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Investigated Signal-to-Noise Ratio for Terrestrial Free Space Optical based on Libya Cities Data

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Abstract— **Free Space Optical (FSO) communication links offer high-speed data transmission but can be affected by weather conditions like rain, haze, fog, and snow. This study investigates the impact of rain on FSO link availability in the Libyan cities of Garian, Elkhoms, and Tripoli. An empirical model based on the ITU Carb. (France) Model is proposed to predict FSO link availability for ranges up to 5 km. Rain data shows that Garian has the highest rainfall, followed by Elkhoms and Tripoli. The study examines the effects of rainfall on FSO link performance for these three cities over a 5 km link distance. The results show that signal-to-noise ratio (SNR) and received power at the FSO link are influenced by both rainfall and path length. For a 2 km link distance, the SNR ranges from 16 dB in Tripoli to 10 dB in Garian. Under the influence of rain, the SNR varies from 45 dB to 5 dB over a link distance of 1 km to 5 km.**

Index Terms: ***Free space optical FSO, Visibility, Signal noise ratio***

I. INTRODUCTION

Free-space optical (FSO) communication employs light waves as the medium for transmitting information between two transceivers, as illustrated in Fig. 1. FSO links rely on a line-of-sight (LOS) path, enabling the propagation of voice, video, and data at high speeds, ranging from megabytes to gigabytes per second, using low-power light beams. FSO becomes an alternative solution for optical transmission over long distances [1]. It continues to be developed by the military and NASA for military and space applications [2].

These transceivers consist of a laser transmitter and a detector to provide the full-duplex capability. The working distance of FSO is over several hundred meters to a few kilometers [3]. Terrestrial FSO has now proven to be a viable complementary technology in addressing the contemporary communication challenges, most especially the bandwidth or high data rate requirements of end users at an affordable cost [4].

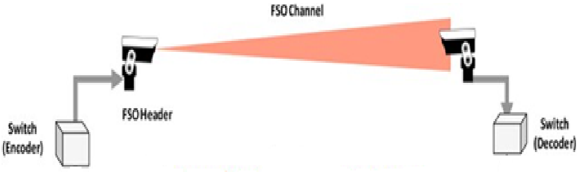

Figure 1. FSO system’s components

FSO is a fibreless, laser-driven technology offering a capacity comparable to optical fiber-based communication, achieving a considerable reduction in cost and deployment time [5]. However, the atmospheric channel in FSO presents a significant challenge, with the performance subjected to abrupt variations within this medium. Diverse atmospheric conditions, including fog, smoke, and turbulence, can introduce degradation to the system performance, necessitating careful analysis of their effects [6]. Initially touted as a promising alternative solution for the last-mile problem, FSO technology has progressively gained acceptance in the telecommunications industry, particularly within enterprise campus networks. Furthermore, the link availability of FSO depends on atmospheric attenuation and link distance. In the temperate climate, fog, dust, and rain are the main parameters, which may affect the availability performance of FSO channels. Furthermore, an analysis of the link outage probability performance of FSO links under a variety of weather conditions is required [7][8][9]. In the literature, few research studies have proposed and presented SNR for Terrestrial Free Space Optical based on data measured. In [10], the article specifically examines the effect of rain on FSO links in the Libyan climate. The authors use a modified FSO link equation based on the ITU Carb. (France) Model empirical model to establish a relationship between rainfall rate and maximum allowable FSO link length. They then simulate the effect of the heaviest rainfall

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recorded in Libya and determine the corresponding maximum allowable link length. However, the relationship between SNR and received power at the FSO link is not reported. In [11], the authors use an empirical method based on the observed relationship between rain attenuation distribution and rain intensity distribution. They find that the attenuation values are significantly higher than those predicted by the French model, suggesting the need for further investigation to develop a more accurate model for Durban.

