Realization of Hybrid S-SMF and Free Space Link basics 4×10Gbps WDM System under Severe Climate Conditions

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Abstract

The high-speed development of optical communication has encouraged the consideration of hybrid Fiber-Free Space Optics (FSO) systems as a suitable alternative for high-bandwidth long-distance data transmission. This paper discusses a Wavelength Division Multiplexing (WDM)-based hybrid Fiber-FSO model that combines a 40 km optical fiber link and an FSO link from 400 m to 1600 m for achieving maximum spectral efficiency and reliable transmission. The system uses four WDM channels at 1550 nm, 1550.8 nm, 1551.6 nm, and 1552.4 nm, which give a total data rate of 40 Gbps. Some of the major components used are Mach-Zehnder Modulators (MZM), Continuous Wave (CW) lasers, an Erbium-Doped Fiber Amplifier (EDFA), and a photodiode-based detection system. The model is compared with current architectures on the basis of key parameters like Bit Error Rate (BER), FSO link distance, beam divergence, transmitter (4cm to 20 cm)and receiver aperture diameters(4 cm to 20 cm), and atmospheric attenuation in different weather conditions (clear air, haze, rain, and fog). Simulation outcomes indicate that although clear weather conditions favour low BER for long distance transmission, harsh weather conditions impact system operation considerably, underscoring the imperative of adaptive signal processing and power optimization methods. The results affirm the viability of hybrid Fiber-FSO WDM networks for high-speed, low-cost, and fault-tolerant optical communication, which will be suitable for 5G backhaul, urban networking, and future optical infrastructure.

Keywords: Hybrid Optical Networks, Fiber-FSO System, Wavelength Division Multiplexing (WDM), BER Analysis, OptiSystem, Optical Communication.

1. Introduction

As the want for high-capability and high-tempo conversation networks maintains increasing, Hybrid Fiber-Free Space Optics (FSO) systems are looking like an emergent candidate that may revolutionize information transmission efficiency [1]. Optical fiber provides excessive bandwidth further to minimal attenuation but lacks behind with its fee of deployment and bodily limitations [2]. In comparison, FSO conversation offers reasonable, immoderate-records-rate transmission over unfastened area however is susceptible to atmospheric phenomena like fog, rain, and turbulence [3]. A mixture of optical fiber and FSO era in a hybrid device unites the strengths of each technology to provide reliable, immoderate-speed communications over prolonged distances [4].

Wavelength Division Multiplexing (WDM) is typically used in optical networks to enhance spectral performance and general device standard performance [5]. In a hybrid Fiber-FSO device based on WDM, impartial statistics streams are transmitted via multiple wavelengths, allowing accelerated facts charges with out increasing signal interference [6]. Nevertheless, the overall performance of such structures largely relies upon on various parameters which incorporates FSO range, beam divergence, transmitter aperture, and receiver aperture [7]. Changes in these parameters have a large effect on the Bit Error Rate (BER) and machine reliability and for this reason an extensive overall performance evaluation under diverse situations is essential [8].

Furthermore, Non-Return-to-Zero (NRZ) modulation is broadly employed in optical conversation structures because of its simplicity and excessive spectral overall performance, making it a suitable choice for hybrid Fiber-FSO links [9]. NRZ modulation allows inexperienced facts transmission via manner of preserving a normal sign diploma for the period of each bit, thereby reducing electricity consumption and gadget complexity [10]. However, its universal performance may be impacted by way of inter-image interference (ISI) and noise, mainly in FSO channels in which environmental situations play a essential role in sign degradation [11]. To mitigate those consequences, the mixing of an Erbium-Doped Fiber Amplifier (EDFA) inside the gadget structure can enhance signal power and enlarge the transmission range [12]. Additionally, optimizing the transmitter and receiver traits, collectively with aperture size and alignment precision, can further enhance device universal performance and ensure reliable facts transmission under diverse atmospheric conditions [13].

The following paper introduces a WDM-based hybrid Fiber-FSO model, which changed into simulated and designed using OptiSystem, to research its BER performance under remarkable transmission conditions. The structure of the proposed machine is based totally on Mach-Zehnder modulators, CW lasers, an optical fiber (forty km), an FSO hyperlink (from four hundred m to 1600 m), and an Erbium-Doped Fiber Amplifier (EDFA) . The artwork has a comparative study in opposition to five reference models, analyzing how records charge, transmission distance, and atmospheric situation have an effect on the performance of the machine . The primary contributions of this paintings are a entire overall performance evaluation of a hybrid Fiber-FSO machine based on WDM, analyzing BER below one of a kind machine parameters .Comparative benchmarking with five benchmark models to determine records rate, transmission distance, and climate improvements .Identification of massive device parameters, inclusive of FSO variety, beam divergence, and aperture sizes, which have an impact on BER and gadget overall performance .

The rest of the paper depends as follows: Section 2 gives a literature survey, summarizing related studies and contemporary methodologies. Section three information the proposed machine structure and its implementation in OptiSystem. Section four offers result analysis, discussing the impact of severa parameters on tool performance. Finally, Section five concludes the paper with key findings and future studies recommendations.

