Performance Analysis of Radio over Free-Space Optical Communication using Advanced Modulation Techniques: An ML-Based Approach.

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Abstract— **The Radio over free space optics (Ro-FSO) technology is a promising solution for high-speed optical carrier transmission, particularly in urban areas where licensing and expensive cables can be a limiting factor. Ro-FSO communication utilizes point-to-point light pulses instead of fibre cables, making it a cost-effective alternative. The channel can be atmosphere, vacuum, or air, and its properties determine the transmission and reception of optical signals in order to design reliable and environmentally friendly communication systems.**

Ro-FSO systems provide high-speed broadband services that can reach up to hundreds of Gbit/s, making it a faster alternative to optical fibre. However, the technology is significantly affected by atmospheric effects such as attenuation, turbulence, and scattering, which can have an impact on the sensitivity and achievable data rates with an acceptable bit error rate (BER) for communication.

This paper discusses the quality of transmission using the Ro-FSO link under various weather conditions such as fog, haze, and other factors that contribute to attenuation and absorption. Rain droplets, fog, snow, and haze can all lead to signal attenuation, fading, and even complete signal loss. And how different advance modulation techniques can be used to achieve high speed data rate with better efficiency.

Keywords- radio-over-free space optics, BER, weather conditions

I. INTRODUCTION

Radio over Free Space Optics (Ro-FSO) is a novel technology that combines free-space optics (FSO) with wireless communication systems [3]. The technology holds great potential for the last mile access networks in urban areas and in regions where the installation of RoFSO links is impractical and expensive [5]. Free-Space Optical Communication (FSOC) has become an indispensable part of our daily lives as it enables efficient voice, video, and data transmission through air [2]. Optical wireless communication (OWC) is an excellent complementary solution to its radio frequency (RF) counterpart [4].

In optical communication networks and laser systems, optical isolators are crucial components [1]. All-fibre optical isolators are highly sought-after, particularly for high-power fibre laser systems, where the restrictions on fibre termination and small free-space beams make it challenging to transmit large amounts of power [1]. Given these considerations, we can conclude that Ro-FSO technology is a promising solution for high-speed optical carrier transmission without any licensing and costly cables [3].

Free space optical communication (FSO) is an alternative to radio frequency technology, similar to optical fibre. It modulates a laser light beam in the transmitter and propagates it in a wireless medium from transmitter to receiver. The performance of the link can be affected by both internal and external factors, such as frequency, wavelength, optical power, visibility, scintillation, cloud and fog conditions. [12, 13].

Machine learning (ML) is the study of computer algorithms where machines can learn to achieve a task or goal for which it is designed without needing to be programmed specifically just with processing data. ML is a topic of research and interest in statisticians and programmers since the 1950s, where the evolution of algorithms was taking place. Optical fibre communication can be thought of as a backbone of communication systems since 1980s where it was introduced for the first time. With which ML approaches have shown potential in helping to deal with physical effects such as fibre loss which generally comes from wavelength changes it can also help in network control etc. And according to the purpose of the project it is generally decided which algorithm we have to apply whether it is classification problem or a regression problem in classification problem we have multiple input parameter and we have to predict the final outcome in form of definite outcome of basically yes or no type while regression is used for continuous value inputs to predict certain parameter which can be any continuous outcome [5]. Table below giving a basic overview on how RoFSO works.

