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Software-based simulation to analyze the variation of digital modulation and atmospheric condition on the free space optic (FSO) link performance

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Abstract — Free Space Optic (FSO) is a telecommunications technology solution that provides fast data speeds, wide bandwidth, and low power consumption. However, the modulation employed in the FSO system should be evaluated in environmental circumstances to maximize the system's performance. This research compares the performance of the FSO communication link under various weather circumstances, such as sunny, rainy, and foggy weather, and different types of digital modulation. Investigation of the effect of weather conditions used the Kim and Kruse attenuation models, with transmission distances ranging from 500 meters to 10 kilometers. Furthermore, among the modulation types employed, at a bit rate of 10 Gbps, QPSK, 8-PSK, 16-PSK, and 16-QAM. The simulation used the OptiSystem 17.0 to design and analyze the FSO model. According to the Kim and Kruse models, sunny weather provides the best visibility compared to rain and fog conditions, with an attenuation value of 0.46 dB/km. PSK modulation provides the best performance, with a BER of less than 1×10^{-12} up to a path length of 8 km in sunny weather, 3 km in rainy weather (moderate rain), and 800 m in foggy weather (moderate fog). The 8-PSK modulation has a BER of less than 1×10^{-12} and a range of 2000 meters in sunny weather and 1500 meters in rainy conditions. However, it did not fulfill the criteria in foggy weather. BER values for 16-PSK and 16-QAM modulation are higher than baseline during rainy and foggy conditions, whereas 16-QAM modulation has BER values of less than 1×10^{-3} at 500 meters.

Keywords – BER, FSO, PSK, QAM

I. Introduction

As one of the optical communication techniques, FSO differs from fiber-optic base link because it uses light propagation as an information carrier between users using free space as a transmission medium [1]–[4]. The FSO technology offers a high data transmission rate and does not require a license to use the spectrum. A Light-Emitting Diode (LED) or Light Amplification by Stimulated Emission of Radiation (LASER) can be utilized in FSO communication. FSO provides several advantages over other communication systems, including lower installation costs than optical fiber, a faster and more accessible data distribution procedure, and a wide bandwidth [2], [3].

FSO is a technology that uses the notion of Line of Sight (LOS) to provide data, phone, and video communications with full-duplex connectivity at data rates up to 10 Gbps. An effective FSO communication system has properties such as functioning at higher power for longer distances and being reliable at high-speed modulation to attain optimal performance. FSO communication systems must operate over a wide temperature range and slightly degrade performance due to air disturbance [3]–[6].

Under moderate to high interference situations, BPSK and 4-QAM modulation showed the best performance, with an average BER of roughly 10^{-3}, according to a study focusing on digital modulation research on FSO communication. The OOK modulation, which is frequently employed in FSO communication systems, is discussed in some papers. Even though the FSO communication link's BER value is inferior to that of other modulations, OOK is still widely employed due to its high-efficiency spectrum [4], [5].

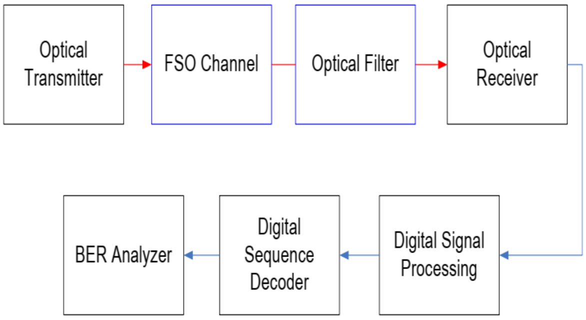


Fig. 1. Block diagram of FSO communication link.

The following research compared the performance of FSO transmission employing BPSK and Quadrature Phase Shift Keying (QPSK) modulation. This investigation performed a BER value of 10^{-3} at 17 dB SNR and QPSK modulation better than BPSK [6]–[8]. The BER of the OOK and PPM modulations was greater than $10^{-0.5}$, indicating that both were very susceptible to atmospheric disturbance conditions. With an average BER of close to 10^{-1}, the use of 16-QAM and 16-PSK modulation also performed poorly. QPSK modulation had BER values ranging from 10^{-2} to $10^{-2.5}$, whereas BPSK and 4-QAM had the best performance, with an average BER of roughly 10^{-3} [9], [10]. The study, however, did not consider atmospheric turbulence or weather conditions.