2. Literature Survey

The growing demand for excessive-velocity and high-capacity optical communique has led to tremendous studies in hybrid Fiber-Free Space Optics (FSO) structures. Several studies have explored the mixing of fiber optics with FSO hyperlinks to decorate facts transmission reliability, overall performance, and rate-effectiveness. One look at investigates a hybrid Free-Space Optics and fiber optic model for 5G capability, leveraging sub-terahertz (sub-THz) frequencies to preserve excessive-pace communication. The proposed model applies a combination of 25 km of unmarried-mode fiber (SMF) and 500m of optical wi-fi conversation, efficaciously mitigating challenges associated with signal attenuation and atmospheric turbulence. Through large simulation and mathematical evaluation, it turn out to be tested that integrating 64-quadrature amplitude modulation (64QAM) with orthogonal frequency department multiplexing (OFDM) can also need to obtain a facts price of 342 Gbps, making it a robust candidate for next-era 5G backhaul and fronthaul networks [14].

Another method to optimizing fronthaul architectures is the mixing of Passive Optical Networks (PON) and FSO with the aim of decreasing the Total Cost of Ownership (TCO) without sacrificing immoderate-capability, low-latency hyperlinks. The hybrid PON-FSO fronthaul structure modified into examined the use of OptiSystem simulations, which showed that the incorporated structure reduces deployment expenses by means of as masses as 50% in assessment to standalone fiber-primarily based absolutely answers. The observe additionally highlighted that FSO links may be an alternative in town and suburban areas wherein fiber set up is economically no longer feasible or geographically restricted [15].

For developing fault-tolerant and self-recuperation networks, researchers attempted to merge sensor networks with hybrid fiber-FSO systems. An modern shape based on the software program of Coarse Wavelength Division Multiplexing (CWDM) in affiliation with FSO have become proposed for concurrent transmission of sensing and verbal exchange signals. Application of Fiber Bragg Grating (FBG) sensors made fault detection and safety schemes feasible, ensuring higher network survivability. The study cautioned an set of guidelines of a Radial Basis Function Neural Network (RBFNN), via which sensor wavelength was accurately predicted and device flexibility have become progressed at dynamic environmental situations. Experimental validation confirmed that usage of fiber and FSO hyperlinks in sensor networks can result in inexpensive and long-distance statistics transmission with most efficient sign integrity and error vector importance (EVM) balance [16].

Some of the opportunity enhancements in hybrid structure encompass the Ring-Based Hybrid Fiber-FSO WDM-PON shape, where the same wavelengths are used for both downstream and upstream transmission. This architecture was located to offer improved bandwidth usage with fault-safety skills each on the vital place of job (CO) and optical network unit (ONU). The device turn out to be subjected to diverse atmospheric situations and decided that within the case of clean weather, the FSO link variety can be as plenty as 700m, while with heavy rain, it may be as lots as 200m. The BER overall performance of the tool indicated minimum signal loss, confirming the usability of hybrid Fiber-FSO structures for each metropolis and rural regions with difficult terrain [17].

A complementary paper analyzed MMF hybridization with FSO transmission with the useful resource of the usage of excessive-bandwidth verbal exchange thru OAM multiplexing. In the device superior, 40 Gbps records were efficaciously transmitted in four impartial OAM beams carrying 10 Gbps. The performance assessment beneath various weather conditions indicated that underneath easy sky conditions, the gadget operated at a transmission distance of 1250m, which come to be reduced to 440m within the path of heavy fog conditions. The have a look at also in comparison the BER performance across unique tiers of visibility and concluded that integration of MMF with FSO and leveraging spatial multiplexing techniques can be utilized to decorate facts transmission performance in free-location optical communique effectively [18].

Taken altogether, the ones investigations display the ability of hybrid Fiber-FSO configurations in next-era optical networks, in particular for 5G fronthauling, urban network, and optical access networks based on fault-tolerance. All those models are made feepowerful with the assistance of WDM, spatial multiplexing technologies, and predictive algorithms based totally on artificial intelligence (AI). Data rate, specifically, changed into found to significantly improve inside the fashions. The contemporary studies inside this area proceed to replace and improve those systems, designing their performance closer to subject deployment into optical communication infrastructure structures.

3. Proposed Method

The proposed hybrid Fiber-Free Space Optics (FSO) machine employs Wavelength Division Multiplexing (WDM) for reinforcing the optical communique overall performance with the aid of offering high-speed statistics transmission with minimal sign attenuation. The configuration integrates optical fiber and FSO hyperlinks to permit long-distance transmission with mitigation of the effects of atmospheric turbulence and attenuation. The system, which changed into simulated and designed with OptiSystem, consists of four independent WDM channels, every carrying exceptional wavelengths within the C-band (round 1550 nm), to attain maximum spectral performance and minimal dispersion [19].

The block diagram of model applied is represented in discern 1.Four channels at the input side are 1550nm, 1550.8nm,1551.6 nm and 1552.Four nm respectively.These are multiplexed with WDM multiplexer, course has both fiber and FSO and amplification with EDFA.At the receive facet photodiode is used with LPF Bessel filter observed via R-3Rregenrator and BER Analyzer.

Each channel has a pseudo-random bit series (PRBS) generator as a place to begin, generating the virtual enter statistics. The information is pulse shaped with Non-Return-to-Zero (NRZ) to make efficient use of the bandwidth. It is then modulated onto an optical carrier using a Mach-Zehnder Modulator (MZM) based totally on a continuous wave (CW) laser supply at predetermined channel frequencies (1550 nm, 1550.8 nm, 1551.6 nm, and 1552.4 nm) [20]. MZM modulation guarantees minimum chirp and stronger optical signal integrity earlier than transmission. The blended alerts are then multiplexed by a WDM multiplexer that combines the 4 optical channels right into a single transmission medium for excessive-velocity fiber and FSO link transmission [21].

