An Effective Design of Hybrid Spectrum Slicing WDM–PDM in FSO Communication System Under Different Weather Conditions

Ekta Vasani[1] · Vrushank Shah[1]

Abstract

The free space optical communication system addressed as optical wireless communication has recently received huge attention. Communication acts as the possible way to address the link capacity and spectral efficiency issues. Due to the requirement of fundamental features like higher data rate transmission, improved data security and congestion-free transmission through the atmosphere, effective research interest is aroused in Free space Optic communication systems. As the Free space Optic technology exchanges a technological legacy with optical fibre communication, the Free space Optic links can deliver effective bandwidth. Even though it provides effective link reliability, the disastrous effect is faced due to the accordance of atmospheric attenuations like rain, snow, fog and so on. Hence, to promote effective data transmission, a hybridized model called spectrum slicing–wavelength division multiplexing–polarization division multiplexing (SS–WDM–PDM) is projected in this research work. The major objective of the projected work is to maximize the link capacity and enhance spectral efficiency. The attenuation noises like light rain, heavy rain, medium rain and light fog are considered to evaluate the outcomes of a Free space Optic communication system. The outcomes of the SS–WDM–PDM-FSO system are analyzed for numerous building heights and wind speeds for distance and received power. The parameters like an optical signal-to-noise ratio (OSNR), bit error rate (BER) and Q factor are contemplated to evaluate the performance. The simulation tool adopted to analyze the performance is MATLAB.

Keywords Optical signal · Electrical signal · Atmospheric attenuations · Link capacity · Spectral efficiency · Free space optic channel

1 Introduction

The huge bandwidth of digital data between various facts with the assistance of light rays is transmitted and received through the adoption of Free space Optic (FSO) communication systems [1]. Because of its significant advantages, FSO communication has possessed

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valuable attention in recent years [2, 3]. Through the utilization of FSO, license-free bandwidth can be acquired. It is highly cost-effective compared to optical fiber and radio frequency communication systems [4]. When the optical fiber link is complex during deployment and seems infeasible, the FSO system renders broader bandwidth by neglecting radio and electromagnetic interference [5]. This operates in data ranging from 100MBPS to 1.2 TBPS. FSO communication systems possess high speed as they can be transmitted effectively through space rather than using fiber optic cables.

FSO system comprises an optical transceiver on either side to offer the full duplex ability. It is a line of sight (LOS) technology that can be used to attain effective communication [6, 7]. High popularity is attained through FSO communication technology in most sectors, including military purposes, outdoor wireless services and natural surroundings [8]. The FSO communication system is recently utilized in most services: Storage area networks, large mile access, fiber backup, enterprise connectivity, metro network extensions, Wide area network access bridging, service acceleration and backhaul [9, 10]. An effective advantage of the FSO system [11] is rendering a flexible network that provides improved speed compared to broadband. Also, an easy installation process, secure system, low initial investment, high data rate, low chances of interference, less power consumption and flexible rollouts can be attained.

The data transmission channel for an FSO link is the atmosphere, whereas the attenuation caused by the FSO system depends upon various conditions [12]. Atmospheric circumstances act as the major source of attenuation, and the particular region where a link is being generated possesses some specified weather conditions [13]. Because of this, the preceding information regarding attenuation can be gathered. For instance, fog and heavy snow were considered to be the two fundamental conditions [14, 15]. Haze and heavy rain are the major weather conditions in tropical regions that hugely affect the FSO link availability in that region. The presence of fog considerably attenuates the radiation exposure, and rain attenuation emerges due to a non-selective scattering of rainfall [16]. During heavy rain, the beam passage gets restricted.

Various research has been conducted to alleviate the influences of atmospheric turbulences like Wavelength division multiplexing (WDM) [17] and Polarization division multiplexing (PDM) [18]. WDM is a significant methodology used to integrate various optical carriers into a single beam for free space transmission [19]. Every carrier holds its wavelength called a channel that enhances the system capability by raising the channel number and space tightening with a single FSO link. But, WDM systems are highly affected by the atmospheric turbulences that tend to lower bit rate transmission. The PDM is used to enhance the efficacy of an FSO system. In contrast, the orthogonal forms of polarization are adopted to transfer optical signals by which the communication system's capacity can be improved efficiently [20].

