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Design and Simulation of a 100 Gbps WDM FSO Communication Link for a 6G Backhaul Network Under Dust Conditions in Iraq

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ABSTRACT

High-data-rate services and applications are evolving continuously, leading to an exponential demand for new and efficient wireless communication systems. The development of next-generation 6G mobile communication technology aims to meet these performance requirements, with the main challenges being high capacity, massive connectivity, and low latency. One prospective solution is to use Free Space Optical (FSO) communication as a backhaul for 6G networks, providing high-capacity transmission without the requirement for physical cables. However, FSO links are highly vulnerable to environmental factors such as rain, fog, and dust storms, which can degrade signal quality and limit the transmission distance. In this paper, the design and simulation of a high-capacity free space optical (FSO) link for 6G backhaul applications in the presence of dust storms, considering the Iraqi environment, were investigated. The performance of the FSO link, operating at a data rate of 100 Gbps, was evaluated using Optisystem software. This evaluation was based on real visibility data related to dust storms collected from northern, central, and southern Iraq during 2008–2022. Dust storms significantly degrade the FSO signal, thereby reducing link distance under low visibility conditions. By incorporating wavelength division multiplexing (WDM) and high-gain Erbium-Doped Fiber Amplifier (EDFA) optical amplifiers, the FSO link achieved a maximum transmission distance of 266 meters under the worst visibility condition (V = 100 meters). This study highlights the viability of FSO technology for 6G networks in regions prone to frequent dust storms.

1. Introduction

The number of smart devices and sensors providing vast amounts of information is increasing rapidly due to advancements in various information technology fields, such as Artificial Intelligence (AI), the Internet of Things (IoT), the Industrial Internet of Things (IIoT), machine learning, and evolving real-time technologies [1]. Additionally, the number of smartphones, tablets, and other devices is also rising to support existing services like internet access, music streaming, and high-quality gaming. This trend leads to the generation of an enormous amount of information [2], [3]. A new generation of 100 gigabits per second (Gbps) 6G mobile communication systems has been proposed to support high-data-rate services [4], [5]. However, existing backhaul links, such as Digital Subscriber Line (DSL), cables, and microwave links, are insufficient to support the backhaul stage for future 6G systems [6]. Free Space Optics (FSO) is a promising technology for ultra-high data rate solutions for 6G backhaul wireless networks, capable of supporting data rates of up to 100 Gbps. FSO

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offers a significant advantage in areas where the installation of optical fibers is challenging due to geographical constraints. The absence of a fiber cable allows for the rapid establishment of a connection with free visual contact, or Line of Sight (LOS), between two points [7], [8]. FSO is designed to transmit data similarly to optical fiber, but it is non-homogeneous and unguided, relying on the transmission of optical signals through the atmosphere. Unlike radio frequency (RF), FSO systems have access to unlicensed bandwidth and are unrestricted, making them a more cost-effective and straightforward solution. Additionally, FSO has several advantages, including enhanced security, immunity to interference, and rapid installation. However, there are challenges to using FSO under adverse weather conditions, such as rain, fog, wind, dust, and storms. In desert areas, sandstorms and severe dust storms are common phenomena, often reducing visibility to only a few hundred meters. These conditions cause significant attenuation, decreasing the received optical power and reducing the FSO link range [9], [10-11].

Several studies have investigated the impact of weather conditions on FSO systems and explored potential methods to mitigate these effects. One of these studies conducted by Kaur et al. [12] demonstrated the effectiveness of aperture averaging in improving the optical link performance of FSO systems under adverse weather conditions, such as fog and dust. Their research highlights the importance of optimizing the optical link to ensure reliable communication in harsh environments. Similarly, Esmail et al. [13] compared the effects of fog and dust on FSO links, concluding that dust introduces significantly higher attenuation than fog, making it the primary impairment in such systems. They also highlighted the potential for FSO links to play a crucial role in future wireless networks.

Singh [14] investigated the use of an optical pre-amplifier to enhance the performance of FSO links due to weather attenuation, especially where maximum link distance is required. This approach improved the overall performance of the system. On the other side, Khalati [15] concentrated on the impact of aerosols on FSO links. Results indicated that dust attenuation is dependent on the wavelength of the laser and that visibility distance decreases when the concentration of the dust particles increases.

In 2019, Ali et al. [16] performed a simulation study of wavelength division multiplexing (WDM)-based radio over FSO (RoFSO) systems, showing that the system could support up to 10 Gbps under different weather conditions, including clear skies, rain, and fog. Yasir et al. [17] examined the performance of a 10 Gbps FSO link under dust and rain conditions using Optisystem software. Their study highlighted the attenuation effects caused by atmospheric conditions such as dust and rain and their impact on the system's Q-factor.

Dust storm scenarios were specifically addressed in later work by [18], [19]. According to [18], the bit error rate (BER) is dramatically increased at data rates of 0.3 and 0.7 Gbps in dusty environments, highlighting the challenges posed by such conditions. Nevertheless, [19] studied the dust impact on BER, observing that while high dust concentrations can severely degrade the link, the system can still maintain sufficient channel capacity.

These studies collectively underline the importance of mitigating atmospheric impairments in FSO communication systems, especially dust, which has been shown to cause significant degradation.

The purpose of this research is to explore the use of FSO in densely populated Iraqi cities, where establishing or extending optical cables is both challenging and costly. The research also considers Iraq's desert environment and the frequent dust storms that affect visibility. Taking these factors into account, the key contributions of this research are:

- A 100 Gbps FSO communication link for a 6G backhaul will be designed using Wavelength Division Multiplexing (WDM) and Erbium-Doped Fiber Amplifier (EDFA), tailored to the environmental conditions in Iraq.
- Simulating the performance of FSO link under dusty conditions in terms of BER,

and comparing the results with theoretical calculations.

- Identifying the maximum distance between transmitter and receiver that can fulfill the designed system performance under the worst visibility conditions.

Moreover, OptiSystem software was used to simulate the 100 Gbps FSO link for the 6G mobile communication system, including the calculation of the BER. The dusty channel attenuation was determined using experimental visibility data from dust storms provided by the Iraqi Meteorological Organization and Seismology [11].

2. Free space optical (FSO) communication systems

The block diagram of the FSO communication system includes an optical transmitter, an atmospheric channel, and an optical receiver, as shown in Figure 1.

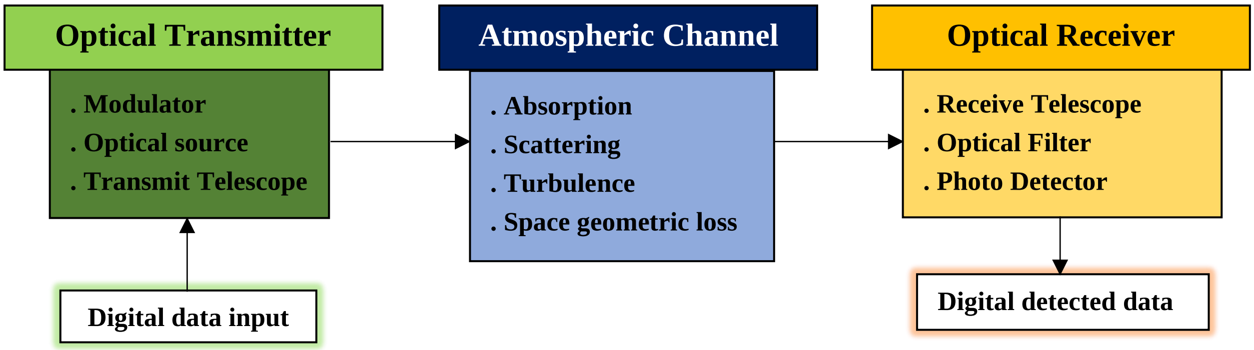

Figure 1. Block diagram of free space optical (FSO) communication systems

The FSO transmitter sends the laser beam through the air medium or free space instead of optical fiber glass. The three components of the FSO communication system are discussed below:

2.1 Optical transmitter

Its primary function is to modulate the incoming high-data-rate message signal onto an optical carrier, which is then propagated through the atmosphere to the receiver. The essential components of the transmitter are the modulator, the laser diode as an optical source, and the transmitting telescope or optical antenna, which are responsible for beam shaping and beam tracking.

