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Comparative analysis of MIMO-based FSO system with ASK, PSK, and FSK modulation techniques under various atmospheric attenuations

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Abstract: The tremendous advancement in wireless communication networks like 5G and 6G requires high bandwidth capacity and high data rate transmission with a lower bit error rate. Free space optics (FSO) is a suitable wireless technology to implement the license-free spectrum and high bandwidth capacity with increased data rate in the modern wireless communication era. The stability of FSO depends on atmospheric attenuation. Due to attenuation, the transmission efficiency degrades, resulting in poor signal strength at the receiver side. In this comparative analysis, various weather conditions of Multi-Input Multi-Output (MIMO)-based linearly polarized FSO links (16 x 4 x 30 Gbit/s data rate) are examined with Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Frequency Shift Keying (FSK) modulation schemes. The proposed system has been analyzed through simulations at four wavelengths: 750 nm, 850 nm, 1050 nm, and 1150 nm. The link range of the system has successfully extended up to 9.5 km in haze weather. For all four wavelengths, by adopting the three modulation techniques, a high range of Q-factor, Signal-to-Noise Ratio (SNR), and minimum Bit Error Rate (BER) values is obtained under all weather conditions.

Keywords: FSO; MIMO; Q-factor; SNR; Attenuation

Primerjalna analiza FSO sistema na osnovi MIMO z modulacijskimi tehnikami ASK, PSK in FSK ob različnih stopnjah atmosferskega slabljenja

Izvleček: Ogromen napredek na področju brezžičnih komunikacijskih omrežij, kot sta 5G in 6G, zahteva visoko pasovno širino in prenos podatkov z visoko hitrostjo ter nižjo stopnjo bitnih napak. Optika v prostem prostoru (FSO) je primerna brezžična tehnologija za izkoriščanje spektra brez licenc ter visoke pasovne širine s povečano hitrostjo prenosa podatkov v sodobni dobi brezžične komunikacije. Stabilnost FSO je odvisna od atmosferskega slabljenja. Zaradi slabljenja se učinkovitost prenosa poslabša, kar povzroči slabo moč signala na strani sprejemnika. V tej primerjalni analizi so preučene različne vremenske razmere za linearno polarizirane FSO-povezave na osnovi tehnologije Multi-Input Multi-Output (MIMO) (hitrost prenosa podatkov 16 × 4 × 30 Gbit/s) z modulacijskimi shemami Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) in Frequency Shift Keying (FSK). Predlagani sistem je bil analiziran s simulacijami pri štirih valovnih dolžinah: 750 nm, 850 nm, 1050 nm in 1150 nm. Doseg povezave sistema se je v meglenem vremenu uspešno podaljšal do 9,5 km. Pri vseh štirih valovnih dolžinah je z uporabo treh modulacijskih tehnik dosežen visok razpon vrednosti Q-faktorja, razmerja signal-šum (SNR) in minimalne stopnje bitnih napak (BER) v vseh vremenskih razmerah.

Ključne besede: FSO; MIMO; faktor Q; SNR; slabljenje

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1Introduction

Free space optics (FSO) is a well-established technology in wireless communication. It has undergone tremendous and infinite enhancements in the field of wireless communication over the past span of time [1]-[4]. The FSO is transmitted directly through the air as line-of-sight communication, while in fiber optic communication, the signal is sent through optical fiber [1]. It offers a better alternative to the Radio Frequency (RF) spectrum for fulfilling the demand for bandwidth in wireless transmission technology [2], [5]. The FSO is also called Infrared (IR) broadband. Here, the information is sent from point-to-point and point-to-multipoint by adopting the IR lasers as a light source. It is a duplex communication that supports all types of data, such as voice, video, etc. The free space optics has the merits of license-free, high data rates, and easy deployment [6]-[9].The development of wireless transmission has rapidly increased in the past decade, which has also increased the need for bandwidth and capacity [10]-[11]. It is not possible to meet these requirements in optical fiber communication with a low implementation cost. The creation of low-power, high-capacity optical communication systems using simple, inexpensive technology continues to be a key standard for contemporary network topologies [12].

The RF system also has a limited spectrum, which is notable. Strong downpours severely deteriorate conventional RF communication. Major signal interference is also introduced by the high density of co-located access networks. To achieve these, FSO is the prominent replacement technology of fiber optics and RF systems with low implementation cost and high-speed data [13]. Low power utilization per bit in transmission, minimum Bit Error Rate (BER), and no need for a waveguide to transmit the signal are the distinct advantages of the FSO system [14]. The optical signal is affected by various interferences when it passes through the free space, which makes the signal weak [9], [15]-[16]. Multibeam FSO improves the signal quality by increasing the visibility distance of the system [1]. By utilizing the Multi-Input Multi-Output (MIMO) technique, the visibility distance is going to increase, and the bit error rate will be minimized.

The usage of MIMO is to reduce the attenuation losses by heavy atmospheric conditions and also boost the channel capacity of the FSO [8], [17]-[20]. The perfect demodulation and recovery of the messages with the least errors from the received signal is the main objective of every communication system design. On the receiver side, the optical signal is diminished due to Inter-Symbol Interference (ISI), surrounding radiations, and power loss [21]. Based on the type of applications, the choice of digital modulation strategy is taking place. The modulation helps to strengthen the signals to propagate in wireless channels [22]. The selection of a better digital modulation strategy is an endless process until the high data rate and minimum BER are achieved in the communication [3], [23]-[25].

Seenivasan and Karpagarajesh [26] investigated a hybrid Quadrature Amplitude Modulation (QAM)-Frequency Shift Keying (FSK) dual-modulation scheme for a high-capacity 6.4 Tbit/s Wavelength Division Multiplexing (WDM)-Multi-Input Multi-Output (MIMO) FSO network under different weather conditions. This paper moves beyond a single hybrid setup and provides a detailed comparison of three basic digital modulation techniques: Amplitude Shift Keying (ASK), FSK, and Phase Shift Keying (PSK). Using a 16 x 4 x 30 Gbit/s MIMO-FSO system with linear polarization, the system's performance is examined at four wavelengths (750 nm, 850 nm, 1050 nm, and 1150 nm). This approach helps to identify the best operating conditions for different levels of atmospheric attenuation. This proposed comparative analysis aims to identify the optimal digital modulation strategy among ASK, FSK, and PSK.

2 Proposed System

The transmitter block diagram of the proposed MIMO–FSO (16 x 4 x 30 Gbit/s) system is depicted in Figure 1. The setup creates a 4 × 4 modulator array with 16 individual modulators spread over four parallel channels. The data rate of each modulator (MOD) is 30 Gbit/s. To establish spatial diversity, the combined outputs from these four channels are mapped onto four independent MIMO paths. This structural arrangement defines the system notation as 16 total modulators x 4 MIMO paths x 30 Gbit/s. Within each modulator, a Pseudo-Random Bit Sequence Generator (PRBSG) with a sequence length of 128 bits generates the baseline data streams. These bit streams are encoded by a Return-to-Zero (RZ) line coder. Anita et al. [9] shows that the RZ line coder maximizes the Q-factor compared to Non-Return-to-Zero (NRZ) line coders. Following this, the signals are modulated using ASK modulators, or FSK modulators configured with a frequency deviation of 10 GHz, or a Mach-Zehnder (MZ) modulator for PSK, utilizing Continuous Wave Lasers (CWL) as the light source. The modulated signal is amplified using the Optical Gain (OG) block. To create an output that is linearly polarized, this amplified signal next travels via the Linear Polarizer (LP) block. Increasing signal level, decreasing atmospheric attenuation, and improving data rate are the primary goals of employing LP. Each channel uses a Polarization Combiner (POC) to combine the LP signals. Ultimately, a central Power Combiner (PC) receives the outputs from all four channels (CH-1 to CH-4). The 4 x 4 MIMO link configuration is essentially established by feeding this combined signal into a 1 x 4 Fork to generate four separate Free Space Optical Channels (FSOC-1 to FSOC-4).