Therefore, this research aims to compare the performance of the FSO communication link under different weather circumstances, such as sunny, rainy, and foggy weather. The Kim and Kruse attenuation models and transmission media lengths ranging from 500 meters to ten kilometers were employed in this investigation. QPSK, 8-PSK (Eight State Phase Shift Keying), 16-PSK, and 16-QAM are the modulation types utilized. OptiSystem 17.0 software was used in this study's simulation.

II. Research Method

This section discusses FSO communication link design and variation of attenuation value based on weather conditions.

A. FSO Communication Link Design

Fig. 1 depicts the FSO communication link block diagram used in this investigation. The block system comprising the transmitter, transmission media, and receiver makes up the design of the FSO communication link. An optical transmitter converts electrical to optical signals with digital data input at a bit rate of 10 Gbps on the transmitter side. This block corresponds to the QPSK 8-PSK, 16-PSK, and 16-QAM digital modulations [11], [12].

QAM (Quadrature Amplitude Modulation) combines ASK digital modulation with Phase Shift Keying (PSK) to represent binary data with amplitude and phase changes simultaneously. The information bit rate is four times greater than the symbol rate (bit rate = baud rate $\times$ m-bit) in 16-QAM modulation because each symbol has four bits m = 4 ($2m$ = 16). The modulation technique QPSK transmits two bits of each symbol. QPSK is a PSK modulation variation with four points on its constellation diagram. To represent data bits, the points are evenly spaced around the circle. The bit rate obtained in QPSK modulation with m = 2 ($2m$ = 4) is double the baud rate. A carrier signal is represented in eight phases to represent eight symbols in the 8-PSK modulation. Three bits make up one symbol. The bit rate obtained with 8-PSK modulation with m = 3 ($2m$ = 8) is three times the baud rate value. The bit rate obtained is four times the baud rate since the 16-PSK modulation has a value of m = 4 ($2m$ = 16). One symbol in this modulation comprises four bits [13], [14].

Table 1. FSO Network Parameter

Parameter	Value	Unit
Bit rate	10	Bbps
Transmitter power	14.8	dBm
Wavelength	780	nm
Beam divergence	5	mrad

According to the datasheet from Acorn Technologies Ltd. Brand G500, the transmitter block employs an optical source. Table 1 shows CW Laser's parameters, with a power of 14.8 dBm and a wavelength of 780 nm. The transmission distance of the FSO Channel transmission medium varies from 500 meters to ten kilometers, depending on whether the weather is bright, wet, or foggy. The Kim and Kruse models simulate the estimated attenuation of the circumstances and wavelengths employed in the experiments. In addition, an optical filter is added to the signal and noise filtering process depending on the signal to be passed.

An optical receiver on the receiver block turns the optical signal back into electricity using a PIN Photo-detector with a 1 A/W responsivity. Additionally, the signal will be routed through the DSP to digital signal processing and synchronized with the sequence decoder's modulation. Then, using a BER analyzer, determine the quality of the received signal. According to the ITU-T standard, the BER value must be less than 10^{-12} [14].

B. Variation of Attenuation Value based on Weather Conditions

The link between visibility and attenuation must be known to forecast optical attenuation data from visibility statistics to estimate the FSO system's scope. For attenuation by the unit of length, there is "specific attenuation," calculated using (1) below [1].

$$\beta(\lambda) = \frac{1}{R} 10 \log \left(\frac{P_0}{P_r} \right) = \frac{1}{R} 10 \log (e^{\gamma(\lambda)R}) \quad (1)$$

with R is the length of the transmission link, P_0 is the optical power emitted by the transmitter, P_r is the the optical power at distance R, and γ is the atmospheric attenuation coefficient.

