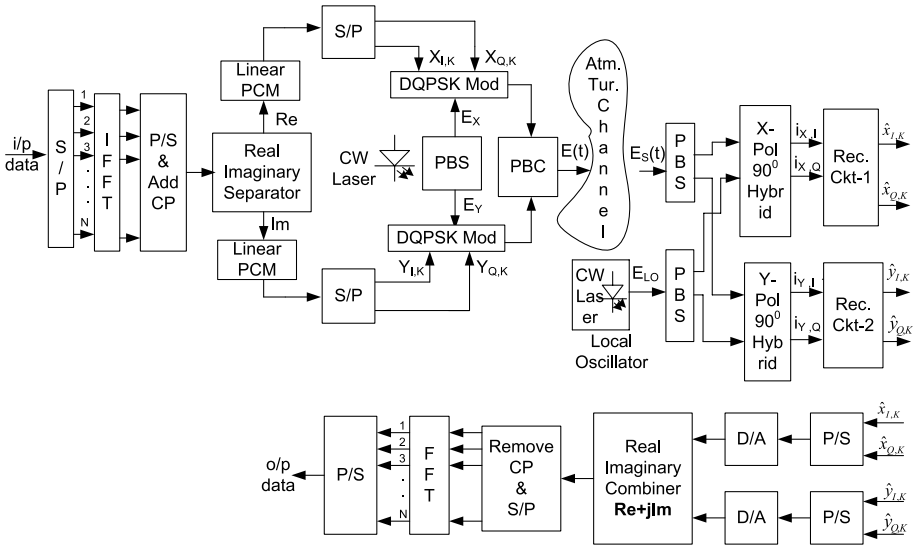
Fig. 1 Full block diagram representation of an OFDM DQPSK FSO system with polarization diversity (Shariful and Majumder 2020)

as a carrier signal for real and imaginary DQPSK modulated data respectively. These two lights are combined by a polarized beam combiner and passed through the atmospheric turbulent channel. At the receiver side, the received signal is again spilled and fed into a 90° hybrid circuit where a reference light is also fed from the local oscillator. By using a receiver circuit, the digital output is found. To retrieve the transmitted data, the reverse process is carried out for the rest part of the system.

3 Channel model

The atmospheric turbulence is the key factor which fades the intensity and changes the phase of the received light. The fading strength mainly depends on the refractive index structure parameter C_n^2 and the optical radiation of the channel. For weak atmospheric turbulent channel, the mostly used fading model is the log-normal distribution. The probability density function of the channel irradiance is expressed by Stephen et al. (2005)

$$f(I) = \frac{1}{\sqrt{2\pi\sigma_l^2}I} \exp\left(-\frac{(\log_e I - \mu_x)^2}{2\sigma_l^2}\right), \quad a > 1 \tag{1}$$

The Gamma-Gamma turbulence fading model is suitable turbulence model for medium atmospheric turbulence. The gamma distribution is expressed by Singh and Malhotra (2021), Bekkali et al. (2010)

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{(\alpha+\beta)}{2}-1} K_{(\alpha-\beta)}(2\sqrt{\alpha\beta I}), I > 0 \tag{2}$$

where, I represents intensity of the optical signal, the modified Bessel function is $K_{\alpha-\beta}$ where $\alpha - \beta$ is its order and symbol Γ is the gamma function. The symbols α and β represents small-scale and large scale eddies respectively.

Negative exponential channel is generally considered under very strong irradiance fluctuations. When the turbulence reaches its saturation level known as the fully developed speckle regime, huge number of independent scatterings occurs. At that time, the field's amplitude fluctuation is experimentally verified to obey the Rayleigh distribution implying negative exponential statistics for the channel irradiance which is expressed as (Wilson et al. 2005)-

$$f(I) = \frac{1}{I_0} \exp(-\frac{I}{I_0}) \tag{3}$$

where, I_0 ($I_0 > 0$) is said as the mean irradiance or noise turbulence variance which is often normalized to unity.

