Optimum Link Distance and BER Performance Investigation for BPSK RF Sub-Carrier Coherent FSO Communication System Under Strong Turbulence

A. K. M. Sharoar Jahan Choyon, Ruhin Chowdhury, S. M. Raiyan Chowdhury

Abstract: Free-space optical (FSO) technology has acquired a growing interest in optical wireless communication system. Although the FSO system presents outstanding advantages, it is highly prone to atmospheric turbulence. To mitigate this effect and enhance the performance of FSO link, a fusion of radio-frequency (RF) with FSO technique is quite prominent in these recent years. A comprehensive analysis is performed here with a view to inspecting the effects of atmospheric turbulence in terms of the BER characteristics of FSO link with RF sub-carrier modulation under strong turbulent channel with Gamma-Gamma (G-G) fading. Here, we consider single sub-carrier for avoiding the complexity of inter carrier interference (ICI) effect. Analysis is performed to find the signal to noise ratio (SNR), bit error rate (BER) and power penalty at the end of the coherent optical binary phase-shift keying (BPSK) receiver with RF sub-carrier optical intensity modulator. Simulation results indicate that the system performance deteriorates due to an increase in FSO link distance, and when the link distance is limited to 2-2.5 km, it requires a lower power penalty to achieve a satisfactory BER.

Index Terms: Free-space optical (FSO) communication, RF sub-carrier modulation, Coherent receiver, Gamma-Gamma (G-G) distribution, Atmospheric Turbulence.

1. INTRODUCTION

FSO communication system emerges to meet the demand of increasing traffic, audio, and video data transmission without requiring fiber optic channel. One of the greatest advantages of FSO system over RF communication system is that FSO communication system provides high-bandwidth transmission link by transmitting modulated optical data through the atmosphere. Being a line of sight (LOS) laser communication system, it has drawn considerable attention due to its license-free and highly secured transmission, short-range indoor wireless communication, last-mile access, easy deployment time and cost, etc. [1], [2]. Although the FSO system has an advantage over the RF system by transmitting data wirelessly through the atmosphere, its performance is extremely vulnerable to atmospheric induced fading conditions due to fog, rain, haze, snow, etc. bad meteorological circumstances. Even though the weather condition is clear, the FSO system performance is corrupted by one of the most vital causes of atmospheric turbulence i.e. scintillation [3]. The fluctuating atmospheric temperature and pressure give rise to continuous alteration in the refractive index resulting in thedeterioration of the power of light transmitting through the atmosphere [4], [5]. The diversity in sizes of the atmospheric molecules affects the transmitted light by changing the type of scattering. Besides, multipath fading and frequency selective fading affects the FSO communication link. This creates narrow-band inter-symbol interference [6]. Therefore, it is difficult to maintain the LOS communication of the FSO link. To overcome this challenge and to make the FSO transmitter and receivers more feasible, the main concern of researchers is to minimize the impacts of atmospheric turbulence on the transmitted laser beam and to maximize the performance of the optical signal [7]. One of the promising techniques to improve the performance and to take advantage of both RF and FSO system is to combine these two technologies [8], [9], [10]. The performance of any wireless system depends greatly on adopting appropriate modulation schemes and selecting a suitable channel model to reduce noise and interference by deploying different techniques. In FSO, different modulation techniques can be deployed such as OOK, BPSK, DPSK, QPSK and 8-PSK, in which, OOK is the easiest and widely used modulation scheme which is severely susceptible to weather turbulence and requires an adjustable threshold develop the system. Besides, for OOK modulation, the capability to prevent the atmospheric turbulence is explicitly vulnerable [11]. The phase modulation schemes provide greater sensitivity and extraordinary qualities which are suited to FSO system. Comparing with the OOK modulation scheme, BPSK, QPSK, DPSK as well as 8-PSK present superior performance in the presence of turbulence. Moreover, information can be encoded with its phase in the DPSK scheme and it can moderate the drastic impact of scintillation more or less [12]. The easiest form of PSK is BPSK which employs two phases 180 degree apart from each other for data modulation. So, this phase modulation is basically 2-PSK with the advantage of canceling noise effectively compared to the OOK format [13]. From our previous work [13], it is seen that BPSK modulation provides the best BER performances in the presence of strong atmospheric turbulence compared to other modulation schemes. Therefore, we have selected BPSK modulation for our proposed model. Considering the impacts of atmospheric turbulence, various channel models