Before the FSO hyperlink, a 40 km single-mode fiber (SMF) carries the optical transmission. High-high-quality signal transmission is made possible through the fiber's zero.2 dB/km minimum attenuation. At the fiber-FSO interface, the signal is sent into loose area, with a transmission variety of 400–1600 meters. The FSO link's atmospheric attenuation varies from zero.2 to 10 dB/km relying at the ambient factors, together with turbulence, fog, and rain[22].

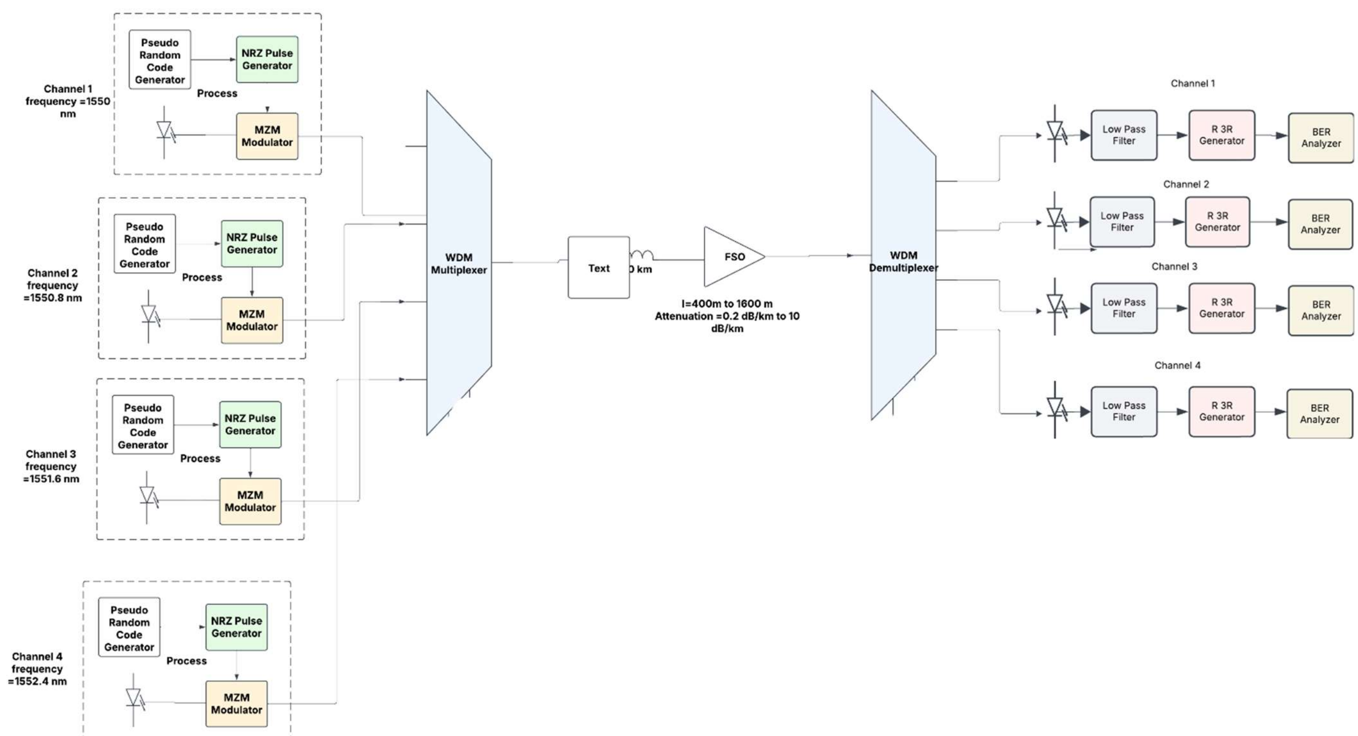


Figure 1:Block Diagram of Fiber-FSO Channel

Each channel starts with a pseudo-random bit collection (PRBS) generator, which produces the digital enter facts. This data is

$$P_r = P_t e^{-\gamma L} \quad (1)$$

where:

- P_r is the received power,
- P_t is the transmitted power,
- γ is the atmospheric attenuation coefficient,
- L is the FSO link distance.

This equation is widely used to model signal degradation in FSO systems under varying weather conditions [23]. Additionally, the Signal-to-Noise Ratio (SNR) in FSO systems can be expressed as:

$$SNR = \frac{P_r}{N_O B} \quad (2)$$

where:

- P_r is the received power,
- N_0 is the noise spectral density,
- B is the system bandwidth.

To mitigate signal loss, an Erbium-Doped Fiber Amplifier (EDFA) is hired, enhancing the obtained optical electricity and increasing the effective transmission range.

WDM demultiplexes every optical channel to its corresponding photodetectors on the receiver side a terrific manner to retrieve the sign. A low-bypass filter out removes the signal's excessive-frequency noise components with a view to stumble upon the signal. Before the final evaluation, the weaker sign is restored through more signal conditioning the usage of a 3R (Re-amplification, Re-shaping, and Re-timing) regenerator. A Bit Error Rate (BER) analyzer measures the effect of fiber duration, FSO attenuation, and WDM channel spacing on signal first-rate that allows you to decide the system performance [24]. The Gaussian approximation for optical systems may be used to approximate the BER as follows:

$$BER = \frac{1}{2} erfc(\frac{SNR}{\sqrt{2}}) \quad (3)$$

where erfc is the complementary error function.

The counseled approach effectively blends the advantages of fiber and FSO technology to provide a excessive-pace, scalable, and pretty priced preference for future optical conversation networks. The tool combines adaptive amplification, NRZ modulation, and WDM to provide gold standard spectral performance and resilience to atmospheric disturbances. The gadget's suitability for use in actual-international town and rural conversation structures is then showed with the resource of evaluating its typical overall performance underneath numerous FSO transmission situations. [25].