Empirical models are commonly used to predict attenuation due to fog based on visibility range information. The wavelength widely used as the reference visibility range is 550 nm, following (2) that describes the specific attenuation of moisture [1], [15].

$$\gamma(\lambda) = \frac{3.91}{v}\left(\frac{\lambda}{550}\right)^{-p} \tag{2}$$

with v is the range of sight (km), λ is the operating wavelength (nm), and p is the coefficient of scattering size distribution.

Based on Kim's model, the p-value is obtained by the following formula:

$$p = \begin{cases} 1.6, & v > 50 \\ 1.3, & 6 < v < 50 \\ 0.16v + 0.34, & 1 < v < 6 \\ v - 0.5, & 0.5 < v < 1 \\ 0, & v < 0.5 \end{cases} \tag{3}$$

and the p-value in the Kruse model can be calculated by the following equation:

$$p = \begin{cases} 1.6, & v > 50 \\ 1.3, & 6 < v < 50 \\ 0.585, & v < 6 \end{cases} \tag{4}$$

The value of visibility can be used to discriminate between different weather conditions [15]. The visibility values for other weather conditions are summarized in Table 2. Meanwhile, the specific findings of attenuation were obtained for sunny, rainy, and foggy weather situations using (1), (2), (3), and (4), as shown in Table 3.

Table 2. The Visibility is based on Weather Conditions

Weather Conditions	Visibility (km)
Thick fog	0.2
Moderate fog	0.5
Light fog	0.77 - 1
Thin fog/heavy rain	1.9 - 2
Haze/medium rain	2.8 - 4
Light haze/light rain	5.9 - 10
Clear/drizzle	18 - 20
Very clear	23 - 50

III. Result

The FSO link propagation parameters are simulated with sunny, rainy, and foggy weather and data rates and link characteristics to determine the value of the received signal quality. The Bit Error Rate (BER) value determines the quality of the received signal. Table 4, Table 5, and Fig. 2 describe the BER values observed in sunny weather (very clear) with modifications in the digital modulation utilized. For the Kim and Kruse models, an attenuation value of 0.46 dB/km is considered, especially for sunny weather circumstances.

Meanwhile, Table 6, Table 7, and Fig. 3 indicate the BER value of the FSO communication link during rainy conditions. For the Kim model, the attenuation value evaluated during link propagation is 4.60 dB/km, while it is 3.42 dB/km for the Kruse model. Table 8, Table 9, and Fig. 4 illustrate the BER value of the FSO communication link during foggy conditions. For the Kim model, the attenuation value evaluated during link propagation is 33.96 dB/km, and for the Kim model, it is 30.66 dB/km.

Depending on the type of digital modulation employed, the value of the derived BER parameter is tightly tied to the constellation diagrams processed by the sequential decoder. In sunny weather with a transmission distance of 1000 meters, Fig. 5 depicts the constellation of the QPSK modulation signal with the Kim model attenuation. Fig. 5(b) represents the constellation pattern of a QPSK modulated signal transmitted over 1500 meters in fog. Fig. 6 shows the results of the constellation diagram using 8-PSK modulation in sunny weather with Kim model attenuation with a transmission distance of 1000 meters and during foggy weather with a transmission distance of 1000 meters.

Fig. 7 shows the results of the constellation diagram using 16-PSK modulation during sunny weather with the Kim model attenuation with a transmission distance of 1000 meters, and Fig. 7(b) shows the signal constellation during foggy weather with a transmission distance of 700 meters.