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are proposed to portray the FSO system. According to several publications, G-G distribution has a good simulation for both strong and weak atmospheric turbulent channels [14]. Therefore, we have adopted the G-G distribution for the FSO communication link. Besides, coherent optical detection scheme produces better performance compared to the direct detection scheme. Coherent detection provides higher spectral efficiencies and data rates. It has a higher probability to mitigate the background and thermal noise, and it provides more improved receiver sensitivity [15]. Therefore, we have taken coherent optical receiver detection scheme into consideration. This paper investigates the RF subcarrier BPSK modulated coherent FSO communication system over strong atmospheric turbulence using the G-G channel model and their effects on the system. The link distances considered that are here ranges from 0.5 km to 4 km to investigate the optimum link distance and the performances of BER, SNR and power penalty for this FSO link and their impact on the received power of the system under strong turbulence. The arrangement of this paper is sectioned as: The RF subcarrier modulated coherent FSO system design and the channel model is expounded in Section-2 and Section-3, respectively. We derived the analytical expression of conditional SNR, average BER of the system in Section-4. The simulation is accomplished by MATLAB, and the results and discussion are presented in Section-5. Section-6 comprises concluding statements.

2 SYSTEM DESIGN

In Fig. 1, we demonstrate a block diagram for our proposed model of RF subcarrier modulated Coherent FSO Communication System. The input data are BPSK modulated and fed into an optical intensity modulator which gives the laser output by electro-optic modulation. This electro-optic intensity-modulated (EOIM) signal passes through the strong atmospheric turbulent channel and is detected in the receiver section using a coherent optical detection scheme following by amplification of output current by the preamplifier. This signal is the combined RF modulated signal with noises from photo-detector and preamplifier. To minimize the noises, a band pass filter (BPF) is used to filter out noises from the RF signal. After combining the output of LO signal with the filtered signal, the final output is sent to the detector to yield the original data.

3 CHANNEL MODEL

When transmitted light radiation passes through the atmosphere (FSO channel), it suffers from small scale scattering and large-scale refraction effects where G-G model can effectively describe the channel effects. In our analysis, G-G model is considered. The pdf of beam intensity for I using the G-G channel model is presented by [16]:

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{(\alpha-\beta)}\left(2\sqrt{\alpha\beta I}\right); I > 0 \#(1)$$

Here, large- and small-scale turbulent eddies are explicated by α and β. The gamma and modified Bessel function are defined by $\Gamma(\cdot)$ and $K_{(\alpha-\beta)}$, respectively. Where, α and β are defined by [16]:

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

$$\beta = \left[\exp\left(\frac{0.51\delta^2}{(1+0.69\delta^{12/5})^{5/6}}\right) - 1\right]^{-1} \#(3)$$

$$\delta^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \#(4)$$

Here, δ^2 =Rytov Variance, C_n^2 =the refractive index structure parameter, k=Optical wave number= $2\pi/\lambda$, λ is wavelength, L is the link distance. For weak atmospheric turbulent channel $\delta^2 < 1$, and for strong atmospheric turbulent channel $\delta^2 > 1$. As we consider strong atmospheric turbulence, in this paper $\delta^2 > 1$. The irradiance fluctuations characterized by scintillation where the changes in C_n^2 leads at the receiver to deflect the optical beam and fluctuate of power. Moreover, C_n^2 is impacted by temperature and the time of day and ranges from $10^{-13}m^{-2/3}$ to $10^{-17}m^{-2/3}$ for strong and weak turbulence [17], respectively. Here, we take $C_n^2 = 10^{-13}\ m^{-2/3}$ for strong turbulent and $C_n^2 = 10^{-14}\ m^{-2/3}$ for moderate strong turbulent conditions.