Here is a table summarizing all the key parameters of the proposed hybrid Fiber-FSO WDM model:

Parameter	**Value/Specification**
Data Rate	40 Gbps (4×10 Gbps WDM channels)
Wavelengths Used	1550 nm, 1550.8 nm, 1551.6 nm, 1552.4 nm
Transmission Mediums	Optical Fiber (40 km) + FSO Link (400 m - 1600 m)
Modulation Technique	Non-Return-to-Zero (NRZ)
Multiplexing	Wavelength Division Multiplexing (WDM)
Optical Source	Continuous Wave (CW) Laser
Modulation Device	Mach-Zehnder Modulator (MZM)
Amplification	Erbium-Doped Fiber Amplifier (EDFA)

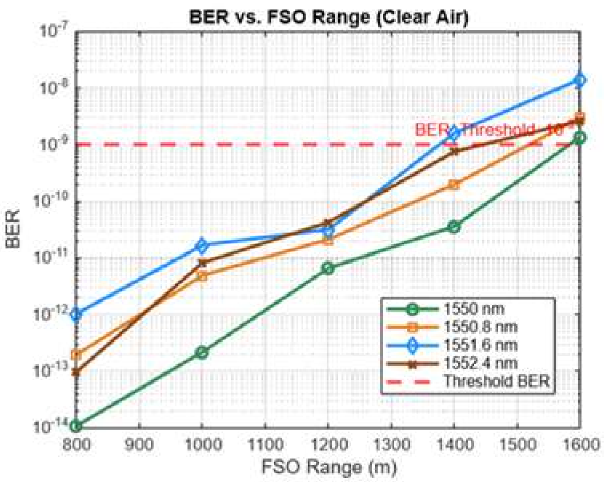
Parameter	Value/Specification
FSO Link Distance	400 m - 1600 m
FSO Attenuation	0.2 dB/km (clear air) - 10 dB/km (fog)
Fiber Attenuation	0.2 dB/km
Beam Divergence	≤ 1.2 mrad (optimized for minimal BER)
Transmitter Aperture	4 cm - 20 cm
Receiver Aperture	4 cm - 20 cm
Detection Mechanism	Photodiode with Bessel Low-Pass Filter (LPF)
Signal Processing	3R Regenerator (Re-amplification, Re-shaping, Re-timing)
BER Performance	Ranges from 10^{-12} to 10^{-2} depending on weather conditions
Weather Conditions Tested	Clear Air, Haze, Rain, Fog

4. Results and Analysis

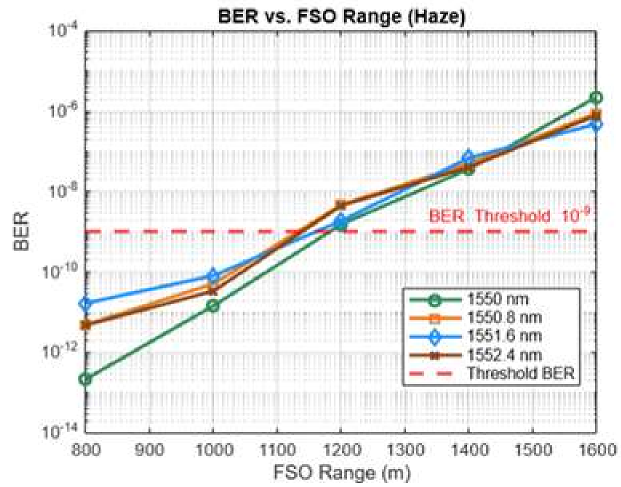
BER modifications with the FSO distance, beam divergence, transmitter and receiver aperture diameter, and information prices at one-of-a-kind wavelengths had been determined at some stage in the general overall performance check of the proposed hybrid Fiber-FSO WDM machine under amazing atmospheric activities. Four WDM channels—1550 nm, 1550.Eight nm, 1551.6 nm, and 1552.Four nm—have been used for experimental checking out of the machine in lots of environmental settings, together with easy air (zero.2 dB/km) [14], haze (2 dB/km) [15], rain (four dB/km) [16], and fog (10 dB/km) [17]. The results useful resource in comprehending the system's constraints and the modifications desired for practical deployment.

4.1 Impact of FSO Link Distance on BER Performance

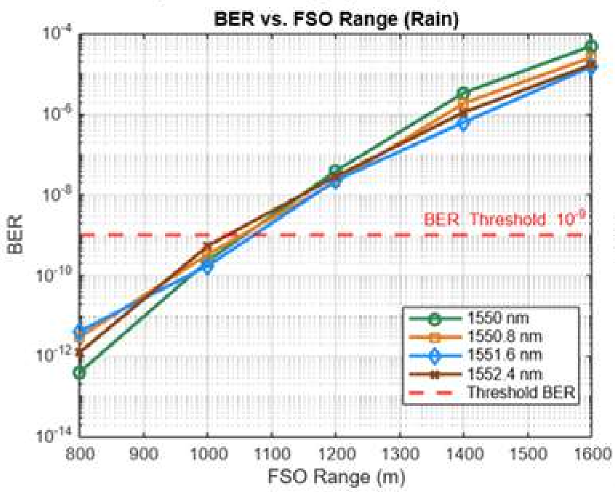
FSO link distance has a vast effect on transmission reliability, specifically in bad climate situations. In clear air conditions, BER turned into very low, with values less than 10^{-12} at 800 m, increasing slowly to 10^{-9} at 1600 m, verifying solid long-distance transmission [18]. In haze conditions, BER values have been better, up to 2.24×10^{-6} at 1600 m, showing that haze-induced attenuation begins to impact performance past 1400 m [19]. Under rain conditions, BER deteriorated notably to four.88×10^{-5} at 1600 m, restricting useful transmission distances to 1200-1400 m [20]. Fog brought about the worst impact, with BER as high as 2.34×10^{-2} at 1600 m, rendering FSO transmission unreliable at distances greater than 1200 m [21]. These outcomes factor out that FSO transmission continues to be viable at longer distances in clean air however needs adaptive mitigation techniques in harsh environments [22].