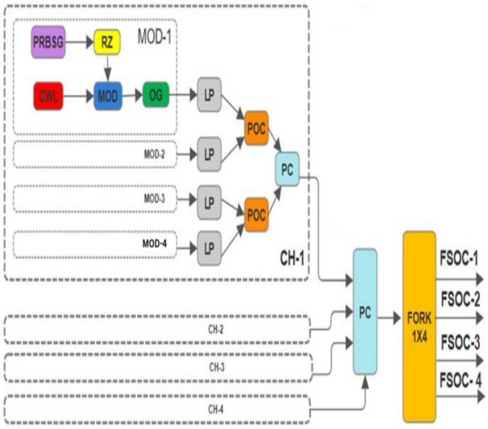


Figure 1: Transmitter Block Diagram of Proposed MIMO–FSO (16 x 4 x 30 Gbit/s) system

The receiver block diagram of the proposed system is shown in figure 2. Here, the received signal is combined by a Power Combiner (PC), and it is amplified by two Optical Amplifiers (OA). After amplification, the signal is fed into the Phase Delay and Time Delay (PD & TD) unit to introduce the proper delay in phase and time. The receiver design includes two independent phase shifters along with a TD block. This setup manages the accurate phase differences between the split signals. It plays a major role in separating the shifting frequencies and reducing phase noise. Consequently, the system can easily decode the ASK, FSK, and PSK signals. One phase shifter alone cannot handle multiple types of modulation simultaneously.

The delay units in FSO systems are especially used to compensate for the scattering which are produced by weather conditions and the channel losses. These units play a vital role in confirming trustworthy communication in FSO systems, specifically in severe atmospheric attenuation. The delayed signal is amplified by the OA and detected by Photo Detectors (PDs). The PDs used in the system are Avalanche Photo Diodes (APDs). A Low-Pass Filter (LPF) is used to eliminate the ripples in the received electrical signals. Here the Bessel LPF is used. Finally, the 3RR (Re-amplification, Re-shaping, Re-timing) will help to re-amplify, reshape, and retime the received signal. The BER analyzer is used to analyze the received signal's Q-factor, BER, and eye opening. Additionally, the Signal-to-Noise Ratio (SNR) is also evaluated.

Snow is just like rain in the form of crystalline ice. The classification of snow is wet snow and dry snow. Due

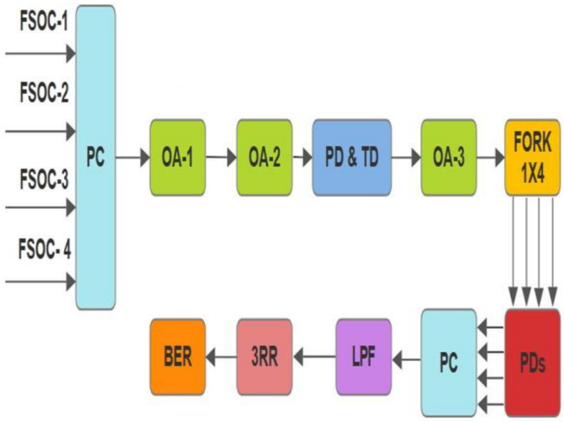


Figure 2: Receiver Block Diagram of Proposed MIMO–FSO (16 x 4 x 30 Gbit/s)

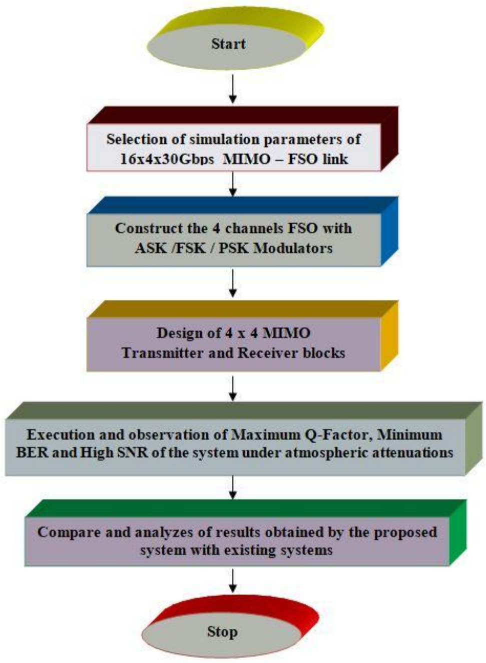


Figure 3: Process Flow Diagram of Proposed system

Figure 3 implies the process flow diagram of the proposed system. The process flow diagram is projected to the workflow as picturing the proposed work. This system adopts a 4 x 4 MIMO technique in the FSO channel.

2.1 Impact of atmospheric attenuation in the proposed system

The atmospheric attenuation is the most important factor that degrades the functionality of the FSO channel in free space. Haze is a phenomenon where smoke, dust, and dry particles make the sky unclear. The lifetime of the haze is high, which leads to attenuation in the transmitted optical signal. Mist is created by very small dewdrops of water that stay in the air.
to water molecules in the atmosphere, rain is produced. Rain causes much higher attenuation than

clear-air conditions because the rain droplets are much larger than the optical wavelength used [8], [27]. For short link lengths, it is reasonable to assume that the attenuation caused by rainfall is constant across the continuous transmission channel [28]. With the external restriction values, the total attenuation can be calculated by using equation (1) [25].

$$\alpha_{Total} = \alpha_r \text{ Rainy} + \alpha_h \text{ Hazey} + \alpha_s \text{ Snowy} + \alpha_f \text{ Fogy} \quad \text{dB/km} \tag{1}$$

α_T is the total attenuation per decibel per kilometer, and γ indicates the functional wavelengths in micrometers [29]. The BER can be calculated by using the SNR given by equation (2) [29].

$$\text{BER}=\frac{2}{\pi \, X \, SNR} e^{\frac{-SNR}{8}} \tag{2}$$

The Kruse and Kim models will be used to calculate the attenuation coefficients as expressed as mathematical equations (3) and (4) [17].

$$\alpha = \frac{13}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \text{dB/km} \tag{3}$$

$$\alpha = \frac{17}{V}\left(\frac{\lambda}{\lambda_0}\right)^{-q} \text{dB/km} \tag{4}$$

Where, λ is wavelength, λ_0 is reference wavelength and α is the attenuation coefficient, and V is the link range in km [4]. For the Kruse model, the q values are calculated by the expression (5) [17].

$$q = \begin{cases} 1.6 & if \ V > 50 \ km \\ 1.3 & if \ 6 \ km < V < 50 \ km \\ 0.585 V^{\frac{1}{3}} & if \ V < 6 \ km \end{cases} \tag{5}$$

The Kruse model approximates the lower optical attenuation for the range of 1 km with low precision at higher wavelengths [17]. Kim has produced different values of size distribution of q when the range is less than 0.5 km with no advantages of using higher wavelengths [17], [24].

