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Evaluation of Free Space Optical Communication Link for Moderate Atmospheric Turbulence

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ABSTRACT

A mathematical model for free space optical communication system was developed for the evaluation of system to analysis the effect of Atmospheric Turbulence. The performance of the system is very good for the link range of small distance at different temperature conditions.

Keywords: Bit Error Rate ,Free Space Optics, Irradiance, Signal to Noise Ratio, Turbulence

I. INTRODUCTION

A communication system is to transmit information which could be accomplished in many ways. One of the emerging communication system is Free-space optical Communication system which depends on the propagation of optical beam through various media, that interact with and affect the quality of the propagating optical signal. For understanding of the atmospheric phenomena and how they affect the propagating light is essential in designing intellectual, efficient and cost-efficient FSO links and reliable networks in order to provide uninterrupted service at the expected excellence [1]. The FSO communication has increasingly attracted attention in the past decade for a number of applications for providing high bandwidth wireless communication links. Many of these applications include satellite-to-satellite links, up-and-down links between space platforms and ships, aircraft and other ground platforms moreover among mobile or stationary terminals to solve the last mile problem through the atmosphere. Still, there are a variety of deleterious conditions of the atmospheric channel that may lead to serious signal fading and even the complete loss of signal is also possible. The atmosphere is composed of dust, gas, aerosols, molecules, water vapor and pollutants. The sizes are comparable to the wavelength of a typical optical carrier affecting the carrier wave propagation not common to a radio frequency (RF) system. Scattering and absorption due to particulate matter may considerably attenuate the transmitted optical signal, whereas the quality of a signal carrying laser beam transmitting through the atmosphere can be rigorously corrupted, causing intensity fading, random signal losses and increased bit error rates at the receiver. Random fluctuation in the irradiance of the received optical laser beam caused by atmospheric turbulence typically refers to an effect called scintillation [2]. Consequently, the atmosphere can be a limiting factor in reliable high-data rate wireless FSO optical communication link performance. Therefore it is important to learn about the interaction of the optical wave with the atmosphere in order that one can predict the FSO communication performance in presence of the atmospheric communication channel [1].

II. ATMOSPHERE TURBULENCE

In describing the power density function of the irradiance fluctuation in a turbulent atmosphere, the beam is first represented by its constituent electric field $\vec{E}$. By using Maxwell's electro-magnetic equations for a spatially variant dielectric such as the atmosphere the equation may derived as [7]

$$\nabla^2\vec{E}+k^2n_{as}^2\vec{E}+2\nabla\left[\vec{E}.\vec{\nabla}In\left(n_{as}\right)\right]=0 \tag{1}$$

where the wave number is $k=2\pi/\lambda$,

The vector gradient operator $\vec{\nabla}=\left(\partial/\partial x\right)i+\left(\partial/\partial y\right)j+\left(\partial/\partial z\right)k$ with i, j and k being the unit vectors along the x, y and z axes, respectively The last term on the left-hand side of Equation 1 represents the turbulence-induced depolarization of the wave In a weak atmospheric turbulence regime, which is haracterized by single scattering event, the wave depolarization is negligible [3]. In fact, it has been shown both theoretically and experimentally that the depolarization is insignificant even for strong turbulence conditions Equation 1 then reduces to.

$$\nabla^2\vec{E}+k^2n_{as}^2\vec{E}=0 \tag{2}$$

The position vector will henceforth be denoted by r and $\vec{E}$ represented by E(r) for convenience.

As the received average power is given by $P_r=P_t\,exp\left(-\gamma_T L\right)$, where γ_T represents the overall channel attenuation, then the average received photoelectron count is given by [2]

$$\langle n\rangle=\frac{\eta\lambda T_b P_r}{hc} \tag{3}$$

where h and c are the Planck's constant and the speed of light in vacuum, respectively, and η is the quantum efficiency of the photo detector However, the instantaneous count n, unlike the average count, is not constant [2] it varies with time due to the following reasons[7]:

1 The quantum nature of the light or photo detection process, that suggests that the instantaneous number of counts n follows the discrete Poisson distribution with an associated quantum noise of variance ⟨ n⟩ accordingly mean and variance of a Poisson distribution are the same.