This study investigates the impact of rain on the performance of a 5 km FSO link in three Libyan cities; Tripoli, Garian, and Elkhoms according to the ITU Carb. (France) Model. Rainfall data from the National Meteorological Center indicates that these cities experience rainy seasons from October to April, with peak rainfall in December and January. The average annual rainfall in Tripoli is 450 mm, in Garian is 500 mm, and in Elkhoms is 400 mm. The study examines and presents the combined effects of rainfall and path length on signal-to-noise ratio and received power in FSO links across these Libyan cities.

The remainder of the article is organized as follows. In section II and Section III, rain intensity and rain attenuation are introduced. Section IV and Section V discusses the received signal power as a function of both rain rate and rate attenuation. The results and discussion are analyzed in Section VI. The conclusion and future work are in Section VII.

II. RAIN INTENSITY

The Rain intensity, defined as the volume or depth of rainfall that occurs in a given period, is the most significant weather parameter for estimating atmospheric attenuation due to rain. It is typically measured in length/time units. The International Telecommunication Union (ITU) recommends that rain intensity data or distributions should be integrated and converted into millimeters per hour (mm/hr) for consistency with various rain attenuation prediction models. Consequently, mm/hr is considered the standard unit for measuring rain intensity [12].

To summarize, rain intensity serves as the primary determinant of rain's immediate impact on FSO signal strength and reliability, while rainfall rate provides insights into the overall rainfall pattern and the potential for prolonged attenuation effects. Both parameters are essential for designing and operating FSO systems that can effectively withstand the challenges posed by rain in diverse weather conditions.

III. RAIN ATTENUATION

Rain attenuation for free-space optical links. Communication system outages may result from equipment failure or propagation constraints, with rain attenuation being particularly severe. Rainfall can lead to several decibels of total attenuation [13].

The optical signal experiences random attenuation from rain and fog droplets. While fog is the primary cause of attenuation, sizable rain droplets can also result in wavelength-independent scattering. Rainfall-induced attenuation increases linearly with the rainfall rate. The specific attenuation against rain rate (R, mm/hr) for an FSO link [9] [14] [15] is as follows:

$$\mathrm{A}_{<1\mathrm{km}}\left(\mathrm{dB}/_{\mathrm{km}}\right) = \mathrm{k}.\,\mathrm{R}^{\propto} \qquad (1)$$

Where, R is the rain intensity (mm/hr), k and α is specific rain attenuation parameter with considered area. For more than one-kilometer FSO link distance d, the total path attenuation of FSO due to rain can be obtained [9] by:

$$\mathrm{A}_{>1\mathrm{km}}\,(\mathrm{dB}) = 5.433187\mathrm{d}\,(\mathrm{A})(\,\mathrm{R}^{-0.377})\exp\,(-0.102\mathrm{d}) \qquad (2)$$

Where, A is the attenuation per kilometer obtained by equation (1).

Table 1. shows the values of k and α for these models. These parameters were developed based on the measured rain attenuation in both temperate and tropical regions.

Table 1. Specific Rain Attenuation Models of FSO [16]

Model	***K***	***α***	**Region**
ITU Carb. (France)	1.076	0.67	Temperate
ITU Japan	1.58	0.63	Temperate
Malaysia (KL)	0.4195	0.8486	Tropical

IV. RECEIVED SIGNAL POWER AS FUNCTION OF RAIN RATE

For a terrestrial FSO link transmitting optical signal through the atmosphere, the equation amounted to the received power is proportional to the amount of power transmitted and the area of the collection aperture. It is inversely proportional to the square of the beam divergence and the square of the link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient (in units of 1/distance) and the link range. For rain attenuation, the impact on received power (P_r) can be calculated by substituting equations, which predicted the rain attenuation depending on the model of power received equation [17] as follows:

$$P_r = P_t.\frac{A_r}{(\theta.d)^2}.R_{atten} \qquad (3)$$

where,

Ar is the receiver area, θ is the full divergence angle, R_{atten} is the rain attenuation (dB/km), P_t is transmitter power, d is distance between receiver and transmitter.