To calculate the values of q, the Kim model is given in expression (6) [17].

$$q = \begin{cases} 1.6 & if \ V > 50 \ km \\ 1.3 & if \ 6 \ km < V < 50 \ km \\ 0.16V + 0.34 & if \ 1 \ km < V < 6 \ km \\ V - 0.5 & if \ 0.5 \ km < V < 1 \ km \\ 0 & if \ V < 0.550 \ \ km \end{cases} \tag{6}$$

The proposed 16 x 4 x 30 Gbit/s MIMO-based FSO work has been analyzed with four different environments, such as haze, rain, mist, snow, and mid-fog with attenuation levels of 21 dB, 30 dB, 40 dB, and 70 dB per kilometer, respectively [29]-[34]. The link range is also extended up to a maximum of 9.5 km under haze conditions and 3 km under mid-fog conditions. This system is simulated by the Opti-System simulator. The above scenario is analyzed by adapting the modulation strategies of ASK, PSK, and FSK with four different wavelengths.

3 Simulation setup

A geometrical loss produces signal losses, and it is also increased concerning the link range. The geometrical losses may be suppressed by choosing a small aperture diameter, a small, suitable lens size, and a small beam divergence angle at the receiver section [4]. To achieve maximum link range with minimum geometrical losses in the proposed simulations, the parameters that are taken into account for the simulation are shown in Table 1. The figure 4 indicates the proposed MIMO–FSO (16 x 4 x 30 Gbit/s) transmitter and receiver's simulation model of the Opti-System simulator.

Table 1: Simulation Parameters of Proposed Work

Parameters	Values/Units
Data rate	30 Gbit/s
FSO channel range	9.5 km
Wavelengths	750 nm, 850 nm, 1050 nm, and 1150 nm
FSO channel attenuations	21dB/km, 30 dB/km, 40 dB/km, and 70 dB/km
Continuous wave laser power	17 dBm
Transmitter / Receiver aperture diameter	50 mm, 75mm
Beam divergence	0.025 mrad
APD receiver responsibility	1 A/W
APD receiver gain	3

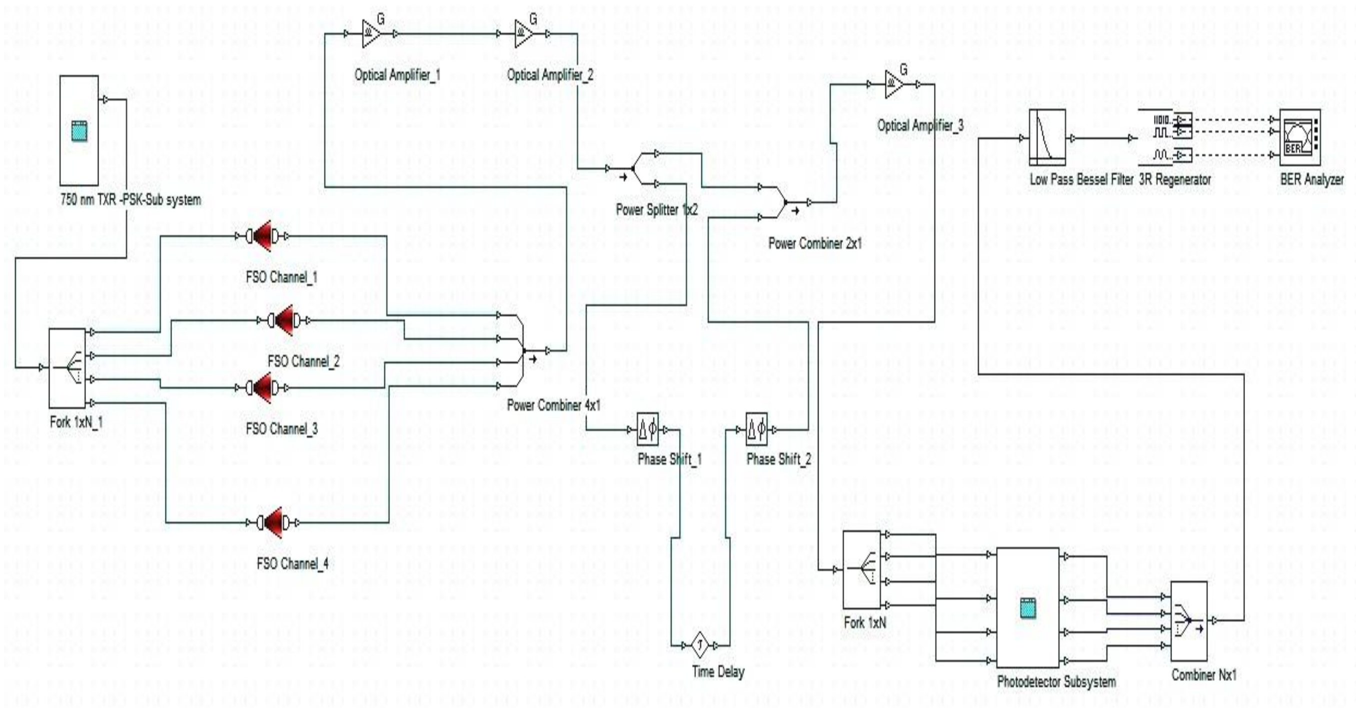


Figure 4: Transmitter and Receiver Simulation Model of Proposed system

The channel-1 subsystem of the simulation model is shown in figure 5. Each channel has four modulator subsystems, which are connected by a linear polarizer and combined in power combiners. The figure 6 illustrates the modulator subsystem, which consists of PRBSG, modulator component, RZ line coder, and CWL.