But due to unforeseen atmospheric attenuations, the link capacity and user consistency cannot be improved to a greater extent. In most cases, some environmental challenges cannot be excluded. Some FSO communication system challenges are due to physical obstructions like trees, tall buildings and birds. The temperature variations, geometric losses and water molecule absorption are also tending FSO as challenging. Still, most research works have been generated to create spectrum slices to boost the weak signal but support more complexity and reduced data rate. Motivated by these challenges, a novel hybrid methodology is proposed in this research article to improve the link capacity and spectral efficiency of the FSO system. Also, atmospheric attenuations, including light rain, light fog, moderate rain and heavy rain, are considered in the proposed model.

Some prominent contributions to enhancing the FSO communication system in the proposed research work are described below:

- A novel hybrid methodology is introduced for system enhancement to improve the link capacity and spectral efficiency of the FSO system.
- The design of an efficient hybrid methodology called SS–WDM–PDM is implemented for effective data transmission in the FSO system.
- The performances of a proposed research work are evaluated by considering the atmospheric attenuations like a light fog, heavy rain, light rain, and moderate rain and are estimated by varying channels.

The structure of proposed research work is organized into various sections. Section 2 describes the survey of recent approaches employed to enhance the FOS system performance. Section 3 represents the proposed methodology with the design specifications of various system configurations through effective approaches. The performance outcomes evaluated in the MATLAB platform are provided in Sect. 4. Finally, the overall conclusion and the future scope with references are given in Sect. 5.

2 Related Works

Depending on various methodologies, most researchers have implemented numerous works for promoting effective data transmission in FSO systems. Some of the recent models adopted by the researchers are surveyed as follows:

The FSO system was developed by Alshaer et al. [21] based on hybrid M-ary pulse position modulation (MPPM) and BB84 protocol through the Gamma-Gamma turbulence medium holding pointing errors. To maximize the system safety and minimize the Quantum Bit Error Rate (QBER), time binning is established through MPPM. Under the guidance of enormous noise and severe photon count attacks, the system's security is discovered. To verify the analytical result validity, the Monte-Carlo simulations are utilized. Some of the asymptotic expressions, including Secret key rate (SKR), Symbol error probability (SEP) and Raw key rate (RKR), were established. The ideal outcomes for an average photon amount per pulse for every symbol distance can support the constancy of FSO. The lowering system performance due to weather condition variations is a major drawback.

Mottaleb et al. [22] introduced Spectral amplitude coding optical code division multiple access (SAC-OCDMA) to investigate the FSO communication system's performance. Improved double-weight codes were utilized in this research as the signature codes simultaneously. Two approaches called Modified AND subtraction and Single photodiode was used to eradicate the phase-persuaded intensity noise and multiple access interferences for efficient detection and improved FSO performance. The gathered results show better system performance through prominent modification. The performance is estimated to Q factor, BER, attained power and propagation distance. The major drawback faced in this research was optimal solution cannot be obtained in the case of long-haul bandwidth transmission networks.

Through the hybridization of Circular polarization division multiplexing (CPDM) and coherent optical orthogonal frequency division multiplexing (CO-OFDM), a prominent design was established by Chowdhury et al. [23]. The performances are evaluated by considering the atmospheric turbulence of Bangladesh. For the turbulent channel model of FSO, Gamma–Gamma distribution was considered. The proposed CPDM technique in this research can maximize the link capacity. The multipath fading is efficiently mitigated through OFDM modulation. The performance evaluation was represented in constellation

diagrams, BER, optical power spectrum, eye drawings and OSNR. The polarization degree of communicated optical signal was not improved, which was the main demerit of this research.

Based on the FSO communication system, Yaseen et al. [24] improved the wavelength division multiplexing performance through the power comparative system (PCS). The simulation of the proposed research was done in Opti System 7, and the investigation was performed through three principal conditions mentioned without Missing pointing losses (MPL), with MPL and MPL-PCS. Three forms of weather conditions were also adopted in association with these situations, including clear, very clear and hazy climates. When comparing the performance of MPL and without MPL, MPL created deprivation in the obtained FSO link variety. The attained link variety of the projected research is improved through the adoption of PCS in the case of different weather conditions. The WDM performance is represented through the integration of multidisciplinary programs called MATLAB and Opti System. Maximum attainable distance is the merit, and the demerit is degraded spectral efficiency.