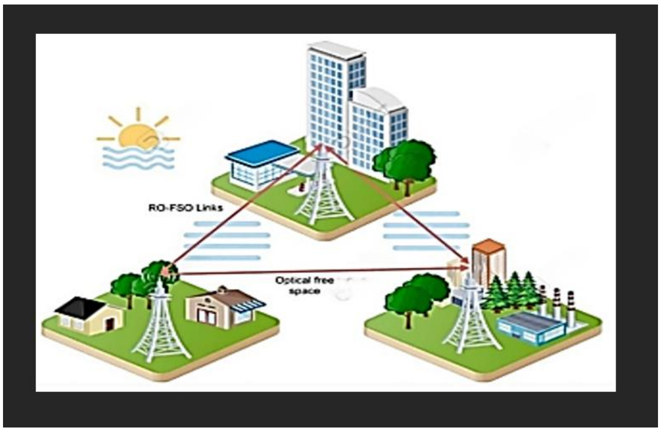


Figure 1. RoFSO link for real time communication

II. SCHEMATIC

The RoFSO link shown in Figure 2 is simulated using Optisystem software, and various sections and their functions are depicted in this diagram. On the transmitter side, there is a Pseudo Random Noise (PRN) sequence generator, NRZ pulse generator, CW laser, modulator, optical power meter, and electric power meter for generating and modulating the transmitting signal at the sender end. In the centre, there is a channel that consists of an FSO channel, optical power meter, and EDFA, which are required for transmission through the medium. This is followed by the receiver end, which consists of a PIN photodetector, low-pass Bessel filter, BER analyser, and electrical power meter.

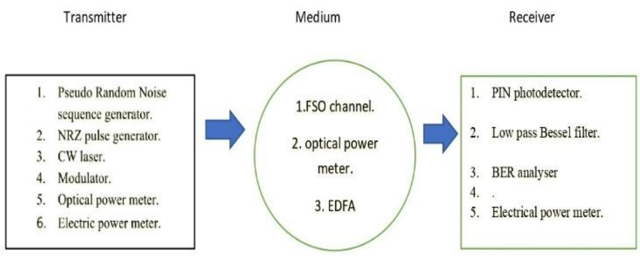


Figure 2. Schematic of QAM RoFSO model.

The bit error rate (BER) and Q-factor of the received signal can be used to assess the system performance. The Q-factor is regarded as a performance metric in the majority of applications to measure the signal quality because the BER in an optical communication system is too low to evaluate. The difference between the number of bits the detector receives and the number of bits broadcast is known as the BER, which is used to calculate the error probability. The minimal signal-to-noise ratio (SNR) necessary to achieve a particular BER for a given signal is known as the Q-factor and is represented as follows:

$$Q = \frac{V1 - V0}{\sigma 1 - \sigma 0} \tag{1}$$

Where V1 and V0 stand for the mean values of signal levels '1' and '0' respectively. An equal amount of Gaussian noise at all signal levels, the noise values for each signal level are represented as σ1 and σ0 which correspond to transmission probabilities of '1' and '0' respectively. The Q-factor and BER relationship is given as follows:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{2}$$

Months	Years	Visibility(Km)	Attenuation (dB/Km) Wavelength(nm)		
			850nm	1300 nm	1550 nm
December	2015	1.095	0.618	0.565	0.544
	2016	0.53	2.87	2.747	2.698
	2017	1.308	0.381	0.342	0.327
	2018	1	0.776	0.714	0.69
	2019	1.02	0.739	0.679	0.656
	2020	0.768	1.422	1.322	1.287
	2021	1.334	0.36	0.322	0.308
	2022	0.83	1.193	1.113	1.082
January	2015	0.613	2.094	2.904	2.051
	2016	0.552	2.551	2.671	2.503
	2017	0.806	1.188	1.271	1.157
	2018	0.484	3.226	3.357	3.127
	2019	0.724	1.499	1.591	1.462
	2020	0.9	0.923	0.954	0.894
	2021	0.42	4.096	4.26	4.065
	2022	0.58	2.327	2.44	2.282
February	2015	1.107	0.601	0.584	0.528
	2016	1.27	0.415	0.357	0.373
	2017	1.071	0.654	0.577	0.599
	2018	1.108	0.601	0.528	0.548
	2019	1.02	0.739	0.656	0.679
	2020	0.87	1.075	1	0.97
	2021	0.81	1.258	1.176	1.144
	2022	1.15	0.544	0.495	0.476
Average Attenuation			1.333	1.357	1.267

Figure 3. Attenuation for 3 diff. Month in order to calculate further data

Visibility is defined as the maximum distance that a normal human eye can see and is generally measured in kilometres. This study focused on the effect of fog in the New Delhi region from December 2015 to February 2022, using data from a time and date weather app. The lowest visibility was observed in

January, while the highest was observed in February. Each year, northern parts of India experience more severe fog conditions during the winter season (November-January) [3]. Fog is a visible aerosol consisting of tiny water droplets or ice crystals suspended in the air at or near the Earth's surface. Beer-Lambert's law, Kim and Kruse mathematical models, and visibility calculations have been used to obtain attenuation data.