2.2 Channel

The atmospheric channel presents several challenges, including absorption, scattering, and turbulence, exacerbated by weather conditions such as snow, fog, rain, and dust. These factors attenuate the optical signal power, thereby reducing the effective transmission distance between the transmitter and receiver.

2.3 Optical receiver

The optical receiver is used to recover the transmitted data. It consists of a receiver telescope, which is also responsible for beam shaping, and a movable part for beam tracking. It is also consisting of a sharp optical band pass filter to reduce background noise and limit the received signal bandwidth, and a photo diode to recover the data signal by converting the On-Off Keying (OOK) received optical signal to an electrical data signal.

3. Free space optical (FSO) challenges

While offering significant advantages in terms of high data rates and easy installation, FSO systems face external challenges such as weather conditions that impact their performance. These conditions attenuate the transmitted optical signal, increasing the BER and reducing the FSO link distance. Figure 2 illustrates the main challenges affecting FSO communication links, including weather conditions, absorption, scattering, scintillation, and pointing errors. These factors affect the optical signal amplitude and, consequently, data detection.

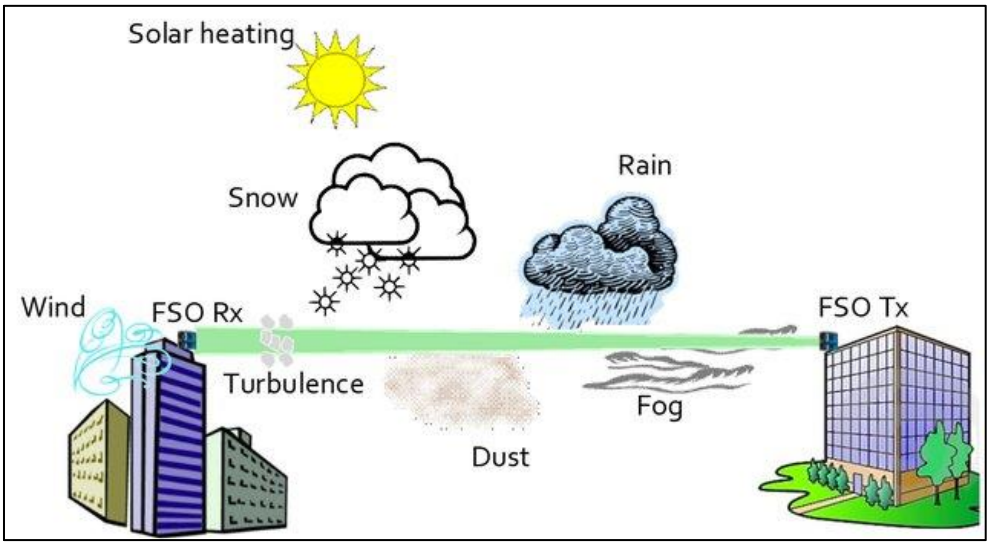

Figure 2. Environmental effects on FSO signals transmitted through the atmosphere [20]

3.1 Weather

The major challenge to FSO communication is fog and dust. Fog can block lasers like a brick wall, significantly attenuating the optical signal and preventing it from reaching the receiver. The high density of water droplets in fog scatters the light, causing severe signal degradation and loss. Dust presents a similar issue by scattering and reflecting the light, which completely hinders the passage of the optical signal and decreases visibility. These conditions not only reduce the signal strength but also increase the BER, thereby compromising the reliability and efficiency of the FSO communication system. Addressing these challenges requires robust system design and adaptive techniques to maintain signal integrity under adverse weather conditions [5], [21], [22].

3.2 Absorption

Absorption occurs when suspended water molecules in the atmosphere extinguish photons. This causes a decrease in the power density (attenuation) of the FSO beam and directly affects the system's availability [23].

3.3 Scattering

Scattering occurs when the wavelength collides with scatterers such as flying birds, buildings, and towers. While there is no loss of energy, there is a directional redistribution of energy that can significantly reduce beam intensity over longer distances [12]. When there are obstacles in the optical signal path, the direction of the signal changes, causing it to spread and lose focus. This scattering reduces the signal strength, leading to an increase in the BER. Factors such as the size and density of scatterers, as well as the wavelength of the transmitted light, can influence the extent of scattering. Scattering is particularly problematic in urban environments, where numerous potential obstacles exist. Therefore, the design of an FSO system must consider these conditions to establish a connection capable of reliable data transmission [24].

3.4 Scintillation

It is a phenomenon that causes rapid intensity fluctuations in FSO signals as they travel through the atmosphere, leading to potential communication disruptions. These fluctuations are caused by temperature variations resulting from heated air rising from the earth or man-made sources such as heating ducts. One way to minimize the effects of scintillation is to have no links longer than 500 m and mount systems farther away from vents, hot roofs, and air-conditioning ducts [25].

3.5 Pointing error

It refers to a misalignment between the transmitter and receiver beams in an FSO communication system. This misalignment can be caused by several factors, including swinging buildings, thermal expansion, earthquakes, and heavy wind [26].

4. FSO Backhaul Network for 6G System

In the future 6G cellular environment, a significant amount of data will be generated due to the proliferation of smart devices and sensors, driven by the adoption of various information technologies such as artificial intelligence (AI), the Internet of Everything (IoET), the Industrial Internet of Things (IIoT), machine learning, and the evolving real-time domain. This substantial increase in data necessitates an ultra-high data rate communication system. The proposed 6G mobile communication systems, with data rates of up to 100 Gbps, aim to support these high data services. Consequently, a high-capacity communication link for cellular backhaul communication is required to connect high-data-rate 6G base stations to core network elements, as illustrated in Figure 3.

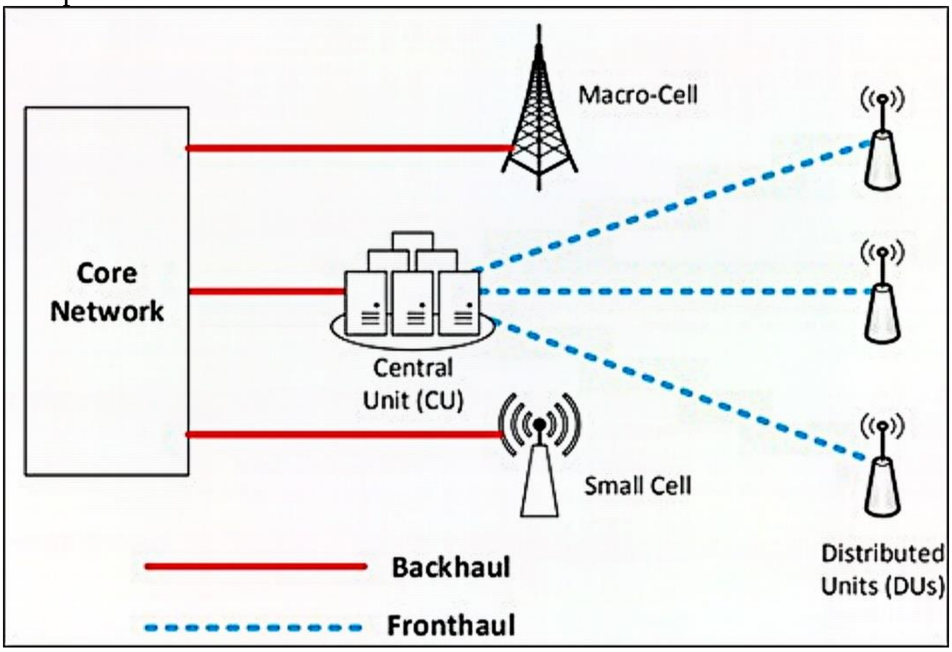

Figure 3. Backhaul and fronthaul architecture in cellular system [27]

While traditional RF and fiber optics backhaul links have been the mainstay for 2G, 3G, 4G, and 5G networks, the enormous data rate requirements of 6G necessitate even higher-capacity backhaul links. Given the small cell radius of 6G systems, approximately 100 meters, installing high-data-rate optical fiber as a backhaul link becomes expensive and complex, particularly in densely populated urban areas. FSO links, with gigabit capacities, are emerging as a promising technology for mainstream connectivity in 6G cellular systems. Additionally, the architecture of the 6G cellular mobile system, characterized by increased base station density within a given geographic area due to the small cell radius, will require a higher number of backhaul links compared to 4G and 5G to ensure comprehensive and sustainable coverage [7], [8].

