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Research article

Investigation of optimum FSO communication link using different modulation techniques under fog conditions

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ABSTRACT

The FSO communication system offers high data rate investigated over the last few decades because of extraordinary advantages like unlicensed frequency and bandwidth at low power consumption, simple design, hasty, and minimal installation cost, including no right of way. It is essential to investigate solutions against degrading factors like absorption and scattering caused by fog, dust, rain, smog, and uncertain temperature variation of environmental channels. In this work various modulation techniques (AM, CS-NRZ, CS-RZ, DB-NRZ, MDB-NRZ, MDB-RZ, RZ, NRZ) are simulated and used to mitigate the weather attenuation of the specific airfield of Lahore, Pakistan under fog conditions, to provide a reliable FSO communication link for high data rate up to 40 Gbps over a link distance from 1.2 to 1.8 km at transmitted power up to 34 dBm in congested region. The real-time visibility data was taken metrological department for the estimation of attenuation under fog conditions and simulated using Optisys software for further investigation. To choose an FSO communication link, analysis for data rate, link distance, SNR, BER and Q-factor are performed under fog conditions using eight different modulation techniques. An increase in signal channel loss has been observed under fog conditions and performance of the FSO communication system is degraded consequently. The 3 R's (range, rate, and reliability) depend on each other if the link range is tarnished in a foggy condition that will also degrade the data rate and subsequently, reliability of the FSO system. It is observed that for maximum link distance, the performance parameters of AM modulation technique are prominent and more efficient, offering better Q-factor value at 6.08 dB, lower bit error rate at 7.03×10^{-10}, and better SNR of 4.29 dB. The results also show that AM modulation technique offers better signal-to-noise power and has good SNR due to well-received signal power as compared to all other modulation techniques. This research will be helpful to design and implement an FSO communication system under foggy conditions in a metropolitan city to provide a high data communication link among different national institutions.

1. Introduction

An increase in the demand for higher data rate values has forced scientist to design a unique communication system that can fulfill the unprecedented requirement for 5th generation mobile applications, HD streaming, online gaming and teaching under the covid-19 pandemic [1]. The growing demand in data rate of users for different applications like social networking, live streaming of HD TV, and videoconferencing has been witnessed in the last few decades [2]. This ever-increasing demand for a high data rate will become in Exabyte in 2021 as per a report by Cisco [3]. Smart grid and energy applications have started using dedicated optical fiber for smooth operation of power system by replacing traditional power line career technology [4]. In existing communication systems, the only fiber-optic network can provide such a high data rate facility because of its provision of high bandwidth terrestrial links [5]. The fiber optical technology requires high installation and maintenance costs with several other concerns like right of way. FSO communication is a wireless system that uses an optical spectrum in which modulated signal is transmitted through the environmental layer, unlike a fiber optical system where the signal is transmitted through a fiber optic cable [6].

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FSO can be an alternating solution for high data rate communication with the advantage of unregulated bandwidth with a high energy level. In the FSO communication system, modulated signals can be transmitted in both visible and invisible spectrum through the environment, the received optical signal converted into electrical signals through avalanche photodetector (APD) or P-intrinsic - N (PIN) diode. The FSO communication system suffers from degrading factors like fog, rain, dust, smog, haze, snow, and scintillation which are randomly appearing issues that limit the range, data rate, and reliability of the system [7]. In clear sky conditions, the FSO communication system is unchallengeable because of its advantages of low power consumption, no influence of radio and microwave radiation, no right of way, easy to install, and highly secure transmission. The FSO communication system performance highly depends upon weather and several studies have been performed to investigate the effect of different weather on the FSO communication system well before the installation [8, 9, 10, 11, 12, 13, 14]. Fog is perceived as one of the most crucial factor that substantially degrades the performance of the FSO communication [8]. Several critical fog events occurred in Lahore, Pakistan for the duration of up to 17 h on the 23rd of December 2014 and during this event, the average attenuation was 350.7 dB/km [15]. It is hard to find an end-user link with suitable bandwidth because the bottleneck issues of existing wireless communication with licensed or regulated bandwidth are a reason which is required to address. FSO communication system can be an option to solve bottleneck issues for the end-user with several advantages of high data rate, uncomplicated installation with higher mobility, and cost effectiveness [16, 17, 18].

There are several investigations made to mitigate the effect of optical attenuation using different techniques. The technique for performance improvement of FSO is to use many in many out (MIMO) in which multiple optical propagation techniques are used for different wavelengths and the optical signal is detected on multiple detectors. In the MIMO technique, the link distance between transmitter and receiver can increase and BER can also be reduced. An investigation has been made to determine the relationship between BER and channel capacity under weather turbulence with a different type of noise and observed that thermal noise is dominant that degrades the FSO channel performance [19]. The authors discuss the improvement of the capacity of communication using MIMO in attenuation. The performance evaluating parameters of the FSO link is SNR and Q-factor of the received signal can also be improved and BER also decreased by increasing transmitter power up to a limit in fog attenuation conditions [15]. Transmitter design factors are considered to be very important for an efficient FSO communication link. Geometrical losses are constant losses for a fixed communication link. These geometrical losses depend upon diameter of transmitter diameter, receiver aperture, link distance and divergence angle. These losses can be reduced by properly choosing receiver aperture and diameter of transmitter with divergence angle that minimizes pointing error at receiver end [20]. FSO link performance for 10 Gbps is investigated for Lahore airfield under dust attenuation for 1523 $\mu g/m^3$ concentration in the railway's station area for 2 km link distance that is easily achievable [21]. The error performance of the coded FSO communication link is investigated and modeled using gamma-gamma distribution under weather turbulence in which pairwise error probability is derived [22]. The different modulation techniques are used to improve reliability and range with a data rate of FSO communication link. The behavior of FSO communication also investigated under dry ice conditions proves that modulation formats of more complex characters e.g. M-QAM are less able to handle the fog attenuation in laboratory conditions [23]. The optical communication link for 6.4 Tbps incorporating Nyquist-WDM super-channel transmission with DP-QPSK signal modulation technique is proposed. The case study reveals beam divergence as a key parameter and bit error rate can be improved with beam divergence angle [24]. The atmospheric turbulence is a random variable that creates fluctuations in the irradiance of the FSO communication link. An investigation was made to mitigate the effect of scintillation by implementing multiple transmitters and apertures (MIMO) [25].

In the optimized design of FSO communication for both terrestrial links especially for long-distance communication, pointing error always plays a vital role. The pointing error depends on several design factors of the optical transmitter such as divergence angle, link distance, the diameter of the receiver, and transmitter aperture. In a laboratory environment experimental setup, results show that in open mode calibration mode, the tracking error has a mean value of 200 μrad with a standard deviation of ±24 μrad, and in a closed-loop, the tracking error is significantly limited to a mean value of 20 μrad with a standard deviation of 10.5 μrad. Thus with a closed-loop tracking system, pointing loss is reduced to a negligible value which can further improve the performance of FSO communication links for long-distance communication links [26].

In this research paper, aim is to investigate a high data rate communication link in an area of a city that has severe environmental attenuation due to fog, dust, smog, and smoke. The investigation of a high data rate of 40 Gbps under environmental conditions itself is novel and will be helpful for future studies. The different modulation techniques are used to investigate the optimized FSO communication link under fog conditions. Eight different modulation techniques are simulated individually and results are generated using Optisys-17 and Matlab for link distance up to 1.8 km for a data rate of 40 Gbps at the 1550 nm wavelength of the optical carrier signal. The FSO communication link is proposed to connect GC University, KE University, State bank of Pakistan, Punjab assembly, BISE, and Governor House Lahore. The specific area is very historical and busy as well a high data link through fiber optical cable has several issues like right of way and disturbance in the highly rushing area including the destruction of historical places. In this area of the city, the most suitable option for high data rata communication was FSO which is easily portable and easy to install without any disturbance and delay.

In this research paper, simulation of the various modulation techniques has been performed on FSO communication under high attenuation conditions for 40 Gbps data rate which is unique for Lahore air field. Moreover, these modulation techniques are mostly used for fiber optic transmission in which signal attenuation is very low. The major contribution of the work is the analyses for Pakistan airfield which have never been performed before and will help the researchers to design FSO communication system in near future.

2. Estimation of specific fog attenuation

In FSO communication, environmental condition plays an important role for assessment of system performance. Severe weather conditions like fog, haze, dust, smoke, smog, snow, and industrial exhaust concentrations highly affect the FSO communication system. These severe weather conditions reduce the visibility of the environmental layer in which optical signals travel toward the receiver side. The low visibility of the environmental channel offers high optical attenuation due to absorption and scattering phenomenon which degrades the efficiency of the communication link by reducing the link margin [15]. The effect of scintillation also has the degradation effects on the communication link performance. Fog is considered the most significant factor amongst all these environmental factors that appears in the months of December and January in the Lahore city of Pakistan. Events of fog appear whenever ambient temperature decreases to 3–5 °C and relative humidity reaches 85% and above. These are randomly appearing factors near the surface of earth and visibility of environmental channels is reduced to a few tens of meters. From various fog attenuation prediction models, Kim, Kruse, and Al-Naboulsi are famous for the estimation of optical attenuation from atmospheric channel visibility.