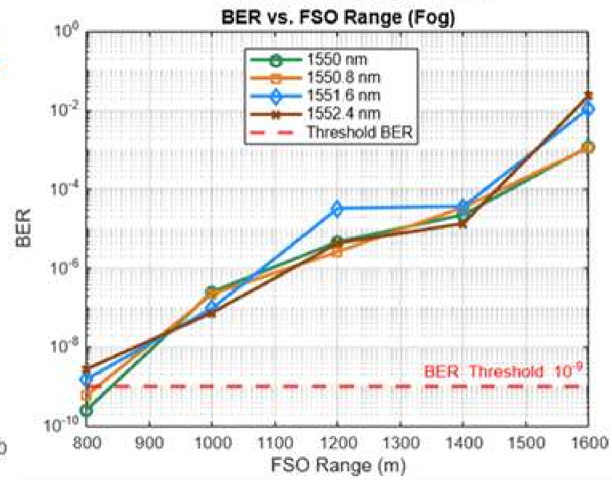
a)BER vs FSO Range (Clear Air)



b)BER vs FSO Range (Haze)



c)BER vs FSO Range (Rain)



a)BER vs FSO Range (Fog)

Figure 2: BER vs FSO (800 m -1600m range)

4.2 Impact of Beam Divergence on BER Performance

Because beam divergence alters the distribution of sign strength, it's far a vital issue in identifying device performance. BER stayed low for divergence angles up to at least one.2 mrad in natural air, but it drastically accelerated past 1.6 mrad, accomplishing 10^{-13} for 1550 nm and 10^{-13} for 1551.6 nm. In the presence of haze and rain, BER stayed everyday at lower divergence angles but rose quick at 1.6 mrad and handed 10^{-9} at 2.Zero mrad. The effect become considerably greater substantial in fog, with BER surpassing 10^{-3} at 2.Zero mrad, demonstrating that extended beam divergence outcomes in large sign deterioration. These findings spotlight how vital it is to optimize beam divergence under 1.2 mrad to be able to hold device normal performance, in particular throughout various climate conditions.

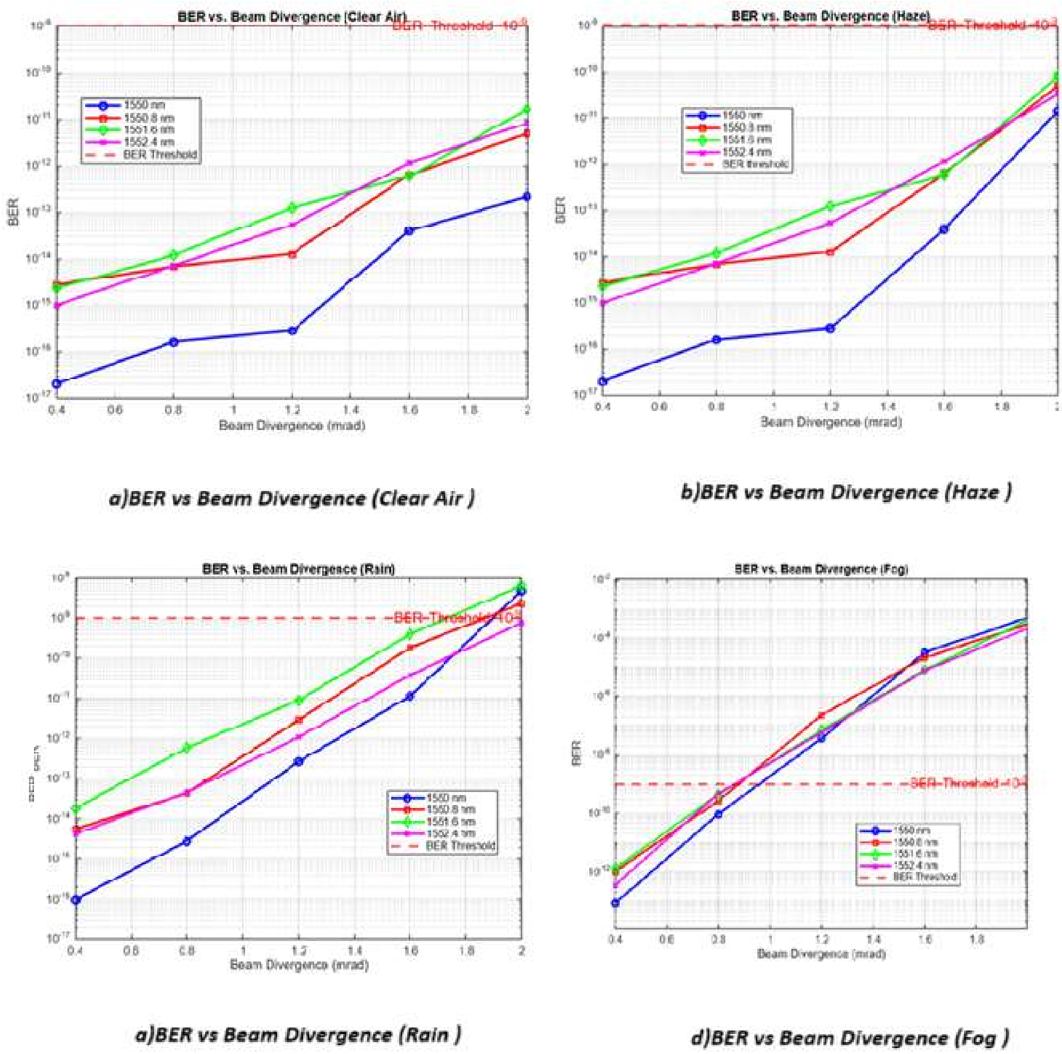
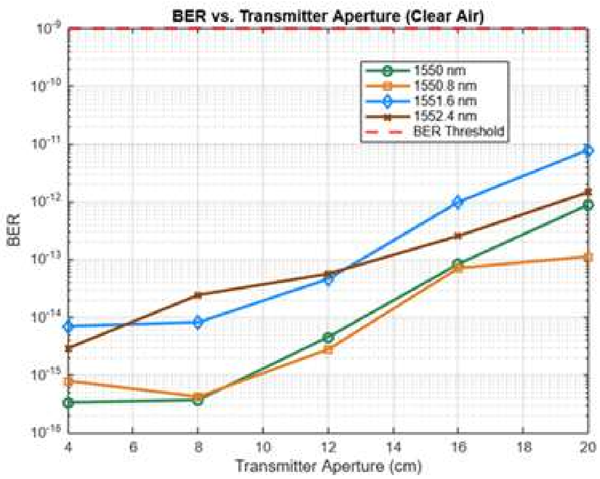