5. Dust storm visibility data in Iraq

A dust storm is generated by strong winds that lift dust particles into the air, spreading them over a wide area. In one year, the Ministry of Environment in Iraq recorded 122 dust storms and 283 dusty days. Sources indicate that within the next decade, Iraq could experience up to 300 dust storms annually [28]. Table 1 presents the variation of visibility values over time from 2008 to 2012, as provided by the Iraqi Meteorological Organization and Seismology (Baghdad Station) [11].

Table 1: Visibility Study During Dust Storm Events (2008–2012) in the Baghdad Area [11]

	Date of storm	Visibility (m)
1	1.10. 2008	6117
2	15.3. 2008	7291
3	17.4. 2008	8447
4	16.5. 2008	**200 (Min)**
5	30-6-1-7. 2008	4129
6	24.9. 2008	5175
7	15-16.3. 2009	267
8	24.3. 2009	4913
9	5-6.5. 2009	4929
10	17.9. 2009	2400
11	16.3. 2010	5209
12	7-8. 6. 2010	1917
13	23-24. 6. 2010	5292
14	20-21. 7. 2010	3455
15	19.9. 2010	4600
16	13.5. 2011	3388
17	27.7. 2011	3568
18	13.10. 2011	4255
19	19.4. 2012	634
20	12.6. 2012	3121

From Table 1, the minimum visibility value recorded on May 16, 2008, is 200 meters. Satellite monitoring over the years following 2012 indicate that severe dust storms occurred in the cities located in central Iraq on May 16, 2022 [29], where the visibility range was reduced to only 100 meters. Additionally, on May 23, intense dust storms hit cities in northern and southern Iraq. Figures 4 and 5 illustrate the minimum visibility values in major cities on these dates [30], [31].

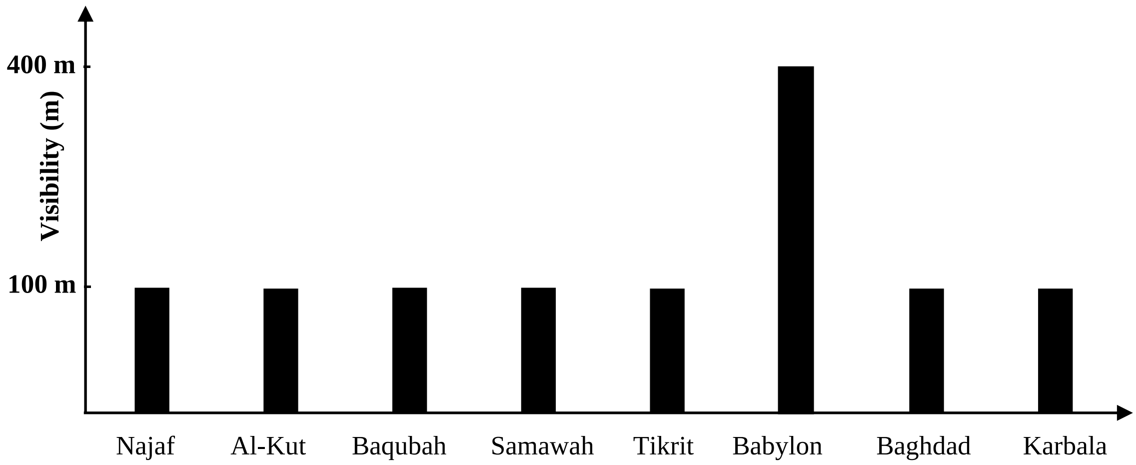

Figure 4. The minimum visibility in the presence of dust storms at 16th May 2022 on the cities located in middle of Iraq

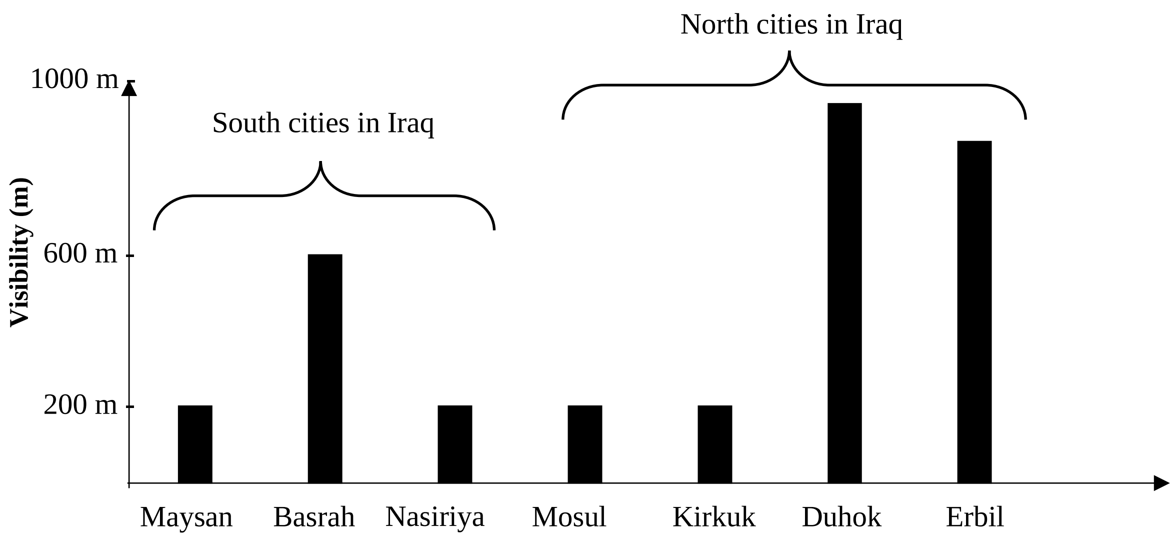

Figure 5. The visibility in the presence of dust storms at 23th May 2022 on the cities located in north and south of Iraq

As seen from Table 1 and previous figures, a strong dust storm on May 16, 2022, covered central Iraq, resulting in the worst visibility (V = 100 m). Therefore, the design of the FSO communication link for the 6G backhaul network will be based on this lowest recorded visibility value.

6. FSO link design for 6G backhaul

The design of the FSO link will consider two types of path loss experienced by the optically transmitted signal:

- Geometric path loss due to optical beam divergence.
- Atmospheric loss due to dust storms, based on previous experimental data presented in Section 5.

6.1 Geometric path loss

When the optical signal propagates through the FSO link, it is affected by geometric loss (g_L) due to optical beam divergence, as illustrated in Figure 6. This loss can be deduced from the following equation [9].

$$g_L = \left[\frac{d_2}{d_1 + D\theta}\right]^2 \qquad (1)$$

Where d_1 and d_2 are the transmitter and receiver aperture diameter (in meters), D is the FSO link range (in kilometers), and θ is the beam divergence angle in milliradians.