2.1. Kim & Kruse model

The atmospheric visibility is the distance at which the 550 nm collimated optical beam may be attenuated to a fraction of the original power [18]. For the transmittance of 2 %, attenuation coefficient using Kim & Kruse model can be calculated as mathematical expression given in Eq. (1).

$$\alpha = \frac{17}{V}\left(\frac{\lambda}{\lambda_{\circ}}\right)^{-q} dB \Big/ km \quad (1)$$

where λ is wavelength, λ_o is reference wavelength, and alpha is attenuation coefficient. For transmittance of 5%, the attenuation coefficient is given by Eq. (2):

$$\alpha = \frac{13}{V}\left(\frac{\lambda}{\lambda_{\circ}}\right)^{-q} dB \Big/ km \quad (2)$$

In Eqs. (1) and (2), visibility in kilometers and symbolized by V, λ is the wavelength of the propagated signal, λ_0 is 550 nm wavelength and q

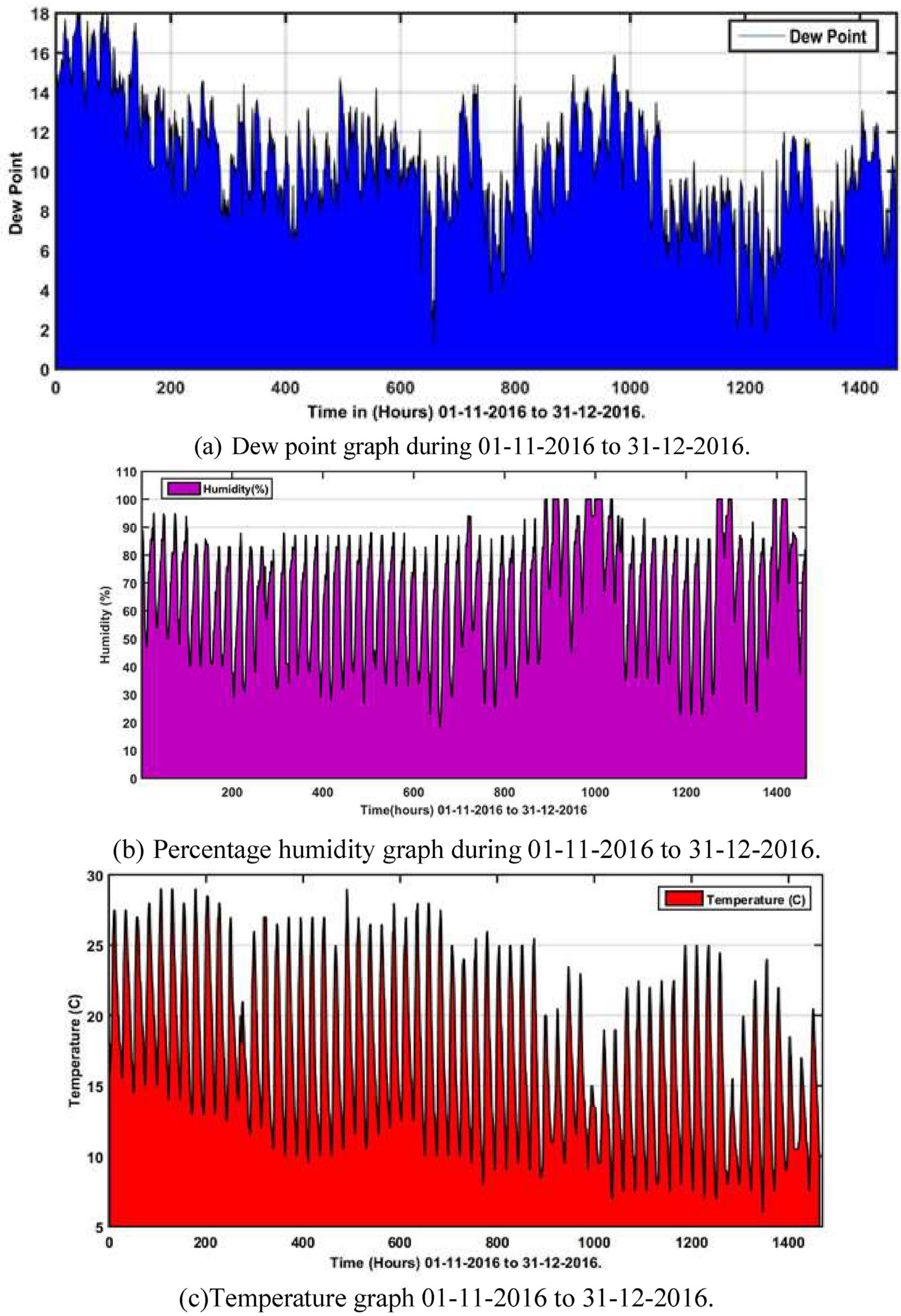


Figure 1. Illustration of (a) dew point, (b) humidity and (c) temperature during 1-11-2016 to 31-12-2016.

is the size distribution of the scattering particles [27]. For the Kruse model, the values of q are given in Eq. (3) [7]:

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

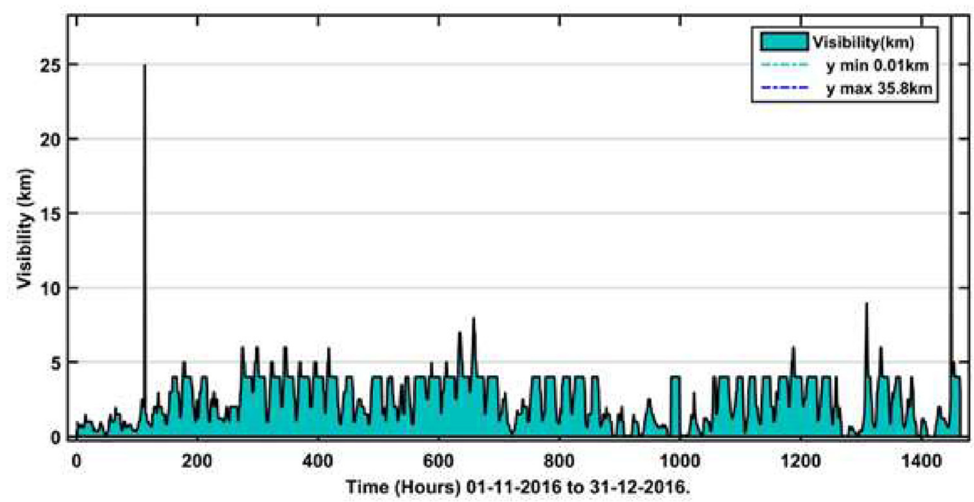
where q is size of distribution of scattering particle.

Kruse model is wavelength sensitive as compared to Kim or Al-Naboulsi models [28]. Kruse model estimates the less optical attenuation for visibility of 1 km with less accuracy at higher wavelengths [7]. Kim has presented different values of size distribution q, when visibility is less than half of km there is no advantage of using a higher wavelength [20]. Values of q for Kim model are given in Eq. (4):

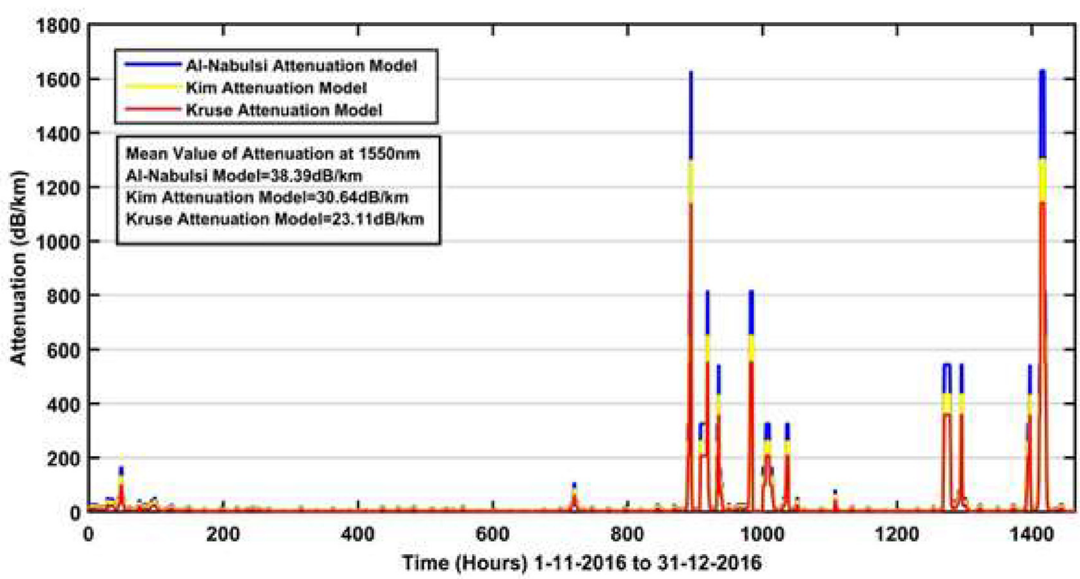
$$q = \begin{cases} 1.6 & \text{if } V > 50\,Km \\ 1.3+ & \text{if } 6\,Km > V > 50\,Km \\ 0.16V + 0.34 & \text{if } 1\,Km < V < 6\,Km \\ V - 0.5 & \text{if } 1\,Km < V < 1\,Km \\ 0 & \text{if } V < 0.5\,Km \end{cases} \tag{4}$$

Table 1. Data statistics of fog events (Time period 01-11-2016 to 31-12-2016).