2 The received signal field varies randomly due to the effect of scintillation. This implies that the number of counts is now doubly stochastic and based on the log-normal turbulence model [7].

III. VARIATION IN ATMOSPHERIC TURBULENCE

Atmospheric turbulence is usually categorized in regimes depending on the magnitude of index of refraction variation and in homogeneities present in atmosphere. These regimes are a function of the distance travelled by the optical radiation through the atmosphere and are classified as strong, moderate, weak. Atmospheric turbulence results in signal fading thus impairing the FSO link performance severely. Different models describing the pdf statistics of the irradiance fluctuation. Unluckily, due to the extreme complexity involved in mathematically modelling of atmospheric turbulence, a single model valid for all the turbulence regimes does not currently exist. These different models are the gamma–gamma, log-normal and negative exponential models. Their relevant ranges of validity of these models as reported in the literature are in the weak, moderate and saturate regimes. The atmospheric turbulence results in random fluctuation of the atmospheric refractive index n along the path of the optical field or radiation traversing the atmosphere. The refractive index fluctuation is the direct end product of random variations in atmospheric temperature from point to point. These random temperature changes are a function of the atmospheric pressure, wind speed and altitude. The smallest and the largest of the turbulence eddies are termed as the inner scale l_0 and the outer scale L_0 of the turbulence, respectively, the values of l_0 and L_0 are typically of the order of a few millimetres and several metres correspondingly [4]. The temporal coherence time τ0 of atmospheric turbulence is stated to be of the order of milliseconds and this value is very large compared to the duration of a typical data symbol, thus the turbulent atmospheric channel could be described as a "slow fading channel" since it is static over the duration of a data symbol. Equation 4 shows the relationship between the temperature of the atmosphere and its refractive index. Whereas for many of engineering applications the rate of change of the refractive index with respect to channel temperature is represented by

$$n_{as} = 1 + 77.6(1 + 7.52 \times 10^{-3} \lambda^{-2}) \frac{P_{as}}{T_e} \times 10^{-6} \qquad (4)$$

$$\frac{-dn_{as}}{dT_e} = 7.8 \times 10^{-5} \frac{P_{as}}{T_e^2} \qquad (5)$$

where Pas is the atmospheric pressure in millibars, λ the wavelength in microns and Te is the effective temperature in Kelvin Near the sea level, $-dn_{as} / dT_e \cong 10^{-6} K^{-1}$. The involvement of humidity to the refractive index fluctuation is not accounted for in Equation 4 because this is negligible at optical wavelengths . Further on the position and time-dependent index of refraction denoted by nas(r, t) can be represented as the sum of its free-space value nas0, and a turbulence induced random fluctuation component nas1 (r, t) Therefore

$$n_{as}(r,t) = n_{as_0} + n_{as_1}(r,t) \qquad (6)$$

In accordance with the Taylor's frozen-flow assumption, which implies that the temporal variations of the index of refraction of the channel are mainly due to the transverse component of the atmospheric wind, the randomly fluctuating part of Equation 6 can then be written as

$$n_{as_1}(r,t) = n_{as_1}(r - v_w t) \qquad (7)$$

where vw(r) is the local wind velocity perpendicular to the field direction of travel in atmospheric turbulence and an important parameter for characterizing the amount of refractive index fluctuation is the index of refraction structure parameter C_n^2 introduced by Kolmogorov. According to which is a function of the wavelength, temperature and atmospheric altitude. A commonly used model to describe C_n^2 in terms of altitude is the Hufnagel–Valley model given below as

$$C_n^2(h) = 0.00594(v_w/27)^2(10^{-5}h)^{10}\exp(-h/1000)$$
$$+2.7\times10^{-16}\exp(-h/1500)+\hat{A}\exp(-h/100) \quad (8)$$

where Â is taken as the nominal value of Cn 2(0) at the ground level in m−2/3 and λ is the altitude in meters. The normally used values for vw is 21 m/s. The value of the index of refraction structure parameter varies with altitude, however for a horizontally propagating field it is usually implicited constant.