4 Theoretical analysis

The Maxwell distribution of the random misalignment angle where θ_m represents the mean misalignment angle is expressed as (Winter et al. 2009; Islam and Majumder 2007; Glauco et al. 2013)

$$P(\theta) = \frac{32}{\pi^2 \theta_m^3} \theta^2 e^{-\frac{(2\theta)^2}{\pi \theta_m^2}} \tag{4}$$

After accounting fading due to PBS misalignment and turbulence, the resultant signal term is (Shariful and Majumder 2020)-

$$i_{x,C} = 4\varepsilon_F R_d A_x \sqrt{I(2 - \frac{4\pi^2 P_{b,X}}{N^2 V_\pi^2})P_{LO,X}} \cos\theta_x \tag{5}$$

And the crosstalk terms due to X-Pol and turbulence is-

$$i_{Xtalk,C} = 4\varepsilon_X R_d A_y \sqrt{I(2 - \frac{4\pi^2 P_{b,Y}}{N^2 V_\pi^2})P_{LO,X}} \cos\theta_y \tag{6}$$

The conditional signal to noise plus crosstalk ratio (SNCR) condition on misalignment angle and turbulence is written as (Shariful and Majumder 2020)

$$\begin{aligned} SNCR(\theta, I) &= \frac{|i_{X,C}|^2}{|i_{Xtalk,C}|^2 + i_B^2 + \sigma_{th}^2 + \sigma_{sh}^2} \\ &= \frac{16 R_d^2 I A_x^2 (2 - \frac{4\pi^2 P_{b,X}}{N^2 V_\pi^2}) P_{LO,X} \cos^2\theta \, \cos^2\theta_x}{} \end{aligned} \tag{7}$$

Now, the conditional BER of the system is represent by-

$$BER_{cond.}(\theta, I) = \frac{1}{2} erfc\left(\frac{\sqrt{SNCR(\theta, I)}}{2} \right) \tag{8}$$

Finally, the average BER can be written as (Shariful and Majumder 2020)-

$$BER_{average} = \int_0^{\frac{\pi}{2}} \int_0^{\infty} BER_{cond.}(\theta, I) \, . f(I) \, . P(\theta) dI \, d\theta \tag{9}$$

Now we can simplify the Eq. (9) by taking some necessary steps. Firstly we rewrite the Eq. (7) as

$$SNCR(\theta, I_{res}) = \frac{C_1 I \cos^2 \theta}{C_2 I \sin^2 \theta + N_0} \tag{10}$$

where,

$$A_1 = 16 R_d^2 A_x^2 (2 - \frac{4\pi^2 E_b}{N^2 V_\pi^2 T_b}) P_{LO,X} \cos^2 \theta_x$$

$$A_2 = 16 R_d^2 A_y^2 (2 - \frac{4\pi^2 E_b}{N^2 V_\pi^2 T_b}) P_{LO,X} \cos^2 \theta_y$$

$$N_0 = i_B^2 + \frac{4kTB}{R_L} + 2eBR_d(P_{b,X} + P_{LO,X})$$

Substituting Eqs. (4) and (8) into (9), then we found the average BER equation as-

$$BER_{average} = \int_0^{\infty} \int_0^{\frac{\pi}{2}} \left[\frac{1}{2} - \frac{1}{2} erf\left(\frac{\sqrt{SNCR(\theta, I)}}{2} \right) \right] \frac{32}{\pi^2 \theta_m^3} \theta^2 e^{-\frac{(2\theta)^2}{\pi \theta_m^2}} f(I) \, d\theta \, dI \tag{11}$$

To eliminate the error function associated in Eq. (11), we can invoke Eq. (3.321.1) reported in Gradshteyn and Ryzhik (1994) and the resultant average BER expression is then

$$BER_{average} = \int_0^{\infty} \int_0^{\frac{\pi}{2}} \left[\frac{1}{2} - \frac{1}{\sqrt{\pi}} \sum_{q=0}^{\infty} \frac{(-1)^q \left[\frac{\sqrt{SNCR(\theta, I)}}{2} \right]^{2q+1}}{q! \, (2q+1)} \right] \frac{32}{\pi^2 \theta_m^3} \theta^2 e^{-\frac{(2\theta)^2}{\pi \theta_m^2}} f(I) \, d\theta \, dI$$

$$\tag{12}$$

To reduce the integral number involved in (12), we can invoke Eq. (3.326.2) reported in Gradshteyn and Ryzhik (1994) and assumed only signal to crosstalk ratio when averaging over Maxwellian distribution to get the more simplified form of the average BER. The final expression of the average BER is -