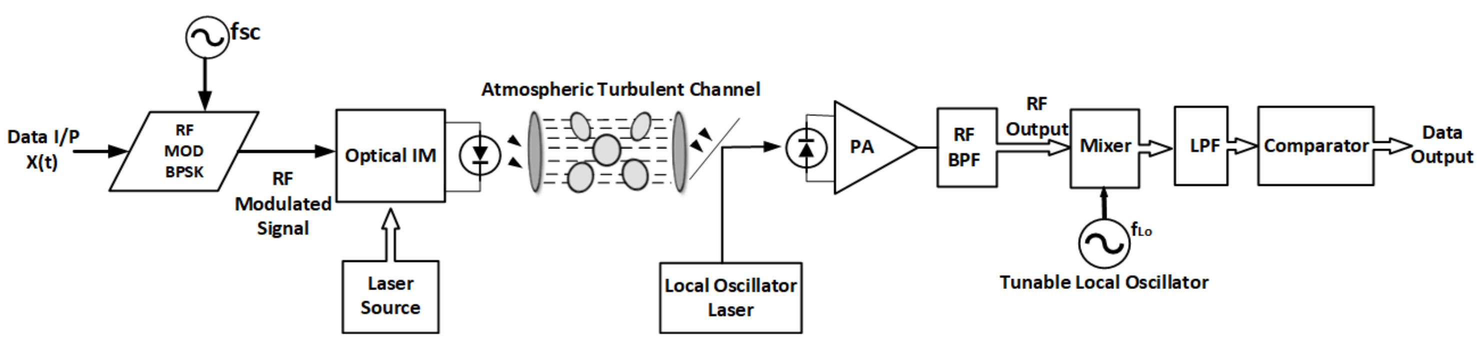

Fig. 1 Simplified Diagram of Coherent FSO link with single RF sub-carrier modulation under strong turbulent channel

4 BER Performance Analysis

Considering the input signal, $x(t)$ is transmitted through a single sub-carrier, we get:

$$x(t) = \sum_{m}^{\infty} b_m p(t - mT_s) \#(5)$$

Where,

T_s = symbol period

$p(t)$ = pulse shape of a bit
b_m = amplitude of the m-th bit

So, the corresponding output electric field of the BPSK RF modulator can be,

$$y_{sc}(t) = \sum_{m}^{\infty} b_m p(t - mT_s) . A_{sc} \cos(\omega_{sc} t + \phi_m) \#(6)$$

where, $\phi_m = 0^0$ for transmission of bits 1, and $\phi_m = 180^0$ for transmission of bits 0.

The RF signal modulated by BPSK is then directed to intensity modulator (IM) and thus the laser output is electro-optic intensity modulated. The output of the IM is,

$$y_{opt}(t) = \sqrt{2P_T}[1 + \mu_k y_{sc}(t)]e^{j\omega_c t} \#(7)$$

Here, $y_{opt}(t)$ is the optical signal, P_T is the transmitted power and μ_k represents the optical modulation index.

This optically modulated signal passes through the atmospheric turbulent channel. The input of the optical receiver is giver by:

$$y_r(t) = \left[y_{sc}(t)\sqrt{2P_o(t)}cos(\omega_{sc}t) + \sqrt{2P_{LO}}cos(\omega_{LO}t)\right]e^{j\omega_c t} + n_b(t)\#(8)$$

where,
$P_o(t) = P_R I(t)$
$P_R = P_T e^{-\zeta L}$ = Received Power

ζ = attenuation coefficient of the atmospheric channel
L = Link Distance
n_b = background noise
P_{LO} = Local oscillator power
I = received optical irradiance

The output photo-current from the PD is:

$$i_d(t) = |y_r(t)|^2 R_d = 2R_d y_{sc}(t)\sqrt{2P_o(t)2P_{LO}} \cos(\omega_{sc}t)\cos(\omega_{LO}t) + i_n(t) \quad (9)$$

The output noise power is given as:

$$\sigma_n{}^2 = \sigma_{sh-SIG}{}^2 + \sigma_{th}{}^2 + \sigma_{sh-LO}{}^2 = 2eB[I_s] + \frac{4k_BT}{R_L}B + 2eB[I_{LO}] = 2eB[R_dP_o(t).\mu_kA_{sc} + R_dP_{LO}.\mu_kA_{LO}] + \frac{4k_BT}{R_L}B \quad (10)$$

where, B is the thermal bandwidth (BW), $\sigma_{sh}{}^2$ is the PSD of shot noise, $\sigma_{th}{}^2$ is the PSD of thermal noise.