III. RESULTS & DISCUSSIONS

The paper presents a detailed analysis of Free Space Optical Communication system, for different temperature conditions at moderate atmospheric turbulence. Parameters used to evaluate the performance of the FSO communication system are Bit Error Rate and Signal to Noise ratio are considered. Evaluation of the system also link is varied for different temperature conditions. A simulation setup for a free space optical communication (FSO) link in Matlab software was developed. Graphs are plotted for the different values of the Signal to Noise ratio versus Bit Error Rate at different atmospheric temperature. Further on the range of the link is also changed from 1 Km to 5 Km for each value of temperature i.e. -20 °C, 0 °C, 20°C and 40 °C .

Table 1 Parameters used for performance analysis of FSO link at moderate atmospheric turbulence .

Parameter	Value
Symbol rate R_b	155 Mbps
Spectral radiance of the sky $N(\lambda)$	$10^{-3} W/cm^2 \mu m Sr$
Spectral radiant emittance of the sun $W(\lambda)$	$0.055 W/cm^2 \mu m$
Optical band-pass filter bandwidth Δλ at λ = 850 nm	1 nm
PIN photodetector field of view (FOV)	0.6 rad
Radiation wavelength λ	1064 nm
Number of subcarriers N	1
Link range L	1 km, 2 km, 3 km, 4km, 5 km
Index of refraction structure parameter C_n^2	$0.75\times10^{-14} m^{-2/3}$
Load resistance RL	50Ω
PIN photodetector responsivity R	1
Operating temperature Te	-20 °C, 0 °C, 20 °C, 40 °C
Optical modulation index ξ	1

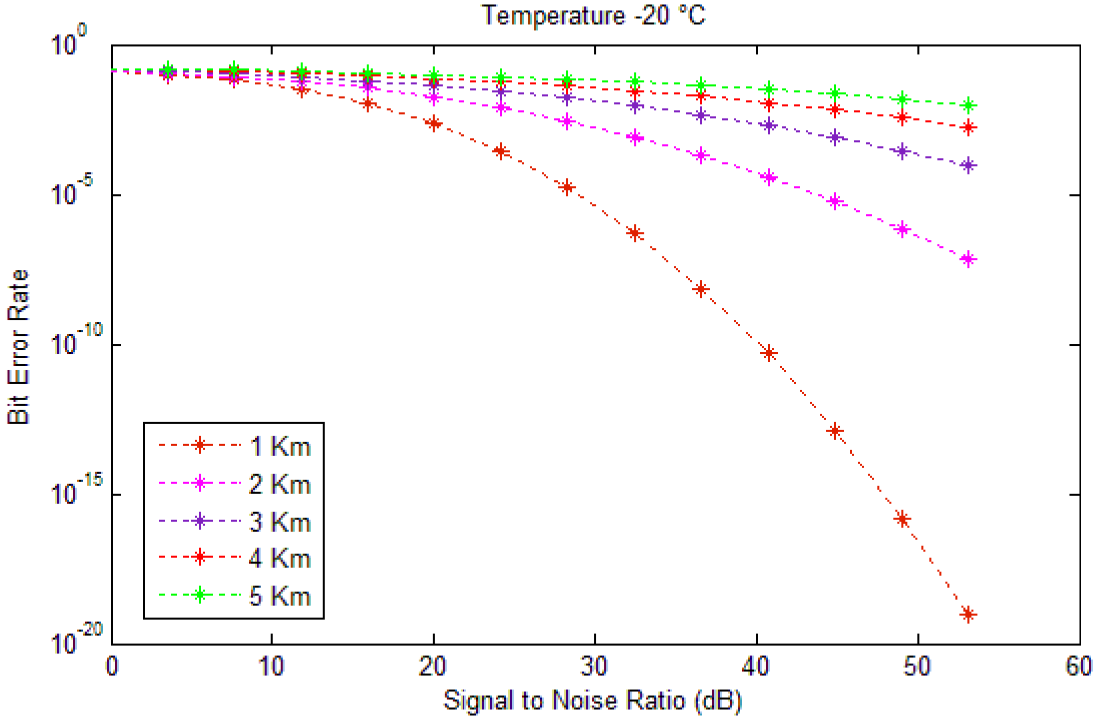

Figure 1 Shows the Signal to Noise Ratio in (dB) and Bit error Rate (BER) at -20 °C temperature for link range 1 Km to 5 Km.