Elsayed et al. [25] enhanced the outcomes of moment-creating function methods, including Modified Chernoff bound (MCB) and Chernoff bound (CB). The outcomes of the WDM technique-based FSO communication system were evaluated based on a passive optical network (PON) by utilizing M-ary digital pulse-position modulation (M-ary DPPM) structures through the consideration of inter-channel crosstalk (ICC), Amplified spontaneous emission (ASE) based noise influences and Atmospheric turbulence (AT). The transmission data rate for eight channels is set to be 2.5 Gbps starting from the wavelength 1550 nm. The advantages of this research were higher data rates, extended leverage, increased bandwidth provision and highly power-efficient. The performances were evaluated regarding high gain, BER, Power and sensitivity. The major drawback faced here was an increased error rate. Table 1 reviews recent research works for improving the FSO performance with respective techniques and contributions.

3 Proposed Methodology

A hybridized model is adopted in the proposed research work to achieve improved performance outcomes. Better transmission of data possesses an important role in the FSO communication system in recent years. Most of the time, the transmitted data is not properly received by the receiver due to external disturbances in the space like atmospheric influences, natural obstacles, huge buildings and geometric losses. Accurate data transmission is still challenging, and to overcome the observed issues, an effective hybridized design in the FSO communication system is proposed to promote better data transmission. The overall system model of the projected system is illustrated in Fig. 1.

Initially, the signal-holding data information is generated to carry out the proposed data transmission process in the FSO communication system. The different processes involved in better data transmission are mentioned as follows:

- Signal generation
- Spectrum slicing
- WDM process
- PDM process
- EDFA amplification

Table 1 Review of FSO communication system improvement techniques

| Author name	Techniques employed	Objective	Merits	Demerits	Performances
Alshaer et al. [21]	MPPM and BB84	To maximize the system security and minimize the QBER	Higher stability	System performance is low	SKR, SEP and RKR
Mottaleb et al. [22]	SAC-OCDMA	To eradicate the interferences and to enhance the FSO performance	Better system performance is attained	An optimal solution cannot be obtained	Q factor, BER, attained power and propagation distance
Chowdhury et al. [23]	CPDM and CO-OFDM	To maximize the link capacity and minimize the multipath fading	Effective bandwidth linkage	Degraded degree of polarization	Constellation diagrams, BER, optical power spectrum, eye drawings and OSNR
Yaseen et al. [24]	WDM	To improve WDM performance through PCS	Maximum attainable distance	Degraded spectral efficiency	Without MPL, with MPL and MPL–PCS
Elsayed et al. [25]	POM using M-ary DPPM	To improve the performance of moment-generating function approaches	Higher data rates, extended leverage, high bandwidth provision and power efficiency	Increased error rate	High gain, BER, Power and sensitivity
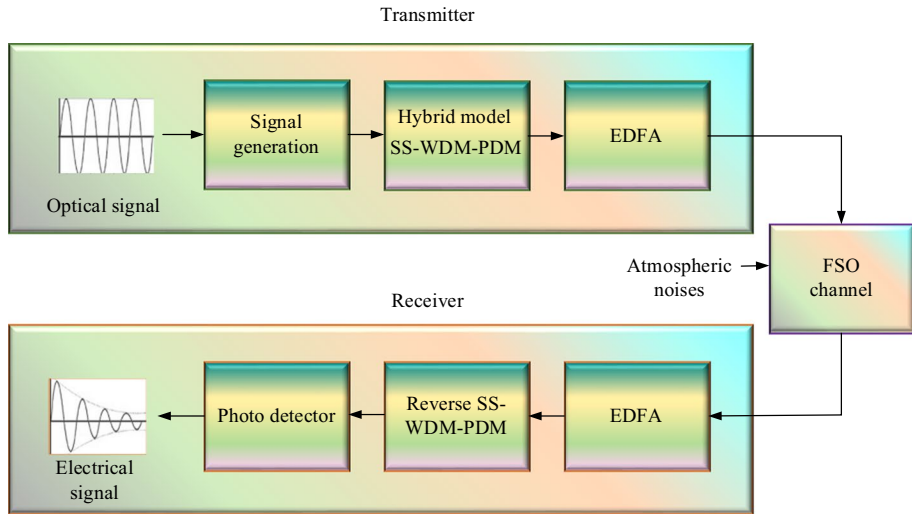
Fig. 1 Overall system model