Fig. 8 shows the results of the constellation diagram

Table 3. Attenuation Value

Weather	Kim	Kruse	Unit
Sunny (very clear)	0.46	0.46	dB/km
Rainy (medium rain)	4.60	3.42	dB/km
Foggy (moderate fog)	33.96	30.66	dB/km

Table 4. BER Value in Sunny Weather (Kim Model)

Distance (m)	Min. BER for Kim Model (a.u)			
	QPSK	8-PSK	16-PSK	16-QAM
1000	1.00E-50	1.00E-44	0.007836	0.000398
2000	1.00E-47	1.00E-15	0.014448	0.000520
3000	1.00E-43	0.000153	0.015496	0.000643
4000	1.00E-38	0.002862	0.019912	0.001041
5000	1.00E-33	0.019132	0.029616	0.001775
6000	1.00E-25	0.068951	0.058283	0.003061
7000	1.00E-22	0.130464	0.302758	0.005939
8000	1.00E-20	0.501485	0.506852	0.007745
9000	0.000031	0.502590	0.503654	0.015979
10000	0.000321	0.509856	0.508542	0.030198

Table 5. BER Value in Sunny Weather (Kruse Model)

Distance (m)	Min. BER for Kruse Model (a.u)			
	QPSK	8-PSK	16-PSK	16-QAM
1000	1.00E-53	1.00E-42	0.010959	0.000490
2000	1.00E-48	1.00E-14	0.011494	0.000306
3000	1.00E-44	0.000122	0.016596	0.000499
4000	1.00E-39	0.002602	0.023907	0.000796
5000	1.00E-34	0.019759	0.032249	0.001928
6000	1.00E-27	0.062599	0.053676	0.002663
7000	1.00E-21	0.135729	0.084869	0.004255
8000	1.00E-18	0.500566	0.499418	0.008663
9000	0.0000612	0.501549	0.509420	0.015122
10000	0.0003673	0.502590	0.505897	0.031560

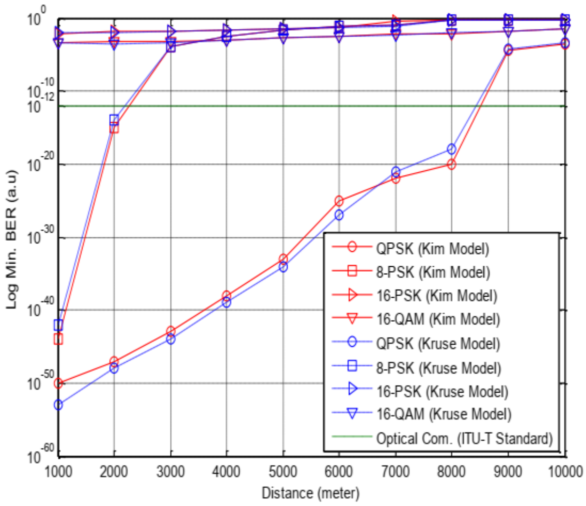


Fig. 2. Comparison of BER values in sunny weather conditions.

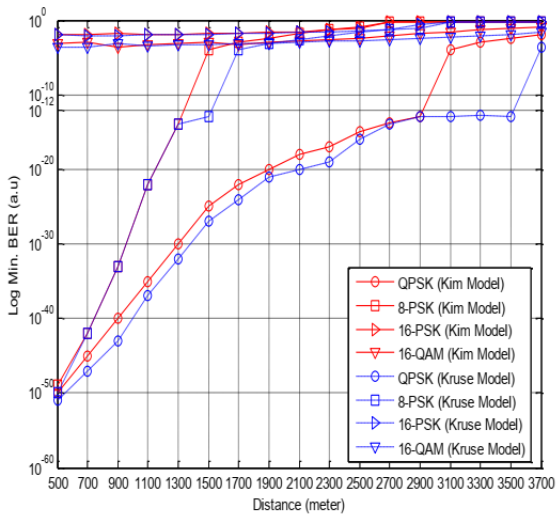


Fig. 3. Comparison of BER values in rainy weather conditions (medium rain).