The conditional SNR on I can be represented as:

$$SNR(I) = \frac{\left((2R_d)(\sqrt{2P_RI})\sqrt{2P_{LO}}.\mu_kA_{sc}\right)^2}{2eB[R_dP_RI.\mu_kA_{sc} + R_dP_{LO}.\mu_kA_{LO}] + \frac{4k_BT}{R_L}B} \#(11)$$

So, the conditional BER can be written as [13]:

$$BER(I) = \frac{1}{2}\text{erfc}\left(\sqrt{SNR(I)}\right)\#(12)$$

Thus, the average BER of the system is,

$$BER = \int B\,ER(I)p(I)dI\#(13)$$

5 Results & Discussions

Accompanied by the analytical method provided in the previous section, in this section, the performances are investigated in terms of SNR, BER and power penalty (PP) of coherent FSO link with single RF sub-carrier modulation under G-G fading for the strong turbulent link. The simulation parameters are presented in TABLE \ref{table}.

Parameters	Values
Sub-carrier No.	1
Data Rate, R_b	10 Gbps
Link distance, L	500 m-4000 m
Laser wavelength, λ	1550 nm
Boltzmann Constant, k_B	1.38065×10^{-23} J/K
Load Resistance, R_L	50 Ω
PIN photodetector Responsivity, R_d	0.95 A/W
Local oscillator power, P_{LO}	1mW
Thermal BW, B	10 GHz
Received power, P_R	40 to 10 dBm
Sub-carrier Amplitude, A_{sc}	1
Optical modulation index, μ_k	0.5 and 1
Temperature, T	300K
Dark current, I	10 nA
Refractive index variation, C_n^2	$10^{-13}m^{-2/3}, 10^{-14}m^{-2/3}$
Power penalty at BER	$10^{-3}, 10^{-6}, 10^{-9}$

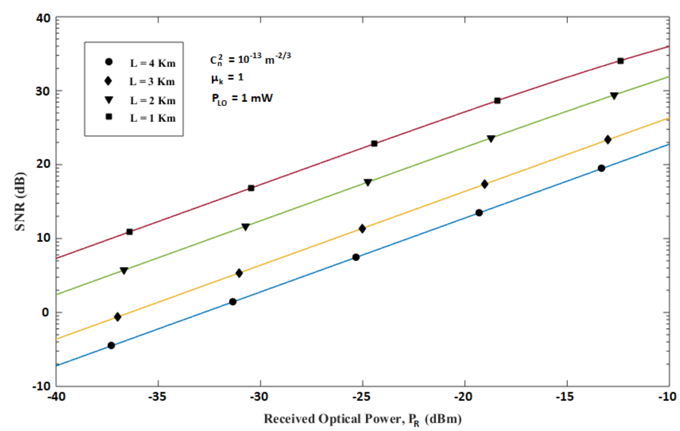

***Fig. 2** SNR vs. Received optical power*

Fig. 2 depicts the graphs of SNR versus received optical power over different FSO link distances ranging from 1 km to 4 km for strong atmospheric turbulent channel, where we set $C_n^2 = 10^{-13}$, $\mu_k = 1$, $P_{LO} = 1mW$. It can be observed from the figure that, as expected, SNR increases with the decrease in FSO link distances. The performance of SNR for RF sub-carrier modulated coherent FSO system is better when the link distance is limited to 2 km to 2.5 km. But for link distance greater than 2.5-3 km the system shows poor performance due to the impact of strong atmospheric turbulence.

