Image Quality Assessment in Haze-Affected FSO Systems : Analyzing Characteristics and Deployment Parameters

Amina DJIR[1], Fatiha MESKINE[2], Mohamed Larbi TAYEBI[1]

[1]Telecommunication and Digital Signal Processing Laboratory (LTTNS),
Djillali Liabes University, Sidi-Bel-Abbes, Algeria

[2]Communication Networks, Architecture and Multimedia (RCAM),
Djillali Liabes University, Sidi-Bel-Abbes, Algeria

E-mail: fatiha.meskine@univ-sba.dz

Abstract - This research examines the transmission of RGB images over an Intensity Modulation/Direct Detection (IM/DD) communication-oriented Free Space Optical (FSO) system under the influence of haze weather atmospheric attenuations. The aim of this study is to identify the best system's characteristics for practical FSO deployment in the presence of haze conditions. Our analysis, conducted through simulations, seeks to strike a balance between receiver aperture diameter, beam divergence angle and range. We consider the advantages and disadvantages of large receiver apertures, taking into account their potential to collect more signal power but also to capture more background noise. The image quality metrics used for evaluation in this study are SSIM (Structural Similarity Index Measure) and PSNR (Peak Signal-to-Noise Ratio). The study considers various severities of haze, specifically light, moderate and heavy haze. By identifying the ideal combination of FSO characteristics, this study attempts to provide valuable guidelines for practical FSO deployments in regions prone to haze, with a specific focus on ensuring reliable and high-quality RGB image transmission.

Keywords - Free Space Optics (FSO), haze attenuation, image quality, beam divergence, receiver aperture size.

I. INTRODUCTION

Free space optics (FSO) communication system is a wireless communication technology that uses light beams to transmit data through the atmosphere, rather than traditional radio waves or cables [1, 2]. It offers high bandwidth and secure data transmission, making it an attractive alternative to traditional communication systems like Radio Frequency (RF) communication systems [2, 3]. In addition, FSO systems have the advantage of being immune to electromagnetic interference, making them ideal for use in environments with high electromagnetic radiation [3]. FSO communication relies on the principle of transmitting light signals in the form of laser beams, which are then received and decoded by a Photo Diode (PD) at the receiving end. This technology has gained significant attention in recent years due to its ability to provide high-speed connectivity in areas where traditional wired or wireless networks are not feasible or cost-effective and due to its potential applications in various fields, including telecommunications, satellite communications, and military communications.

However, one major drawback of FSO communication is that it is highly susceptible to atmospheric conditions, which can significantly degrade the quality and reliability of the transmitted signals [2, 3-6]. Factors such as fog, rain and haze can obstruct the laser beams, resulting in signal loss. These weather conditions can scatter and absorb light. This makes FSO communication less reliable in areas prone to adverse weather conditions, limiting its effectiveness in certain environments. Challenges posed by haze weather conditions can greatly affect the image quality in an FSO communication system. Haze, which is caused by the presence of fine particles and pollutants in the atmosphere, can scatter and absorb light signals, leading to reduced visibility and degraded image quality. This can result in a decrease in the

signal-to-noise ratio (SNR), ultimately impacting the reliability and efficiency of the system. To model the atmospheric propagation of FSO, we need to consider various types of input information.

Deployment Parameters that depend on the location and application of the FSO system installation, such as range, bandwidth, and wavelength, FSO system parameters, which are specific to the FSO system that has been installed, including the number of transmitters (T_X) and receivers (R_X), the diameters of the T_X and R_X, the power of the T_X, the sensitivity of the R_X, and others. Another input parameter is weather parameters. This parameter depends on the weather conditions, such as meteorological visual range (visibility), temperature, relative humidity (or dew point) and fog model [7].

Atmospheric absorption of light is a major obstacle for FSO communication, especially when the buildings are far apart in urban areas. One way to overcome this challenge is to use a wavelength that has low absorption in the atmosphere, such as 1550 nm [6,8]. Another way to deal with atmospheric attenuation is to optimize the design of the FSO system, including the transmitter power, receiver diameter and divergence angle.

This paper analyzes FSO atmospheric propagation, and focuses on attenuation due to haze and geometrical loss due to the beam divergence in the air. We investigate how different levels of haze affect the quality of image transmission and suggest strategies for optimizing FSO communication systems based on the beam angle and receiver aperture size under hazy weather conditions.