Values	Dew Point	Humidity (%)	Temp. (°C)	Visibility (km)	Optical Attenuation (dB/km) at 1550 nm wavelength		
					Kim model	Kruse Model	Al-Naboulsi
Maximum	18.2	18	29	35.8	0.36	0.049	0.455
Minimum	1.2	100	06	0.01	1300	1141	1626
Mean	10.4	67.85	17.27	2.5	30.64	23.11	38.39



(a) Visibility graph due to fog events during 01-11-2016 to 31-12-2016.



(b) Attenuation graph due to fog events during 01-11-2016 to 31-12-2016.

Figure 2. Illustration of (a) visibility and (b) attenuation graph due to fog events during 1-11-2016 to 31-12-2016.

2.2. Al-Naboulsi model

Al-Naboulsi model is utilized to estimate optical fog attenuation. The attenuation coefficient for advection fog presented by Al-Naboulsi is given in Eq. (5);

$$\gamma(\lambda) = \frac{0.11478\lambda + 3.8367}{V} \tag{5}$$

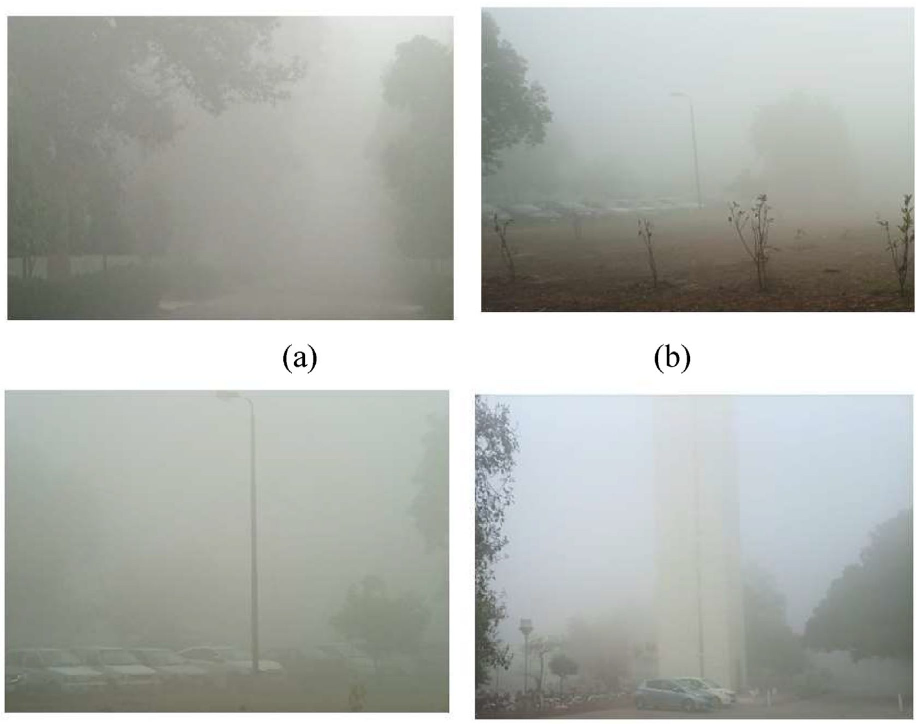
where, fog due to the cooling of the earth's surface after sunset is known as convection or radiation fog. The attenuation coefficient of a radiation fog provided by Al-Naboulsi is given in Eq. (6):

$$\gamma(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \tag{6}$$

V is visibility in km and λ is the wavelength of the transmitted beam in Eqs. (5) and (6). The optical attenuation for advection and radiation fog can be estimated using Eq. (7).

$$\alpha = \frac{10}{In10}\gamma(\lambda) \tag{7}$$

where $\gamma(\lambda) = \frac{0.11478\lambda + 3.8367}{V}$ is the specific attenuation and $\alpha = \frac{10}{In10}\gamma(\lambda)$ is the attenuation coefficient which depends upon the type of fog. Visibility



(a) (b) (c) (d)

Figure 3. Fog Events captured in different areas of Shiekh Zaid Hospital Lahore; (a) main entrance (b) park (c) parking stand and (d) main tower of hospital building.

Figure 4. Aerial view of the proposed FSO links.

data for November to December 2016 is collected from Pakistan Meteorological Department (PMD) Lahore and using Kim, Kruse, and Al-Naboulsi model at wavelengths of 1550 nm, the optical attenuation is estimated. Dew point, humidity, and temperature in Figure 1 show the appearance of fog attenuation with data statistics given in Table 1.

Temperature and humidity graphs in Figures 2 and 3 shows, the possibility of the fog events in December. Figure 2(a), illustrates the visibility of the airfield. The temperature, humidity, and visibility graph verify the incidence of these fog events whereas high optical attenuation spikes illustrate the reduction of visibility due to fog events as shown in Figure 2(b). Data statistics show that at a wavelength of 1550 nm, optical attenuation for maximum visibility of 35.8 km is 0.36 dB/km for Kim, 0.049 dB/km for Kruse, and 0.455 dB/km for the Al-Naboulsi model. Optical attenuation for minimum visibility of 0.01 km is 1300 dB/km for Kim, 1141 dB/km for Kruse, and 1626 dB/km for the Al-Naboulsi model. The Kruse model is more sensitive to wavelength and shows the lowest attenuation values. There are randomly captured fog events shown as in Figure 3 in different areas of Lahore, Pakistan.

Table 2. Simulation parameters of FSO communication system.

Parameter	Value
Laser Frequency	193.1 THz
Line Width	0.1 MHz
Laser Power	20-34 dBm
Transmitter Aperture	5 cm
Beam Divergence	1.5 mrad
Receiver Aperture	20 cm
Attenuation	25–40 dB/km
EDFA Length	5 m
APD Gain	3
Responsivity	0.5 A/W
Ionization Ratio	0.9
Dark Current	10 nA
Thermal Power Density	100 e-024 W/Hz
LPF cut-off frequency	0.8*Bitrate
Bitrate	40 Gbps
Sequence Length	128
Sample per bit	32
Link Range	0.05–1.8 km

FSO communication system has not been implemented practically in Pakistan. In this research article, we have estimated fog events to realize an FSO communication link for a high data rate of 40 Gbps using different modulation techniques. This connects G.C. University, K.E. University, and State bank of Pakistan, Punjab assembly, B.I.S.E. Lahore, and Governor House as illustrated in Figure 4 taken from Google earth. These areas of the city are very busy and historic so right of way and digging of channels for laying optical cables network is highly discouraged. These institutions are approximately 1 km distant from each other as shown in Figure 4. Furthermore, these institutions are situated approximately at a distance of 1 km from each other and under critical fog and smog conditions so this investigation will help out to design a practical implementation of FSO communication link in future.

3. FSO communication system design

FSO communication is a unique communication system for its unlicensed and prominence high bandwidth with several other advantages. To provide a high data rate to various national institutions and backhaul

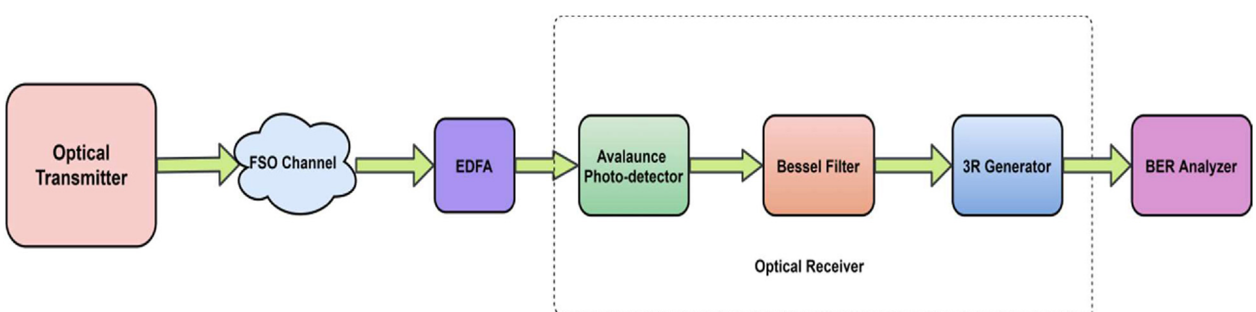


Figure 5. FSO link system block diagram.