For the specific rain attenuation, equation (1). is substituted into equation (3), using the k and α parameters obtained from both ITU Carb. (France) Model and ITU Japan Model for the temperate region. The equation for received power as a function of specific attenuation [18] is presented below:

$$P_r = P_t.\frac{A_r}{(\theta.d)^2}.k.R^{\alpha} \qquad (4)$$

where,

R^{α} is the rain attenuation (dB/km), k and α parameters are obtained from both ITU Carb. (France) Model and ITU Japan Model for the temperate region.

V. SNR ANALYSIS FOR EFFECT OF RAIN ATTENUATION

The coherent detection scheme is applicable to very weak incoming optical signals. Therefore, the dark current and background illumination noise cannot be disregarded when evaluating the SNR performance. Moreover, the signal power is determined by the mean-squared value of the IF current. Since the SNR is a function of power, an Intensity Modulation Direct Detection (IM/DD) based system will naturally require high transmitted power and limited path loss. These distinctions have a significant impact on the system design, particularly on FSO links, which necessitates higher optical power to achieve the same level of performance, as well as limited path loss. The SNR for Intensity Modulation Direct Detection (IM/DD) and coherent receivers [19] can be defined as follows:

$$SNR_{IM-DD} = \frac{I_p^2}{2qB(I_p + I_D) + \frac{4KTBF_n}{R_L}} \qquad (5)$$

Where,

I_p is the average photocurrent

q is the charge of an electronic(C)

B represents the bandwidth.

I_D is the dark current

T is the absolute photodiode temperature (K)

F_n is the photodiode figure noise equal to 1 for PIN photodiode.

R_L is the PIN load resistor.

The average photocurrent I_p can be expressed as:

$$I_r = P_r . R \qquad (6)$$

Where,

P_r is the average optical power received to the photodetector. R is the photodetector responsively.

For a terrestrial FSO link transmitting an optical signal through the atmosphere, the received signal power can be calculated based on signal-to-noise ratio, distance L, and visibility. The SNR for direct detection is divided into three parts: geometric attenuation, transmitter power (dBm), and weather attenuation (dB) as given by [20][21].

$$SNR_{IM-DD} = R.P_t \frac{A_r}{L^2.\theta^2} e^{-\partial L} \qquad (7)$$

Where,

R is the photodetector responsivity

θ is the angle of separation between the optical axes of the transmitter and receiver beams.

A_r is the effective receiver area,

P_t is the transmitter power (dBm).

L is the link distance between the transmitter and receiver (km).

∂ is the atmospheric extinction coefficient (dB/km).

According to equation (3), the signal-to-noise ratio (SNR) for a free-space optical system using intensity modulation with direct detection (IM/DD) is a function of the power received at the receiver, which is discussed in Section 3. The SNR is also affected by rain attenuation and path length distance. Depending on the model used to predict rain attenuation, the equation based on two models (ITU Carb. (France) Model and ITU Japan Model) can be rewritten by substituting equation (1), which represents rain attenuation, into equation (4). This gives the SNR as a function of rain rate under temperate climate conditions, as shown in equation (8) below [20]:

$$SNR_{IM-DD} = R.P_t \frac{A_r}{(d^2.\theta^2)} K.R^{\alpha} \qquad (8)$$

where,

A_r is the receiver area, θ is the full divergence angle, R is the rain attenuation (dB/km), P_t is transmitter power, d is distance between receiver and transmitter.

VI. SIMULATION RESULTS ANALYSIS AND DISCUSSION

The MATLAB code was employed to calculate the design parameters and predict FSO link availability for ranges up to 5 km. The simulation results of the proposed empirical model are presented and analyzed. The study investigates the effects of rainfall on FSO link performance for these three cities over a 5 km link distance. The values of the simulation parameters and constants are given in Table 2.