Table 1 Required system parameters value used in simulation

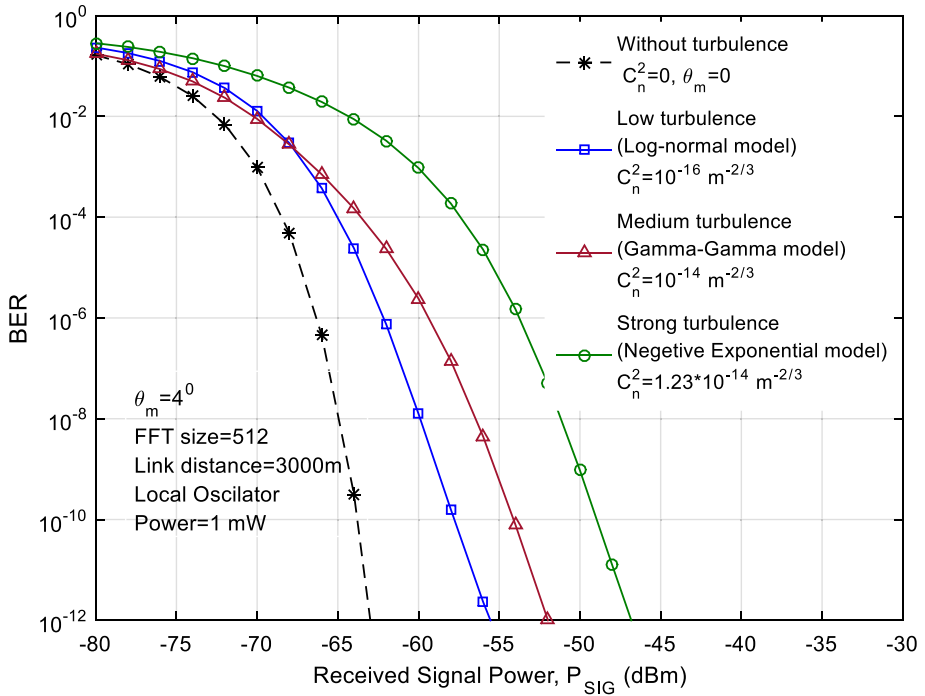| Parameters	Values
Photodetector Responsivity, Rd	0.85
Characteristic of the MZ, $V0$	500 mV–8 V
Temperature, T	300 K
Thermal Resistance, RL	50 Ω
Laser wavelength, λ	1550 nm
Phase of the X-polarized signal, $\Phi X,I$	450
Phase of the Y-polarized signal, $\Phi Y,I$	450
Background noise	10–8 W

Fig. 2 BER performance results comparison between without atmospheric turbulence and polarization crosstalk with different atmospheric turbulence with polarization crosstalk

$$BER_{average} = \frac{32}{\pi^2 \theta_m^3} \int\limits_0^\infty \left[\frac{\Gamma\left(\frac{3}{2}\right)}{4\left(\frac{\pi\theta_m^2}{4}\right)^{\frac{3}{2}}} - \frac{1}{\sqrt{\pi}} \sum_{q=0}^\infty \frac{(-1)^q \left[\sqrt{\frac{A_1 I}{4A_2 I + 4N_0}}\right]^{2q+1} \Gamma\left(\frac{-2q+2}{2}\right)}{q! \, (2q+1) \, \times 2\left(\frac{\pi\theta_m^2}{4}\right)^{\frac{-2q+2}{2}}} \right] f(I) \, dI$$

(13)