The FSO system comprises three major parts: the transmitter, the FSO channel and the receiver. The main signal is modulated in the transmitter and passed to the laser for gathering the optical signals. The turbulent atmospheric channel at varying wind speeds is the centre part, and the receiver receives the attenuated transmitted signal. The optical signal is generated through several steps, and spectrum slicing is performed to different wavelengths for four channels. The resulting output is fed into the WDM process for acquiring the output signal with different wavelengths. The resultant signal after the WDM process is given to the PDM process for generating polarization. The signal amplification is carried out by Erbium Doped Fiber Amplifiers (EDFA) amplification process.

When the amplified signal is transferred to the spectrum sliced channel, atmospheric noises like heavy rain, light fog, light rain and moderate rain gets added, and four forms of the signal are generated. Finally, the reverse process is carried out to receive the attenuated electrical data signal by the receiver.

To acquire the optical signal, the steps of signal generation are undertaken. The optical signal is transformed into the electrical signal initially. The block diagram for signal generation in the transmitter section of an FSO communication system is shown in Fig. 2.

3.1 Signal Generation

Signal generation is the initial step to be carried out in the proposed method to promote better data transmission. The steps involved in the signal generation transmitter are described in detail.

3.1.1 Pseudo Random Bit Generator

Before data transmission to the FSO channel, the bits are generated through a Pseudo Random Bit generator (PRBS). The binary arrangement of pseudo-random bits is

Fig. 2 Signal generation in the transmitter

Optical signal
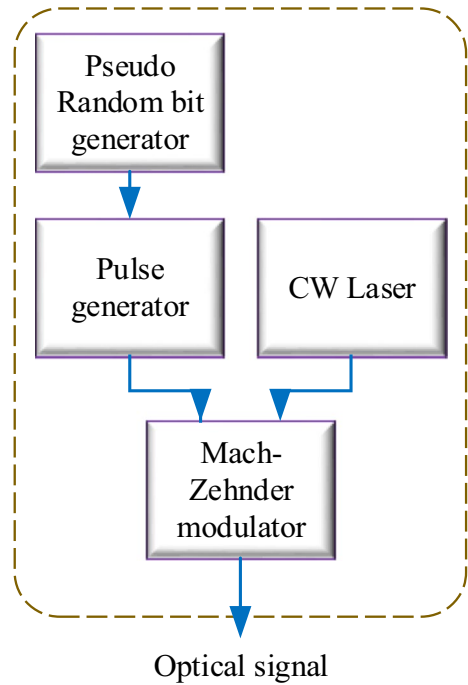
established through PRBS, which can be connected to the visualizer so that the output sequence bit can be seen. The PRBS is a form of intermittent, deterministic signal holding white noise possessions which swings between two values. The signal is considered characteristically periodic, holding the supreme period length of $2^n - 1$ where n denotes the periodic order.

3.1.2 NRZ Pulse Generator

The Non-Return to zero (NRZ) pulses are generated through the NRZ pulse generator coded by the digital signal input. The signal is then passed to a modulator that gets an optical signal from a Constant wave (CW) laser comprising the data signal and needed power.

3.1.3 Mach Zehnder Modulator

The Mach Zehnder modulator (MZM) is used here to establish the interferences through amplitude division. Here the light beam is initially divided into two sections by the beam splitter, which are remerged through the second beam splitter.

The mathematical description of the FSO link is described in the following expression,

$$S_{\text{Received}} - S_{Transmitted} = \frac{A_R^2}{\left(A_T + \delta R\right)^2} \, 10^{\beta R/10} \tag{1}$$

The geometric losses that are emerged by the transmitted beam spreading can be denoted as,

$$G_L(dB) = 20 \log \frac{A_R}{A_R + \delta R} \qquad (2)$$

From the above equations, the receiver aperture diameter is denoted as A_R, the transmitter opening diameter is signified as A_T, the beam divergence is represented as δ, R denotes the range, and the atmospheric attenuation coefficient is represented as β.