The relationship between transmitted power, data rate, and transmission range has been examined, taking into account three transmission windows at 850, 1300, and 1550 nm. In order to compare the effectiveness of two attenuation models, the statistical data obtained for two mathematical models have also been examined. The data was collected for each day of three months over a period of eight years. The information was used to generate a table in which the average attenuation and respective visibility for January, February, and December are listed. For a given wavelength, the Kruse model returns higher values for these parameters. Both models perform better at 1550 and 1300 nm wavelengths than at 850 nm wavelength. It can be seen that the Kruse model has the lowest mean and median values of attenuation, and the highest [2].

Table 1: Calculation of q using Kim and Kruse models

Kim model	Kruse model
1.6 for $V > 50$ km	1.6 for $V > 50$ km
1.3 for 50 km $> V >$ 6 km	1.3 for 6 km $< V <$ 50 km
0.16 + 0.34 v for 6 km $> V >$ 1 km	0.585 $V^{1/3}$ for $V < 6$ km
0.5 for 0.5 km $< V <$ 1 km	
0 for $V < 0.5$ km	

Model	Kruse			kim		
Wavelength	Mean	Median	Range	Mean	Median	Range
850(nm)	2.367	2.507	1.091	2.867	2.607	0.991
1300(nm)	1.876	1.996	1.003	2.776	2.496	0.848
1550(nm)	1.704	1.816	0.902	2.404	2.196	0.793

Table 2: Mean, median, and range statistical parameters for different models at three different wavelengths.

In radio over free space systems, the mean, median, and range parameters are important measures for performance analysis. The mean and median values are measures of central tendency, providing information about the average value of a set of data. In signal analysis, higher mean or median values of signal strength indicate better signal quality, while higher mean or median values of noise level indicate higher levels of interference. On the other hand, the range parameter provides information about the spread of the data, which can be used to evaluate signal coverage and transmission distance. Wider ranges of signal strength indicate broader coverage areas, while smaller ranges indicate shorter transmission distances. These parameters help in evaluating system performance and making necessary adjustments to optimize performance. They can also be used to compare the performance of different radio over free space systems to choose the most suitable one for a particular application.

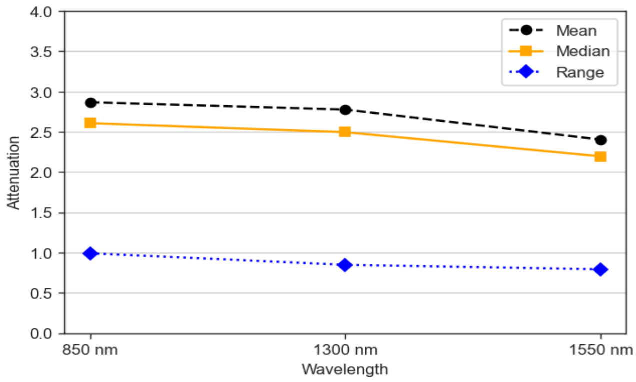


Figure 4: Mean, median, and range statistical parameters for the Kim model at three different wavelengths.

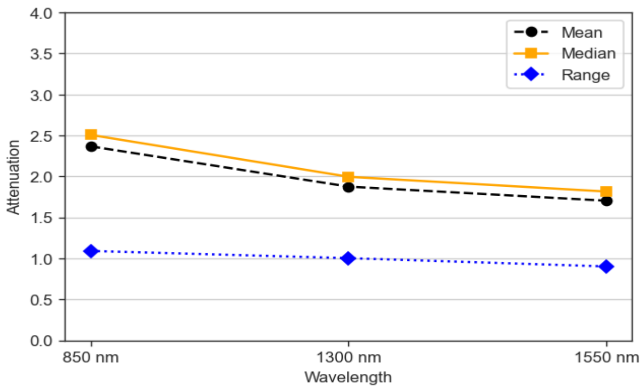


Figure 5: Mean, median, and range statistical parameters for the Kruse model at three different wavelengths.