The paper will be organized into several sections, each dedicated to examining different aspects of image transmission performance evaluation.

These sections will encompass the system and channel description, providing a detailed overview of the system and the channel used for image transmission, results and Analysis section presenting the outcomes of the study, along with a thorough analysis of these results and a conclusion section summarizing the key findings.

II. METHODOLOGY ANALYSIS

Figure 1 presents a comprehensive scenario detailing the process from the transmitter to the receiver of a typical FSO terrestrial line-of-sight (LOS) link, specifically designed for color image transmission over an FSO channel. This schematic diagram provides an overview of the key elements that constitute an FSO transmission system, with a particular focus on the beam divergence process. A modulation technique is employed to reformat the images, which have been converted into binary form, prior to their transmission through the FSO channel. The experiment is executed in the following sequence of steps involved in preparing and sending the images through the FSO communication channel:

Step 1: The color images are first digitized into binary data and then reshaped to make them suitable for transmission over the FSO channel.

Step 2: The transmission process uses modulation techniques to encode and send the data efficiently over the FSO link. The binary data stream is modulated using the On-Off Keying (OOK) modulation scheme based on the Non-Return-to-Zero (NRZ) format, which is also known as incoherent optical communications.

Step 3: The modulated signal is used to drive a laser diode, which emits light pulses corresponding to the data. In OOK, the presence of a bit is signaled by the presence of the carrier, while its absence is signaled by the absence of the carrier.

Step 4: The modulated laser beam is transmitted through free space channel, which is affected by atmospheric conditions such as haze, which can cause signal attenuation. This needs to be accounted for in the system design.

Step 5: At the receiver end, the decoding process depends on the direct detection of photons at the receiver, which produces a photocurrent that is proportional to the received instantaneous power through the PD. The PD acts as a square-law detection device, enabling effective signal detection.

Step 6: The electrical signal is demodulated using the OOK scheme. The demodulated binary data is then converted back into RGB values. This gives the received image.