Table 2 Different values of Noise to Ratio and Bit Error rate for Signal to at link range of 1Km, 2 Km, 3Km, 4 Km & 5 Km at -20 °C.

SNR	Bit Error Rate				
	1 Km	2 Km	3 Km	4 Km	5 Km
3.4793	9.9195E-02	1.1104E-01	1.2523E-01	1.3885E-01	1.5077E-01
7.6172	6.4018E-02	8.4408E-02	1.0507E-01	1.2356E-01	1.3953E-01
11.7552	3.1486E-02	5.7535E-02	8.3652E-02	1.0700E-01	1.2633E-01
15.8931	1.0607E-02	3.4356E-02	6.2199E-02	8.9358E-02	1.1313E-01
20.0310	2.2059E-03	1.7595E-02	4.3372E-02	7.1045E-02	9.8272E-02
24.1689	2.5881E-04	7.6176E-03	2.7601E-02	5.5116E-02	8.1884E-02
28.3069	1.5925E-05	2.7325E-03	1.6424E-02	3.9925E-02	6.7935E-02
32.4448	4.8526E-07	7.9809E-04	8.6902E-03	2.7575E-02	5.4709E-02
36.5827	7.0143E-09	1.9290E-04	4.3306E-03	1.8645E-02	4.0830E-02
40.7207	4.6585E-11	3.7089E-05	1.8652E-03	1.1153E-02	3.0543E-02
44.8586	1.3584E-13	5.4970E-06	7.6578E-04	6.7400E-03	2.2776E-02
48.9965	1.4425E-16	7.1620E-07	2.6639E-04	3.7824E-03	1.4996E-02
53.1345	9.1032E-20	6.5990E-08	8.7672E-05	1.8282E-03	9.7428E-03

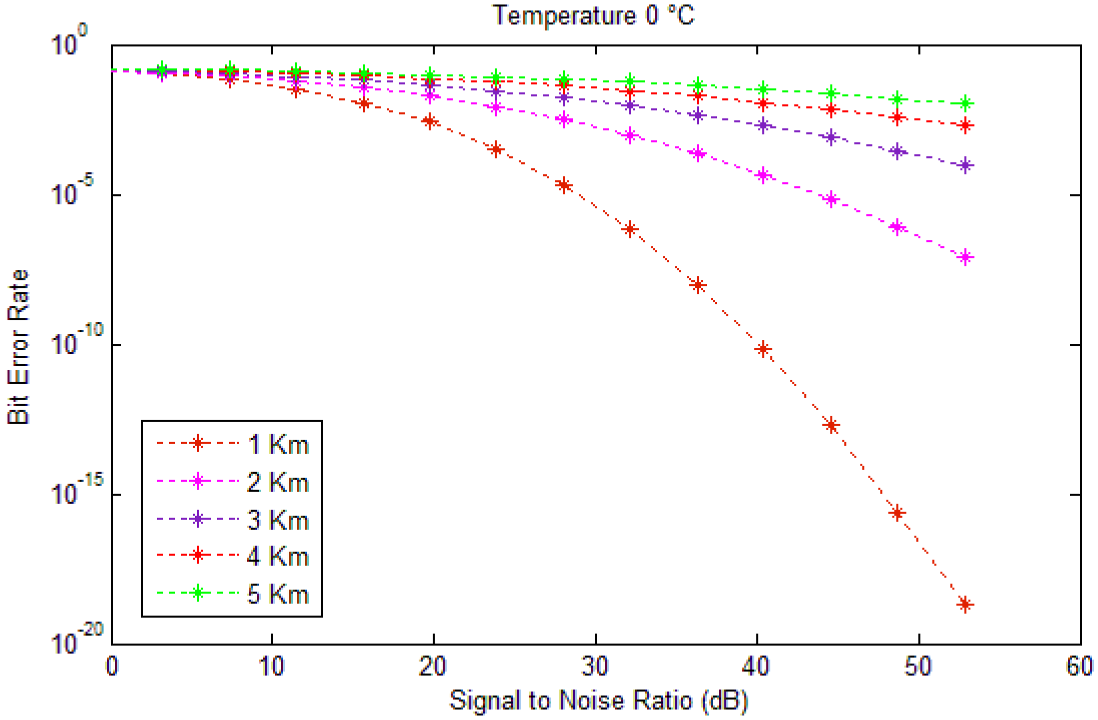

Figure 2 Shows the Signal to Noise Ratio in (dB) and Bit error Rate (BER) at 0 °C temperature for link range 1 Km to 5 Km.