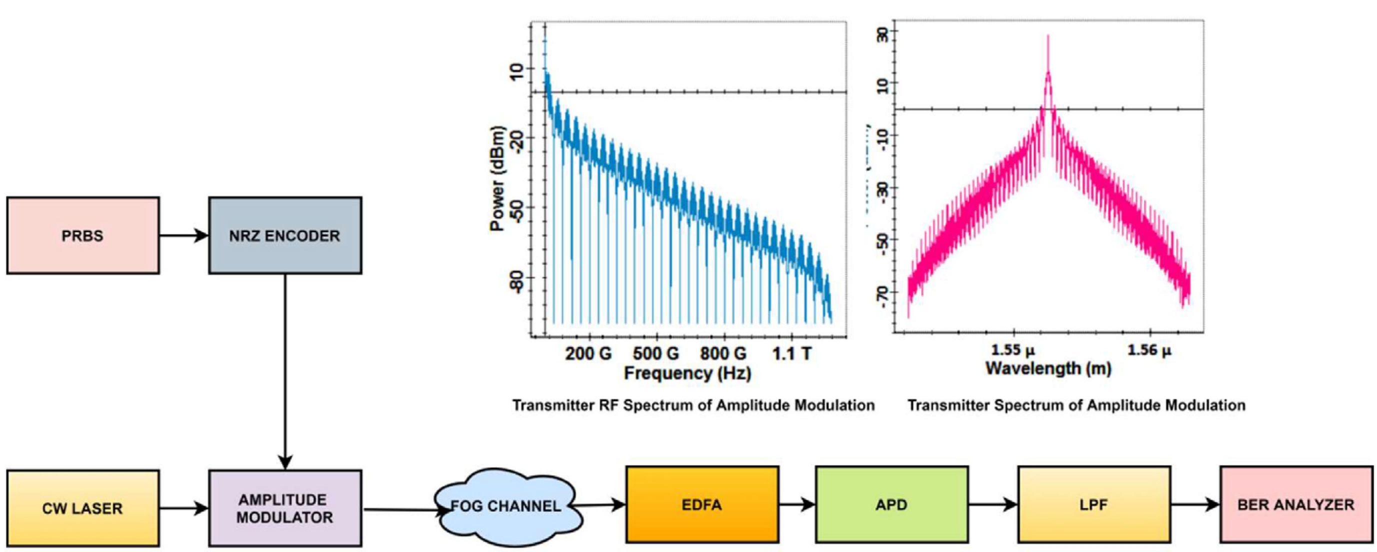


Figure 6. Schematic layout for Amplitude modulation.

communication links in the country, an investigation is carried out to provide an optimum design solution for the FSO system under severe fog attenuation conditions. Moreover, an effective modulation technique is also investigated to mitigate fog attenuation for high data rate communication links. Table 2 shows design parameters for simulation of FSO communication system selected from previous investigated geometrical design parameters of FSO system [29] and block diagram m is presented in Figure 5. In this study, we have simulated eight different modulation techniques, and FSO system performance is determined for specific attenuation of 25 dB/km to 40 dB/km at transmitter power of 20 dBm to 34 dBm for 40 Gbps data rate. A 5 m long Erbium-Doped Fiber Amplifier (EDFA) is used for amplification of received signal. This propagated optical signal experiences fog attenuation (25 dB/km–40 dB/km) for maximum link distance 1.8 km. The propagated signal power reduces due to fog attenuation loss. At the receiver photo-detector has a responsivity of 0.5 W/A with a gain of 3 and ionization ratio of 0.9. The simulation diagrams with optical spectrums are described in the following section.

4. Modulation techniques for proposed FSO communication system

There are following modulation techniques investigated to propose a reliable FSO communication link for data rate of 40 Gbps.

4.1. Amplitude modulation

In amplitude modulation (AM), Pseudo Random Bit Sequence (PRBS) generator is applied for generation of 40 Gbps randomly binary bits (0s, 1s). These bits are encoded into electric signals using a non-return zero (NRZ) encoder. These generated bits of 0's and 1's are converted into double sided band electronic signal where 1's for high (+5) and 0's for low (−5). These electric signals are further processed and modulated with CW laser of the optical power of 34 dBm of 193.1 THz frequency using Amplitude modulator and transmitted through FSO channel [30]. The amplitude of the modulated optical signal changes according to NRZ encoded data. The schematic of amplitude modulation with transmitter optical spectrum and RF spectrum is shown in Figure 6.

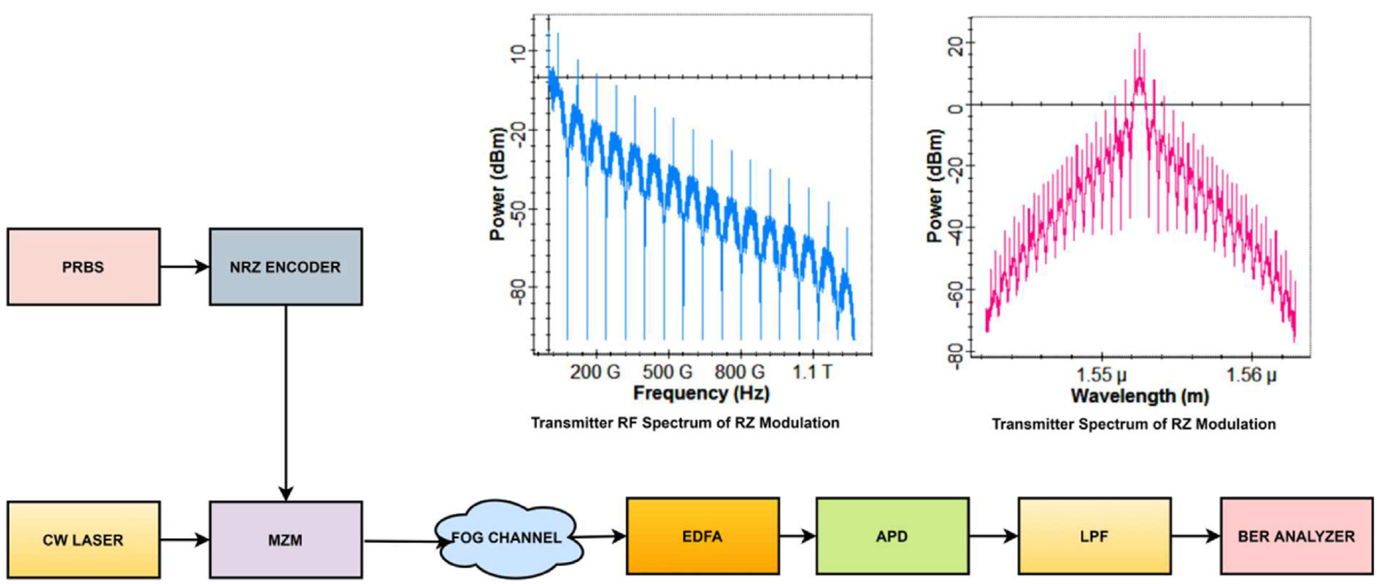


Figure 7. Schematic layout for RZ modulation.

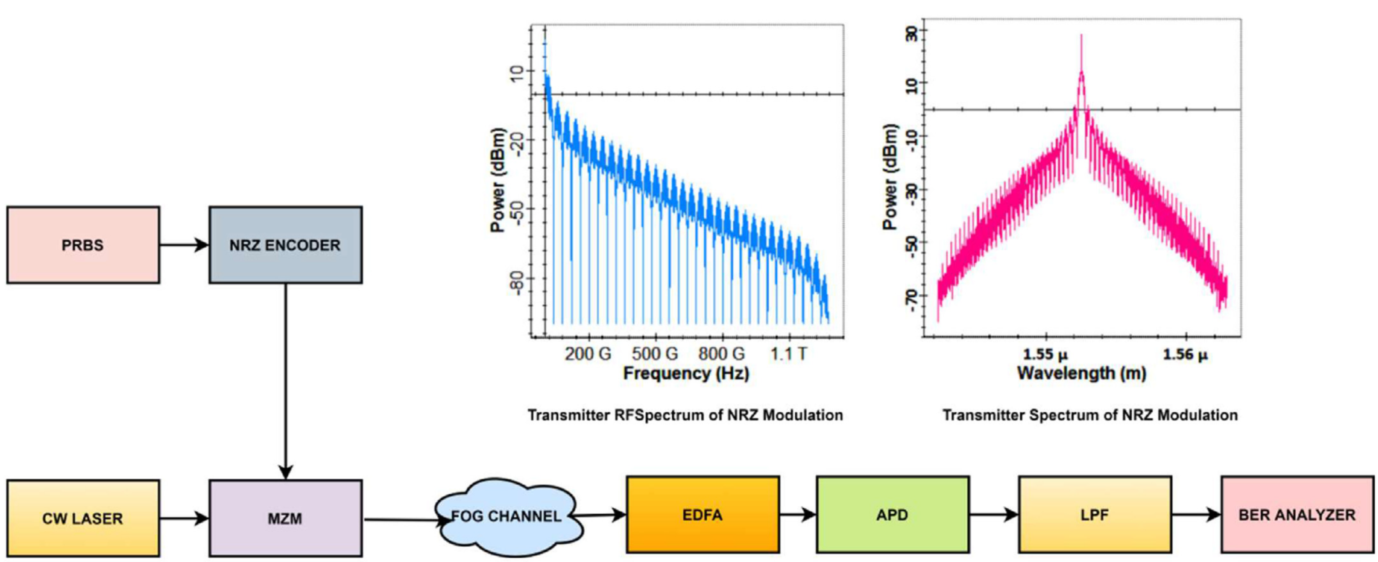


Figure 8. Schematic layout for NRZ modulation.

4.2. RZ modulation

In return to zero modulation (RZ), the PRBS generator generates 40 Gbps randomly binary bits (0s, 1s). These bits are encoded into electric signals using the RZ encoder. These internally modulated convert 1's for high (+5) and 0's for low (−5) called a bipolar return to zero. After every bit conversion in the electric signal, the signal returns to zero and utilize a time taken by a bit so RZ modulation takes more time and bandwidth for electronic processing. These electronically processed signals are further modulated with CW laser of the optical power of 34 dBm of 193.1 THz frequency using Mach-Zehnder modulator (MZM) and transmitted through the FSO channel. The amplitude of the modulated optical signal changes according to RZ encoded data. The schematic of amplitude modulation with transmitter optical spectrum and RF spectrum of RZ encoder is shown in Figure 7.