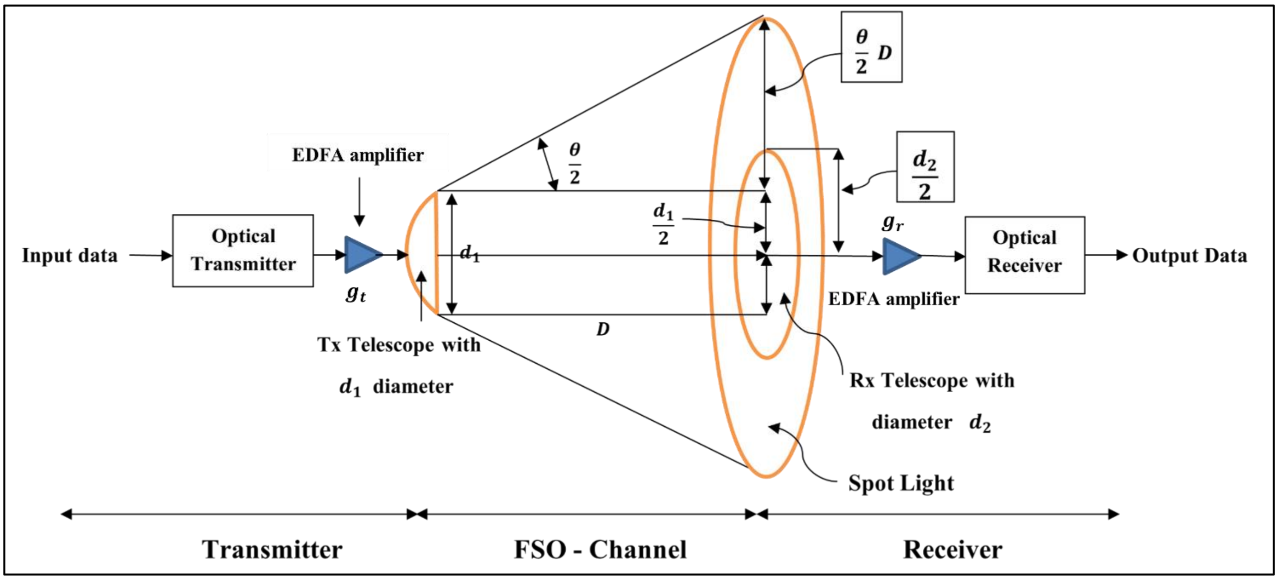

Figure 6. FSO link geometrical configuration

6.2 Atmospheric loss due to dust storms

The presence of dust in the atmosphere scatters the optical signal, reducing visibility. Consequently, dust particles affect the performance of the FSO link by attenuating the optical signal and reducing the received power. The attenuation constant α in dB/km, due to dust particles in arid and semi-arid regions, can be calculated using the following empirical formula based on measurements given by [10].

$$\alpha_{dust} = 52V^{-1.05} \text{ dB/Km} \qquad (2)$$

Where V is the visibility in km. This empirical model uses the 1550 nm wavelength in FSO systems because it introduces very low attenuation. This model will be used to determine the FSO link performance in terms of BER. The atmospheric loss $AL(D)$ can be calculated using the following formula [9].

$$AL(D) = \mathrm{e}^{-0.1\,\alpha_{\mathrm{dust}}\mathrm{D}} \qquad (3)$$

6.3 Atmospheric loss due to fog particles

The attenuation of the optical signal available at the input of the optical receiver of the FSO link in the presence of fog particles in the atmosphere can be obtained from the Kim model. This model provides the signal attenuation constant in terms of visibility V in km, as shown in equation (4) [32], [33].

$$\alpha_{FOG}\left(\frac{dB}{Km}\right) = \frac{13}{V}\left(\frac{\lambda}{0.55}\right)^{-q} \qquad (4)$$

where λ is the wavelength of the optical signal in µm, and the factor (q) can be calculated by equation (5):

$$q = \begin{cases} 0 & V < 0.5\ km \\ V - 0.5 & 0.5 < V < 1\ km \end{cases} \qquad (5)$$

6.4 Comparison between dust and fog attenuation constants

In this work, the attenuation constants in the presence of dust and fog particles, given by (2) and (5), are plotted in terms of visibility, as shown in Figure 7. It can be seen from this figure that dust produces a higher attenuation in dB/km than fog for the same visibility value. This is because water in fog particles causes less scattering of the penetrating optical signal compared with dust particles. Therefore, our study of the FSO link performance will focus on the presence of dust.

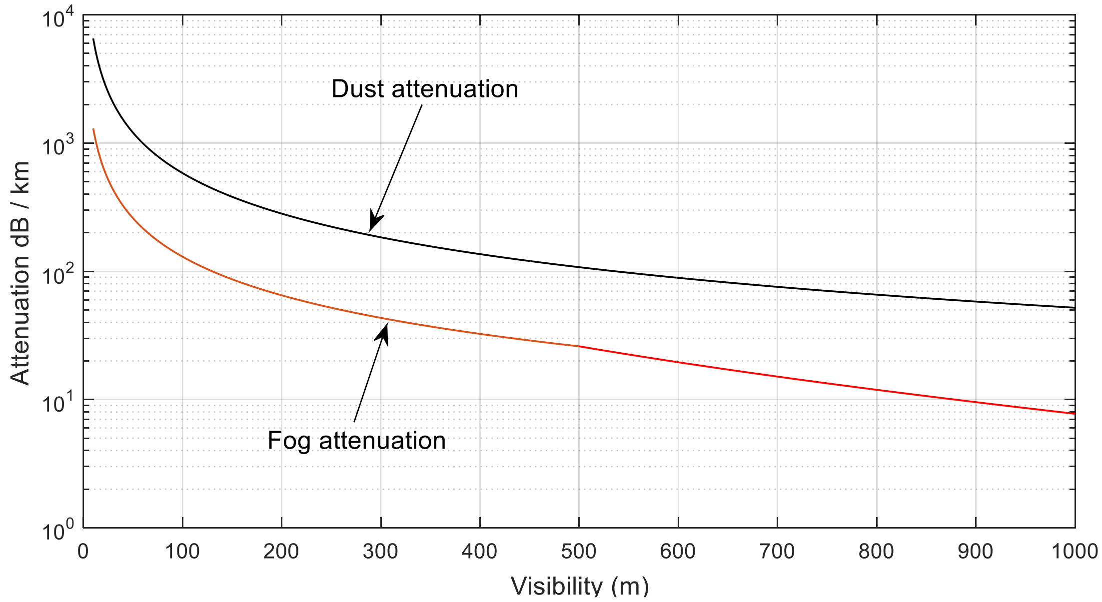

Figure 7. Attenuation constant dB/km due to the presence of dust and fog

6.5 Single Channel Point-to-Point FSO Communication link block diagram configuration.

The block diagrams of a single-channel FSO link are shown in Figure. 8 and consist of the following:

- *Optical transmitter*

The optical transmitter consists of a Mach-Zehnder optical modulator, a continuous wave (CW) optical laser, and an optical amplifier.

i. Mach-Zehnder optical modulator

The Mach-Zehnder optical modulator, shown in Figure 8, is used to modulate the amplitude of the optical signal with a wavelength of 1550 nm, produced by a CW single-mode laser diode. This modulation is based on the amplitude of the non-return-to-zero (NRZ) data signal from the data source at a data rate of b bits per second. The output of the modulated is an OOK optical signal.

ii. Optical amplifier

The output of the Mach-Zehnder optical modulator is fed to an EDFA optical amplifier with gain (g_t) to amplify the transmitted optical power [34]. The amplified signal is then directed to the transmitting telescope with a diameter d_1, which radiates it through the FSO channel.

- *Optical receiver*

The optical receiver consists of a receiving telescope, an EDFA optical amplifier with gain (g_r), an avalanche photodiode (APD), a transimpedance amplifier, a low-pass Gaussian filter, and a data detector.

i. Avalanche photo detector (APD)

An avalanche photodiode (APD) is a reverse-biased diode with high sensitivity and gain that converts the received optical signal into an electrical signal. It provides a higher signal-to-noise ratio than PIN photodiodes [35]. The main source of noise at low gain is Johnson noise from the interpixel resistance, while at high gain, shot noise from the bulk dark current becomes dominant. There is an intermediate narrow gain region (M = 10–25), where M is the gain of the avalanche photodiode [35].

ii. Low Pass Bessel Filter

This filter is used to pass the low-frequency components of the received digital electrical signal and reject those with frequencies higher than the cutoff frequency, which is set to 0.75 times the digital signal bit rate.