Table 3 Different values of Noise to Ratio and Bit Error rate for Signal to at link range of 1Km, 2 Km, 3Km, 4 Km & 5 Km at 0 °C.

SNR	Bit Error Rate				
	1 Km	2 Km	3 Km	4 Km	5 Km
3.1837	1.0155E-01	1.1283E-01	1.2657E-01	1.3984E-01	1.5147E-01
7.3216	6.6568E-02	8.6367E-02	1.0658E-01	1.2472E-01	1.4042E-01
11.4596	3.3498E-02	5.9377E-02	8.5201E-02	1.0820E-01	1.2728E-01
15.5975	1.1636E-02	3.5814E-02	6.3672E-02	9.0681E-02	1.1408E-01
19.7354	2.5127E-03	1.8559E-02	4.4617E-02	7.2285E-02	9.9426E-02
23.8733	3.0792E-04	8.1389E-03	2.8588E-02	5.6206E-02	8.3008E-02
28.0113	1.9884E-05	2.9561E-03	1.7090E-02	4.0970E-02	6.8846E-02
32.1492	6.3807E-07	8.7759E-04	9.1291E-03	2.8301E-02	5.5711E-02
36.2871	9.7212E-09	2.1562E-04	4.5606E-03	1.9248E-02	4.1747E-02
40.4251	6.7857E-11	4.1819E-05	1.9923E-03	1.1594E-02	3.1132E-02
44.5630	2.0663E-13	6.3571E-06	8.1573E-04	6.9769E-03	2.3344E-02
48.7009	2.3764E-16	8.4283E-07	2.9012E-04	3.9723E-03	1.5501E-02
52.8389	1.8950E-19	7.7158E-08	9.4344E-05	1.9197E-03	1.0005E-02

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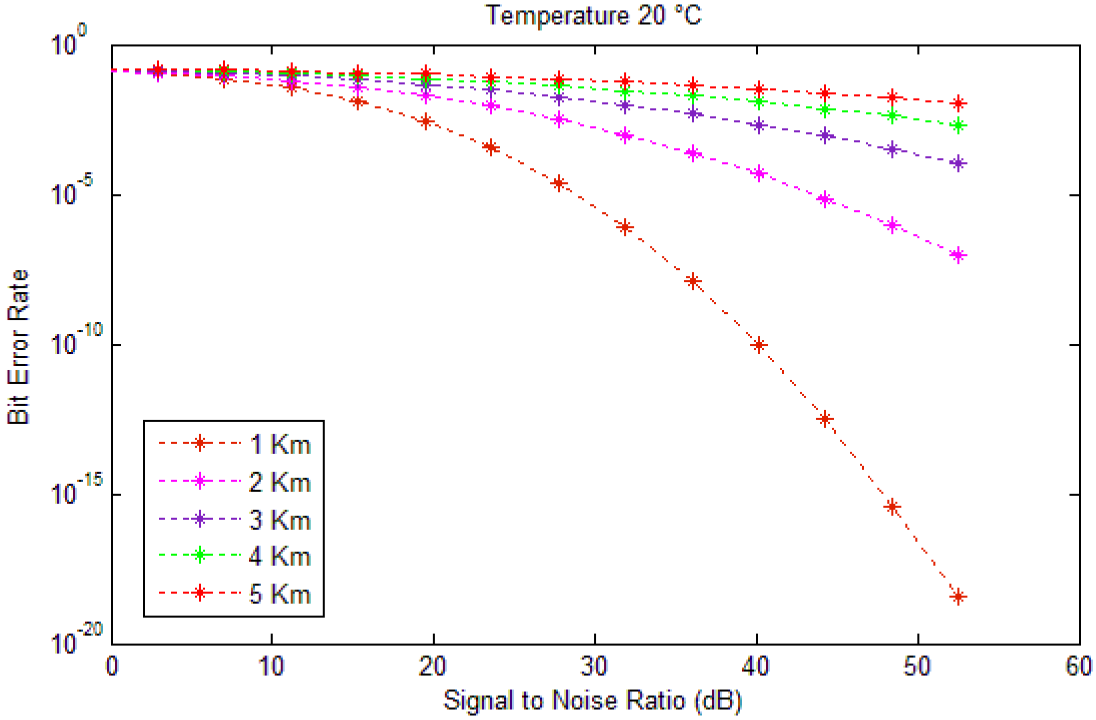