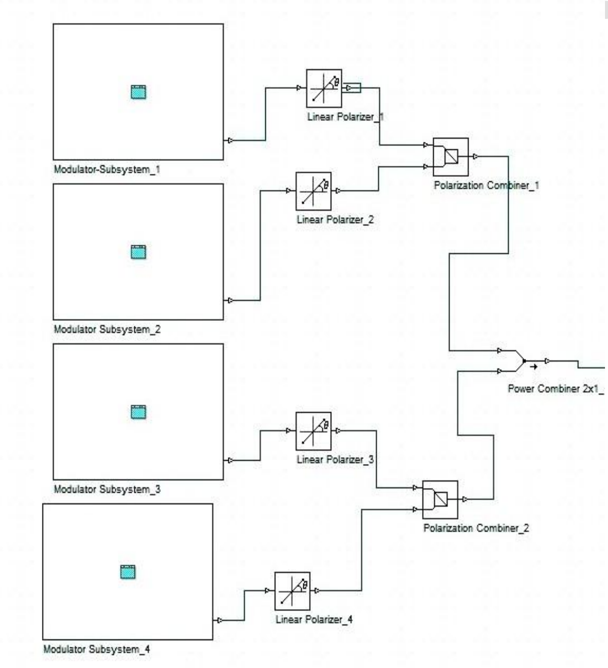


Figure 5: MIMO–FSO Channel-1 Subsystem

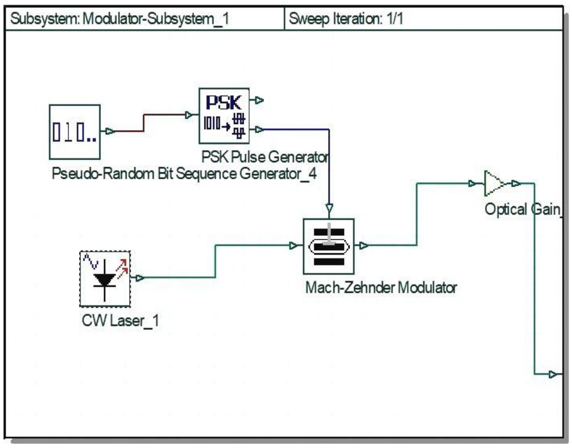


Figure 6: MIMO–FSO Modulator Subsystem

4 Results and discussion

The unique merits of this proposed system in the free space optic are its high data rate, minimum bit error rate, and the ability to increase the link range under various atmospheric conditions. In this model, the 4 x 4 MIMO technique is used to increase the Q-factor of the system. A detailed discussion of the simulation findings of the proposed study under a variety of atmospheric attenuation circumstances, including haze, rain, mist, snow, and mid-fog environments, is provided in the following sections.

4.1 Results under haze condition

Under haze weather conditions, 21 dB/km attenuation is applied to the system. Table 2 shows the comparative analysis of the proposed system and the existing system of haze conditions. From the table, it is confirmed that the link range obtained by the existing system is between 1.5 and 4.85 km, whereas the link range obtained in the proposed system is 9.5 km. Under the haze condition, a 10 Gbit/s bit rate is used in the existing system, and a 30 Gbit/s data rate is enhanced in the proposed system. From the comparative analysis, it is clear that all four wavelengths of the proposed modulation techniques have achieved a maximum Q-factor when compared to existing systems. The CWL power used here, 17 dBm, is comparatively lower than the other literature results shown in table 2. Exclusively, the maximum Q-factors are achieved at 9.5 km in 850 nm wavelength as 96.994 for PSK modulation, 42.894 for ASK modulation, and 13.925 for FSK modulation, respectively. From the results, the BER is equal to zero for ASK and PSK modulation schemes for all proposed wavelengths. As per FSK's concern, the obtained BER values are in the acceptable range. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 750 nm wavelength under haze condition is illustrated graphically in figure 7. Based on the Q-factor values, the figure 7 designates that the PSK is the best scheme of modulation under this wavelength with the highest Q-factor values of 88.6304 for PSK, 27.1565 for ASK, and 11.934 for FSK techniques at 9.5 km.

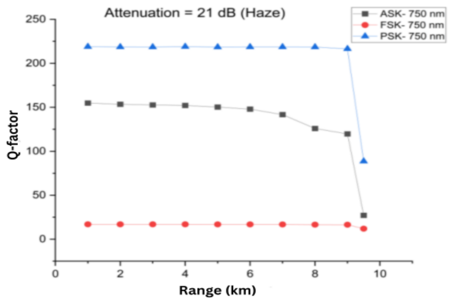


Figure 7: Range vs. maximum Q-factor for 750 nm (Haze)

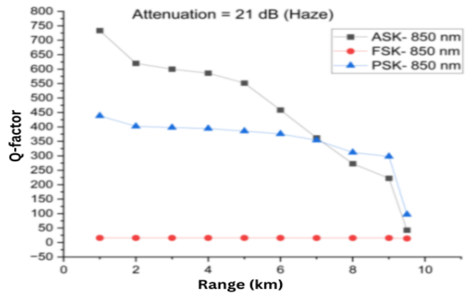


Fig 8: Range vs. maximum Q-factor for 850 nm (Haze)

Table 2: Comparative analysis of the proposed system and the existing systems under haze

Reference/Year/Technique used	Attenuation (dB/km)	Wave length (nm)	CWL Power (dBm)	Range (km)	Q-factor	BER	SNR (dB)	Bit Rate (Gbit/s)
Ref. [30] /2018/ (ASK) (PSK)	20	1550	60	3.5	56.5069	0	--	10
	20	1550	60	3.5	57.0486	0	--	
Ref. [31]/ 2020 /(Optimization)	20	1553	60	4.685	58.762	0	--	10
Ref. [33] /2021/ (PSK)	20	1553	1	1.5	61.2633	0	--	--
Ref. [34] /2023/ (Optimization)	20	1550	60	5	81.3102	0	--	10
Ref. [29] /2025 /(32 X 32 MIMO)	20	1550	50	4.85	72.29	0	--	10
Proposed work (ASK)	21	750	17	9.5	27.157	0	46.72	30
	21	850	17	9.5	42.894	0	51.3	30
	21	1050	17	9.5	40.95	0	50.94	30
	21	1150	17	9.5	38.401	0	50.54	30
Proposed work (PSK)	21	750	17	9.5	88.63	$1.02e^{-162}$	53.21	30
	21	850	17	9.5	96.994	0	54	30
	21	1050	17	9.5	94.712	0	53.57	30
	21	1150	17	9.5	92.673	$5.93e^{-323}$	53.77	30
Proposed work (FSK)	21	750	17	9.5	11.934	$3.81e^{-33}$	62.6	30
	21	850	17	9.5	13.952	$1.53e^{-44}$	55.5	30
	21	1050	17	9.5	12.646	$5.79e^{-37}$	62.1	30
	21	1150	17	9.5	11.226	$1.36e^{-29}$	39	30

The maximum Q-factor versus link range in km of proposed modulation schemes for 850 nm wavelength under haze conditions is clarified through figure 8. Based on the Q-factor values, figure 8 shows that the ASK is a good modulation technique for the range of 1 to 7km. From 7 km to 9.5 km link range, the PSK modulation performs better.

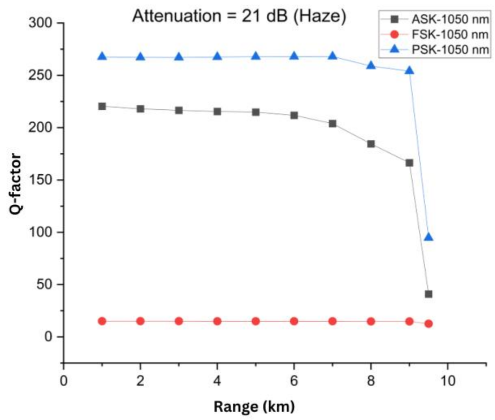


Figure 9: Range vs. maximum Q-factor for 1050 nm (Haze)

Figure 9 depicts the maximum Q-factor values versus the link range in km of proposed modulation schemes for 1050 nm wavelength under haze weather. Based on the Q-factor values, figure 9 indicates that the PSK scheme shows its efficiency under this wavelength with the notable Q-factors of 94.712 for PSK, 40.95 for ASK, and 12.646 for FSK techniques at 9.5 km.