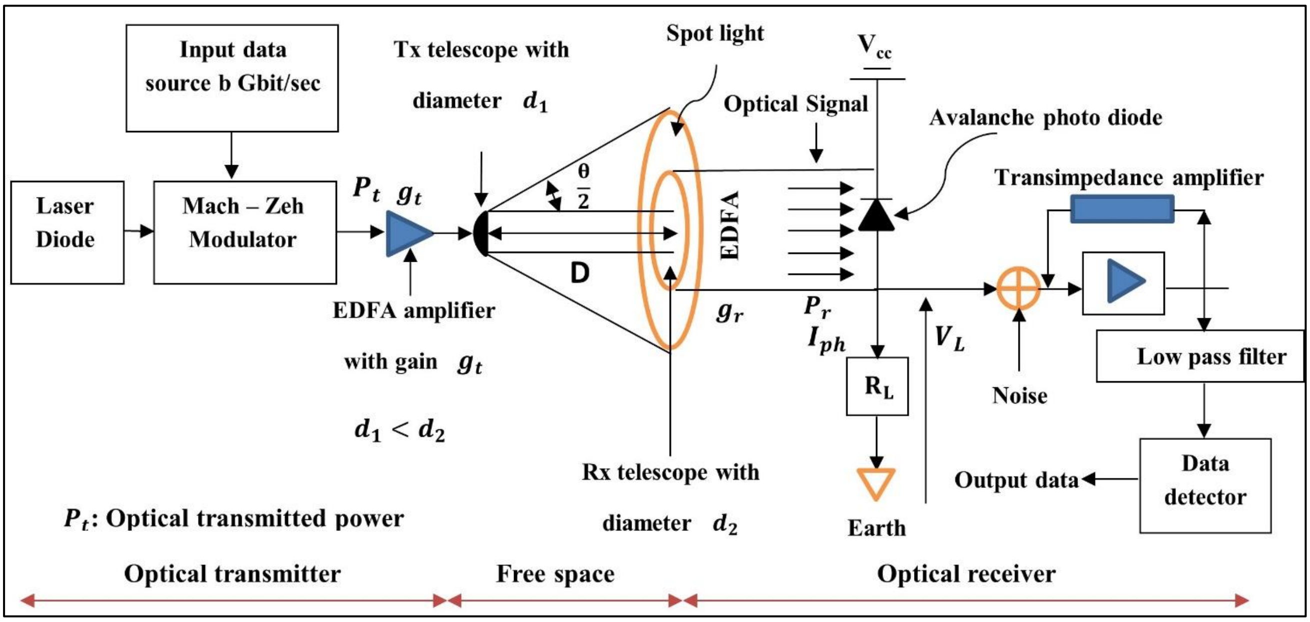

Figure 8. Single Channel FSO link block diagram configuration

6.6 Received optical power calculation

The optical transmitted signal through the FSO link is affected by both atmospheric loss due to dust and geometric loss. The received optical power P_r can be determined as follows [9].

$$P_r = P_t\, g\left[\frac{d_2}{d_1 + \theta\, D}\right]^2 e^{-0.1\alpha_{dust}D} \quad (6)$$

Where P_t is the optical transmitted power, $g = g_t g_r$ represents the total optical amplifier gain, where g_t is the EDFA amplifier gain at the optical transmitter, and g_r is the EDFA amplifier gain at the optical receiver, D is the FSO link distance, and α_{dust} is the atmospheric attenuation constant in dB/km due to the presence of dust. The APD used in the receiver, as shown in Figure 8, converts the power of the received optical signal into an electrical signal with photocurrent I_{Ph}, which is given by [36].

$$I_{Ph} = RM\, P_r \quad (7)$$

Where R is the responsivity of the avalanche photodiode (A/W).

6.7 Signal to noise ratio

The signal-to-noise ratio (ρ) of the avalanche photodiode is given by [36],

$$\rho = \frac{{I_{ph}}^2}{2eK_m MbI_P + \frac{4N_o b}{R_L}} \quad (8)$$

where e is the charge of an electron, R_L is the load resistor as shown in Figure 8, b is the bit rate, N_o is the thermal noise power spectral density $\left(4 \times 10^{-21}\,\frac{\text{watt}}{\text{Hz}}\right)$ generated by the load resistor, and K_m is the noise excess factor of the avalanche photodiode, given by [35].

$$K_m = kM + (1-k)\left(2 - \frac{1}{M}\right) \quad (9)$$

Where k is the ionization coefficient ratio. Substituting I_{Ph} from (7) into (8), the SNR (ρ) will be

$$\rho = \frac{R^2M^2{P_r}^2}{2e\, M^2K_m b\, RP_r + \frac{4N_o b}{R_L}} \quad (10)$$

6.8 Theoretical calculation of BER for FSO Link

The performance of the FSO communication link can be evaluated by the probability of error, or BER. The modulation technique, such as non-return-to-zero on-off keying (NRZ-OOK), is used in FSO optical communication due to its cost-effectiveness and bandwidth efficiency. In this case, the BER as a function of SNR (ρ) is given by [36].

$$BER = \frac{1}{2}\, erfc \frac{1}{2}\sqrt{\frac{\rho}{2}} \quad (11)$$

By substituting (10) into (11), the BER is given by

$$BER = \frac{1}{2} erfc \frac{1}{2} \frac{RMP_r}{\sqrt{2(2e\, M^2K_m b\, RP_r + 4N_o b/R_L)}} \quad (12)$$

When the avalanche gain of the photodiode $M > 10$, then the shot noise is predominant, therefore the thermal noise term $4\mathrm{N_o b/R_L}$ will be neglected [36], then (12) becomes

$$BER = \frac{1}{2}\, erfc\sqrt{\frac{RP_r}{16\, e\, K_m b}} \quad (13)$$

Substitute P_r from (6) into (13), then the BER is given by

$$BER = \frac{1}{2} erfc\sqrt{\frac{RP_t g\left[\frac{d_2}{d_1 + \theta D}\right]^2 e^{-0.1\alpha_{dust}D}}{16\, e\, K_m b}} \quad (14)$$

The theoretical BER is plotted against FSO link distance (D) using equation (14), as shown in Figure 9, with the parameter values provided in Table 2.

Table 2: Theoretical parameter values used in the calculation of BER

Theoretical Parameters	Values
Responsivity of photodiode R	1 A/W
Charge of electron e	1.6×10^{-19} C
Optical transmitted power	10 mW
Transmitter aperture diameter d_1	0.12 m
Receiver aperture diameter d_2	0.3 m

Total amplifier gain ($g_t = g_r$)	15, 20, 25 dB
Laser Bean divergence angle θ	2 mrad
FSO Link distance D	50 – 300 m
Bit Rate b for single channel	25 Gbps
Avalanche multiplication gain M	10
Ionization ratio k	0.4

Due to the presence of dust, the attenuation constant α_{dust} (dB/km) shown in (14) is calculated using (2), with the worst visibility $V = 100$ m in central Iraq. Figure 9 shows that the maximum distance of the FSO link is determined when the BER meets the criterion $\text{BER} \leq \frac{1}{\text{bit rate}}$. Therefore, for a bit rate of approximately 100 (4×25) Gbps in the future 6G mobile communication system, the BER must be $\text{BER} \leq 4 \times 10^{-11}$.

Based on Figure 9 and the above BER value, the maximum theoretical FSO link distances are shown for different EDFA gains.

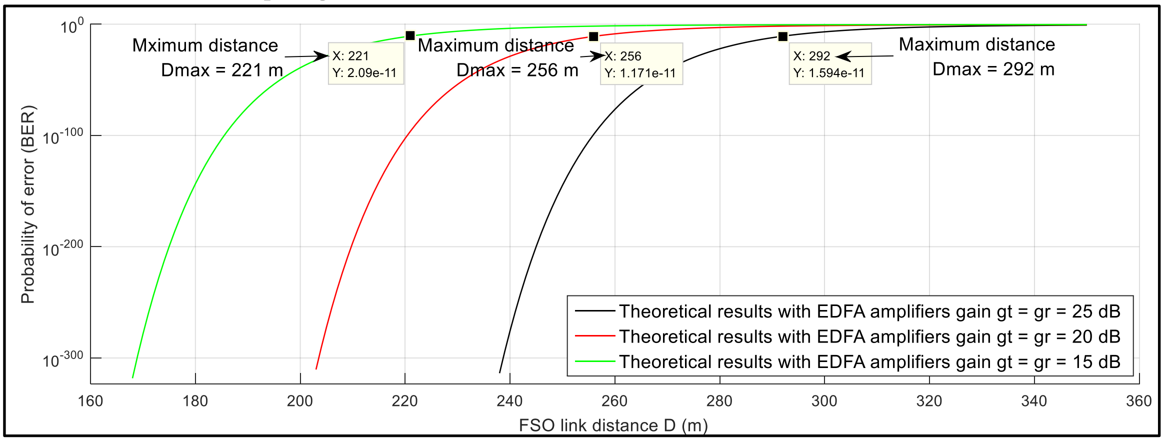

Figure 9. Theoretical results of BER as a function of single-channel FSO link distance with visibility $V = 100$