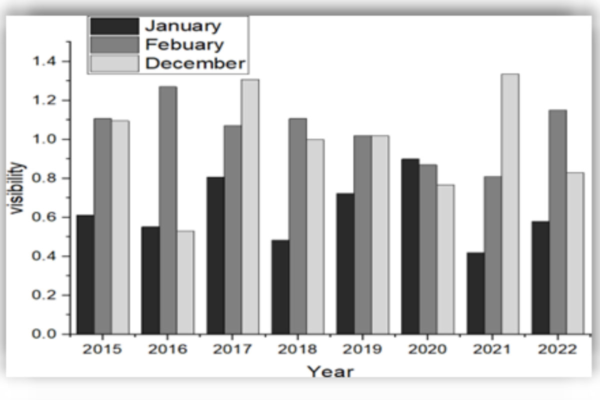


Figure 6. depicts the attenuation as a function of visibility curve at different frequency windows.

Radio over Free Space Optics (RoFSO) is a communication technology that utilizes optical beams in the free space to transmit data. The RoFSO system faces various challenges, including the attenuation effect, which can negatively impact the system's performance. The attenuation effect refers to the reduction in the signal strength during transmission due to absorption, scattering, and beam divergence [2]. In this article, we discuss the attenuation effect on RoFSO and the different models used to predict it. Attenuation Effect on RoFSO The attenuation effect is a significant challenge in RoFSO communication systems as it causes a reduction in signal strength, which leads to lower data rates and decreased system performance. Several factors contribute to attenuation, including absorption, scattering, and beam divergence [3].

Absorption occurs when the optical signal is absorbed by the atmosphere or the transmitting media, leading to a reduction in signal strength. Scattering, on the other hand, refers to the redirection of the optical signal due to atmospheric turbulence, causing signal loss. Beam divergence, the third factor, refers to the spreading of the optical beam, leading to signal loss at longer distances. Models for Predicting Attenuation To address the attenuation effect, several models have been developed to predict it accurately. These models can help in the design and optimization of RoFSO communication systems [4]. The two most commonly used models are the Kim model and the Kruse model. The Kim model is a widely used empirical model that predicts the attenuation due to absorption and scattering. The model is based on the Beer-Lambert law, which states that the attenuation of a signal is proportional to the length of the medium traversed and the attenuation coefficient. The attenuation coefficient is the sum of the absorption and scattering coefficients. The Kim model includes parameters such as the wavelength of the signal, the atmospheric temperature, and the relative humidity, among others. The Kruse model, on the other hand, is a theoretical model that predicts the attenuation due to atmospheric turbulence. The model is based on the Kolmogorov spectrum, which describes the statistics of atmospheric turbulence. The Kruse model includes parameters such as the aperture size, the atmospheric turbulence strength, and the distance between the transmitter and receiver [8].