5　Results and discussion

The required system's parameters value considered during analytical simulations are provided in Table 1. The BER performance of the considered system is evaluated for different atmospheric turbulence. The BER versus received signal power for different atmospheric turbulence condition are shown in Fig. 2. Results show that the system suffers almost 7.5, 11 and 16 dB power penalty due to polarization crosstalk along with weak, medium and strong turbulence respectively at a BER of 10^{-12} when the system link length is 3000 m. When the number of OFDM subcarrier increases it reduces the power penalty of the system which is shown in Fig. 3. The system BER performance for different link distances and for different mean misalignment angles are provided in Figs. 4 and 5 respectively. The power penalty due to random mean misalignment angle for all turbulence regimes is
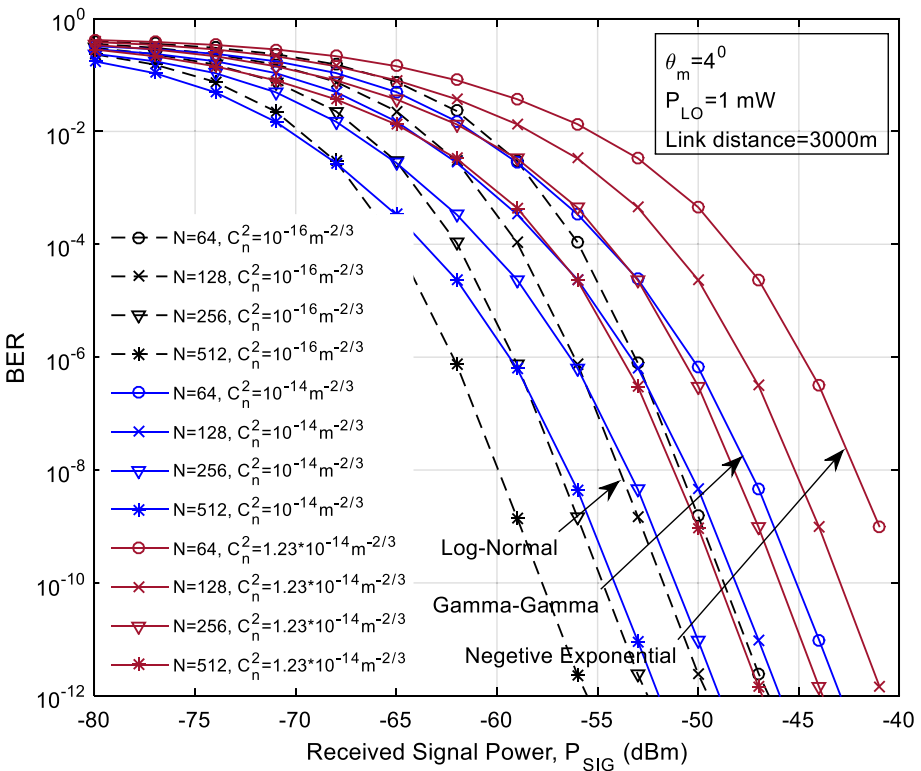

Fig. 3 System's BER performance results for various atmospheric turbulent conditions when number of OFDM subcarriers is as input variable
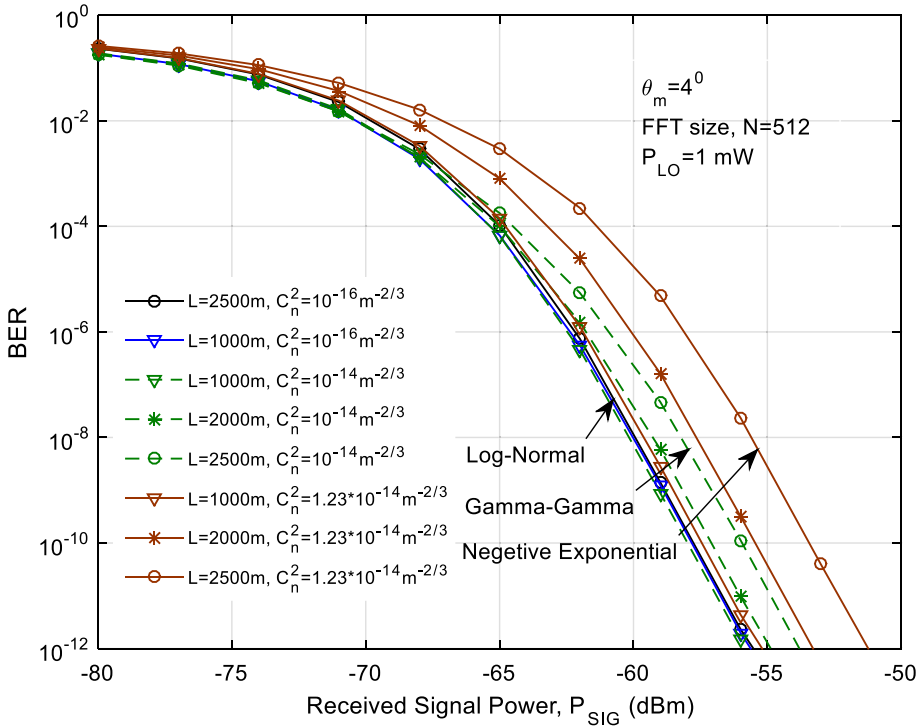
Fig. 4 Effect of increasing system's link distance on BER performance considering different atmospheric turbulence condition