4.3. NRZ modulation

In non-return to zero modulation (NRZ), the PRBS generator generates similarly 40 Gbps randomly binary bits (0s, 1s). These bits are encoded into electric signals using an NRZ encoder. These internally modulated convert 1's for high (+5) and 0's for low (−5) called bipolar non-return to zero. These electronically processed signals are further modulated with CW laser has an optical power of 34 dBm at 193.1 THz frequency using Mach-Zehnder modulator (MZM) and transmitted through the FSO channel. Amplitude of the modulated optical signal changes according to NRZ encoded data. The schematic of amplitude modulation with transmitter optical spectrum and RF spectrum of NRZ encoder is shown in Figure 8. The received optical spectrum is shown in Figure 8.

4.4. MDB-RZ modulation

In modified duo-binary return to zero (MDB-RZ) modulation is shown in Figure 9 with RF spectrum and optical spectrum. In modified duo-binary, phase of the signal is alternated 0 and 180 for bit 1. PRBS generator is used to generate bit sequence for 40 Gbps data rate with a return to zero using duo-binary precoder delay and a subtractor circuit that is used to drive first MZM with electric gain 1. This modulator is connected with a second modulator with electric gain 1 which is driven

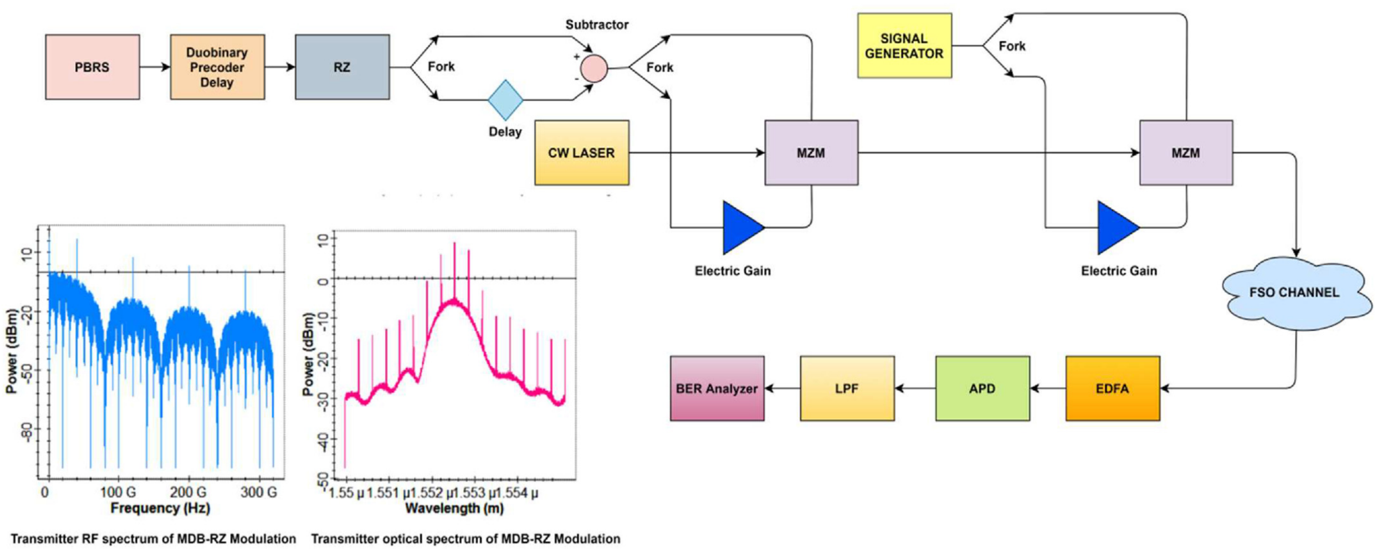


Figure 9. Schematic layout for MDB-RZ Modulation.

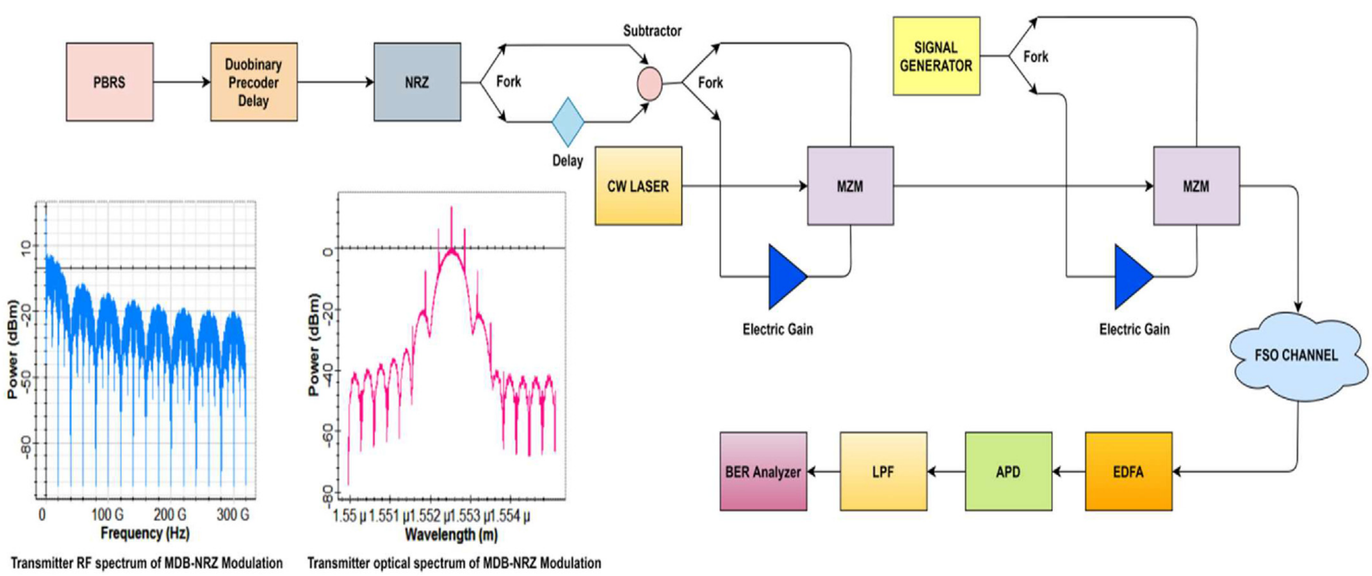


Figure 10. Schematic layout for MD-NRZ Modulation.

by the signal generator of 20 GHz with −90° phase. The MZM is used to modulate the electronically processed signals with continuous wave (CW) laser having an optical power of 34 dBm at 193.1 THz frequency. The modulated signal is transmitted through the FSO channel. The received optical spectrum is shown in Figure 9.

4.5. MD-NRZ modulation

In modified duo-binary non-return to zero (MDB-NRZ) modulation, a suppressed duo-binary signal is shown in Figure 10 with RF spectrum and optical spectrum. PRBS generator is used to generate bit sequence for 40 Gbps data rate with non-return to zero using duo-binary precoder delay and a subtractor circuit that is used to drive the first MZM with electric gain 1 concentrated with the second modulator with electric gain 1 which is driven a the signal generator of 20 GHz with −90° phase. These electronically processed signals are modulated with CW laser having an optical power of 34 dBm at 193.1 THz frequency using Mach-Zehnder modulators (MZM) and transmitted through the FSO channel. In modified duo-binary, the phase of the signal is alternated 0 and 180 for bit 1.

4.6. DB-NRZ modulation

The Duo-binary non-return zero (DB-NRZ) modulated signal is generated with PRBS generator of 40 Gbps data rate with duo-binary precoder, NRZ generator, and duo-binary pulse generator. This duo-binary precoder will further drive the first MZM to have CW laser as an optical source with an optical power of 34 dBm and 193.1 THz frequency. The second MZM is a cascade-connected with the first MZM, which has a signal generator of 40 GHz frequency and phase of −90° with electric gain 1 as shown in Figure 11 with RF spectrum and optical spectrum.

4.7. CS-NRZ modulation

The suppressed carrier non-return zero (CS-NRZ) modulated signal is generated with PRBS generator of 40 Gbps data rate with NRZ generator. This further drives the first MZM to have a CW laser as an optical source with an optical power of 34 dBm and 193.1 THz frequency. The second MZM is a cascade-connected with the first MZM, which has a signal generator of 20 GHz frequency and phase of 0° with electric gain 1 as shown in Figure 12 with RF spectrum and optical spectrum. There will be zero-phase shifts between two adjacent bits. The received optical spectrum is shown in Figure 12.