Table 2. System Parameters Used in Simulation [21]

Parameters	**Value**
Transmitter power ($\boldsymbol{P_t}$)	50 mw
Receiver area (A)	10 cm
divergence angle ($\boldsymbol{\theta}$)	1 mred
Responsively (R)	0.6 A/W

The findings and discussions of the availability analysis provide potential availability figures for deploying FSO links up to 5 km in length. The study examines the effects of rain rate and path length on the signal-to-noise ratio for different cities in Libya, specifically Garian, Elkhoms, and Tripoli. Receiver signal power varies with distance and can be considered at the average rainfall level for Libyan cities. Fig. 2 illustrates the curves of the receiver signal power function as the distance for temperate region rain model, namely the ITU Carb. (France) model. For Tripoli city, the receiver signal power is -12.5 dBm at a rainfall of 54.7 mm and a distance of 0.5 km. In contrast, the receiver signal power in Garian city is -15.5 dBm at the same distance, with a rainfall of 100 mm.

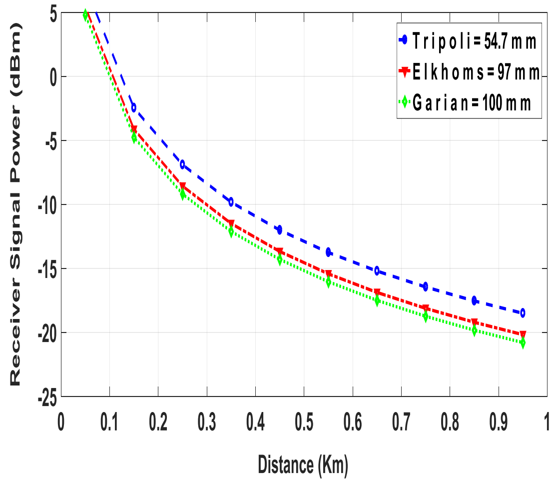

Figure 2. Receiver Power with Distance Length for a Rainfall Tripoli, Elkhoms and Garian

A. SNR as a Function of Distance

Rain disrupts free-space optical (FSO) connections by weakening the signal. Scientists use two models, the ITU Carb. (France) and ITU Japan models, to predict this signal degradation. Fig.3 compares these models, showing how rain intensity affects signal-to-noise ratio (SNR). Simulations assumed a constant rain rate and 1 km link distance. Both models require increasing SNR with longer distances to maintain signal strength under the same rain. At a very short distance (100 meters) and low rain, both models predict a strong signal (20 dB SNR). However, even a slightly longer distance (0.5 km) with the same low rain significantly reduces predicted SNR (to 5 dB). The ITU Carb. (France) model exhibits greater sensitivity to rainy weather conditions compared to the ITU Japan Model. This discrepancy stems from the ITU Carb. (France) Model's foundation on data from France, whose climate closely resembles that of Libya, unlike Japan's.