3.2 Hybridized SS–WDM–PDM

To maximize the link volume of an FSO system and also to enhance the spectral efficiency, the Hybridized model of SS–WDM–PDM is employed. After the generation of signals, the outcomes of a polarization controller are transmitted through the FSO channel. The presented FSO model consists of a noise adder and optical attenuator. The transmitter's input optical signal through the FSO channel is subjected to attenuation. The level of attenuation is indicated based on the weather conditions. Based on the polarization states, the polarization splitter is employed to split the received signal into odd and even signals at the receiver side. The optical demultiplexer separates every channel transmitted with a triangular optical filter. The individual optical network receives the channels at the receiver section. The highly sensitive avalanche photodiode detects and converts optical to electrical signals. Also, the proposed SS–WDM–PDM model includes a BER analyzer and optical power meter as evaluation tools for simulation value visualization.

3.2.1 Spectrum Slicing

Spectrum slicing is an attractive dense wavelength division multiplexed approach that facilitates exchanging a multi-wavelength optical source between many users. Spectrum slicing is performed to allocate different wavelengths in the four channels of an FSO communication system. This adversely improves the link range and promotes better ability. The four channels enhance communication performance to several influences like atmospheric noises, building heights, etc. The spectrum-slicing procedure is utilized to process the optical signals. The necessary Spectrum is divided into different wavelengths for optical signal modulation; consequently, the Spectrum is analyzed with various parameters. The process of spectrum slicing holds a huge capability for fiber access that can be incorporated with any form of optical system, preferring less power consumption.

3.2.2 Wavelength Division Multiplexing

In WDM, every wavelength is allotted to the individual user and requires more coherent laser sources that are expected to generate appropriate frequencies. The Spectrum slicing

in WDM promotes a stream of data effectively. WDM is a knowledge that multiplexes numerous numbers of optical carrier signals into a single optical fiber through the utilization of various wavelengths. The WDM system uses a multiplexer and a transmitter to merge several signals. In contrast, a demultiplexer is used on the receiver side to split the signals. The WDM systems are highly popular in the communication system field as they permit them to elaborate the network capacity. Every channel includes a CW laser and MZM modulator, whereas two sections consisting of four channels have been multiplexed by a WDM multiplexer possessing the channel spacing of 0.1 and 0.08 nm. The data rate of 5 GBPS is transmitted from every channel holding the optical power of 5 mW. In the WDM approach, each wavelength is allocated to the independent user, requiring a high-quantity laser source.

3.2.3 Polarization Division Multiplexing

The PDM employed in the proposed models acts as the physical multiplexing approach. It permits the respective information channels to be transferred with a similar carrier frequency. The PDM allows for the user capacity multiplication and maximization of spectral efficiency, whereas high tolerance can be provided over polarization mode dispersion. Every data channel possesses an independent polarization angle. Every input optical signal holding different polarization angles is modulated to represent one digital data channel. These signals are integrated into a single incident light signal travelling over the free space system. For a four-channel system, the polarization angles for the data channel are considered to be 0, 45, 90, and 135 degrees. WDM multiplexers' productivity is directed to the Polarization controller (PC), whereas the PC output is merged and directed to the EDFA amplifier. Adjusting the signal orientations, the input polarization state at a corresponding wavelength can be transformed into any output polarization state. The hybrid methodologies of SS–WDM–PDM and EDFA permit the broadcast of numerous channels over a similar filter, making it possible to transfer terabits of data over huge distances. This tends to fulfil the capacity of data and improves the spectral efficiency needed for current and future communication networks.

3.2.4 Erbium-Doped Fiber Amplifiers

The primary aim of using an EDFA amplifier in the proposed model is to compensate for the optical fiber loss during long-distance optical communication. Another significant feature of EDFA amplifiers is the simultaneous amplification of multiple optical signals. The primary characteristic of EDFA technology is the Erbium-doped fiber (EDF), a conventional silica fiber doped with erbium. Normally, EDFA comprises EDF length, pump wavelength and WDM–PDM integrator. This integrates the signal and pumps wavelength to transfer simultaneously through EDF. EDFAs are intended so that the pump energy transfers in a similar direction in the case of forwarding and backward pumping. The advantages of EDFAs are cost-effective, highly reliable, and they have less power. The simulation setup for a four-channel SS–WDM–PDM-based FSO communication system is depicted in Fig. 3.