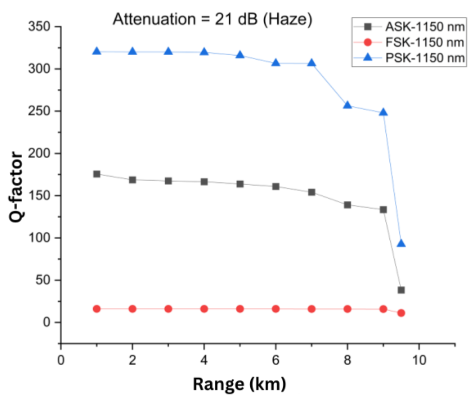


Figure 10: Range vs. maximum Q-factor for 1150 nm (Haze)

The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1150 nm wavelength under haze atmosphere is described in figure 10. From the Q-factor values, the figure 10 illustrates that the PSK scheme provides its efficiency under this wavelength with the prominent Q-factors of 92.6731 for PSK, 38.401 for ASK, and 11.226 for FSK techniques at 9.5 km. The eye diagram of the proposed PSK system for 850 nm wavelength at 9.5 km under Haze conditions is represented in figure 11. It depicts the Q-factor as 96.9943 with zero BER with good eye opening.The graphical illustration of all wavelengths versus maximum SNR for ASK, PSK & FSK modulations are shown in the figure 12. As per SNR concern, at 9.5 km range of haze condition, the FSK produces the highest value of 62.6 dB for 750 nm wavelength, the PSK produces the maximum value of 54 dB for 850 nm wavelength, the ASK produces the peak value of 51.303 dB for 850 nm wavelength.

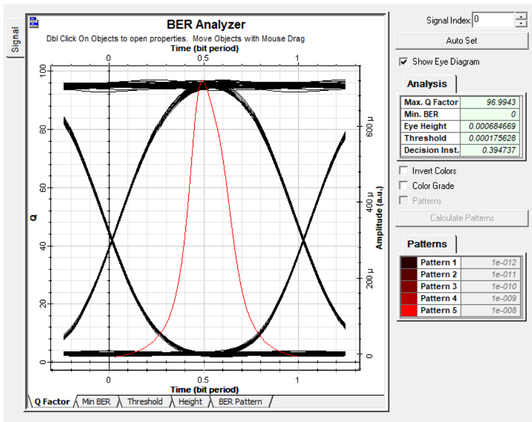


Figure 11: Eye diagram of proposed PSK system for 850 nm wavelength at 9.5 km under Haze

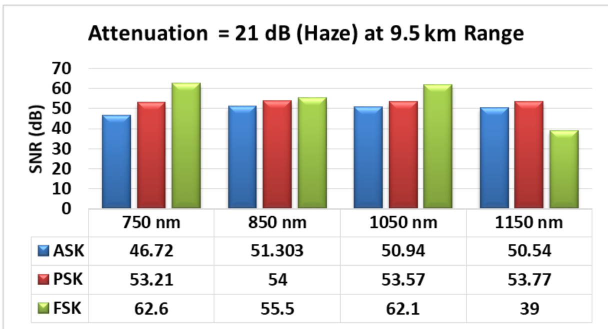


Figure 12: Maximum SNR values vs. wavelength for ASK, PSK & FSK (Haze)

From the comparative analysis, it is clear that all four wavelengths of the proposed modulation techniques have achieved a maximum Q-factor when compared to existing systems. The CWL power used here, 17 dBm, is comparatively lower power than the other literature results shown in table 3. Absolutely, the maximum Q-

4.2 Results under rain and mist conditions

Under rain and mist conditions, a 30 dB/km attenuation is applied to the system. Table 3 presents a comparative analysis of the proposed system and the existing systems for rain and mist conditions. According to the table, it is confirmed that the link range obtained by the existing system is between 1 and 3.5 km whereas the link range obtained in the proposed system is 6.75 km. Under the rain and mist conditions, a 10 Gbit/s bit rate is used in the existing system, and a 30 Gbit/s data rate is attained in the proposed system.

factors are achieved at 6.75 km in 850 nm wavelength as 87.943 for PSK modulation, 38.139 for ASK modulation, and 13.649 for FSK modulation, respectively. From the results, the BER is equal to zero for the PSK modulation scheme for all proposed wavelengths. As per FSK and ASK, the obtained BER values are in the acceptable range. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 750 nm wavelength under rain and mist condition is illustrated graphically in figure 13. Based on the Q-factor values, the figure 13 designates that the PSK is the best scheme of modulation under this wavelength with the highest Q-factor values of 80.267 for PSK, 23.967 for ASK, and 11.412 for FSK techniques at 6.75 km.

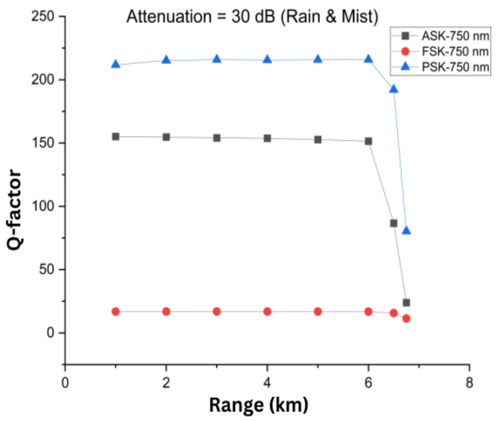


Figure13: Range vs. maximum Q-factor for 750 nm (Rain & Mist)

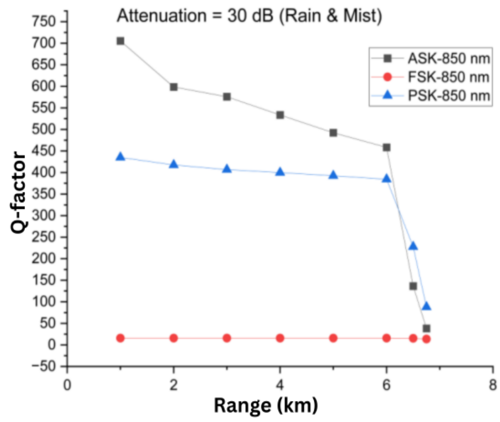


Figure 14: Range vs. maximum Q-factor for 850 nm (Rain & Mist)

Table 3: Comparative analysis of the proposed system and the existing systems under rain & mist

Reference/Year/Technique used	Attenuation (dB/km)	Wave length (nm)	CWL Power (dBm)	Range (km)	Q-factor	BER	SNR (dB)	Bit Rate (Gbit/s)
Ref. [30] /2018/ (ASK) (PSK)	30	1550	60	3.5	56.5069	0	--	10
	30	1550	60	3.5	57.0486	0	--	
Ref. [31]/ 2020 /(Optimization)	30	1553	60	3.314	34.20	$1.15e^{-256}$	--	10
Ref. [32] /2021/ (PSK) (FSK)	30	1550	50	1	5024.3	--	50.41	50
	30	1550	50	1	4859.05	--	51.28	50
Ref. [33] /2021/ (PSK)	30	1553	1	1.5	50.9812	0	--	--
Ref. [34] /2023/ (Optimization)	30	1550	60	3.5	52.7276	0	--	10
Ref. [29] /2025 /(32 X 32 MIMO)	30	1550	50	3.5	40.51	0	--	10
Proposed work (ASK)	30	750	17	6.75	23.967	$2.93e^{-127}$	45.5	30
	30	850	17	6.75	38.139	$1.39e^{-318}$	50.1	30
	30	1050	17	6.75	36.48	$8.51e^{-292}$	49.7	30
	30	1150	17	6.75	34.318	$1.99e^{-258}$	49.3	30
Proposed work (PSK)	30	750	17	6.75	80.267	0	52.46	30
	30	850	17	6.75	87.943	0	53.2	30
	30	1050	17	6.75	85.655	0	52.82	30
	30	1150	17	6.75	84.323	0	53.02	30
Proposed work (FSK)	30	750	17	6.75	11.413	$1.76e^{-30}$	61.8	30
	30	850	17	6.75	13.649	$1.03e^{-42}$	54.21	30
	30	1050	17	6.75	12.328	$3.14e^{-35}$	61.1	30
	30	1150	17	6.75	10.613	$1.18e^{-26}$	37.72	30

The maximum Q-factor versus link range in km of proposed modulation schemes for 850 nm wavelength under rain and mist conditions is clarified through figure 14. Based on the Q-factor values, figure 14 displays that the ASK is a good modulation technique for the range of 1 to 6 km. From 6 to 6.75 km link range, the PSK modulation performs better.