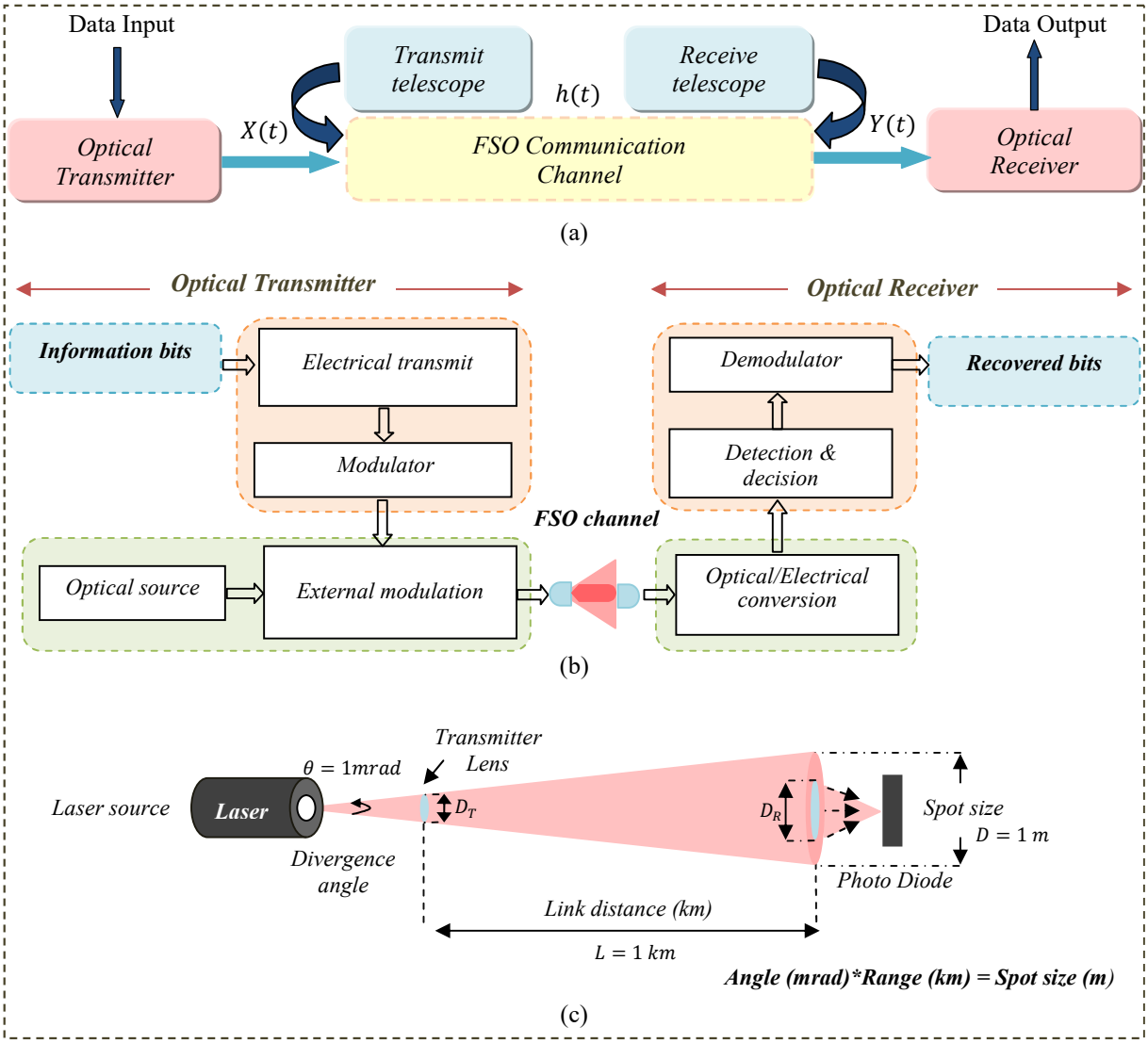

Fig. 1. (a) Basic block diagram of FSO terrestrial transmission system structure, (b) transmitter and receiver components (c) beam divergence process.

III. FSO Link Estimation

FSO communication is a promising technology for high-speed data transmission. However, the performance of FSO links can be significantly affected by atmospheric conditions such as haze, fog, and other adverse weather conditions. The transmission power decreases along the path due to attenuation effects caused by weather conditions. For instance, under hazy conditions, the scattering of light increases, leading to a decrease in the received power.

Therefore, it's important to design the system in such a way that sufficient power is available at the receiver to retrieve the information. The loss of optical power due to the atmospheric particles can be calculated using the exponential Beers-Lambert Law (BLL). The BLL, often used in the field of optics and atmospheric science, indicates that the attenuation of light (or laser power) through the atmosphere has an exponential relationship. In mathematical terms, this relationship can be expressed as follows [9,10]:

$$\tau(\lambda, L) = \frac{P_R}{P_T} = e^{[-\gamma_T(\lambda)L]} \quad (1)$$

Where the total attenuation coefficient (per unit length) is denoted by $\gamma_T(\lambda)$ (in km^{-1}), P_T and P_R represents the transmitted and received power respectively and $\tau(\lambda, L)$ the total transmittance of the atmosphere at a wavelength λ.

To predict haze-induced attenuations of the optical signal based on visibility range estimates, two widely empirical models are commonly employed: the KRUSE (since 1962) and KIM (2001) models [2, 3, 11]. Generally, the atmospheric attenuation coefficient depends on various factors. The specific haze attenuation, for the KRUSE and KIM models, is done by the following expression, which represents the scattering coefficient $\beta_a(\lambda)$ in terms of visibility and wavelength [2]:

$$\gamma_{Haze}(\lambda) = \frac{3.912}{V(km)}\left(\frac{\lambda(nm)}{550(nm)}\right)^{-p} \quad (2)$$

In KRUSE's model, the parameter p is variable and can take on different values depending on the weather conditions [12].

$$P = \begin{cases} 1.6 \ \ for \ V > 50\ km \\ 1.3\ for \ 6 < V < 50\ km \\ 0.585\ V^{\frac{1}{3}}\ for \ V < 6\ km \end{cases} \quad (3)$$

On the other hand, KIM's model is a modified version of the KRUSE model. KIM's model allows the parameter p to take different values, which vary according to specific weather conditions.

KIM's model provides an estimation of the attenuation experienced by optical signals as they pass through foggy or hazy atmospheric conditions.