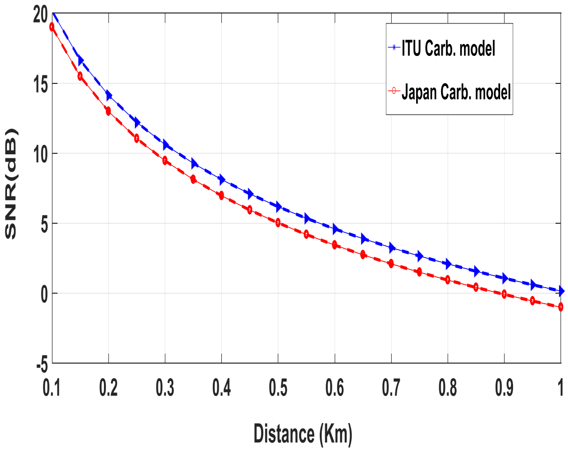

Figure 3. SNR (dB) versus distance for two models at a specific rain attenuation

B. SNR as a Function of Rain Rate

The SNR presented in Fig.4 was calculated using equation (8) for three link distances: 0.8 km, 1 km, and 1.1 km. the SNR_{rain} maximum when applied two models was 10 dB at low rain rate, while it was less than 2 dB at all distances for 40 mm\hr. that is all SNR values inside range required when applied ITU Carb. (France) Model and the ITU Japan Model. Adjusting the link distance can optimize the availability of the FSO link based on the signal-to-noise ratio requirements. An FSO link at a distance of 1 km can achieve an SNR ranging from 2 dB at a high rain rate of 140 mm/hr to 10 dB at the lowest rain rate of 12 mm/hr. A 1.1 km FSO link exhibits an SNR range of 0.4 dB at a rain rate of 140 mm/hr to 8 dB at a low rain rate of 12 mm/hr. To quantify the impact of distance on SNR, three rain rate values are considered: 80 mm/hr, 120 mm/hr, and 140 mm/hr.

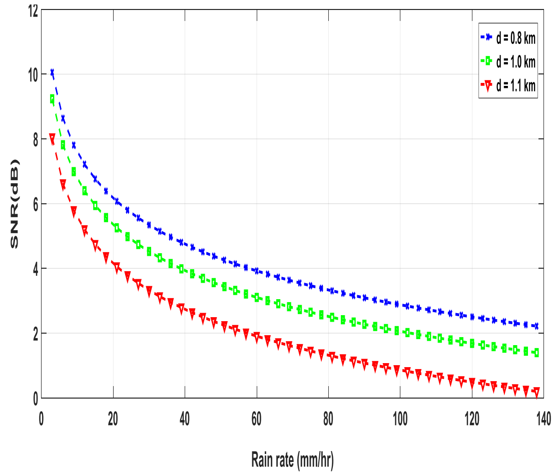

Figure 4. SNR rate of rain for total path rain attenuation with different distance

Fig. 5 shows the signal strength (SNR) for various rain intensities in Libyan cities. Garian city had the highest SNR (38 dB) during heavy rain (100 mm/h). These results are helpful for rain models in moderate climates, like the ITU Carb. (France) Model. In Tripoli, SNR was 11 dB with moderate rain (54.7 mm/h) at 3 km distance. In contrast, Garian had a lower SNR (5 dB) at the same distance with heavy rain.

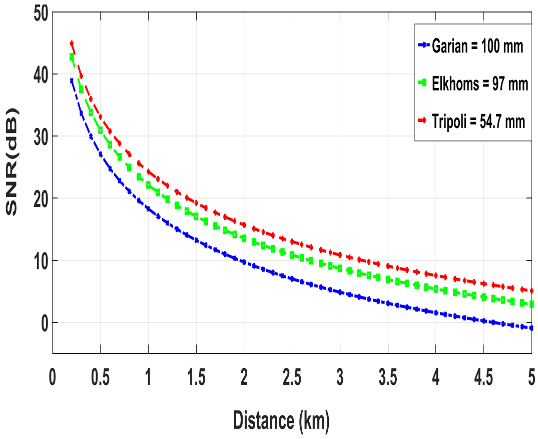

Figure. 5. SNR path lengths for three different cities Tripoli, Elkhoms and Garian

VII. CONCLUSION AND FUTURE WORK

This research examined signal strength (SNR) and received power for FSO links in Tripoli, Elkhoms, and Garian, Libya. Tripoli fared best, achieving a 5 dB SNR over a 5 km distance. Garian's maximum achievable distance with an acceptable SNR (using the ITU Japan Model) was only 2.8 km. For the shortest distances, SNR was 45 dB and 38 dB in Tripoli and Garian, respectively. Importantly, rain significantly weakens the signal, with attenuation following a logarithmic curve relative to rainfall rate. Future studies could explore how fog and dust storms impact various optical signals. Additionally, using regression analysis on the Libyan city data could lead to a new, location-specific model for different attenuation types, benefiting the deployment of FSO or hybrid FSO/RF systems.

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