The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1050 nm wavelength under rain and mist condition is depicted in figure 15. By comparing the Q-factor values, the figure 15 indicates that the PSK scheme shows its efficiency under this wavelength with the notable Q-factors of 85.655 for PSK, 36.48 for ASK, and 12.328 for FSK techniques at 6.75 km.

The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1150 nm wavelength under rain and mist atmosphere is described in figure 16. From the Q-factor values, the figure 16 illustrates that the PSK scheme provides its efficiency under this wavelength with the prominent Q-factors of 84.323 for PSK, 34.318 for ASK, and 10.613 for FSK techniques at 6.75 km.

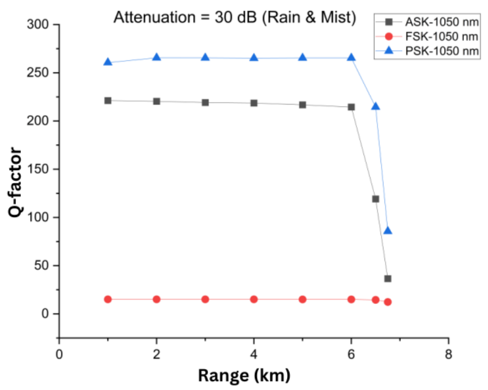


Figure 15: Range vs. maximum Q-factor for 1050 nm (Rain & Mist)

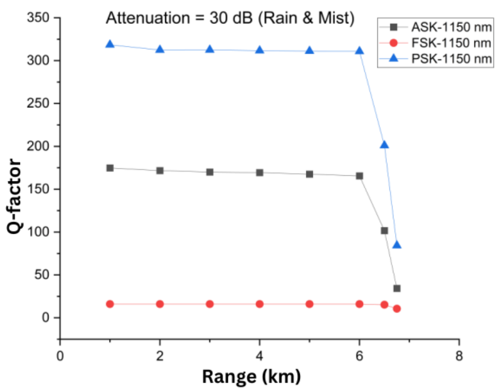
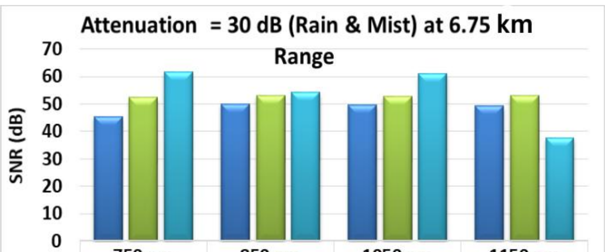


Figure 16: Range vs. maximum Q-factor for 1150 nm (Rain & Mist)



	750 nm	850 nm	1050 nm	1150 nm
ASK	45.5	50.1	49.7	49.3
PSK	52.46	53.2	52.82	53.02
FSK	61.8	54.21	61.1	37.72

Figure 17: Maximum SNR values vs. wavelength for ASK, PSK & FSK (Rain & Mist)

The graphical representation of all wavelengths versus maximum SNR of proposed modulation schemes are shown in the figure 17. As per SNR concern, at 6.75 km range of rain and mist condition, the FSK produces the highest value of 61.8 dB for 750 nm wavelength, the PSK produces the maximum value of 53.2 dB for 850 nm wavelength, and the ASK produces the peak value of 50.1 dB for 850 nm wavelength.

4.3 Results under snow condition

Under the snow conditions, a 40 dB/km attenuation is applied to the system. Table 4 shows the comparative analysis of the proposed system and the existing systems of snow conditions. From the table, it is confirmed that the link range obtained by the existing system is between 1.9 km and 2.55 km, whereas the link range obtained in the proposed system is 5 km.

Under the snow condition, a 10 Gbit/s bit rate is used in the existing system, and a 30 Gbit/s data rate is accomplished in the proposed system. From the relative analysis, it is clear that all four wavelengths of the proposed modulation techniques have reached a maximum Q-factor when compared to existing systems. The CWL power used here is 17 dBm, which is a low power compared to the other literature outcomes exposed in table 4.

The maximum Q-factors are achieved at 5 km in 850 nm wavelength as 67.97 for PSK modulation, and 15.06 for FSK modulation, respectively. The Q-factor 44.17 is obtained for ASK modulation for 1150 nm. From the results, the BER is equal to zero for the PSK and ASK modulation schemes for all proposed wavelengths. In FSK, the achieved BER values are in the acceptable range. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 750 nm wavelength under snow is showed realistically in figure 18.

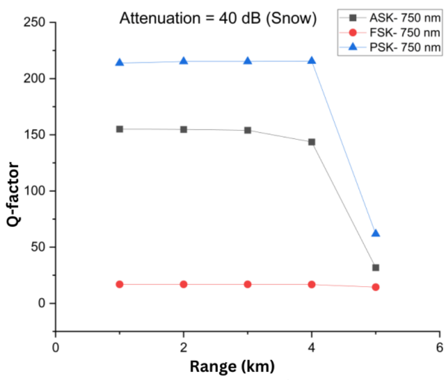


Figure 18: Range vs. maximum Q-factor for 750 nm (Snow)

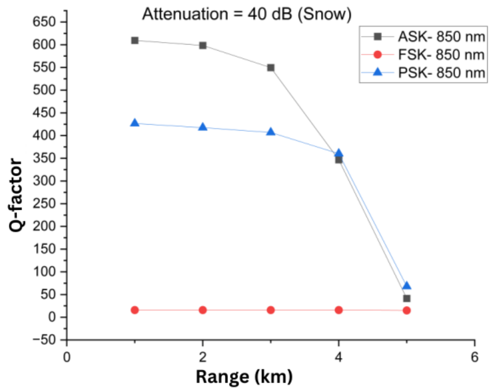


Figure 19: Range vs. maximum Q-factor for 850 nm (Snow)

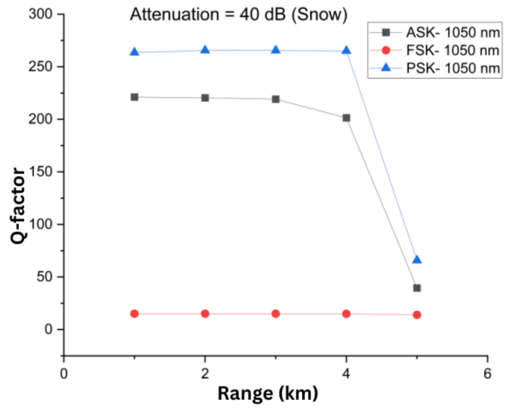


Figure 20: Range vs. maximum Q-factor for 1050 nm (Snow)

Based on the Q-factor values, the figure 18 designates that the PSK is the best scheme of modulation under this wavelength with the highest Q-factor values of 61.75 for PSK, 31.82 for ASK, and 14.44 for FSK techniques at 5 km. The maximum Q-factor versus link range in km of proposed modulation schemes for 850 nm wavelength under snow conditions is illustrated through figure19. Based on the Q-factor values, figure 19 displays that the ASK is a good modulation technique for the range of 1 to 3 km. From 3 km to 5 km range, the PSK modulation performs better. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1050 nm wavelength under snow is depicted in figure 20.