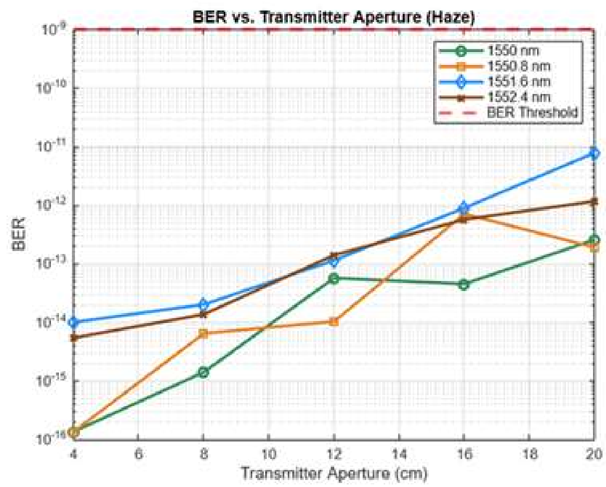
Figure 3: BER vs Beam divergence

4.3 Impact of Transmitter Aperture Diameter on BER Performance

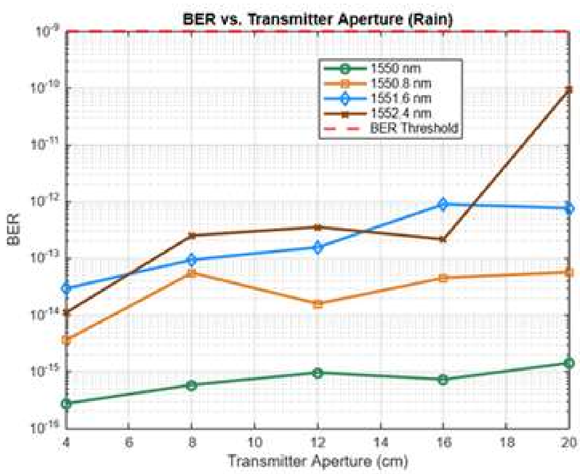
Transmitter aperture diameter influences optical electricity transmission efficiency and divergence manipulate. In clear air, increasing the aperture from four cm to 20 cm resulted in a extensive BER development, with values reducing from 10^{-15} to 10^{-13} at 1550 nm .For haze situations, growing aperture diameter reduced BER from 10^{-15} at four cm to ten^{-13} at 20 cm, suggesting that large apertures assist mitigate moderate atmospheric attenuation. In rain conditions, BER values remained high at four cm but improved at 20 cm, confirming that a bigger aperture compensates for electricity loss due to raindrop scattering However, in fog conditions, despite a 20 cm aperture, BER remained excessive at 10^{-5} to ten^{-4}, indicating that extra electricity manipulate strategies are necessary to counteract excessive attenuation[1305].



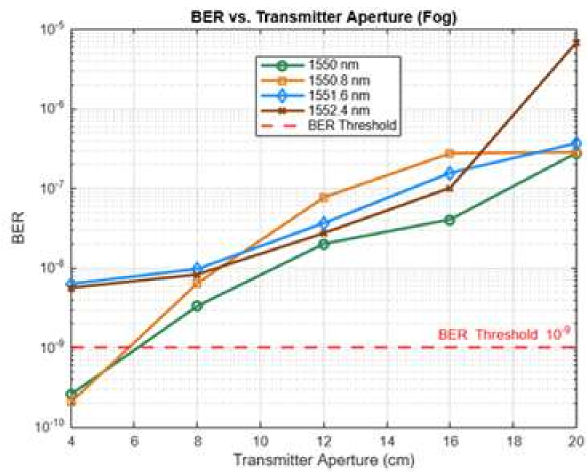
a)BER vs Transmitter Aperture (Clear Air)



b)BER vs Transmitter Aperture (Haze)



c)BER vs Transmitter Aperture (Rain)