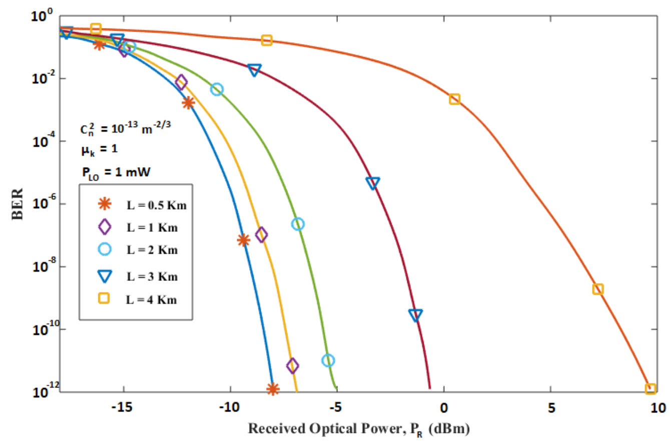

Fig. 3 *BER vs. Received optical power for* $\boldsymbol{\mu_k = 1}$

In Fig. 3, the BERs as a function of received optical power for different FSO link distances ranging from 0.5 km to 4 km are shown under the strong atmospheric channel condition where we set $C_n^2 = 10^{-13}$, $\mu_k = 1$, $P_{LO} = 1mW$. Analysis explicates that, the BER performance worsens as link distance rises from 0.5 km to 4 km. It is noted from the figure that the BER performance worsens rapidly after 2 km link distance. Therefore, the performance deterioration is more severe compared to the performance for link distances from 0.5 km to 2 km.

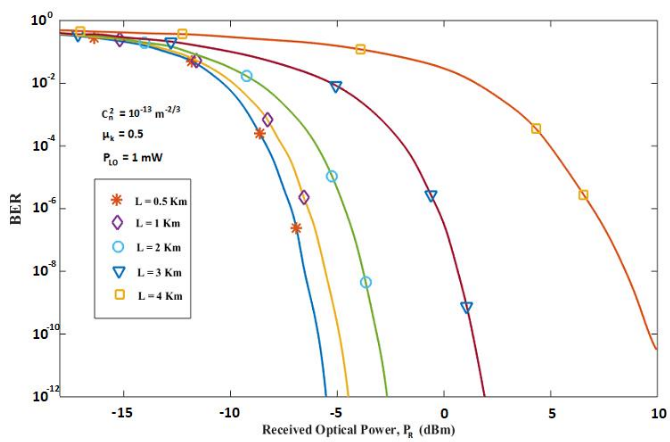

Fig. 4 *BER vs. Received optical power for* $\boldsymbol{\mu_k = 0.5}$

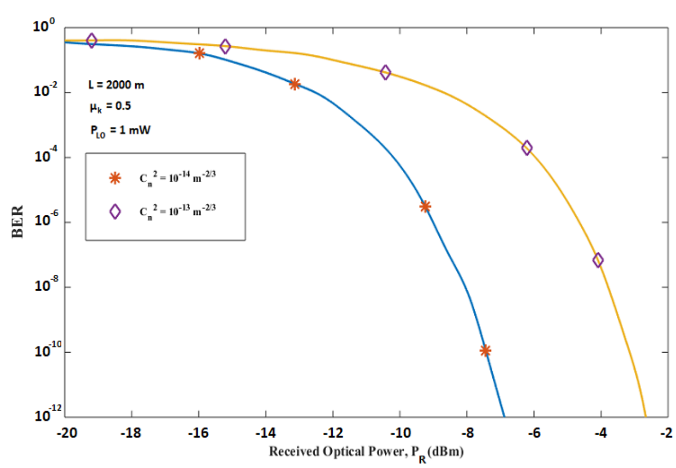

Fig. 5 *BER vs. Received optical power over different refractive index variations for L = 2 km.*

Similarly, Fig. 4 describes the BER performances with the change of link distances (0.5 km to 4 km) for $\mu_k = 0.5$. It is observed that the system suffers more owing to the impact of strong atmospheric turbulence with a lower modulation index.

The impact of strong and moderate strong atmospheric turbulence on the BER performance for link distance L = 2 km with $\mu_k = 0.5$ is depicted in Fig. 5. It is evident from the figure that the system performance degrades because of increasing the refractive index variation, C_n^2 from 10^{-14} $m^{-2/3}$ to 10^{-13} $m^{-2/3}$.