Table 4: Comparative analysis of the proposed system and the existing systems under snow

Reference/Year/Technique used	Attenuation (dB/km)	Wave length (nm)	CWL Power (dBm)	Range (km)	Q-factor	BER	SNR (dB)	Bit Rate (Gbit/s)
Ref. [30] /2018/ (ASK) (PSK)	40	1550	60	1.9	44.99	0	--	10
	40	1550	60	1.9	46.13	0	--	
Ref. [29] /2025 /(32 X 32 MIMO)	40	1550	50	2.55	58.31	0	--	10
Proposed work (ASK)	40	750	17	5	31.82	0	48.34	30
	40	850	17	5	41.41	0	50.9	30
	40	1050	17	5	39.57	0	50.6	30
	40	1150	17	5	44.17	0	52.2	30
Proposed work (PSK)	40	750	17	5	61.75	0	50.55	30
	40	850	17	5	67.97	0	51.3	30
	40	1050	17	5	65.76	0	50.92	30
	40	1150	17	5	65.64	0	51.13	30
Proposed work (FSK)	40	750	17	5	14.44	$1.29e^{-47}$	67.23	30
	40	850	17	5	15.06	$1.46e^{-51}$	63.1	30
	40	1050	17	5	13.96	$1.33e^{-44}$	67.14	30
	40	1150	17	5	14.07	$2.12e^{-45}$	46.6	30

By relating the Q-factor values, the figure 20 indicates that the PSK scheme shows its efficiency under this wavelength with the notable Q-factors of 65.76 for PSK, 39.57 for ASK, and 13.96 for FSK techniques at 5 km. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1150 nm wavelength under snow atmosphere is described in figure 21. From the Q-factor values, the figure 21 illustrates that the PSK scheme provides its efficiency under this wavelength with the prominent Q-factors of 65.64 for PSK, 44.17 for ASK, and 14.07 for FSK techniques at 5 km. The graphical representation of all wavelengths versus maximum SNR of proposed modulation schemes under snow weather are shown in the figure 22. In the point of SNR, at 5 km range of snow condition, the FSK produces the highest value of 67.23 dB for 750 nm wavelength, the PSK produces the maximum value of 51.3 dB for 850 nm wavelength, and the ASK produces the peak value of 50.9 dB for 850 nm wavelength.

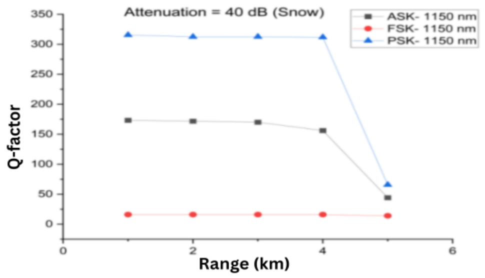


Figure 21: Range vs. maximum Q-factor for 1150 nm (Snow)

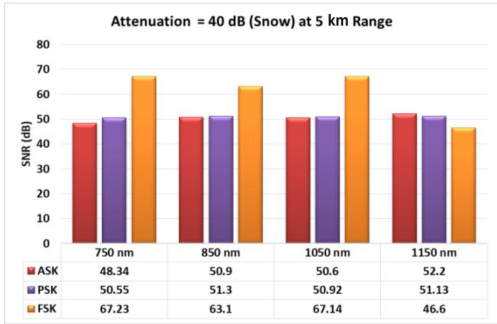


Figure 22: Maximum SNR values vs. wavelength for ASK, PSK & FSK (Snow)

4.4 Results under mid-fog condition

Under mid-fog conditions, 70 dB/km attenuation is applied to the proposed system. Table 5 displays the comparative analysis of the proposed system and the existing systems of mid-fog conditions. According to the table, it is confirmed that the link range obtained by the existing system is between 1.2 and 1.65 km, whereas the link range obtained in the proposed system is 3 km. Under the mid-fog condition, a 10 Gbit/s bit rate is used in the existing system, and a 30 Gbit/s data rate is achieved in the proposed system. From the relative analysis, it is clear that all four wavelengths of the proposed modulation techniques have extended a maximum Q-factor when compared to existing systems.

Table 5: Comparative analysis of the proposed system and the existing systems under mid-fog

Reference/Year/Technique used	Attenuation (dB/km)	Wave length (nm)	CWL Power (dBm)	Range (km)	Q-factor	BER	SNR (dB)	Bit Rate (Gbit/s)
Ref. [30] /2018/ (ASK) (PSK)	70	1550	60	1.2	16.1147	$1.004e^{-58}$	--	10
	70	1550	60	1.2	17.5354	$3.84e^{-69}$	--	
Ref. [31]/ 2020 /(Optimization)	70	1553	60	1.55	19.8265	$8.73e^{-88}$	--	10
Ref. [33] /2021/ (PSK)	70	1553	1	1.5	82.1668	0	--	--
Ref. [34] /2023/ (Optimization)	70	1550	60	1.65	27.9164	$5.97e^{-172}$	--	10
Ref. [29] /2025 /(32 X32 MIMO)	70	1550	50	1.65	28.21	$4.22e^{-18}$	--	10
Proposed work (ASK)	70	750	17	3	13.835	$7.68e^{-44}$	40.2	30
	70	850	17	3	22.714	$1.56e^{-114}$	44.8	30
	70	1050	17	3	21.807	$9.59e^{-106}$	44.41	30
	70	1150	17	3	20.667	$3.32e^{-95}$	44	30
Proposed work (PSK)	70	750	17	3	51.151	0	49.2	30
	70	850	17	3	56.397	0	50	30
	70	1050	17	3	54.365	0	49.57	30
	70	1150	17	3	54.758	0	49.78	30
Proposed work (FSK)	70	750	17	3	8.93	$2.09e^{-19}$	58.35	30
	70	850	17	3	11.831	$1.36e^{-32}$	48.93	30
	70	1050	17	3	10.579	$1.86e^{-26}$	55.82	30
	70	1150	17	3	7.7138	$5.85e^{-15}$	32.44	30

The CWL power used here is 17 dBm, which is lower power than the other literature outcomes exposed in table 5. The maximum Q-factors are achieved at 3 km in 850 nm wavelength as 56.397 for PSK modulation, 22.714 for ASK modulation, and 11.831 for FSK modulation, respectively. From the results, the BER is equal to zero for the PSK modulation scheme for all proposed wavelengths. In FSK and ASK, the achieved BER values are in the up-to-standard range.

The maximum Q-factor values versus the link range in km of proposed modulation schemes for 750 nm wavelength under mid-fog conditions is exhibited in figure 23. Based on the Q-factor values, figure 23 describes that the PSK is the best scheme of modulation under this wavelength with the highest Q-factor values of 51.151 for PSK, 13.835 for ASK, and 8.93 for FSK techniques at the range of 3 km.