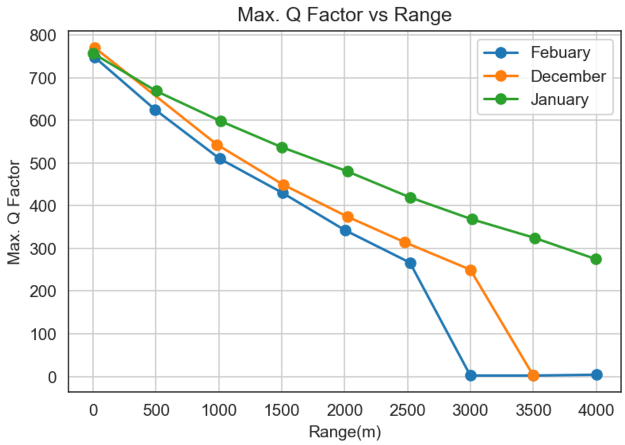


Figure 7: Graph representing Q factor vs range for 1550 nm

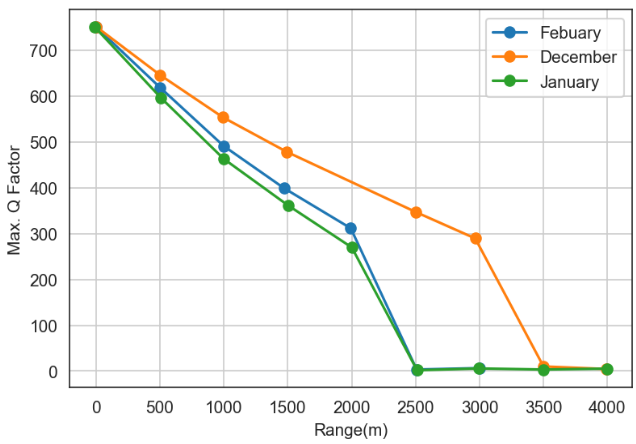


Figure 8: Graph representing Q factor vs range for 850 nm

With increasing wavelength, the range of RoFSO (Radio over Free Space Optics) transmission decreases due to the higher susceptibility of longer wavelengths to attenuation caused by atmospheric absorption and scattering. The attenuation of light in the atmosphere is caused by several mechanisms including molecular absorption, Rayleigh scattering, Mie scattering, and aerosol scattering. These mechanisms affect different parts of the electromagnetic spectrum differently, with some wavelengths being more strongly affected than others. In general, longer wavelengths are more susceptible to atmospheric attenuation than shorter wavelengths. This is because longer wavelengths have lower energy and are more easily absorbed by the molecules in the air. They are also more susceptible to

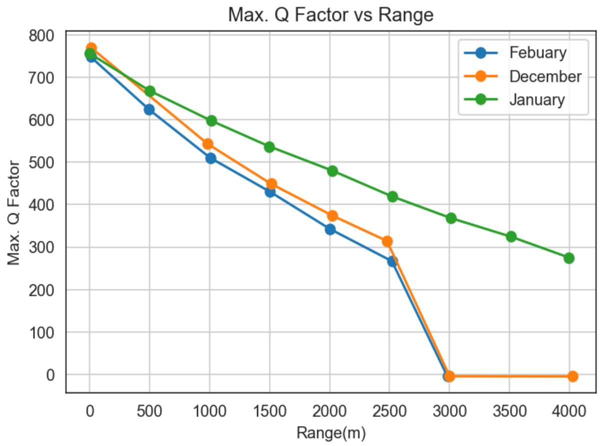


Figure 9: Graph representing Q factor vs range for 1300 nm

They are also more susceptible to scattering, especially by larger particles such as water droplets and aerosols, which can cause the light to deviate from its original path and spread out, reducing the intensity of the transmitted signal. As a result, longer wavelengths are more affected by atmospheric attenuation and have a shorter transmission range compared to shorter wavelengths. In addition, longer wavelengths also have lower data rates due to their lower bandwidth, which further limits their transmission range. Therefore, in RoFSO systems, shorter wavelengths such as infrared and visible light are typically used for longer range transmissions, while longer wavelengths such as microwave and radio frequencies are used for shorter range applications where atmospheric attenuation is less of a concern.

III. BACKGROUND OF ML TECHNIQUES

Different ML techniques have been employed for performance estimation of the proposed system. The input power, attenuation, and FSO range values have been considered as the predictors or input parameters of the proposed RoFSO system, while SNR and BER have been considered as the responses or output parameters.

Artificial Neural Networks (ANNs), K-Nearest Neighbors (KNN), and Decision Tree analysis are three popular machine learning algorithms that can be used to solve a variety of problems. Each of these techniques has its unique strengths and limitations, which can be beneficial in different situations. ANNs are a type of machine learning algorithm modelled after the human brain. They are capable of learning from large amounts of data and identifying complex patterns in that data. ANNs can be used for tasks such as image recognition, speech recognition, and natural language processing. The primary benefit of ANNs is their ability to learn and generalize from large amounts of data, making them powerful tools for solving complex problems. KNN is a non-parametric algorithm that is used for classification and regression problems. It works by finding the k-nearest data points to a new observation and then classifying the new observation based on the class labels of those nearest neighbors. KNN is simple and easy to implement, making it a good choice for small datasets or datasets with a small number of features. Additionally, KNN is a versatile algorithm that can be used for a variety of applications, such as text classification, gene expression analysis, and medical diagnosis. Decision Tree analysis is a machine learning algorithm that is used for classification and regression problems. It works by constructing a tree-like model of decisions and their possible consequences. Decision Trees are easy to understand and interpret, making them an excellent tool for visualizing and explaining complex decision-making processes. Additionally, Decision Trees can handle both categorical and numerical data and can be used for a variety of applications, such as predicting customer behaviour, identifying fraud, and medical diagnosis.