6.9 Wave Division Multiplexing (WDM)

In practical backhaul FSO links, WDM is applicable to achieve high bit rates over long FSO link distances. WDM is a multiplexing technology that combines N-parallel optical modulated signals, each containing the same digital information with a bit rate b, but with N different wavelengths, into a single serial optical wavelength. This combined signal is transmitted on the same FSO optical link, achieving a high total bit rate $B = Nb$. In this work, the basic principles of WDM are illustrated in Figure 10. A passive optical multiplexer is used to combine four parallel modulated optical carriers, each with a bit rate of 25 Gbps and different wavelengths spaced 2 nm apart within the 1552-1558 nm band. The results in a total link bit rate of $B = 4 \times 25$ Gbps $= 100$ Gbps. These four channels are transmitted serially over the same FSO link. At the optical receiver, a passive optical demultiplexer is used to separate the received serial optical wavelengths of the modulated carriers into parallel form. Each optical modulated carrier is then demodulated to extract the digital information at a bit rate $b =$ 25 Gbps. This information is subsequently combined using time division multiplexing (TDM) to reconstruct the original transmitted data with a total bit rate $B = 100$ Gbps. The advantages of WDM technology include system simplification, cost reduction, and the ability to achieve high bit rates over long-distance optical fiber and FSO links.

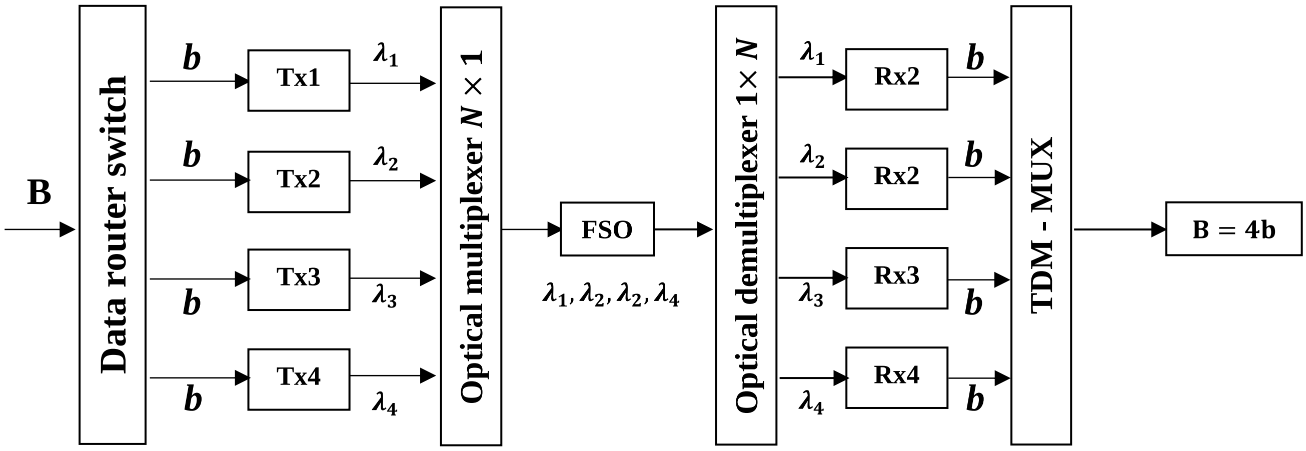

Figure 10: Proposed 100 (4×25) Gbps WDM-FSO Link configuration

7. Simulation setup

According to the 4-channel WDM-FSO link configuration shown in Figure 10, a simulation of a 100 Gbps (4 × 25 Gbps) WDM-FSO transmission link was conducted using OptiSystem software, as illustrated in Figure 11. Each channel was generated by random bit sequences at a data rate of 25 Gbps and fed into NRZ electrical signal generators. These four signals were then modulated with different laser optical signals at wavelengths of 1552 nm, 1554 nm, 1556 nm, and 1558 nm, respectively, using Mach-Zehnder modulators. The parallel modulated signals are then fed to a (4 × 1) passive optical multiplexer, and the output serial optical signals are directed to an optical amplifier with different gains $(g_t + g_r) = 30$, 40 and 50 dB. The optical receiver contains an APD, which converts the received optical signal into an electrical data signal, having an avalanche gain of $M = 10$ [35] and a responsivity of $R = 1\ A/W$. These electrical signals are then fed to a different low-pass Bessel electrical filters, each with a cutoff frequency of 0.75 times the bit rate of the data signal. All parameters used in the simulation are summarized in Table 3.

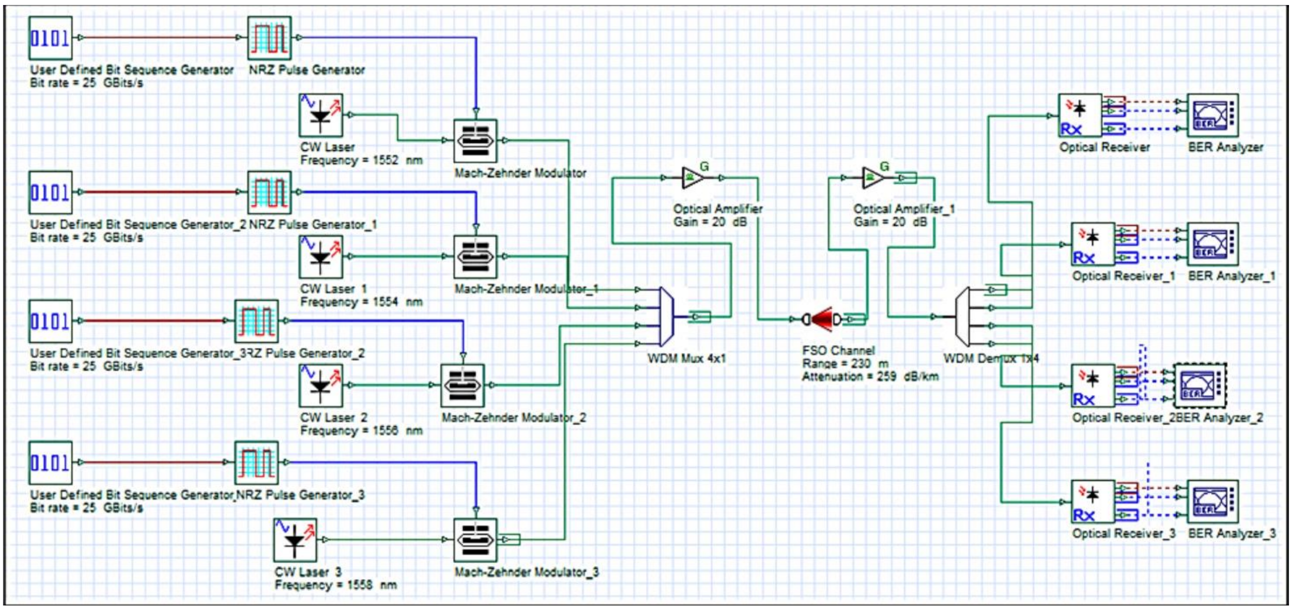

Figure 11: Simulation Setup of WDM-FSO Link Using OptiSystem 7.0 Software

Table 3: Simulation parameter values of WDM system used in the calculation of BER

Simulation Parameters	**Values**
Responsivity of photodiode R	1 A/W
Wavelength λ of 1st channel	1552 nm
Number of channels	4
Channel spacing	2 nm
Optical transmitted power	10 mW
FSO transmitter aperture diameter d_1	0.12 m
FSO receiver aperture diameter d_2	0.3 m
Total Amplifiers gain ($g_t = g_r$)	15, 20, 25 dB
Laser Bean divergence angle θ	2 mrad
FSO Link distance D	50–300 m
Total data rate	100 Gbps
Data Rate/channel b	25 Gbps
Avalanche multiplication gain M	10
Ionization ratio k	0.4
Cutoff frequency at receiver	25 GHz

The BER analyzer, shown in Figure 11, is used to measure the BER. The simulation results of the maximum BER at maximum distance are plotted against the four wavelengths (in nm) of the WDM-FSO link, as illustrated in Figure 12, for different optical amplifier gains.