KIM defined the parameter p as [13]:

$$p = \begin{cases} 1.6 \ \ for \ V > 50\ km \\ 1.3\ for \ 6 < V < 50\ km \\ 0.16V + 0.34\ for\ 1 < V < 6\ km \\ V - 0.5 \ \ for \ 0.5 < V < 1\ km \\ 0 \ \ for\ V < 0.5\ km \end{cases} \quad (4)$$

However, it is important to note that these models are empirical in nature and may have limitations in certain conditions or geographical locations. The international visibility range for various weather conditions and attenuation coefficients at $1550\ nm$ is shown in Table 1.

Considering haze atmospheric losses, the total received power (P_{Rx}), post-transmission through a transmitting aperture with a diameter of D_{Tx} and received through a receiving aperture with a diameter of D_{Rx} over a link length L with a transmitting beam divergence of θ_{div} from the transmitter, which initially had a power P_{Tx}, can be numerically expressed by the following equation [14-16]:

$$P_{Rx} = \mathrm{P_{Tx}}\left(\frac{(D_{Rx})^2}{(D_{Tx}+\theta_{div}L)^2}\right) 10^{-(\gamma_{haze}(\mathrm{dB/km})\times \mathrm{L}/10)}\ \tau_{Tx}\tau_{Rx} \quad (5)$$

In this equation, τ_{Tx} and τ_{Rx} denote the optical efficiencies of the transmitter and receiver, respectively. The haze attenuation due to scattering is symbolized by γ_{haze} given in dB/km.

Table 1. International visibility standards corresponding to weather conditions according to KIM's & KRUSE's models

Weather condition	*KIM*		*KRUSE*	
	V (km)	***Attenuation (dB/km)***	***V (km)***	***Attenuation (dB/km)***
Light Haze	*5.9 - 10*	*0.76 - **0.44***	*5.9 - 10*	*5.9 - 0.44*
Moderate Haze	*2.8 - 4*	*2.68 - **1.53***	*2.8 - 4*	*2.58 - 1.62*
Heavy Haze	*1.9 - 2*	*4.58 - **4.28***	*1.9 - 2*	*4.21 - 3.95*

Note: *Bold values indicate the specific attenuation attributed to each weather condition that has been employed in this paper.*

IV. Results and Data Analysis

The performance of a 4 km FSO link with a 10 Gbps data rate is calculated in terms of PSNR and SSIM, a metric used to quantify the similarity between two images in different atmospheric hazy conditions. The optical beam does not stay the same size as it travels through the atmosphere. The further the beam propagates, the more it spreads out. This is called beam divergence. The divergence angle refers to the angle at which the light beam spreads out from its original path. One way to reduce the amount of beam divergence is to change the divergence angle. This can help avoid losing too much light due to bad weather conditions like haze. Haze

conditions can affect the propagation of light, and thus the quality of the received image.

Figure 2 provides a visual representation of how the angle of the optical beam, the amount of haze in the air, and image quality are related. The analysis is conducted in varying levels of haze, including light, moderate, and heavy conditions. The results presented in this figure offer insights into how changes in the divergence angle affect the SSIM of images in different atmospheric conditions. This information is valuable for optimizing systems that rely on divergence angles, such as optical communication, under diverse levels of atmospheric haze.

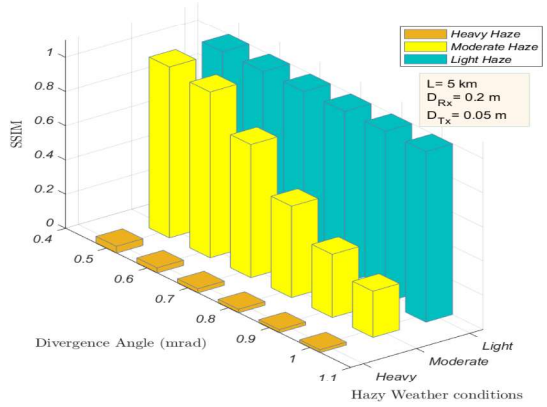

Fig. 2. SSIM vs. divergence angle in light, moderate, and heavy haze conditions

By examining the bars across different beam divergence angles and haze levels, the shifts in image quality become apparent. The graphical findings demonstrate that an increase in beam divergence, from 0.5 to 1, corresponds to a gradual decline in SSIM values, as the bars decrease in height. This means that a wider optical beam can adversely affect image quality, leading to a reduced SSIM between transmitted and original images. Moreover, this increased divergence is concurrently linked to a reduction in the maximum achievable range for the optical communication system. On the other hand, haze levels have a clear impact on image quality. In general, as the haze level intensifies, there is a consistent reduction in SSIM values. This implies that adverse atmospheric conditions, particularly heavy haze, severely affect the quality of transmitted images.