provided in Fig. 6. The Fig. 7 shows the receiver sensitivity improvement due to increasing the number of OFDM subcarrier for different turbulence fading model. Results show that, almost 19, 16 and 10 dB receiver sensitivity improves when number of subcarrier increase into 512 for weak, medium and strong turbulence condition respectively at a BER of 10^{-12}. The maximum allowable link distance of the considered system for different turbulent conditions are approximately 3650 m for weak, 3300 m for moderate to strong and 2800 m for very strong turbulence to maintain a constant BER of 10^{-12} and received optical power of -50dBm when the number of OFDM subcarrier is 512. The allowable link distance versus number of OFDM subcarriers is provided in Fig. 8. Results show that, for the same system's constraints, the allowable link distance is higher for weak turbulence regime and the allowable link distance is decreasing with increasing turbulences, the change of allowable link distance with number of OFDM subcarrier is also less for weak turbulence and the change increasing with increasing turbulences.
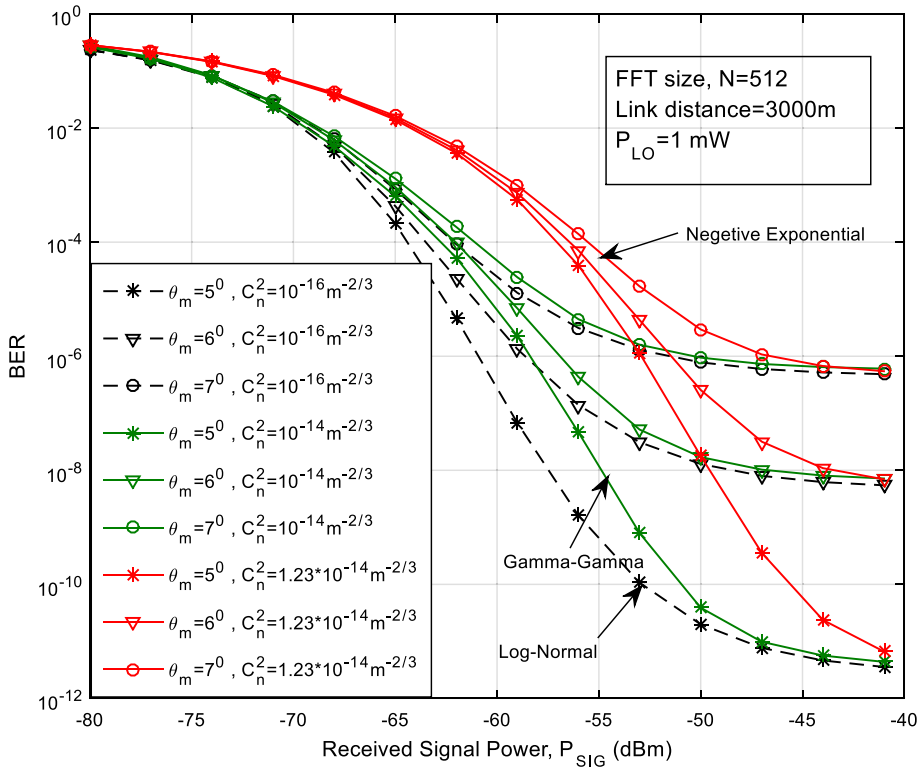
Fig. 5 Effect of increasing random mean angular misalignment angle on system's BER performance considering different atmospheric turbulence condition