4.8. CS-RZ modulation

The suppressed carrier return zero (CS-RZ) modulated signal is generated with PRBS generator of 40 Gbps data rate with RZ generator. This will further drive the first MZM to have a CW laser as an optical

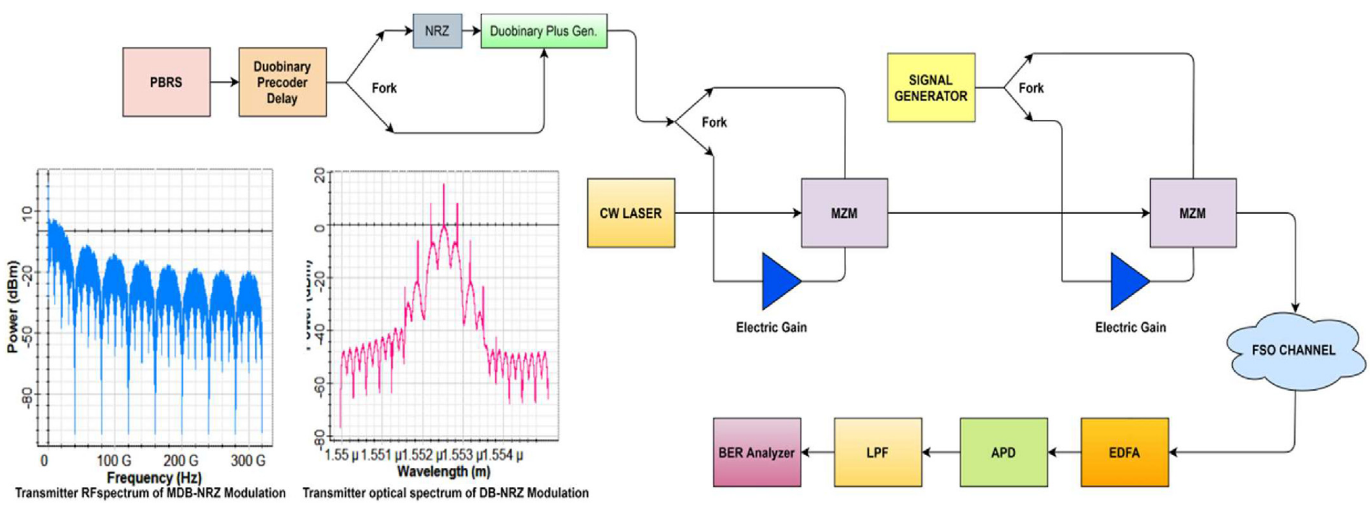


Figure 11. Schematic layout for DB-NRZ Modulation.

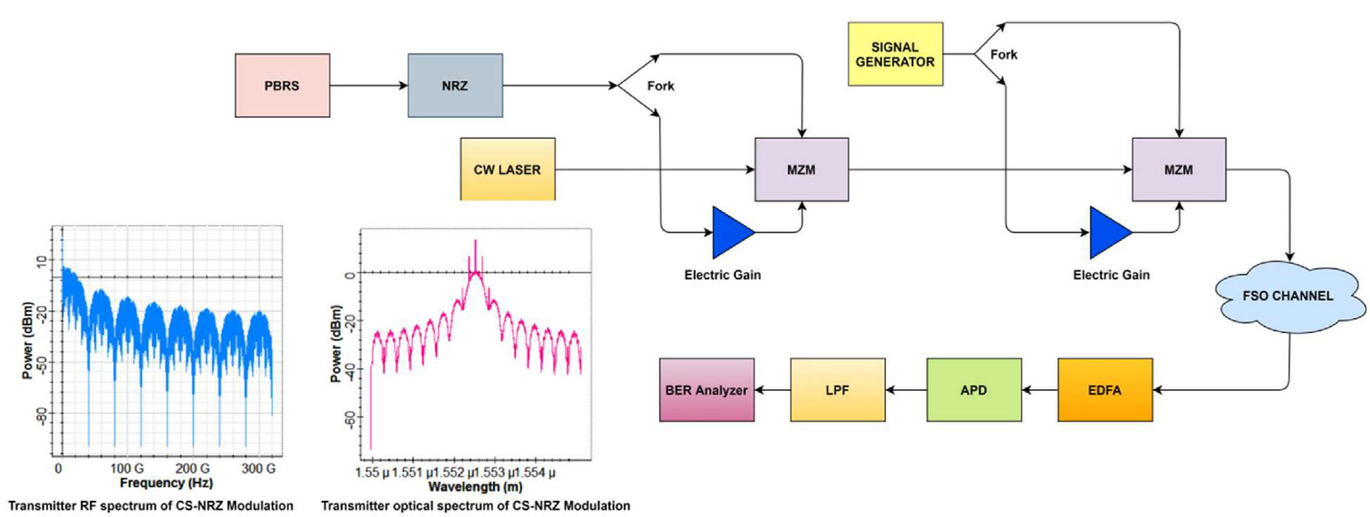


Figure 12. Schematic layout for CS-RZ Modulation.

source with an optical power of 34 dBm and 193.1 THz frequency. The second MZM is a cascade-connected with the first MZM, which has a signal generator of 20 GHz frequency and phase of 0° with electric gain 1 as shown in Figure 13 with RF spectrum and optical spectrum. There will be a zero-phase shift between two adjacent bits. The received optical spectrum is shown in Figure 13.

5. Results and discussions

In this study and analysis, eight different modulation techniques are employed to investigate an optimum FSO communication link for a 40 Gbps data rate. We have evaluated modulation techniques by investigating various communication parameters like received power, SNR,

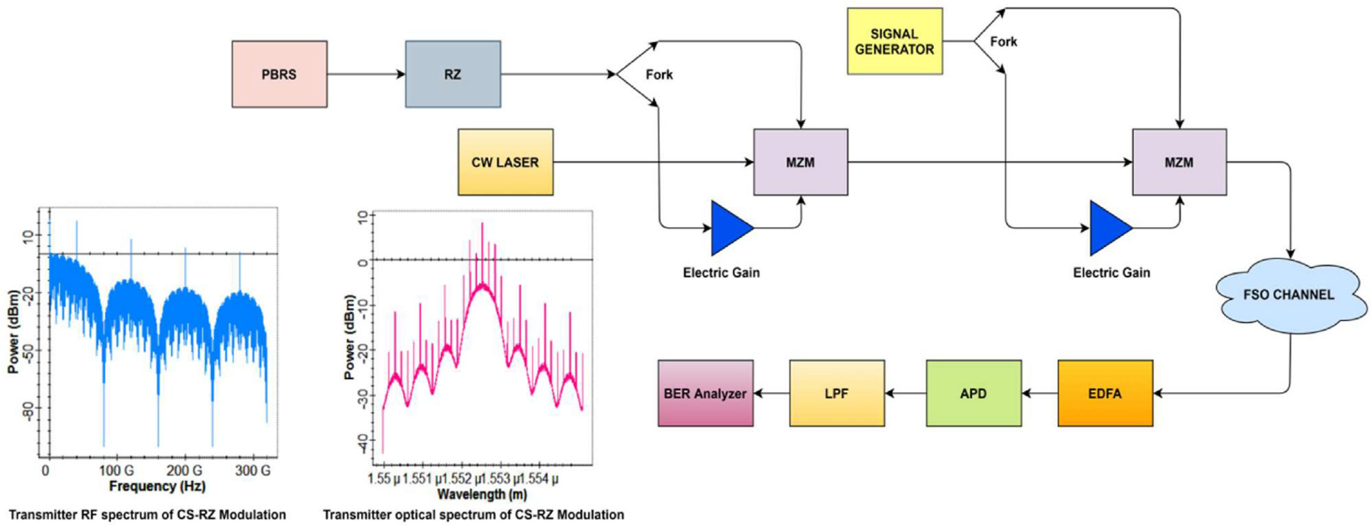


Figure 13. Schematic layout for CS-RZ Modulation.

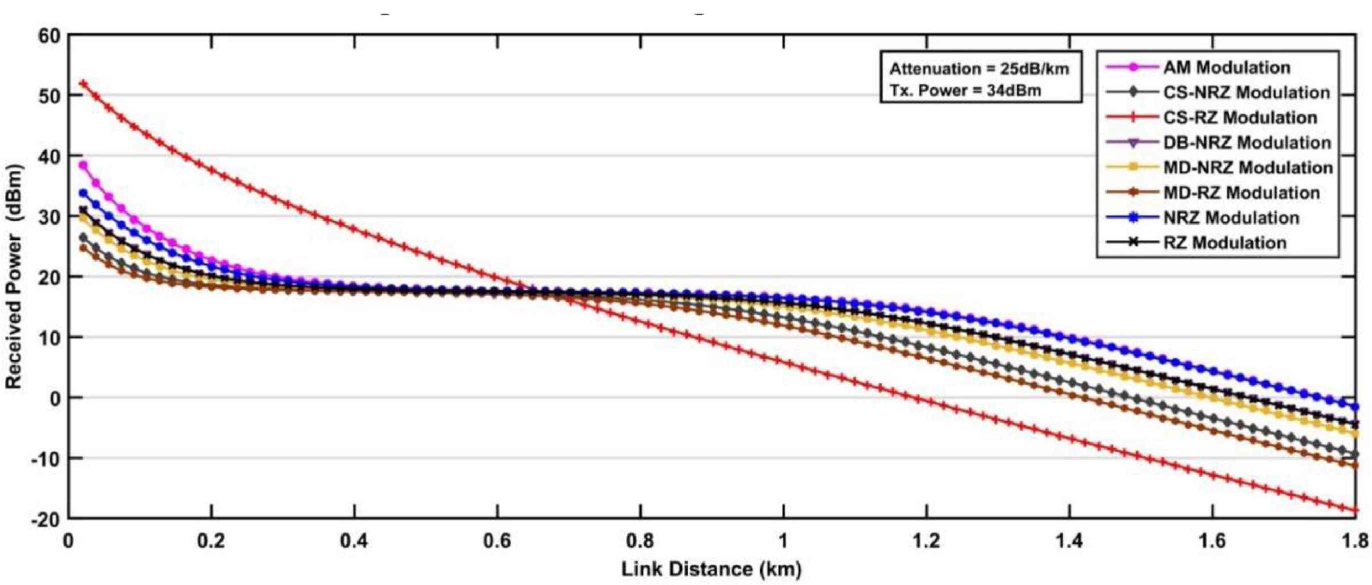


Figure 14. Illustration of link distance and received power for different modulation techniques.

Table 3. Performance evaluation parameters for different link distances.