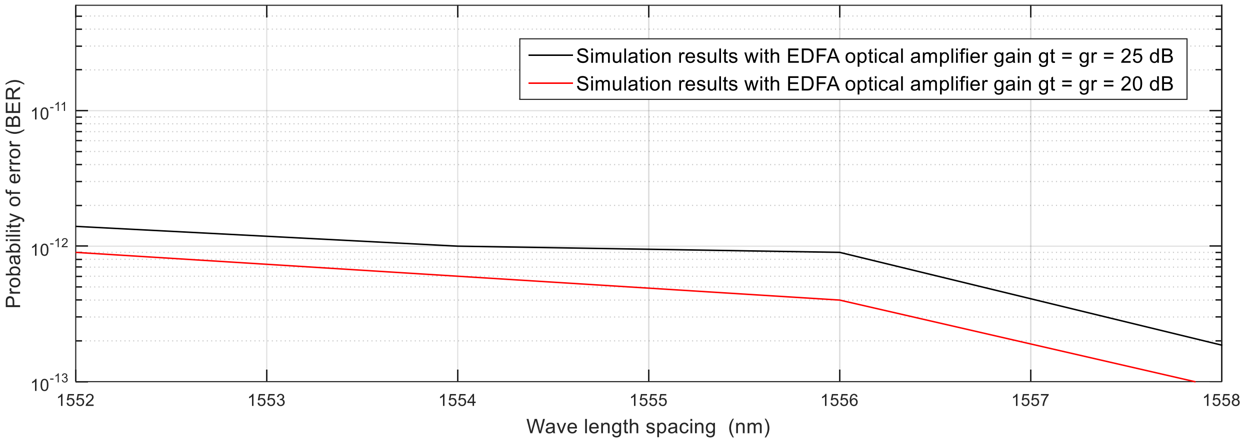

Figure 12: Simulation Results of Maximum BER as a Function of FSO-WDM Wavelengths for Different Optical Amplifier Gains

It can be seen from Figure 12 that the measured BER results have a maximum value at the 1552 nm wavelength for the FSO link with EDFA amplifiers gain $g_t = g_r = 20$ and 25 dB. Therefore, the design of the FSO link is based on the simulation results of BER at 1552 nm, which are plotted against the FSO link distance (D) in Figure 13 for different optical amplifier gains.

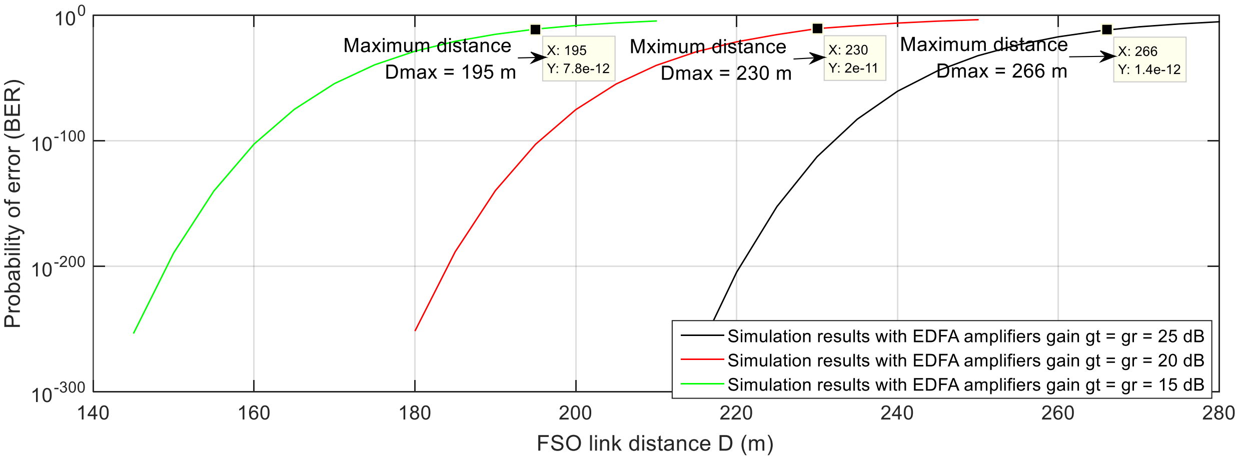

Figure 13: Simulation Results of BER at 1552 nm Wavelength for WDM-FSO Link as a Function of Link Distance with Visibility $V = 100$ m and Bit Rate $B = 100(4 \times 25)$ Gbps.

For the worst visibility value $V = 100$ m in the presence of dust, the simulated results for the maximum distances of the FSO link, chosen with a maximum BER $\leq 4 \times 10^{-11}$ are shown in Figure 13.

8. Results and discussion

The comparison of the theoretical and simulation performance results, as depicted in Figures 9 and 13, is summarized in Table 4 for the WDM-FSO link used in the 6G backhaul network. This comparison considers the worst visibility case ($V = 100$ m), a total bit rate of $B = 100$ Gbps (4×25 Gbps), a BER $\leq 4 \times 10^{-11}$, and different values of total optical amplifier gain ($g_t + g_r = 30, 40,$ and 50 dB).

Table 4. Performance comparison of WDM-FSO link distance with visibility V = 100 m.

Optical amplifier gain (dB)	Theoretical distance (m)	Simulation distance (m)
$g_t = g_r$ =15	211	195
$g_t = g_r = 20$	256	230
$g_t = g_r = 25$	292	266

The theoretical and simulation results presented in Table 4 clearly indicate that the FSO communication link has a limited range due to the performance degradation caused by the presence of dust. It can be seen from Table 4 that using two EDFA optical amplifiers with a total gain of $g_t + g_r = 30$ dB results in a maximum distance of 195 meters for the designed WDM-FSO backhaul link, which is a critical value needed to cover the required distance between the base station and the core network by considering a 100 m cell radius in the future 6G mobile system. In contrast, using two EDFA optical amplifiers with total gains of $g_t = g_r = 20$ dB or $g_t = g_r = 25$ dB is sufficient to meet the backhaul requirement.

9. Conclusion

This work demonstrates that dust causes significantly higher attenuation compared to fog, which has a dominant effect on the performance of FSO links in Iraq. Increased dust concentration leads to decreased visibility, higher BER, and consequently, a reduced FSO link distance. As the distance between the transmitter and receiver increases, the BER also increases. In this work, an FSO system using WDM technology and high-gain EDFA optical amplifiers has been designed to address these dust-related challenges and improve system performance, enabling the transmission of 100 Gbps over an FSO link. Results show that the designed FSO link can achieve a maximum distance of approximately 266 meters under the worst visibility condition at visibility ($V = 100$ m). This distance is sufficient for backhaul links for connecting base stations to the core network in 6G mobile communication systems, considering a cell radius of 100 m.

References

[1] H. A. Al-Tayyar and Y. E. Mohammed Ali, “A Review on Metamaterial Used in Antennas Design: Advantages and Challenges,” *Al-Rafidain Engineering Journal (AREJ)*, vol. 29, no. 1, pp. 106–117, 2024.

[2] A. M. Ahmed, S. A. Majeed, and S. A. Hasan, “Non-Terrestrial Networks Based on Non-Orthogonal Multiple Access Towards 6G,” *Diyala Journal of Engineering Sciences*, pp. 1–26, 2024.

[3] S. H. Ali and A. K. Jassim, “Single Layer Metamaterial Superstrate for Gain Enhancement of a Microstrip Antenna Array,” *Diyala Journal of Engineering Sciences*, pp. 144–172, 2024.

[4] S. A. Hasan, A. M. Ahmed, M. N. Abdulqader, and Y. S. Dawood, “Design and Simulation of 2 × 2 Micro Strip Circular Patch Antenna Array at 28 GHz for 5G Mobile Station Application,” *International Journal of Electronics and Telecommunications*, vol. 68, no. 4, 2022, doi: 10.24425/ijet.2022.143878.