Receiver aperture optimization is the process of adjusting the receiver aperture size to collect more optical signals. The receiver aperture is the opening that allows light to enter the receiver. The size of the receiver aperture affects the image quality, especially in hazy conditions. Figure 3 shows the relationship between the SSIM and the size of the receiver aperture under different haze conditions (light, moderate, and heavy).

The figure demonstrates how the SSIM changes with different receiver aperture sizes. The analysis is conducted under different haze conditions, ranging from light to heavy. This information is crucial for understanding the impact of atmospheric haze on the performance of a receiver system and how adjusting the aperture size may influence the quality of received images. The results may provide insights into optimizing receiver parameters for various atmospheric conditions, ensuring reliable performance in scenarios with different levels of haze.

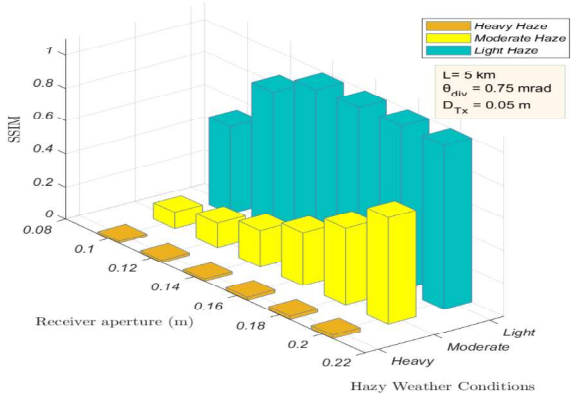

Fig. 3. SSIM vs. Receiver aperture size in light, moderate, and heavy haze conditions

Similarly, when analyzing the bars across varying receiver aperture sizes and different haze conditions, valuable insights emerge regarding their influence on image quality. The graphical results depict a notable trend: as the receiver aperture size increases, there is a significant improvement in SSIM values, as illustrated by the ascending bar height. This indicates that a larger receiver aperture positively affects image quality, leading to a higher SSIM between the transmitted and original images.

The graphical results of Figures 2 and 3 provide valuable insights into the relationship between the SSIM, receiver aperture sizes, divergence angles, and varying haze conditions. The analysis indicates that SSIM is influenced by changes in both receiver aperture size and divergence angle across different levels of haze, including light, moderate, and heavy conditions. This observation suggests that optimizing the receiver aperture size and divergence angle is crucial for maintaining high-quality images under diverse weather conditions. The findings contribute to a better understanding of how atmospheric factors impact image quality and provide a basis for determining the optimal parameters for receiver systems to ensure high-quality performance across varying weather conditions. Figure 4 presents a set of received images considering different atmospheric haze conditions at a distance of 5 km. The images are organized in columns, each representing a specific divergence angle value (ranging from 0.5 mrad to 1 mrad), and in lines, corresponding to different levels of haze conditions (light, moderate, and heavy). This analysis allows for an examination of how divergence angle and haze conditions influence the quality and clarity of received images over a significant distance.