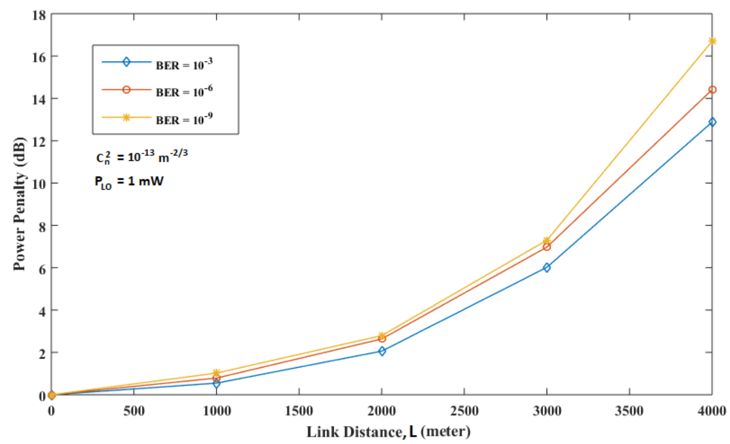

Fig. 6 *Power Penalty vs. Link Distance to acquire different BERs*

Fig. 6 depicts the PP versus link distances ranging from 0 to 4 km for different BERs at $P_{LO} = 1mW$ and $C_n^2 = 10^{-13}$. Analysis explicates that, the BER performance degrades gradually with the increasing link distances due to the turbulent noise signal. Consequently, the LO requires to be provided with additional power for bit separation from the receiver and accordingly this additional power mitigates for the PP to acquire a definite BER. From the PP graph, it is evident that, PP is more to acquire BER of 10^{-9} than to BER of 10^{-6} and 10^{-3}. It is observed that the systemundergoes a PP of 0.39 dB, 0.96 dB, 2.73 dB, 4.92 dB, 7.32 dB and 16.75 dB to attain a BER of 10^{-9} at 0.5 km, 1 km, 2 km, 2.5 km, 3 km and 4 km link distances respectively. Moreover, it is noticed from Fig. 3 and Fig. 4 that the provision of optical power is adjusted with the change of optical modulation index but the corresponding PPs remain constant. The impact of turbulence on the performances of single RF sub-carrier BPSK modulated coherent FSO link can be concluded from the graph of turbulence variance versus PP, presented in Fig. 7. The figure depicts that the PP increases with the variance of the turbulence regardless of the BER. It is evident from the graph that, PP is higher for lower BER at the same turbulence stage. From the figure, when the turbulence variance is 15, the PP became ~ 5.93 dB, 6.87 dB and 7.27 dB at BER of 10^{-3} , 10^{-6} and 10^{-9} respectively.

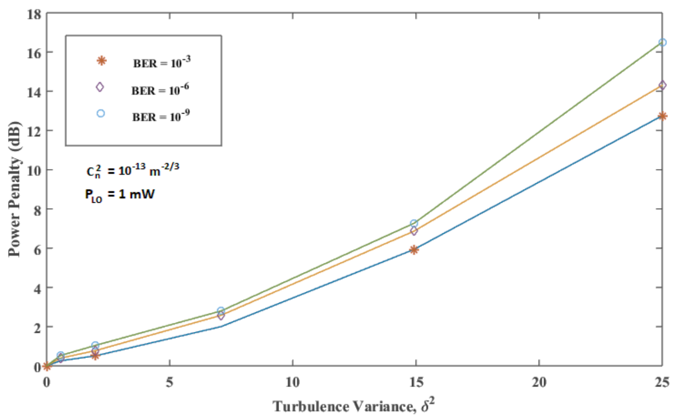

Fig. 7 Power Penalty vs. Turbulence variance to acquire different BERs

6 CONCLUSION

To sum up, we have presented a thorough analytical approach to inquire the performance of the FSO link with RF sub-carrier modulation FSO communication link over strong turbulent channel which is modeled by G-G distribution. In this investigation, BPSK modulation scheme has been studied for sub-carrier modulated FSO communication system with optical coherent receiver. The expression of the unconditional BER for coherent FSO system has been derived. On the basis of the mathematical representation above, the influence of strong atmospheric turbulence on FSO link has been investigated. The outcomes of our investigation show that atmospheric turbulence is one of the major causes that degrade the overall system performance especially when it is under strong atmospheric turbulent conditions. The BER performance of this FSO link degrades due to an increase in link distance L, and when L is limited to 2-2.5 km and the optical modulation index is greater than 0.5, it has satisfactory BER performance i.e. BER of 10^{-9}. The results also portraits that the system experiences a significant power penalty because of strong atmospheric turbulence which is more noticeable at higher link distance and higher turbulence variance. It is observed that the system undergoes a power penalty of 16.75 dB to attain a BER of 10^{-9} at 4 km link distance. Moreover, to reduce the power penalty and obtain a particular BER, local oscillator power needs to be increased which eventually enhances the system performance. Further improvement could be done implementing circular polarization division multiplexing with RF-FSO link [18], [19], [20].

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