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

A. K. M. Sharoor 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 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 the deterioration 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 to 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 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 modulation 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.

![Simplified Diagram of Coherent FSO link with single RF sub-carrier modulation under strong turbulent channel](image)

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

\[ \delta^2 = 1.23C_n^2k^{12/7}L^{11/6} \]  #(4)

Here, \( \delta^2 = \text{Rytov Variance} \), \( C_n^2 = \text{the refractive index structure parameter} \), \( k = \text{Optical wave number} = 2\pi/\lambda \), \( \lambda = \text{wavelength} \), \( L = \text{link distance} \). 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 \( 10^{-13} \text{m}^{-2/3} \) to \( 10^{-17} \text{m}^{-2/3} \) for strong and weak turbulence [17], respectively. Here, we take \( C_n^2 = 10^{-13} \text{m}^{-2/3} \) for strong turbulent and \( C_n^2 = 10^{-14} \text{m}^{-2/3} \) for moderate strong turbulent conditions.

4 BER PERFORMANCE ANALYSIS

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

\[ x(t) = \sum_{m} b_m p(t - mT_s) \]  #(5)

Where,

\( T_s = \text{symbol period} \)
\( p(t) = \text{pulse shape of a bit} \)
\( b_m = \text{amplitude of the m-th bit} \)

So, the corresponding output electric field of the BPSK RF modulator can be,
\[ y_{sc}(t) = \sum_{m} b_{m} p(t - mT_s) \cdot A_{sc} \cos(\omega_{sc} t + \phi_{m}) \] 

where, \( \phi_{m} = 0^\circ \) for transmission of bits 1, and \( \phi_{m} = 180^\circ \) 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,

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

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

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

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

where,

\[ P_o(t) = P_{th} I(t) \]
\[ P_{th} = P_T e^{-\zeta L} = \text{Received Power} \]
\[ \zeta = \text{attenuation coefficient of the atmospheric channel} \]
\[ L = \text{Link Distance} \]
\[ n_p = \text{background noise} \]
\[ P_{LO} = \text{Local oscillator power} \]
\[ I = \text{received optical irradiance} \]

The output photo-current from the PD is:

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

The output noise power is given as:

\[ \sigma_n^2 = \sigma_{sh-IG}^2 + \sigma_{th}^2 + \sigma_{sh-LO}^2 = 2eB[I] + \frac{4kT}{R_L} B + 2eB[I_L] \]
\[ = 2eB[R_p P_o(t) \mu_k A_{sc} + R_d P_{LO} \mu_k A_{LO}] + \frac{4kT}{R_L} B \] 

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:

\[ \text{SNR}(I) = \frac{(2R_d)[\sqrt{2P_o(T) \sqrt{2P_{LO} \mu_k A_{sc}}}]^2}{2eB[R_p P_o(t) \mu_k A_{sc} + R_d P_{LO} \mu_k A_{LO}] + \frac{4kT}{R_L} B} \] 

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

\[ \text{BER}(I) = \frac{1}{2} \text{erfc} \left( \sqrt{\text{SNR}(I)} \right) \] 

Thus, the average BER of the system is, \[ 13 \]
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 $C_\mu^2 = 10^{-13}$, $\mu_k = 1$, $P_{LO} = 1mW$. 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.

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, $C_\mu^2$ from $10^{-14}$ $m^{-2/3}$ to $10^{-13}$ $m^{-2/3}$.

Fig. 6 depicts the PP versus link distances ranging from 0 to 4 km for different BERs at $P_{LO} = 1mW$ and $C_\mu^2 = 10^{-13}$. 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 $10^{-10}$ than to BER of $10^{-6}$ and $10^{-9}$. It is observed that the system undergoes 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 $10^{-10}$ 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 $\sim 5.93$ dB.
dB, 6.87 dB and 7.27 dB at BER of $10^{-3}$, $10^{-6}$ and $10^{-9}$ respectively.

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 portrays 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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