S. No.	ML Algorithms	Root Mean Square Error (RMSE)		R-squared (R^2)	
		Training Set	Testing Set	Training Set	Testing Set
1	ANN	0.686	0.079	0.99	0.99
2	KNN	0.891	0.633	0.990	0.989
3	Decision Tree	1.485	0.971	2.107	0.934

Table 2: RMSE and R squared values of training and testing dataset on different models.

OFDM and QAM are two commonly used modulation techniques in modern communication systems. OFDM is a multi-carrier modulation technique that is widely implemented in high-speed digital communication systems, such as Wi-Fi, 4G, and 5G. On the other hand, QAM is a digital modulation technique that encodes digital data onto an analog carrier wave.

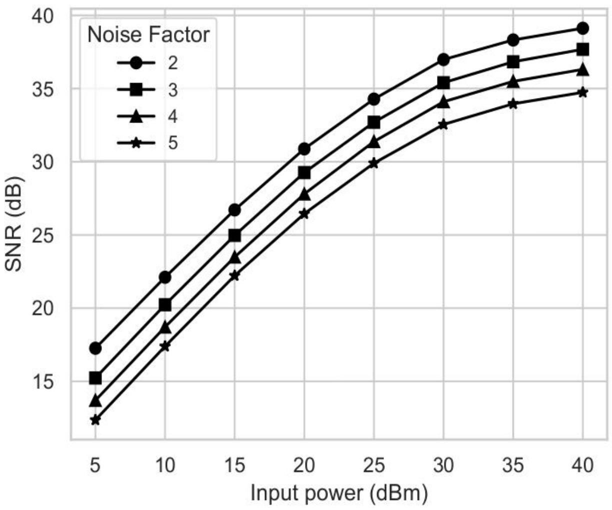
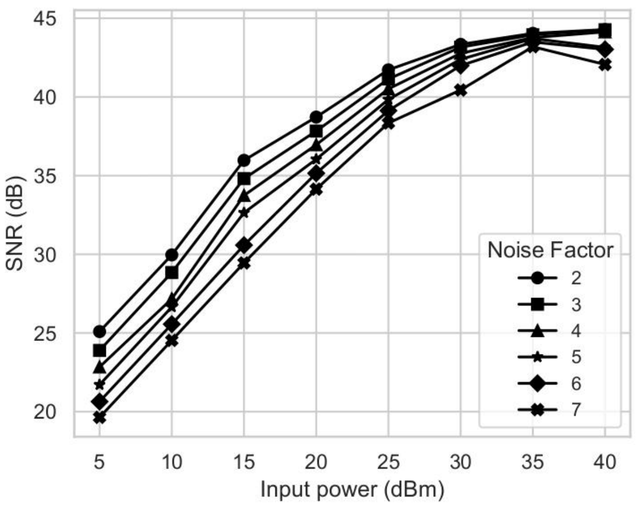


Figure 10. For fog conditions OFDM based 32qam



F*igure 11. For clear weather OFDM based 32qam*

OFDM works by dividing the available bandwidth into several sub-carriers that are orthogonal to each other, meaning that there is no interference between them. Each sub-carrier carries a small amount of data, and together they form the transmitted data stream. This approach enables higher data rates, providing better spectral efficiency and making it suitable for high-speed digital communication.

QAM, on the other hand, encodes digital data onto an analog carrier wave by varying the amplitude and phase of the carrier wave. This technique enables more data to be transmitted within a given bandwidth, providing higher spectral efficiency. Nevertheless, both OFDM and QAM are vulnerable to noise in the communication channel, which can significantly degrade the quality of the received signal. Various sources of noise can cause interference in the channel, such as thermal noise, intermodulation distortion, and crosstalk.