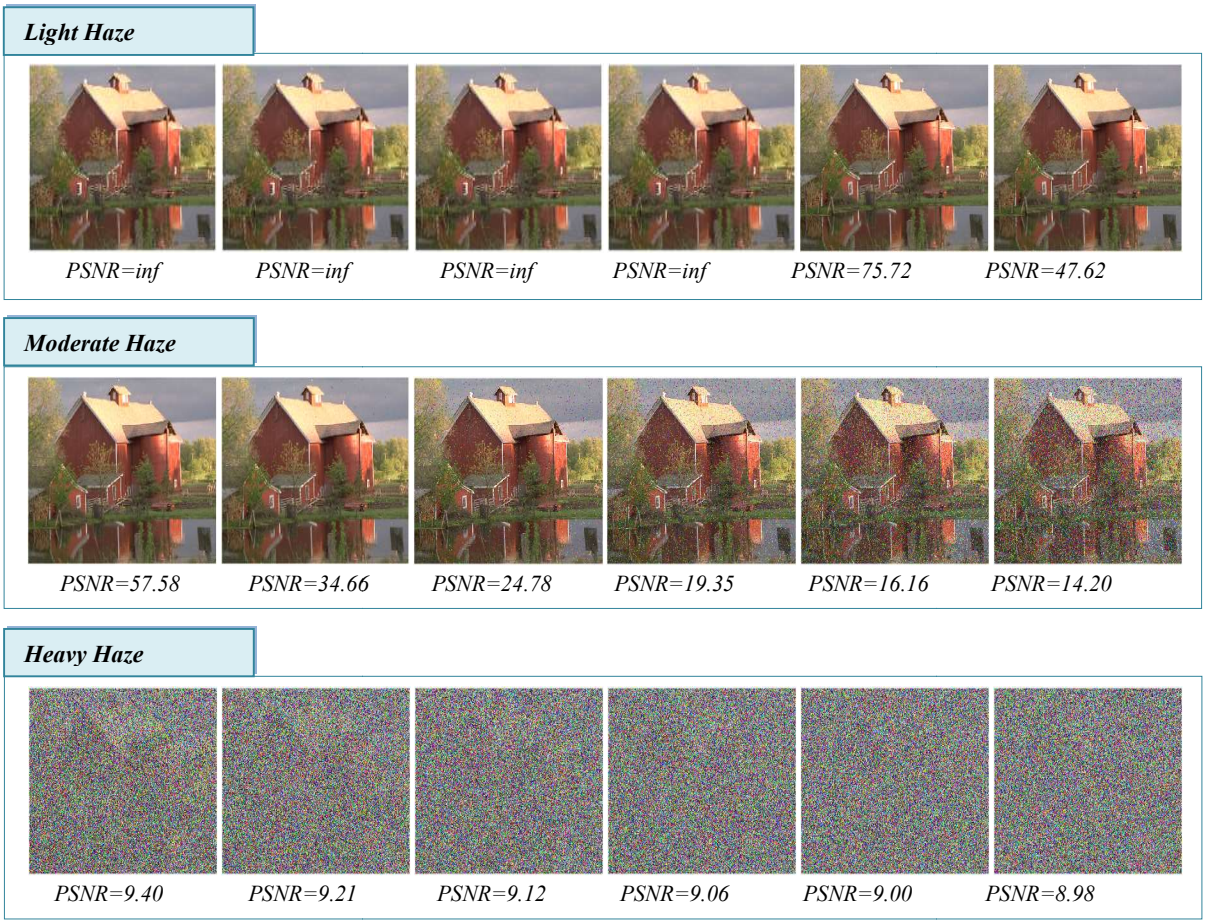

Fig.4. Impact of divergence angle on received images at 5 km across haze conditions

It provides insights into optimizing divergence angles for specific atmospheric conditions, contributing to a better understanding of image reception. The figure shows that as the beam divergence increases, the image quality decreases. This phenomenon is attributed to increased attenuation caused by haze. Therefore, they have an inverse relationship. Moreover, Figure 5 illustrates the influence of the receiver beam size on the quality of received images at a distance of 5 km, considering different levels of haze conditions.

The analysis likely explores the relationship between the beam size and image quality,

providing insights into optimizing receiver parameters for optimal performance under diverse weather conditions. The results prove that there is a proportional relationship between the receiver aperture size and image quality under light and moderate haze conditions. Specifically, as the receiver aperture size increases, the image quality also increases in these conditions. While a larger receiver aperture is beneficial in improving image quality under light and moderate haze, it may not be as effective in heavy haze conditions.

Table 5 summarizes the range limits for different Haze weather conditions that were simulated in this paper for image transmission under the proposed FSO communication system. The effect of receiver aperture size and beam divergence angle on the maximum communication range is studied.