Table 6. BER Value in Rainy Weather (Kim Model)

Distance	Min. BER for Kim Model (a.u)			
(m)	QPSK	8-PSK	16-PSK	16-QAM
500	1.00E-50	1.00E-49	0.009459	0.000857
700	1.00E-45	1.00E-42	0.010653	0.000918
900	1.00E-40	1.00E-33	0.015673	0.000275
1100	1.00E-35	1.00E-22	0.012612	0.000429
1300	1.00E-30	1.00E-14	0.011969	0.000673
1500	1.00E-25	0.000107	0.014693	0.000980
1700	1.00E-22	0.000980	0.016193	0.000582
1900	1.00E-20	0.003811	0.021550	0.001041
2100	1.00E-18	0.018367	0.028744	0.001653
2300	1.00E-17	0.050830	0.045442	0.003275
2700	1.00E-13	0.496709	0.501699	0.013836
3100	0.000122	0.498225	0.507906	0.024351
3300	0.000964	0.499174	0.508769	0.047646
3500	0.003964	0.497934	0.505984	0.082956
3700	0.011770	0.498607	0.506379	0.130740

Table 7. BER Value in Rainy Weather (Kruse Model)

Distance	Min. BER for Kruse Model (a.u)			
(m)	QPSK	8-PSK	16-PSK	16-QAM
500	1.00E-51	1.00E-50	0.009688	0.000214
700	1.00E-47	1.00E-42	0.009214	0.000245
900	1.00E-43	1.00E-33	0.008678	0.000643
1100	1E-37.6	1.00E-22	0.011801	0.000398
1300	1.00E-32	1.00E-14	0.011663	0.000429
1500	1.00E-27	1.00E-13	0.012903	0.000490
1700	1E-24.5	0.000107	0.014219	0.000735
1900	1E-21.1	0.000658	0.016851	0.000857
2100	1.00E-20	0.002097	0.020678	0.001224
2300	1.00E-19	0.008556	0.023785	0.001561
2500	1.00E-16	0.024290	0.031269	0.001408
2700	1E-14.5	0.050585	0.050279	0.002326
2900	1.00E-13	0.095430	0.284453	0.003551
3100	1.33E-13	0.499939	0.499556	0.005388
3300	1.45E-13	0.498000	0.499000	0.009091
3500	1.00E-13	0.498714	0.499988	0.013346
3700	0.000245	0.497918	0.498737	0.024198

Table 8. BER Value in Foggy Conditions (Kim Model)

Distance	Min. BER for Kim Model (a.u)			
(m)	QPSK	8-PSK	16-PSK	16-QAM
500	1.00E-50	0.00031	0.01590	0.001041
600	1.00E-22	0.01653	0.03366	0.001837
700	1.00E-12	0.16153	0.49943	0.006183
800	0.000903	0.49818	0.49504	0.045473
900	0.024917	0.49504	0.49593	0.188763
1000	0.331027	0.49593	0.49858	0.314161
1100	0.456211	0.49858	0.49917	0.382056
1200	0.496265	0.49917	0.49553	0.434906
1300	0.494811	0.49553	0.50080	0.469527
1400	0.496356	0.50080	0.50126	0.495745
1500	0.493566	0.50126	0.49755	0.506379

Table 9. BER Value in Foggy Conditions (Kruse Model)

Distance	Min. BER for Kruse Model (a.u)			
(m)	QPSK	8-PSK	16-PSK	16-QAM
500	1.00E-53	0.000107	0.012443	0.000612
600	1.00E-45	0.003627	0.023050	0.001316
700	1.00E-16	0.068722	0.497521	0.002908
800	1E-13	0.500566	0.498270	0.013285
900	0.003505	0.496617	0.499857	0.083032
1000	0.040238	0.496021	0.498039	0.216833
1100	0.321278	0.499801	0.499958	0.327262
1200	0.402183	0.497597	0.500554	0.392219
1300	0.493311	0.499526	0.500235	0.419447
1400	0.497918	0.497061	0.500725	0.461951
1500	0.494169	0.503566	0.501594	0.495470