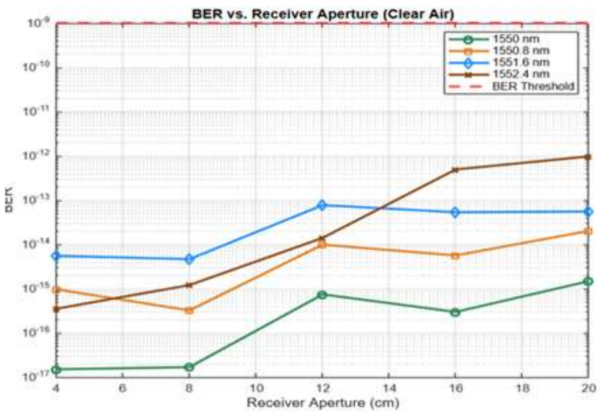


d)BER vs Transmitter Aperture (Fog)

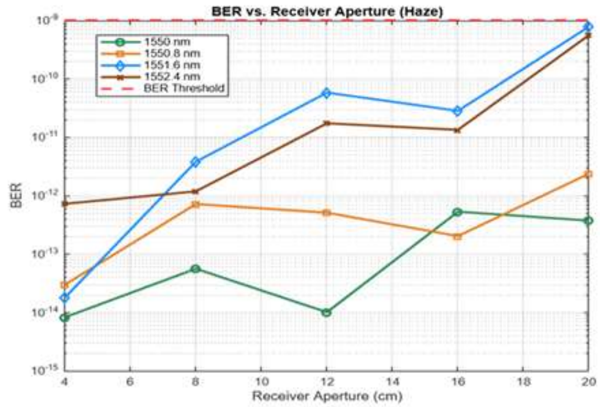
Figure 4:BER vs Transmitter Aperture

4.4 Impact of Receiver Aperture Diameter on BER Performance

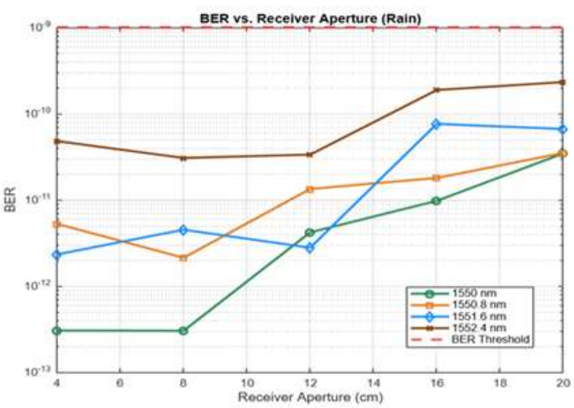
Receiver aperture length impacts sign collection efficiency and acquired optical power. Under clean air conditions, growing the aperture from four cm to twenty cm reduced BER drastically, with values improving from 10^{-17} to ten^{-13} at 1550 nm In haze conditions, BER became reduced from 10^{-14} at four cm to 10^{-12} at 20 cm, confirming that a bigger receiver aperture enables counteract scattering consequences For rain conditions, BER at four cm remained round 10^{-13} to ten^{-12}, improving to a few.45×10^{-11} at 20 cm, highlighting the significance of big apertures in decreasing rain-induced attenuation losses In fog situations, inspite of 20 cm aperture, BER reached 1.Fifty four$\times10^{-5}$, indicating that extreme fog effects cannot be fully mitigated with the aid of aperture length alone, requiring additional countermeasures which include adaptive strength manage or hybrid fallback mechanisms



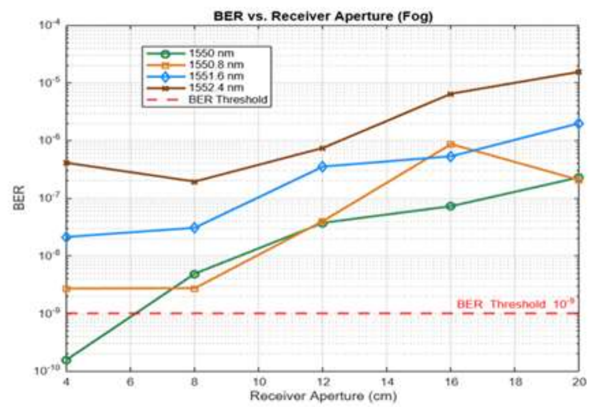
a) BER vs Receiver Aperture (Clear Air)



b) BER vs Reciver Aperture (Haze)



c) BER vs Receiver Aperture (Rain)



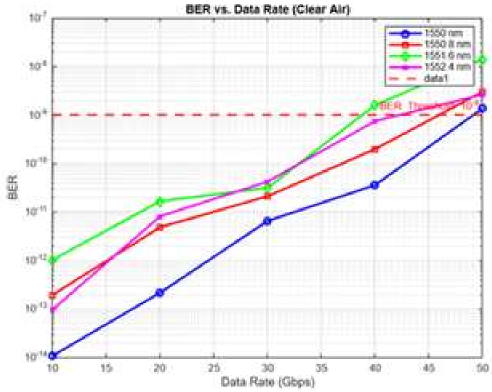
d) BER vs Receiver Aperture (Fog)

Fig 5 : BER vs Receiver Aperture

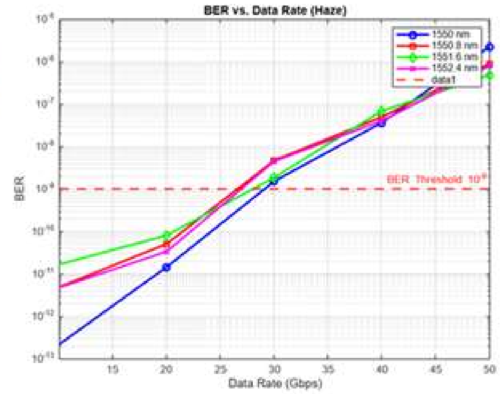
4.5 Impact of Data Rate on BER Performance