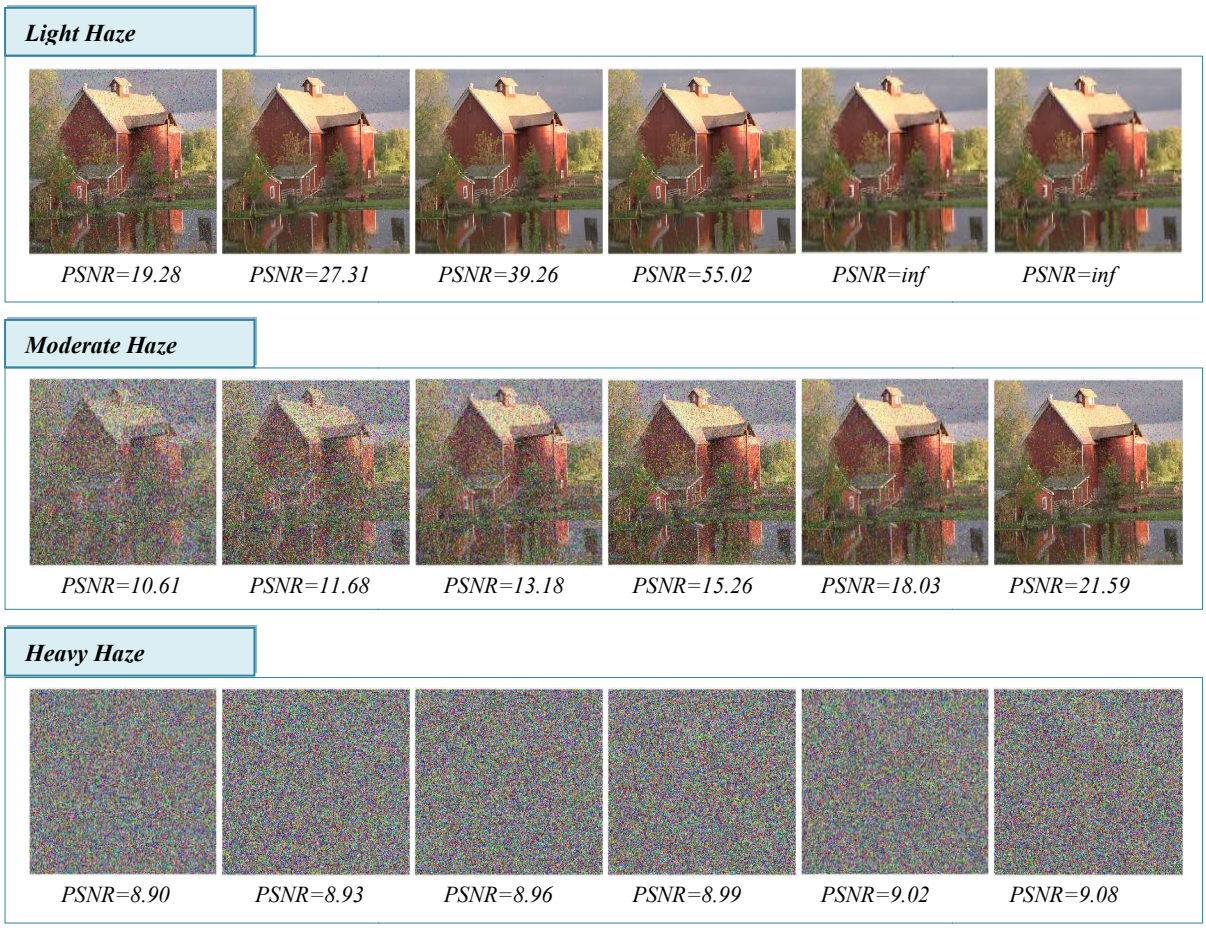

Fig.5. Impact of receiver beam size on received images at 5 km across haze conditions

It is found that a larger aperture and a smaller divergence angle can increase the range significantly. For example, in the first case, the range can reach 6 km in light haze, 4.8 km in moderate haze and 2.5 km in heavy haze. However, in the second case, the aperture is smaller and the divergence angle is larger, the range drops to 4.3 km, 3 km and 1.9 km for the same haze conditions, respectively.