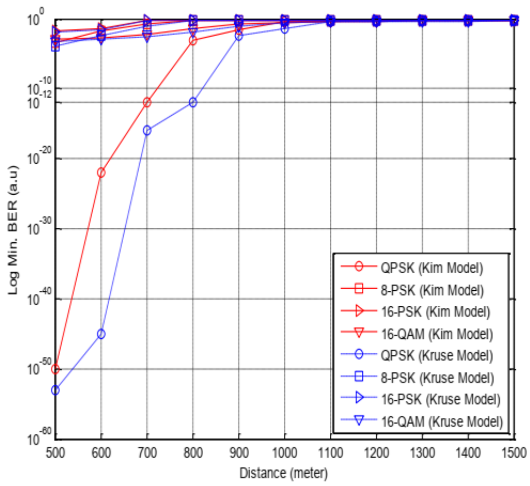
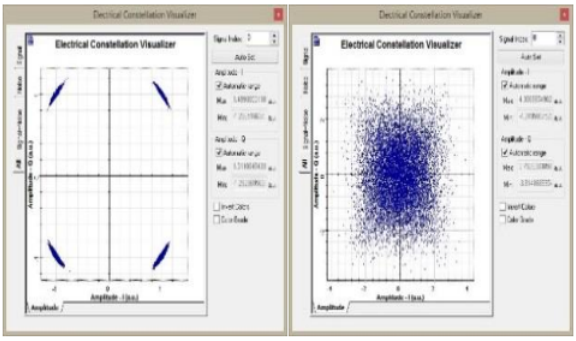
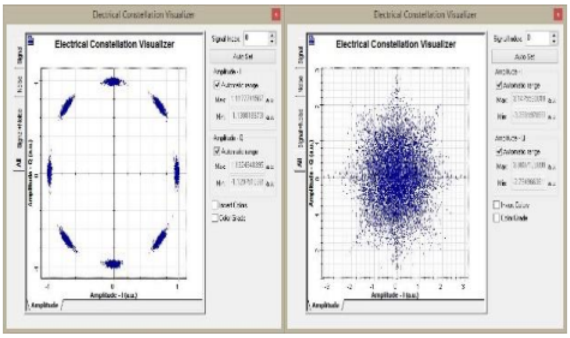


Fig. 4. Comparison of BER values in fog weather conditions (moderate fog).



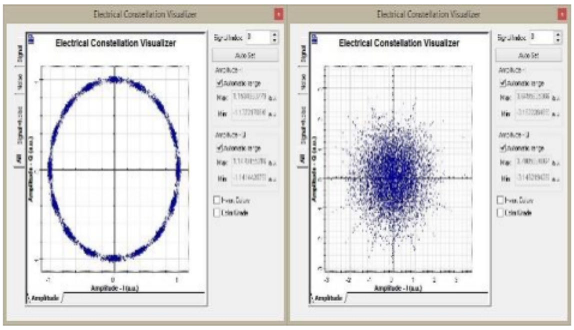
(a) (b)

Fig. 5. Diagram of the QPSK modulation constellation on the Kim model attenuation (a) in sunny weather and (b) in foggy weather.



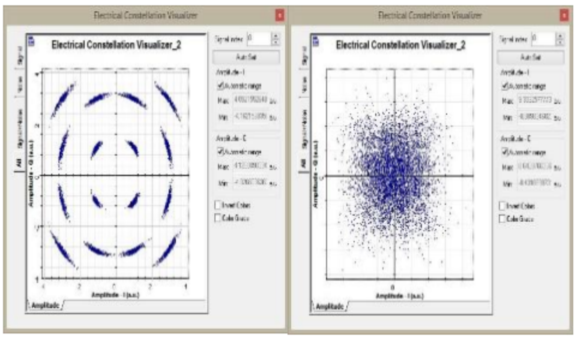
(a) (b)

Fig. 6. Constellation diagram of 8-PSK modulation on Kim model attenuation (a) in sunny and (b) foggy weather.



(a) (b)

Fig. 7. Constellation diagram of 16-PSK modulation on Kim model attenuation (a) in sunny weather and (b) in foggy.



(a) (b)

Fig. 8. Diagram of the 16-QAM modulation constellation on the Kim model attenuator (a) in sunny and (b) in foggy weather.

using 16-PSK modulation during sunny weather with the Kim model attenuation with a transmission distance of 1500 meters, and Fig. 8(b) shows the signal constellation during foggy weather with a transmission distance of 1500 meters.