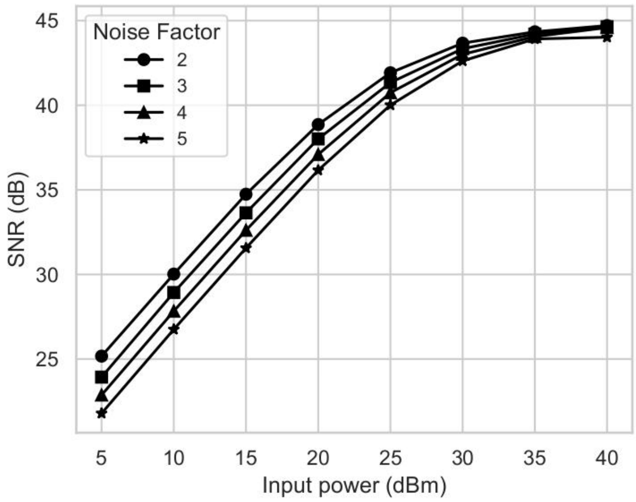


Figure 12. For fog conditions OFDM based 64qam

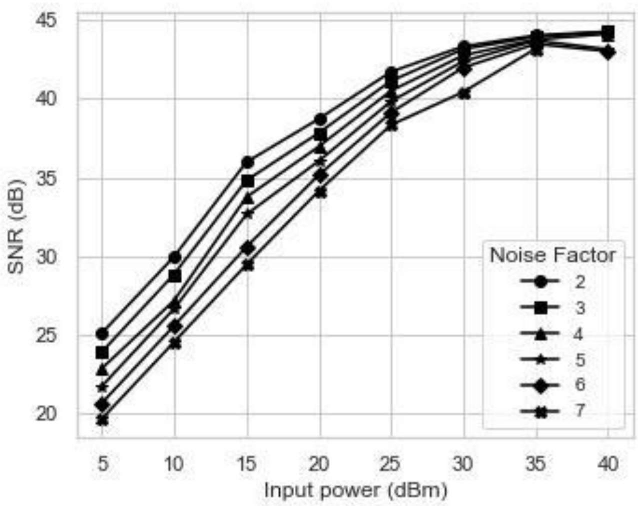


Figure 12. For clear weather OFDM based 64qam

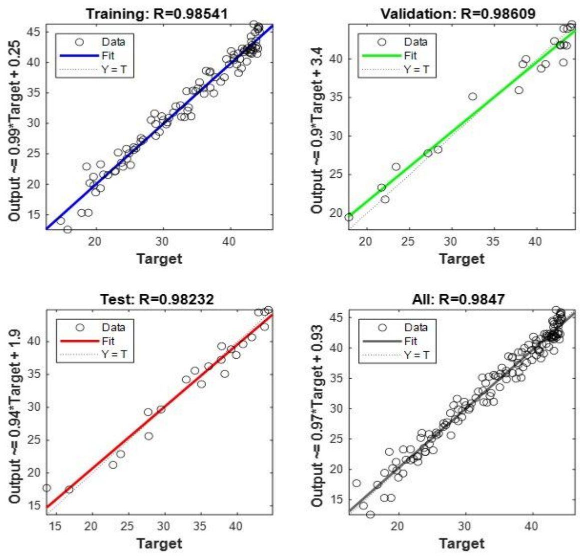


Figure 13. Regression fit plot

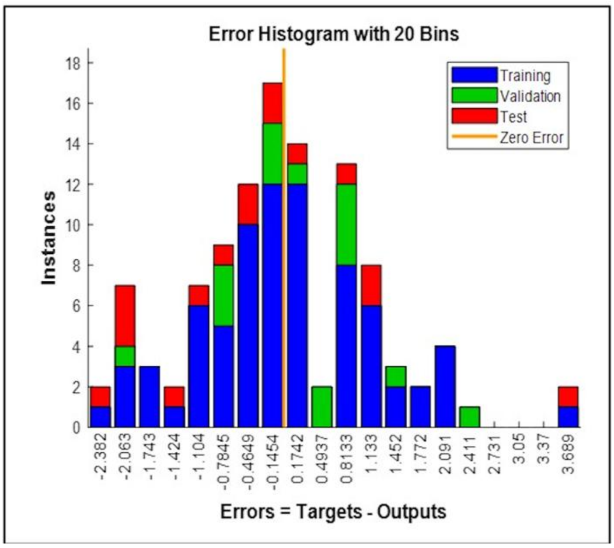


Figure 14: Regression fit plot and error histogram with 20 bins for BER target set