Figure 3 Shows the Signal to Noise Ratio in (dB) and Bit error Rate (BER) at 20 °C temperature for link range 1 Km to 5 Km.

Table 4 Different values of Noise to Ratio and Bit Error rate for Signal to at link range of 1Km, 2 Km, 3Km, 4 Km & 5 Km at 20 °C.

SNR	Bit Error Rate				
	1 Km	2 Km	3 Km	4 Km	5 Km
2.9069	1.0373E-01	1.1449E-01	1.2780E-01	1.4075E-01	1.5211E-01
7.0449	6.8965E-02	8.8199E-02	1.0798E-01	1.2580E-01	1.4124E-01
11.1828	3.5438E-02	6.1118E-02	8.6649E-02	1.0932E-01	1.2818E-01
15.3207	1.2661E-02	3.7209E-02	6.5066E-02	9.1913E-02	1.1498E-01
19.4587	2.8310E-03	1.9496E-02	4.5794E-02	7.3461E-02	1.0050E-01
23.5966	3.6123E-04	8.6505E-03	2.9537E-02	5.7227E-02	8.4075E-02
27.7345	2.4400E-05	3.1794E-03	1.7727E-02	4.1961E-02	6.9703E-02
31.8725	8.2191E-07	9.5863E-04	9.5578E-03	2.9001E-02	5.6643E-02
36.0104	1.3166E-08	2.3889E-04	4.7835E-03	1.9815E-02	4.2625E-02
40.1483	9.6489E-11	4.6752E-05	2.1186E-03	1.2023E-02	3.1698E-02
44.2863	3.0795E-13	7.2880E-06	8.6485E-04	7.2050E-03	2.3872E-02
48.4242	3.8919E-16	9.7747E-07	3.1406E-04	4.1545E-03	1.5987E-02
52.5621	3.6097E-19	8.9463E-08	1.0104E-04	2.0117E-03	1.0264E-02