Modulation Techniques	Link Distance of 1.2 km					Link Distance of 1.8 km				
	Rx. Signal Power	BER	SNR	Q-Factor	Signal Noise	Rx. Power	BER	SNR	Q-Factor	Signal Noise
AM	14.16	2.3E-256	30.75	34.16	7.97	-1.475	0.006	-6.534	2.5	-20.18
CS-NRZ	8.60	3.38E-70	14.60	17.65	11.67	-9.31	High(1)	-22.33	0	-20.05
CS-RZ	-0.23	8.25E-219	26.09	31.54	11.67	-18.7	0.014	-9.854	2.168	-20.05
DB-NRZ	9.808	8.5E-290	26.06	29.34	12.51	-4.39	High (1)	-12.32	0	-20.14
MDB-NRZ	11.37	6.58E-136	21.77	24.77	10.58	-5.959	High (1)	-15.58	0	-20.12
MDB-RZ	6.79	4.01E-43	10.67	13.69	12.05	-11.33	High (1)	-26.35	0	-19.97
NRZ	14.288	1.07E-268	31.30	34.99	7.78	-1.475	0.0062	-6.53	2.49	-20.16
RZ	12.47	1.30E-168	25.30	27.63	9.84	-4.451	High(1)	-12.5	0	-20.19

BER, and Q-factors of FSO communication links. The effect of received optical power and link distance for various modulation techniques is shown in Figure 14.

Graphs show that in every modulation technique, with the increase in link distance, the received power decreases. The different received power for link distance is tabulated in Table 3 for a maximum link distance of 1.8 km at 25 dB/km optical attenuation. It is understandable from an analysis that under clear sky conditions, the received power for all modulation techniques must be much better. It observed that modulation techniques with return zero pulse generators consume more power and bandwidth and for that reason, the received power is low as compared to non-return zero modulation techniques.

The behavior of link distance and log of bit error rate (BER) illustrated in Figure 15 for different modulations. With the increase in link distance, the BER is due to the larger signal print on the APD widow. This loss can be improved using a low divergence angle of the transmitter aperture. The maximum and minimum BER for various modulation techniques are tabulated in Table 3 for 1.8 km link distance at 25 dB/km attenuation. The result shows that the maximum BER for a suitable link distance is 10–9. It can be observed that none of these techniques give better results for a 1.8 km link distance [12]. It is obvious that under clear sky conditions, the system performance can be more impressive and reasonable but for an attenuation level of 25 dB/km link distance is limited [15]. It is obvious that under clear sky conditions, the system performance can be

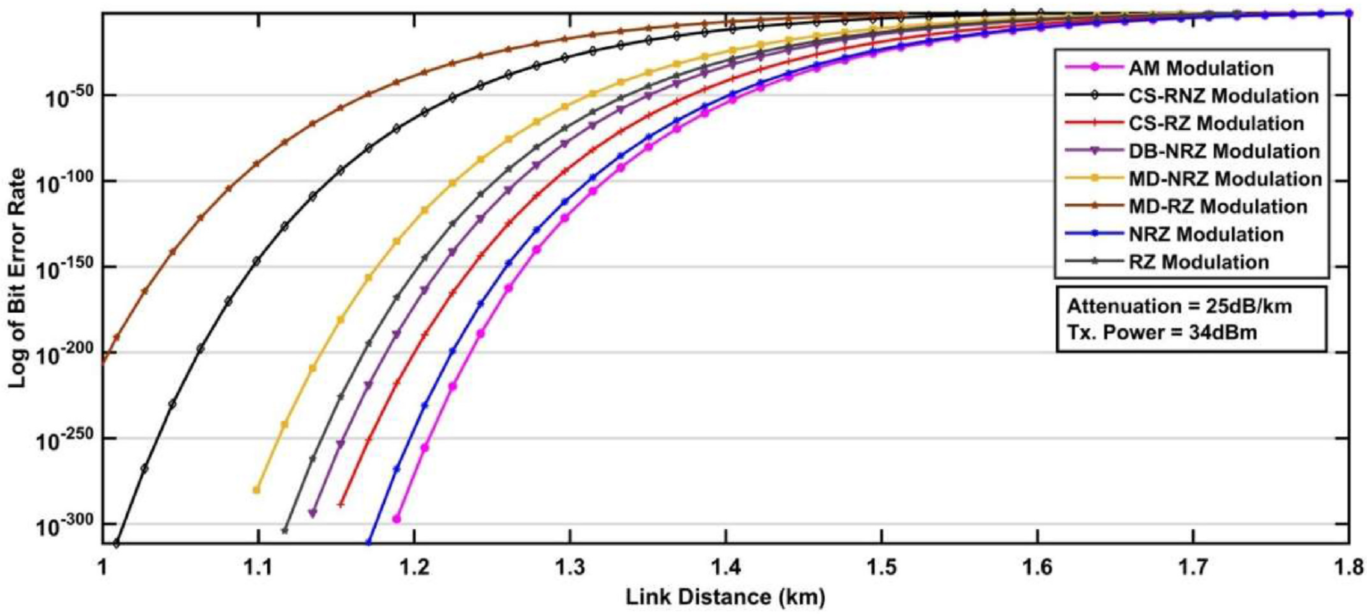


Figure 15. Illustration of link distance (km) and BER.

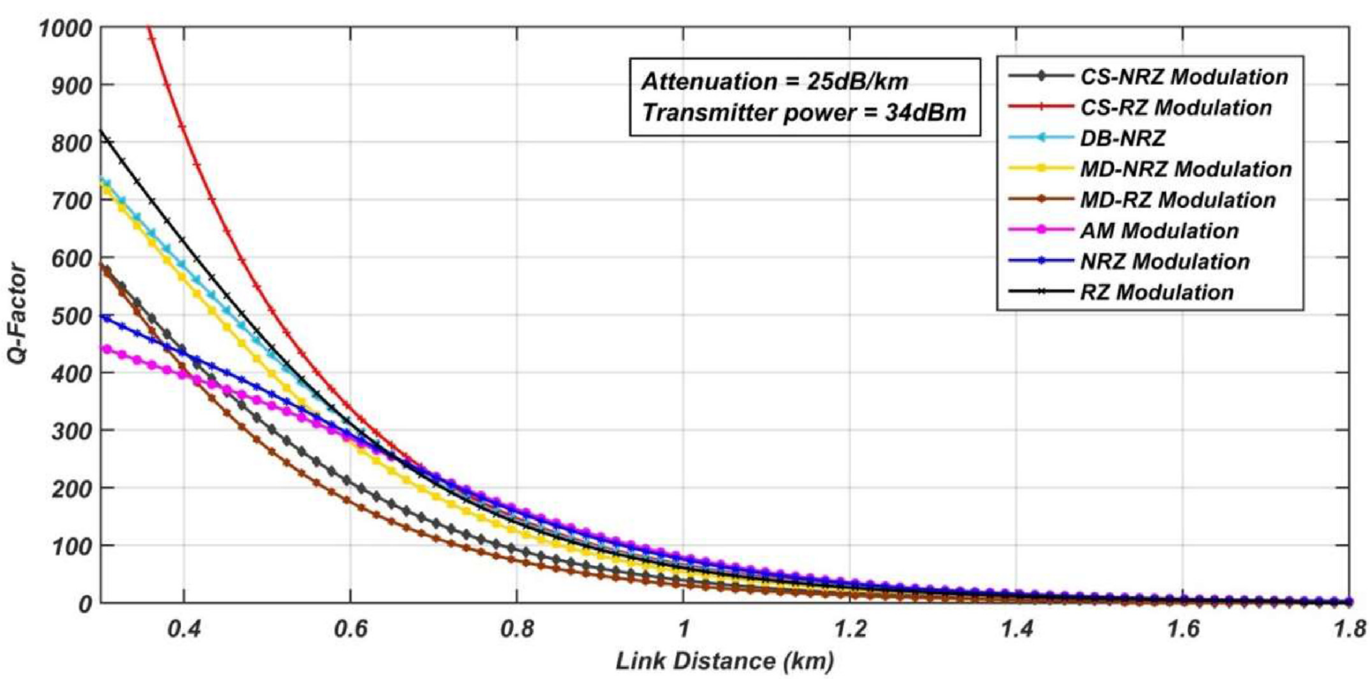


Figure 16. Illustration of link distance (km) and Q-Factor.

more impressive and reasonable but for an attenuation level of 25 dB/km link distance is limited.

The behavior of the Q-factor against link distance is illustrated in Figure 16 for various modulations. It is observed that with an increase in link distance, Q-factor decreases. The quality of the signal can be improved by increasing transmitter power [28]. Table 3 shows maximum and minimum values of the Q-factor for maximum link distance from 0.05 km to 1.8 km. Under attenuation of 25 dB/km, the Q-factor for link distance of 1.8 km is not suiTable. The poor-quality factor also reflects the high BER and low SNR of the optical communication link. Under clear sky conditions at low attenuation, the link performance will be much improved for the same link distance and data rate.

The SNR and link distance relationship is illustrated in Figure 17 for different modulation techniques. The SNR is performance evaluation parameter for a FSO communication system which decreases with increase in link distance. Table 3 shows maximum and minimum values of SNR (dB) for link distance of 0.05 km–1.8 km.

Signal noise increases by increasing link distance presented in Figure 17 for various modulation techniques. The main origin of signal noise is electronic processing in the communication system where the signal is generated and amplified by the amplifier. The heat generated through electronic signal processing is the main reason for noise production. The behaviors of different modulation techniques are illustrated in Figure 18. The thermal noise of 1×10^{-24} W/Hz was added due to conversion of the signal from optical to an electronic signal in avalanche photo-detector (APD) on receiver side with noise dynamic of 3 dB from CW laser and EDFA amplifier. Table 3 shows different values of received signal noise for 1.2 km and 1.8 km link distance for optical attenuation level of 25 dB/km.