Table 2. Maximum range values

Weather condition	*Maximum range (km)*	
	$P = 5$ mW $\theta_{div} = 0.75$ mrad $D_{Rx} = 0.2$ m	$P = 5$ mW $\theta_{div} = 1$ mrad $D_{Rx} = 0.16$ m
Light Haze	6	4.3
Moderate Haze	4.8	3
Heavy Haze	2.4	1.9

V. CONCLUSION

In practical FSO systems, optimization involves considering trade-offs between factors like range, beam divergence angle, receiver size and atmospheric conditions to achieve the best compromise for the specific application and environmental conditions. Increasing the receiver aperture size substantially enhances SSIM values, improving image quality. However, larger apertures also capture more background noise, impacting the PSNR. Beam divergence inversely affects SSIM values, highlighting the need to control it for high-quality image transmission. Moreover, an increase in divergence is associated with a reduced maximum communication range. Haze conditions consistently degrade image quality, emphasizing the necessity for advanced strategies to mitigate atmospheric impact on image transmission. In summary, selecting the optimal balanced between divergence, receiver size and range is critical for achieving high quality image transmission under varying haze scenarios for reliable and robust FSO communication systems.

VI. REFERENCES

[1] H. Henniger, and O. Wilfert, An introduction to free-space optical communications, *Radioengineering*, *19(2),* 2010, 203–212.

[2] S. A. Al-Gailani, M. F. M. Salleh, A. A. Salem, R. Q. Shaddad, U. U. Sheikh, N. A. Algeelani, T. A. Almohamad, A Survey of Free Space Optics (FSO) communication systems, links, and networks, *IEEE Access*, 9, 2020, 7353-7373.

[3] H. Willebrand and B. S. Ghuman, *Free-Space Optics: enabling optical connectivity in today's networks*, SAMS Publishing, USA, 2002.

[4] Aditi Malik and Preeti Singh, Free Space Optics: Current Applications and Future Challenges, *International Journal of Optics*, 2015.

[5] S. Chaudhary and A. Amphawan, The role and challenges of free-space optical systems, *J Opt Commun.*, *35(4)*, 2014, 327-334.

[6] M. A. Khalighi and M. Uysal, Survey on free space optical communication: a communication theory perspective, *IEEE Communications Surveys & Tutorials*, *16(4)*, 2014, 2231-2258.

[7] M. Achour, Simulating Atmospheric Free-Space Optical Propagation; Part II: Haze, Fog, and Low Clouds Attenuations, in *Proc. SPIE 4873, Optical Wireless Communications V*, Dec. 6, 2002.

[8] S. Bloom, E. Korevaar, J. Schuster, and H. Willebrand, Understanding the performance of free space optics, *Journal of Optical Networking*, *2(6)*, 2003, 178-200.

[9] A. G. Alkholidi and K. S. Altowij, Free Space Optical Communications-Theory and Practices, in [Mutamed, K], *Contemporary Issues in Wireless Communications*, IntechOpen, 2014, 159-212.

[10] M. K. El-nayal, M. M. Aly, H. A. Fayed, and R. A. AbdelRassoul, Adaptive free space optic system based on visibility detector to overcome atmospheric attenuation, *Results in Physics*, *14*, 2019, 102392.

[11] D. Anandkumar and R. G. Sangeetha, A survey on performance enhancement in free space optical communication system through channel models and modulation techniques, *Optical and Quantum Electronics*, *53(1)*, 2021, 1-39.

[12] P. W. Kruse, L. D. McGlauchlin, and R. B. McQuistan, *Elements of Infrared Technology: Generation, Transmission and Detection*. New York: Wiley, 1962.

[13] I. I. Kim, B. McArthur, and E. J. Korevaar, Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications, in *Optical wireless communications III*, vol. 4214, 2001, 26-37.

[14] Z. Ghassemlooy, W. Popoola, S. Rajbhandari, *Optical wireless communications: system and channel modelling with MATLAB®*, 2nd ed. Taylor & Francis Group, 2018.

[15] A. Djir, F. Meskine, and M. L. Tayebi, Study of atmospheric attenuation on image quality assessment in FSO transmission operating at 850, 1064, and 1550 nm wavelengths, in *IEEE International Conference on Advances in Electronics, Control and Communication Systems*, Blida, March 2023, 1-6.

[16] A. Djir, F. Meskine, and M. L. Tayebi,Free Space Optical Communication Study for Image Transmission Under Foggy Conditions, in *Proceeding of the 2nd International Conference on Advanced Electrical Engineering*, Constantine, October 2022, 1-6.