The performance metrics of an QAM RoFSO model were analysed using ANN, KNN, and DT techniques. SNR data set inputs include atmospheric attenuation, input power levels, and noise figure. Similarly, for BER estimation, attenuation, data rate, and FSO range are input features of the ML models. For training and testing data sets, the RMSE and R-squared performance metrics were considered and evaluated. Higher R-squared and lower RMSE values indicate that the training and testing data are closely related. The neural fitting application was used in the ANN algorithm to evaluate performance using regression analysis and RMSE. 70% of the total data has been designated as the training subset, while 15% has been designated as the validation and testing subsets, respectively. A two-layer feed forward network with 20 sigmoid hidden neurons and linear output neurons was considered for analysis. Because it requires less memory, the scaled conjugate gradient algorithm was chosen. The algorithm's performance was investigated for BER and SNR values calculated from the RoFSO model under three meteorological weather conditions. Figures 15 and 16 show the regression fits and error histograms for the BER and SNR target sets. Next, accuracy of the training and testing data have been plotted for different number of neighbors by employing KNN algorithm. Further DT algorithm has also been employed for performance investigation and prediction of optimum values of SNR and BER for the proposed model.

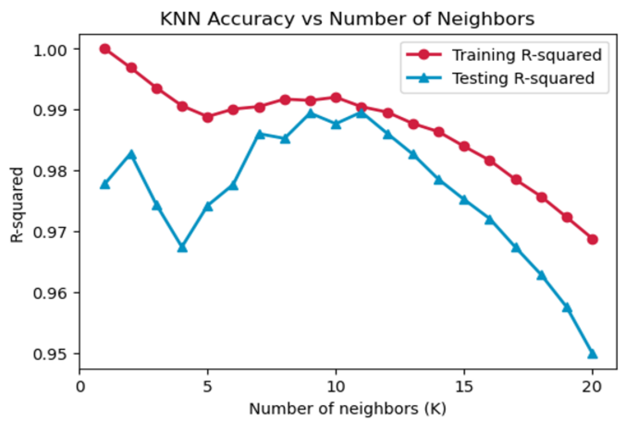


Figure 15. Knn accuracy against number of neighbors for training and testing dataset.

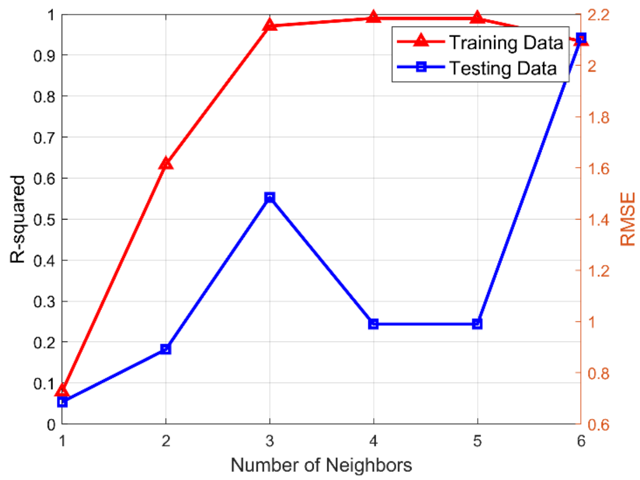


Figure 16. performance of different model for training and testing dataset.

IV. CONCLUSION

In this work, attenuation caused by fog conditions in the New Delhi region has been reported in this work. Average visibility and corresponding attenuation for the three possible fog months (January, February, and December) for seven consecutive years from 2015 to 2022 have been calculated using available fog data. For calculated values of attenuations at three transmission wavelengths of 850, 1300, and 1550 nm, the received signal quality was examined as a function of transmitted power, propagation range, and attenuation. The effect of fog induced attenuation is greater in January, followed by December and February, imposing a 1-2 dBm increase in transmitted power to maintain the quality of received signal. We discovered that for a given transmission range and attenuation, the received signal quality is comparable when operating at 1300 and 1550 nm wavelengths. The operation at 850 nm wavelength yields no comparable results, and the maximum transmission range obtained is also less than 2500 m. The Kim model outperforms in terms of signal quality for a given value of range and transmitted power, according to the results of descriptive statistical analysis of referred visibility data and corresponding optical attenuation.

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