The maximum Q-factor versus link range in km of proposed modulation schemes for 850 nm wavelength under mid-fog weather is illustrated in figure 24. From the Q-factor values, figure 24 shows that the ASK is a good modulation scheme for the range of 1 to 2 km. From 2 to 3 km range, the PSK modulation performance was found to be the best one. The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1050 nm wavelength under mid-fog is depicted in figure 25.

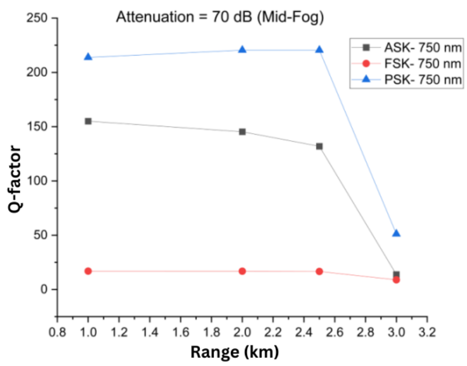


Figure 23: Range vs. maximum Q-factor for 750 nm (Mid-Fog)

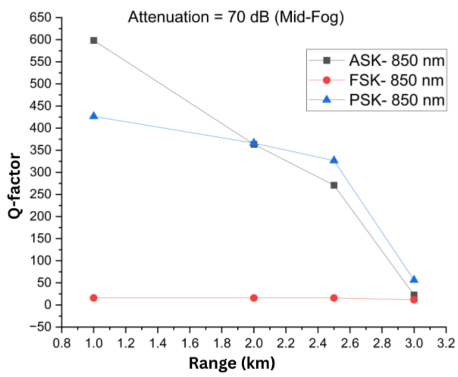


Figure 24: Range vs. maximum Q-factor for 850 nm (Mid-Fog)

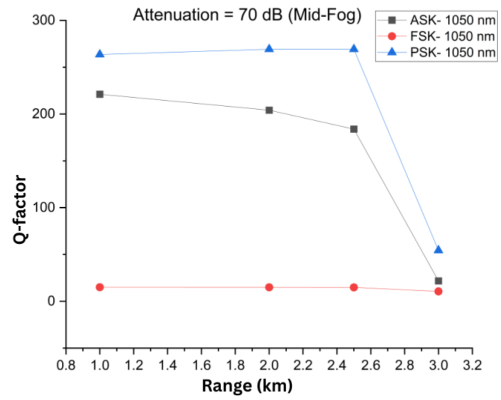


Figure 25: Range vs. maximum Q-factor for 1050 nm (Mid-Fog)

By relating the Q-factor values, the figure 25 directs that the PSK scheme shows its effectiveness under this wavelength with the outstanding Q-factors of 54.365 for PSK, 21.807 for ASK, and 10.579 for FSK techniques at 3 km of link range.

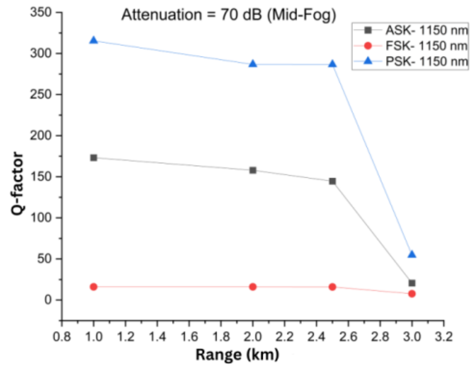


Figure 26: Range vs. maximum Q-factor for 1150 nm (Mid-Fog)

The maximum Q-factor values versus the link range in km of proposed modulation schemes for 1150 nm wavelength under mid-fog atmosphere is described in figure 26. From the Q-factor values, the figure 26 demonstrates that the PSK scheme provides its proficiency under this wavelength with the prominent Q-factors of 54.758 for PSK, 20.667 for ASK, and 7.7138 for FSK techniques at 3 km range.The eye diagram of the proposed PSK system for 850 nm wavelength at 3 km under mid-fog conditions is represented in figure 27. It portrays the Q-factor as 56.3969 with zero BER with good eye opening.

The representation of all wavelengths versus maximum SNR of proposed modulation schemes under mid-fog weather are shown in the figure 28. In the view of SNR, at 3 km range, the FSK produces the highest value of 58.35 dB for 750 nm wavelength, the PSK produces the maximum value of 50 dB for 850 nm wavelength, and the ASK produces the peak value of 44.8 dB for 850 nm wavelength.

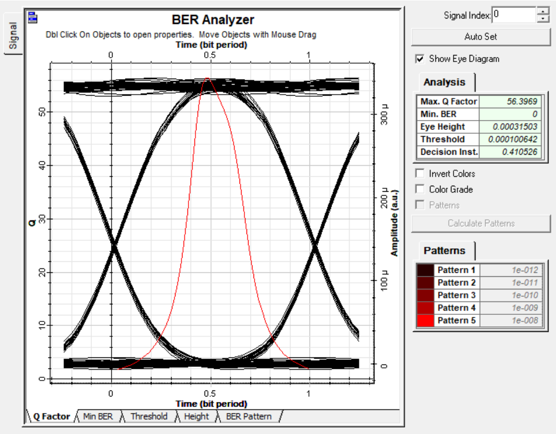


Figure 27: Eye diagram of proposed PSK system for 850 nm wavelength at 3 km (Mid-Fog)

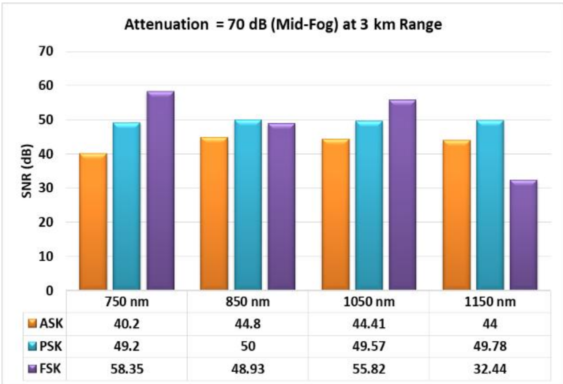


Figure 28: Maximum SNR values vs. wavelength for ASK, PSK & FSK (Mid-Fog)

5 Conclusions

The MIMO-based linearly polarized FSO links have been effectively simulated using ASK, PSK, and FSK modulation techniques, achieving a data rate of 30 Gbit/s. The proposed system demonstrates superior performance under various atmospheric disturbances, including haze, rain, mist, snow, and mid-fog conditions, utilizing wavelengths of 750 nm, 850 nm, 1050 nm, and 1150 nm. An advantage of this work is the extended link range of up to 9.5 km in haze conditions. For all four wavelengths, the implementation of the three modulation techniques results in a high range of Q-factors, SNR, and minimal BER across all atmospheric scenarios. Among these, the 850 nm PSK modulation method has been identified as the most effective, achieving a peak Q-factor of 96.994 in haze at 9.5 km, 87.943 in rain and mist at 6.75 km, 67.97 in snow at 5 km, and 56.397 in mid-fog at 3 km, with a BER of zero across all weather conditions. From the perspective of wavelength selection, the 850 nm wavelength proves to be the best option for ASK, PSK, and FSK modulation-based FSO channels in order to improve channel performance. Furthermore, enhancing the MIMO level can lead to additional improvements in system performance.

6 Conflict of Interest

The author declares no conflicts of interest in the publication of this paper.

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