[5] A. M. Ahmed, S. A. Majeed, and Y. S. Dawood, “A Survey of 6G Mobile Systems, Enabling Technologies, and Challenges,” *International Journal of Electrical and Electronic Engineering & Telecommunications*, vol. 12, no. 1, pp. 1–21, 2023, doi: 10.18178/ijeetc.12.1.1-21.

[6] S. N. Abdullah, F. E. Mohmood, and Y. E. M. Ali, “Study of the Impact of Antenna Selection Algorithms of Massive MIMO on Capacity and Energy Efficiency In 5G Communication Systems,” *Al-Rafidain Engineering Journal (AREJ)*, vol. 26, no. 2, pp. 164–170, 2021.

[7] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M. S. Alouini, “FSO-Based Vertical Backhaul/Fronthaul Framework for 5G+ Wireless Networks,” *IEEE Communications Magazine*, vol. 56, no. 1, 2018, doi: 10.1109/MCOM.2017.1600735.

[8] S. Chia, M. Gasparroni, and P. Brick, “The next challenge for cellular networks: Backhaul,” *IEEE*

Microwave Magazine, vol. 10, no. 5, pp. 54–66, 2009.

[9] S. Bloom, E. Korevaar, J. Schuster, and H. Willebrand, "Understanding the performance of free-space optics [Invited]," *Journal of Optical Networking*, vol. 2, no. 6, p. 178, Jun. 2003, doi: 10.1364/jon.2.000178.

[10] M. A. Esmail, H. Fathallah, and M. S. Alouini, "An Experimental Study of FSO Link Performance in Desert Environment," *IEEE Communications Letters*, vol. 20, no. 9, 2016, doi: 10.1109/LCOMM.2016.2586043.

[11] A. M. Al-Salihi and T. H. Mohammed, "The effect of dust storms on some meteorological elements over Baghdad, Iraq: Study Cases," *IOSR Journal of Applied Physics*, vol. 7, no. 2, 2015.

[12] P. Kaur, V. K. Jain, and S. Kar, "Effect of atmospheric conditions and aperture averaging on capacity of free space optical links," *Optical and Quantum Electronics*, vol. 46, pp. 1139–1148, 2014.

[13] M. A. Esmail, H. Fathallah, and M.-S. Alouini, "Effect of dust storms on FSO communications links," in *2016 4th international conference on control engineering & information technology (CEIT)*, IEEE, 2016, pp. 1–6.

[14] M. Singh, "Enhanced performance analysis of inter-aircraft optical wireless communication link (IaOWC) using EDFA pre-amplifier," *Wireless Personal Communications*, vol. 97, no. 3, pp. 4199–4209, 2017.

[15] J. A. Khalati, "Experimental Study of the Influence of Dust Particle on Link Range of Free Space Laser Communication System," *journal of the college of basic education*, vol. 24, no. 102, pp. 27–32, 2018.

[16] M. A. A. Ali, S. A. Adnan, and S. A. Al-Saeedi, "Transporting 8× 10 Gbps WDM Ro-FSO under various weather conditions," *Journal of Optical Communications*, vol. 41, no. 1, pp. 99–105, 2019.

[17] S. M. Yasir, N. Abas, and M. S. Saleem, "Performance Analysis of 10Gbps FSO Communication Link Under Suspended Dust and Rain Conditions in Lahore, Pakistan.," *Nonlinear Optics, Quantum Optics: Concepts in Modern Optics*, vol. 50, no. 4, 2019.

[18] M. A. A. Ali, F. K. Shaker, and H. A. Kadhum, "Investigation and analysis of data rate for free space optical communications system under dust conditions," *Wireless Personal Communications*, vol. 113, no. 4, pp. 2327–2338, 2020.

[19] M. A. A. Ali, Z. H. Baqi, and S. K. Rahi, "On the performance of free space optical communication link over dust environment," in *AIP conference proceedings*, AIP Publishing, 2020.

[20] A. Trichili *et al.*, "Retrofitting FSO Systems in Existing RF Infrastructure: A Non-Zero-Sum Game Technology," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2597-2615, 2021. doi: 10.1109/OJCOMS.2021.3130645.

[21] M. Z. Chowdhury, M. Shahjalal, M. K. Hasan, and Y. M. Jang, "The role of optical wireless communication technologies in 5G/6G and IoT solutions: Prospects, directions, and challenges," 2019. doi: 10.3390/app9204367.

[22] Abdulsattar M. Ahmed, Salim Abdullah Hasan, and Sayf A. Majeed, "5G Mobile Systems, Challenges and Technologies: A Survey," *Journal of Theoretical and Applied Information Technology*, vol. 97, no. 11, pp. 3214–3226, 2019, doi: 10.5281/zenodo.3256485.

[23] A. M. Ahmed, S. A. Majeed, and Y. S. Dawood, "6G THz-band facing propagation and atmospheric absorption losses," in *4th International Conference on Communication Engineering and Computer Science (CIC-COCOS'22), Erbil: Cihan University*, 2022, pp. 162–168.

[24] S. Ghatwal and H. Saini, "Investigations on challenges faced by hybrid FSO/RF high-speed networks," *Journal of Optics (India)*, vol. 52, no. 2, 2023, doi: 10.1007/s12596-022-00898-w.

[25] A. Ahmed, S. Gupta, Y. Luthra, K. Gupta, and S. Kaur, "Analysing the Effect of Scintillation on Free Space Optics Using Different Scintillation Models," in *2019 6th International Conference on Signal Processing and Integrated Networks, SPIN 2019*, 2019. doi: 10.1109/SPIN.2019.8711574.

[26] D. K. Borah and D. G. Voelz, "Pointing Error Effects on Free-Space Optical Communication Links in the Presence of Atmospheric Turbulence," *Journal of Lightwave Technology*, vol. 27, no. 18, 2009, doi: 10.1109/JLT.2009.2022771.

[27] P. H. Kuo and A. Mourad, "Millimeter wave for 5G mobile fronthaul and backhaul," in *EuCNC 2017 - European Conference on Networks and Communications*, 2017. doi: 10.1109/EuCNC.2017.7980750.

[28] UN Country Team in Iraq, "Sand and Dust Storm Fact Sheet," Feb. 2013.

[29] D. Francis, R. Fonseca, N. Nelli, D. Bozkurt, J. Cuesta, and E. Bosc, "On the Middle East's severe dust storms in spring 2022: Triggers and impacts," *Atmospheric Environment*, vol. 296, 2023, doi: 10.1016/j.atmosenv.2022.119539.

[30] NASA Earth Observatory, "Persistent Dust Storms Batter Iraq," Earth Observatory. Accessed: Aug. 25, 2024. [Online]. Available: https://earthobservatory.nasa.gov/images/149838/persistent-dust-storms-batter-iraq

[31] MSN Weather., "Iraq Weather Forecast," MSN Weather. Accessed: Nov. 29, 2023. [Online]. Available: https://www.msn.com/en-us/weather/forecast/

[32] M. A. Esmail, H. Fathallah, and M. S. Alouini, "Outdoor FSO Communications under Fog: Attenuation Modeling and Performance Evaluation," *IEEE photonics journal*, vol. 8, no. 4, 2016, doi: 10.1109/JPHOT.2016.2592705.

[33] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, and E. Bentley, "Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions,"

Journal of Lightwave Technology, vol. 31, no. 11, 2013, doi: 10.1109/JLT.2013.2257683.

[34] T. A. Taha, S. A. Ayoob, and M. T. Yaseen, "Raman/EDFA Hybrid System to Enhance the Optical Signal in the Optical Network," *Journal of Communications*, vol. 18, no. 10, 2023, doi: 10.12720/jcm.18.10.621-628.

[35] E. Gramsch, "Noise characteristics of avalanche photodiode arrays of the bevel-edge type," *IEEE Trans Electron Devices*, vol. 45, no. 7, 1998, doi: 10.1109/16.701493.

[36] J. M. Senior and M. Y. Jarno, *Optical fiber communication principles and practice*, 3rd Ed. Pearson Education, Edinburgh Gate, Harlow, Essex, England. 2009.