6 Conclusions

The effect of atmospheric turbulence along with polarization crosstalk on BER performance of a non-Hermitian OFDM based DQPSK system is determined. The performance of the system in terms of BER for different turbulent channel considering different fading model is compared. It is clearly noticeable from different results that the system BER performance deteriorated drastically due to very strong turbulence along with higher polarization crosstalk. System's allowable link distance varies with the variation of atmospheric turbulence. To reduce the fading due to atmospheric turbulence, different channel coding like Read Solomon code, Convolutional code, Low Density Parity Check code etc. may considered along with our proposed system. The results of our proposed system may use to find application in design of OFDM FSO link over atmospheric turbulent channel.
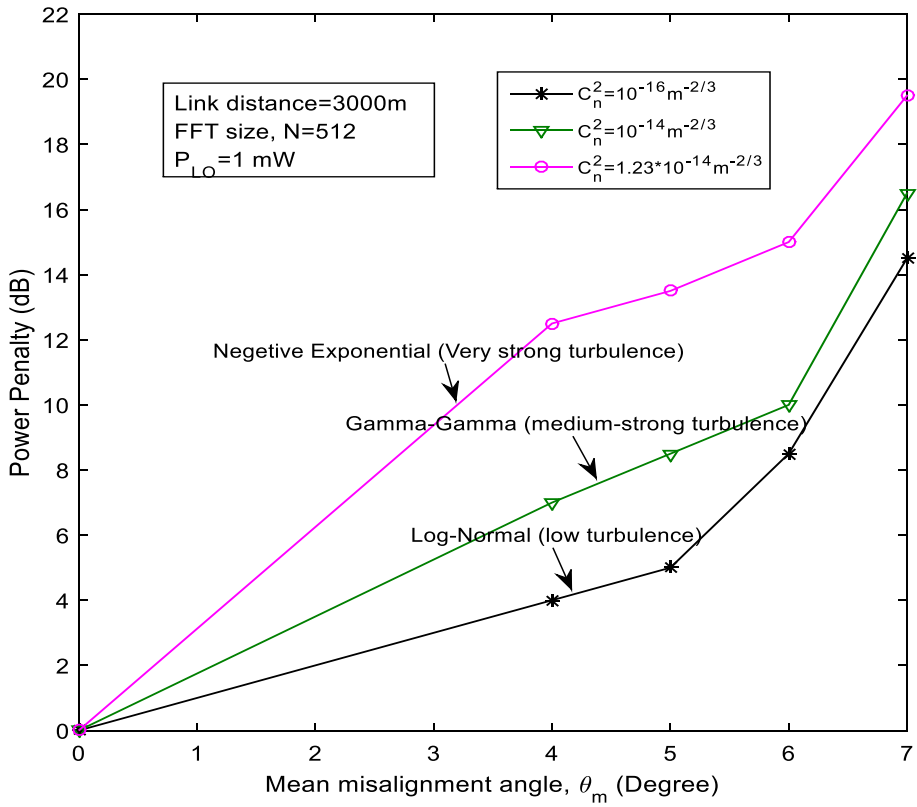