IV. Discussion

Compared to other high-level modulators, QPSK modulation has the lowest BER value in sunny weather circumstances, as shown in Table 4. This can be observed in the simulation results of the Kim model; at a transmission distance of 8000 meters or more than 8 kilometers, their value from utilizing QPSK modulation is 1×10^{-20} (meets the optical communication minimum BER standard of 1×10^{-12}). 8-PSK modulation, on the other hand, has a BER of 0.501485, 16-PSK modulation has a BER of 0.506852, and 16-QAM modulation has a BER of 0.007745. However, at transmission distances of 9000 meters and 1000 meters, there was a considerable rise in BER; QPSK has BER values of 0.000031 and 0.000321, respectively.

Table 5 further demonstrates that even using the Kruse model in sunny weather, QPSK modulation still has the shortest BER value compared to other modulations. The BER value calculated is smaller than the Kim model. QPSK modulation, like Kim, has a low BER up to 8000 meters of transmission distance. The comparison of BER values in Fig. 2 demonstrates this. With 16-PSK and 16-QAM modulation, the same BER values were produced. However, at a transmission distance of 3000 meters to 4000 meters, 16-QAM modulation has a lower BER value than 16-PSK, with a BER value of less than 1×10^{-3}. According to Tables 4 and 5, 8-PSK modulation meets optical communication standards when the BER value is less than 1×10^{-12} at a transmission distance of up to 2000 meters in sunny weather.

Meanwhile, in the event of rainy weather, as demonstrated, Table 6 shows that over a transmission distance of 3000 meters, the BER value is less than 1×10^{-12} when the Kim model is employed for QPSK modulation. When the transmission distance is increased, the BER value climbs significantly. Up to a transmission distance of 1300 meters, 8-PSK modulation still passes the criteria in this situation. At a transmission distance of 500 meters, however, the BER values for 16-QPSK and 16-QAM modulation are enormous, respectively 0.009459 and 0.000857. Because the bit rate per symbol increases in rainy conditions, high-level modulation is highly vulnerable to noise, as seen in Fig. 3.

QPSK still fulfills the requirement up to a transmission distance of 3500 meters, while 8-PSK meets the average up to a transmission distance of 1500 meters when using the Kruse model based on

Table 7. At a transmission distance of 500 meters, the BER values for 16-PSK and 16-QAM modulation are 0.00968 and 0.000214, respectively, and the BER value grows dramatically with increasing transmission distance.

Foggy conditions have a significant impact on BER values for all modulation methods. Tables 8 and 9 demonstrate this, with QPSK modulation only meeting the criteria in the transmission distance range of 700 meters to 800 meters. Meanwhile, even at 500 meters, the BER value produced for 8-PSK, 16-PSK, and 16-QAM modulation is enormous, as illustrated in Fig. 4's BER comparison graph. This demonstrates that fog particles significantly impact the FSO signal spectrum. When compared to rain particles, the moderate fog has a sound attenuation of more than 30 decibels.

The increase in the BER value can also be seen in the constellation diagram of the received signal, which is illustrated in Fig. 5, Fig. 6, and Fig. 7. Due to changes or increases in the attenuation and distance values utilized, the constellation diagram becomes unevenly dispersed. Constellation diagrams show more evenly distributed and regular points with smaller attenuation values and smaller distances. The resulting issues are irregular at higher attenuation and higher spacing.

V. Conclusion

Based on the restudy and simulation results, QPSK modulation's scheme is more reliable for sunny, rainy, and foggy translations. QPSK modulation has the best performance with a BER value of less than 1×10^{-12} up to a transmission distance of 8 km in sunny weather, 3 km in rainy weather, and 800 m in foggy weather. The 8-PSK modulation has a BER value of less than 1×10^{-12} with a range of 2000 m in sunny weather and 1500 m in rainy weather but does not meet the standards in foggy weather conditions. 16-PSK and 16-QAM modulation have tremendous BER values during rainy and foggy conditions, but 16-QAM modulation still has a BER value of less than 1×10^{-3} during foggy conditions at 500 m.

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