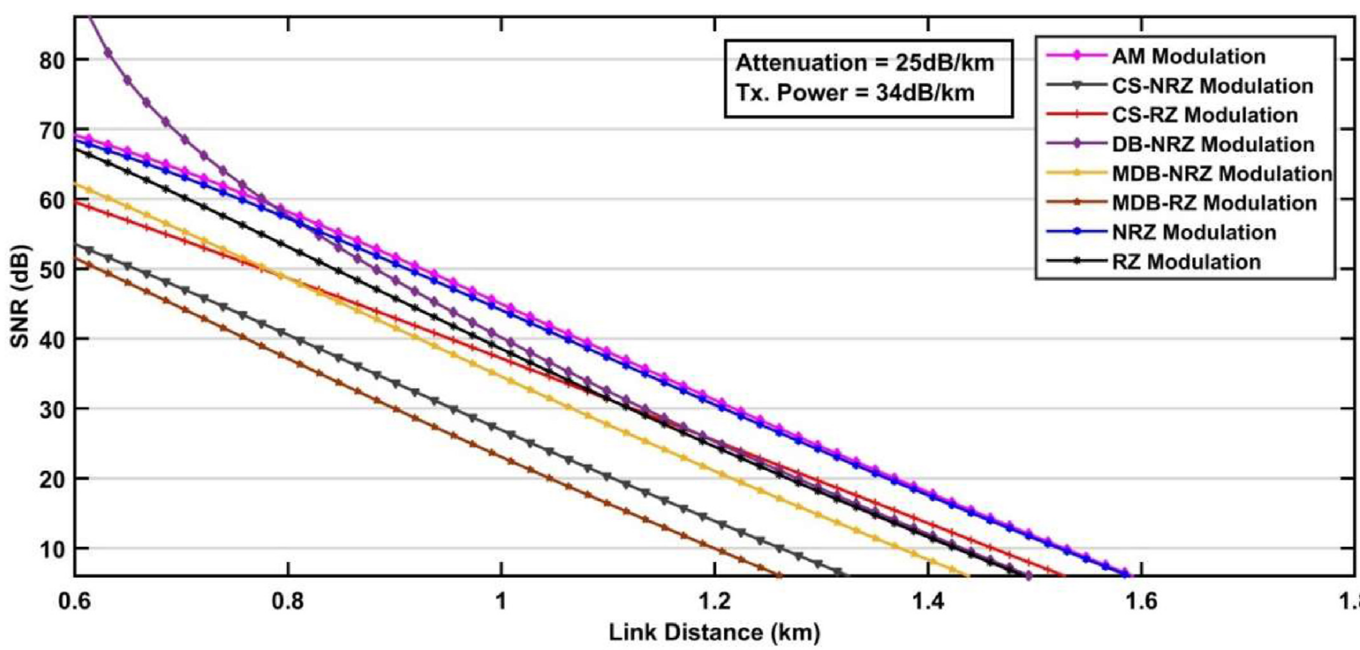


Figure 17. Illustration of link distance (km) and SNR.

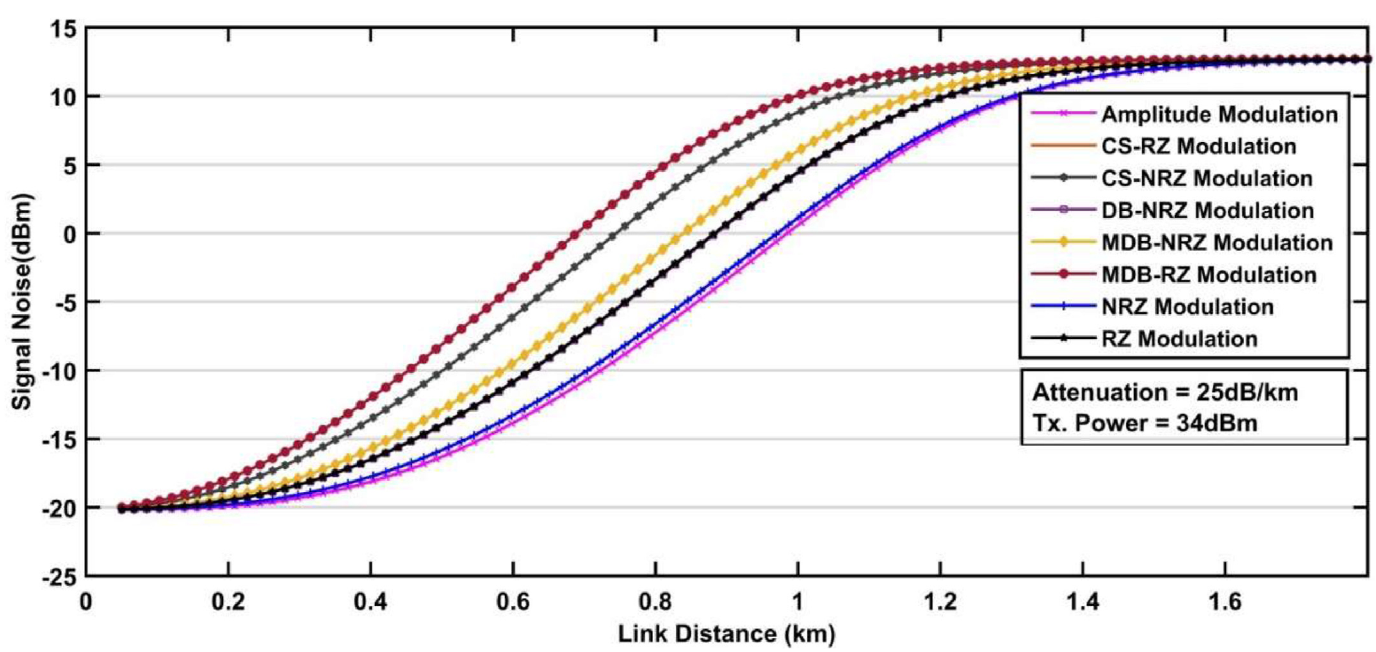


Figure 18. Illustration of link distance (km) and Signal Noise.

Table 4. Performance evaluation data statistics of different modulation techniques.

Modulations	Performance Evaluation Parameters					
	Range (km)	Q Factor (dB)	BER	SNR (dB)	Noise Power (dBm)	Signal Power (dBm)
AM	1.62	6.08	7.03E-10	4.29	12.39	3.79
CS-NRZ	1.44	5.72	4.56E-09	-0.97	12.54	1.29
CS-RZ	1.60	5.67	6.11E-09	1.67	12.66	-12.86
DB-NRZ	1.57	5.66	6.57E-09	1.67	12.48	2.41
MDB-NRZ	1.53	5.79	2.97E-09	0.42	12.51	1.93
MDB-RZ	1.39	5.60	9.58E-09	-1.66	12.55	0.92
NRZ	1.62	5.91	1.48E-09	4.11	12.40	3.70
RZ	1.55	5.91	1.38E-09	2.48	12.46	2.87

Data statistics for different modulation techniques under optical attenuation of 25 dB/km for transmitted power of 34 dB/km are shown in Table 3. It is also studied that under observation techniques behave differently under predicted optical attenuation level of Lahore airfield. The performance evaluation factors are observed to be very critical for a link distance of 1.8 km. The FSO communication system link availability for 1.8 km is not possible for a data rate of 40 Gbps for these specific modulation techniques. It is observed that the relationship between 3 R's (range, rate, and reliability) is very important for any FSO communication system. If we increase range or link distance, rate (data rate) and reliability suffer. If we increase rate (data rate), range or link distance suffers so these 3 R's are highly correlated with each other. The parameters for the process of evaluation of performance of a link distance of 1.2 km are given in Table 3 which shows that for 1.2 km link distance, all modulation techniques will work efficiently. The performance evaluation criterion understudy of these modulation techniques can be the maximum link distance, BER, SNR, and Q-factor. The maximum reliable link distance availability with other performance evaluation parameters can be a performance criterion for a data rate of 40 Gbps under optical attenuation for an efficient modulation technique. Table 4 shows performance evaluating data statistics for under observation modulation techniques.

6. Conclusion

An FSO communication system has been investigated to develop a link of 40 Gbps to interconnect different educational and governing institutions without disturbing these really busy and historical areas of Lahore under dense fog conditions. For the mitigation of the dense fog conditions, different modulation techniques are investigated to investigate a reliable high data rate communication link. It is observed that AM and NRZ modulation techniques are comparatively better and more effective modulation techniques but AM technique performs the best with Q-factor value of 6.07 dB, BER value of 7.03×10^{-10}, SNR of 4.29 dB, and maximum noise power of 12.39 dBm for maximum link distance of 1.62 km. The link distance between these public sector institutions is up to 1 km. The performance parameters for a 40 Gbps FSO link of 1 km using amplitude modulation technique are Q-factor 76.51 dB, zero BER, SNR of 44.34 dB, and maximum noise of 1.455 dBm.

Declarations

Author contribution statement

Sultan Mahmood Yasir: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Naeem Abas: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Shoaib Rauf: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Nauman Riaz Chaudhry: Conceived and designed the experiments; Analyzed and interpreted the data.

Muhammad Shoaib Saleem: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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