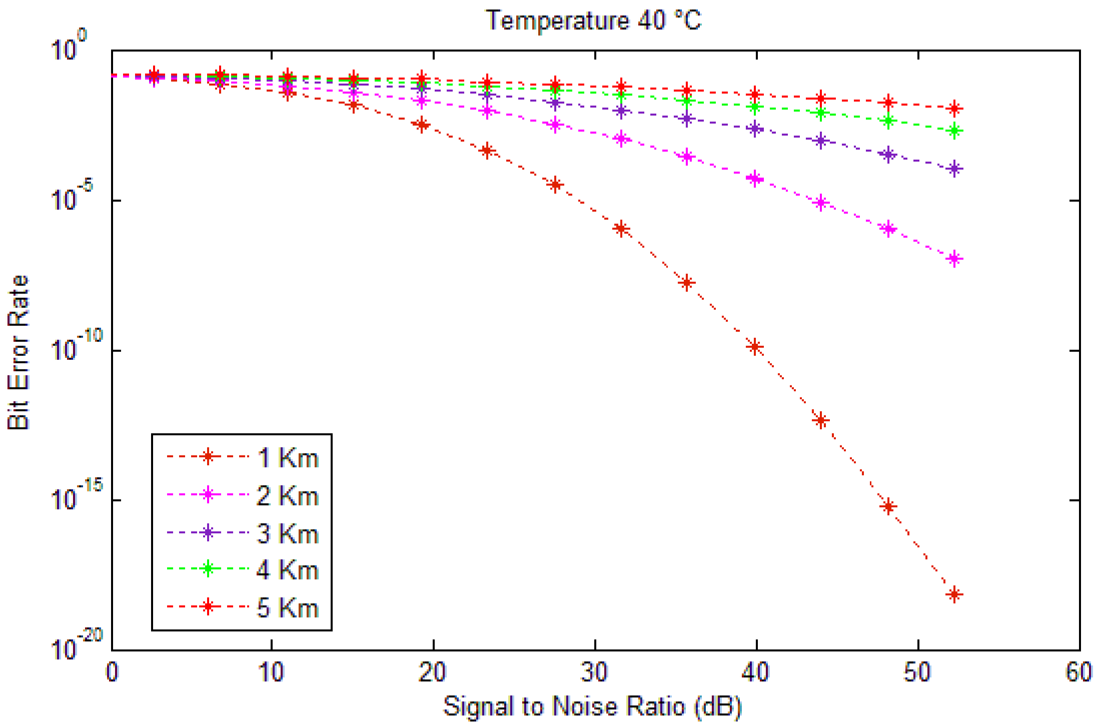

Figure 4 Shows the Signal to Noise Ratio in (dB) and Bit error Rate (BER) at 40 °C temperature for link range 1 Km to 5 Km.

Table 5 Different values of Noise to Ratio and Bit Error rate for Signal to at link range of 1Km, 2 Km, 3Km, 4 Km & 5 Km at 40 °C.

SNR	Bit Error Rate				
	1 Km	2 Km	3 Km	4 Km	5 Km
2.6468	1.0575E-01	1.1604E-01	1.2895E-01	1.4159E-01	1.5270E-01
6.7847	7.1221E-02	8.9917E-02	1.0929E-01	1.2681E-01	1.4201E-01
10.9226	3.7309E-02	6.2767E-02	8.8008E-02	1.1037E-01	1.2902E-01
15.0606	1.3681E-02	3.8547E-02	6.6388E-02	9.3065E-02	1.1581E-01
19.1985	3.1596E-03	2.0405E-02	4.6911E-02	7.4578E-02	1.0149E-01
23.3364	4.1863E-04	9.1529E-03	3.0449E-02	5.8189E-02	8.5088E-02
27.4744	2.9490E-05	3.4024E-03	1.8339E-02	4.2902E-02	7.0516E-02
31.6123	1.0398E-06	1.0410E-03	9.9764E-03	2.9677E-02	5.7511E-02
35.7502	1.7475E-08	2.6263E-04	5.0004E-03	2.0351E-02	4.3464E-02
39.8882	1.3437E-10	5.1896E-05	2.2437E-03	1.2440E-02	3.2245E-02
44.0261	4.5101E-13	8.2875E-06	9.1336E-04	7.4257E-03	2.4365E-02
48.1640	6.2878E-16	1.1195E-06	3.3807E-04	4.3290E-03	1.6453E-02
52.3019	6.3893E-19	1.0305E-07	1.0779E-04	2.1039E-03	1.0520E-02

The above fig. 1 to 4 shows variation of Bit Error Rate and Signal to Noise Ratio due to the effect of Temperature at -20 °C, 0°C, 20 °C & 40 °C for different values of link range from 1Km, 2 Km, 3Km, 4 Km & 5 Km respectively. The graphically representation shows that only if the link range is kept up to 1 Km the system will work for the sustainable values of SNR and BER and the communication is better and with minimum losses . It is also observed that the characteristics of the system remain approximately same for all the link range from 2 Km to 5 Km at temperature of -20 °C, 0 °C and 20 °C. The evaluation results shows that as the temperature increases the BER is improved as the value of SNR increases 50 dB.

Precise numerical values for different Signal to Noise Ratio and Bit Error Rate at Link range of 1 Km, 2 Km, 3 Km, 4 Km and 5 Km in Tables.

IV. CONCLUSION

This paper elaborates a detailed performance evaluation of Free Space Optical Communication system, for different temperature conditions at moderate atmospheric turbulence. Signal to Noise and bit error Rate are parameters used to analysis the system. Results shows that the effect of temperature is almost same for different link range. The system is highly sustainable for link range of minimum distance.

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