Fig. 6 Power penalty curves due to polarization crosstalk for different atmospheric turbulent channel at a BER of 10^{-6}
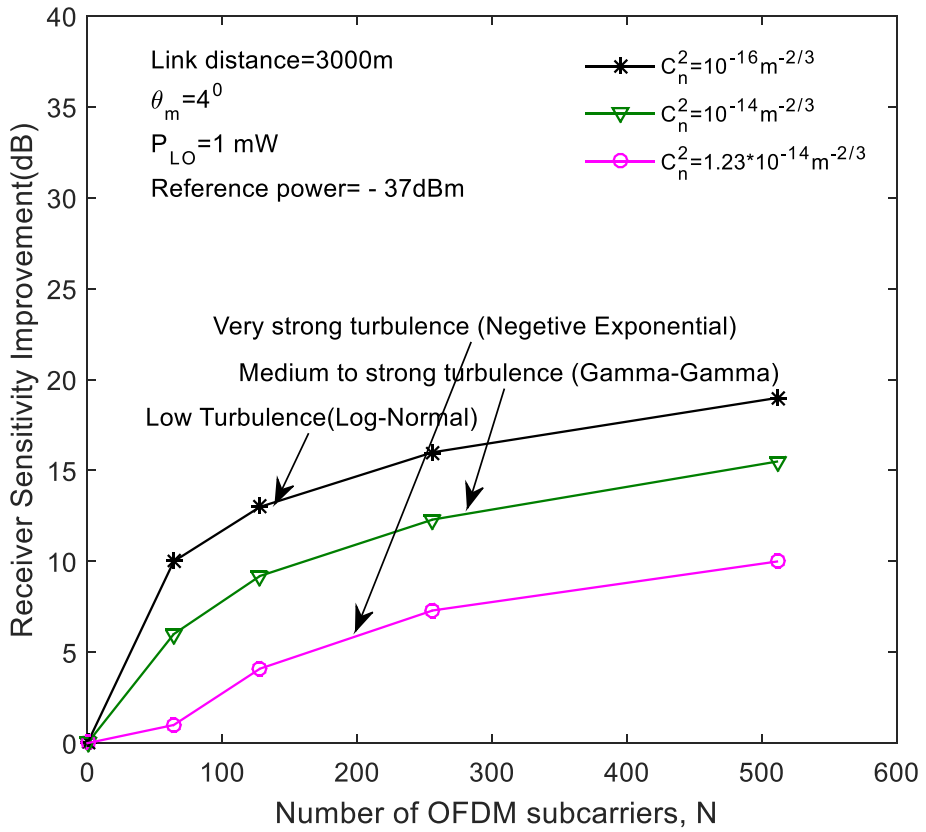
Fig. 7 Receiver sensitivity improvement curves due to increasing number of OFDM subcarrier for different atmospheric turbulent channel at a BER of 10^{-12}
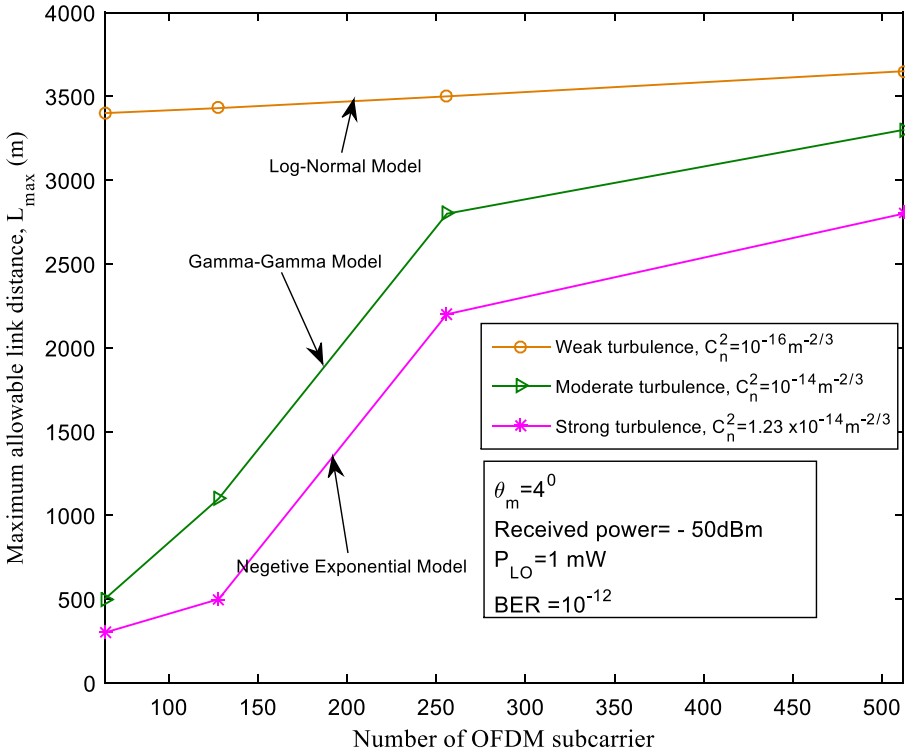
Fig. 8 Maximum allowable system link distance versus number of OFDM subcarrier for a fixed BER of 10^{-12} and a constant received optical power of -50dBm

Availability of data and material Available if required.

Code availability Available if required.

Declarations

Conflicts of interest The authors declare no conflicts of interest.

Consent to participate Not applicable.

Consent for publication Not applicable.

Ethics approval We agreed all terms and conditions for Ethics approval.

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