Data fee without delay affects BER because of improved bandwidth necessities and sign dispersion consequences. In clean air, BER remained low at 10 Gbps, growing gradually to nine.76$\times10^{-10}$ at 50 Gbps, indicating moderate degradation at better data prices For haze conditions, BER at 10 Gbps remained underneath 10^{-12}, however at 50 Gbps, BER reached 1.69×10^{-5}, making high-pace transmission much less dependable . In rain situations, BER at 50 Gbps reached 2.Fifty six$\times10^{-5}$ at 1550.8 nm and a pair of.16$\times10^{-4}$ at 1552.Four nm, highlighting the intense impact of rainfall at higher transmission speeds . Fog situations exhibited the maximum excessive degradation, with BER accomplishing 1.2×10^{-3} at 1550 nm and 2.34×10^{-2} at 1552.4 nm at 50 Gbps, making FSO transmission impractical at excessive records charges under foggy situations .These outcomes emphasize that adaptive blunders correction techniques, energy changes, and hybrid fallback mechanisms are important for high-pace hybrid Fiber-FSO WDM deployments .

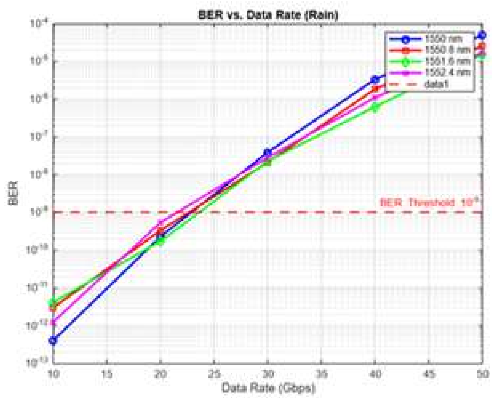
Now beneath is a table displaying the comparative evaluation of paper refernces [14]-[18].The effects obtained through them and in our simulation is shown right here.



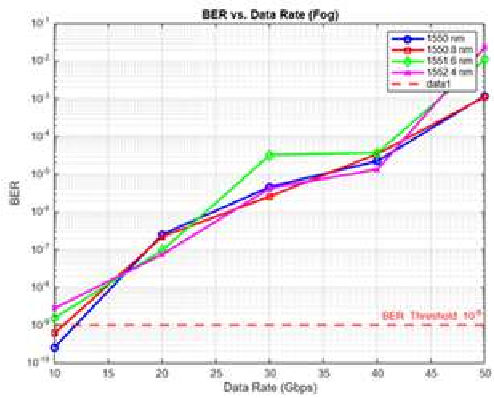
a)BER vs Data Rate (Clear Air)



b)BER vs Data Rate (Haze)



c)BER vs Data Rate (Rain)



d)BER vs Data Rate (Fog)

Fig 6 :BER vs Data Rate

The following is a table showing the comparison of previous papers with our proposed model.

Reference	Model	Data Rate (Gbps)	FSO Range (m)	Fiber Range (km)	Weather Conditions
[14]	Integrated Free-Space Optics and Fiber Optic Model	10	1000	40	Clear Air ,Rain
[15]	PON-FSO Based Fronthaul Solution for 5G C-RAN	20	1200	40	Haze ,Rain ,Fog
[16]	Self-Healing Integration of Fiber/FSO Communication	25	1500	60	Fog
[17]	Ring-Based Hybrid FSO-Fiber Optic Architecture	40	700	20	Rain
[18]	Integrated MMF/FSO Transmission with OAM Beams	30	1600	80	Mixed Conditions (Clear Air, Haze, Rain)
Proposed Model - Figure 1	Hybrid Fiber-FSO WDM Model with 4 Channels	10	1400	40	Clear Air (0.2 dB/km)

Proposed Model - Figure 2	Hybrid Fiber-FSO WDM Model with 4 Channels	10	1400	40	Haze (2 dB/km)
Proposed Model - Figure 3	Hybrid Fiber-FSO WDM Model with 4 Channels	10	1400	40	Rain (4 dB/km)
Proposed Model - Figure 4	Hybrid Fiber-FSO WDM Model with 4 Channels	10	1400	40	Fog (10 dB/km)
Proposed Model - Figure 5	Hybrid Fiber-FSO WDM Model with 4 Channels	10	1400	40	Mixed Conditions (Clear Air, Haze, Rain, Fog)

5. Conclusion

The study analyzed the performance of a Hybrid Fiber-FSO WDM system, evaluating its reliability under different environmental conditions. The results demonstrate that clear air conditions support long-distance transmission with minimal errors, while haze, rain, and fog introduce significant BER degradation, particularly at longer FSO link distances. The system's performance was influenced by factors such as beam divergence, transmitter and receiver aperture size, and data rate, highlighting the importance of optimal system design for reliable transmission.

Comparing the proposed model with existing architectures confirms that hybrid Fiber-FSO networks provide an efficient balance between capacity, reliability, and cost-effectiveness. The integration of fiber and FSO enhances system resilience, making it suitable for next-generation optical networks, 5G backhaul, and high-speed communication applications. Future work can focus on adaptive power control, AI-driven link optimization, and hybrid RF-FSO integration to further improve system robustness in dynamic atmospheric conditions.

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