The amplified signal from EDFA is transmitted to the FSO channel. The noise adder and the optical attenuator comprise the FSO channel model of the communication system. The attained incoming optical signal is transferred to the FSO channel that experiences attenuation. The level of attenuation is specified based on different weather conditions.
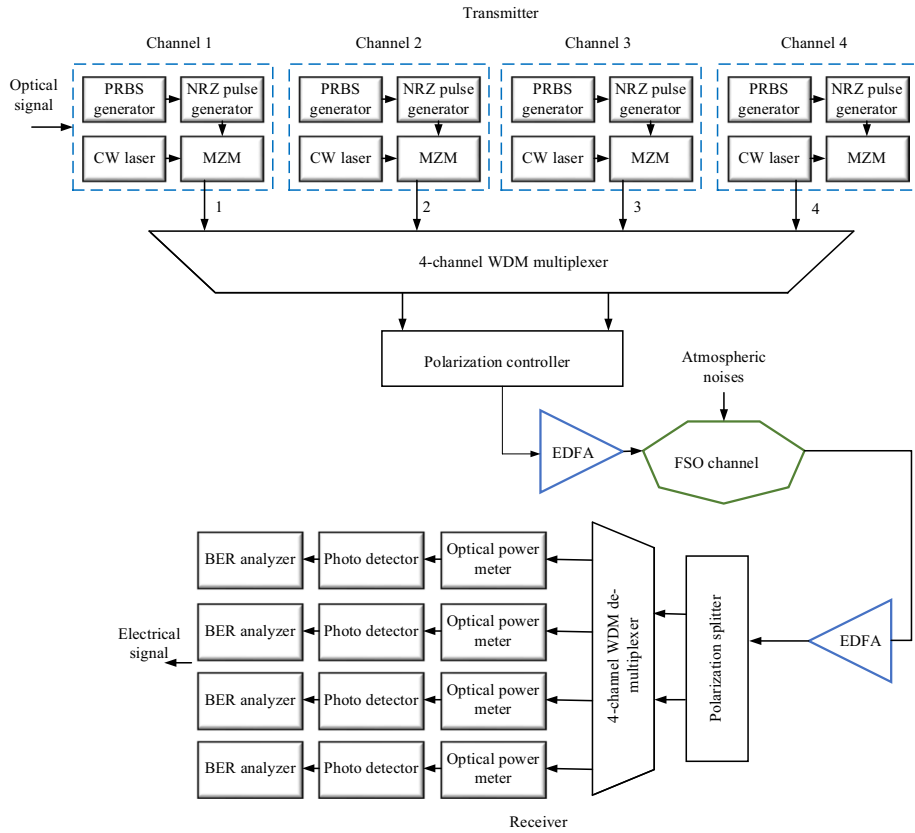
Fig. 3 Hybridized SS–WDM–PDM model

3.3 Atmospheric Attenuation and Turbulences

The FSO communication system's main challenges are atmospheric attenuation and turbulence at varying wind speeds. The atmospheric attenuation that was modelled by Beers-Lambert law can be assumed as,

$$A_L = e^{-\theta D} \tag{3}$$

where θ represents the weather and wavelength-dependent attenuation coefficient, and the broadcast distance is represented as D.

Based on inhomogeneity and refractive index variations, atmospheric turbulence is categorized into moderate, strong, weak, and saturation. Various mathematical models are established for weak to strong, strong and widespread turbulences to demonstrate the turbulence regimes such as log-normal, negative exponential, gamma-gamma and M-distribution.

3.3.1 Log-Normal

The statistics of irradiance variations follow log-normal distribution in this approach. This model is considered by the solo scattering event and is well-suitable in case of weak turbulences. The probability density function (PDF) can be represented as,

$$F(I) = \frac{1}{\sqrt{2\pi\delta_I^2}}\frac{1}{I}\exp\left(-\frac{\left(\ln\left(\frac{I}{I_0}\right) - L(I)\right)^2}{2\sigma_I^2}\right), \quad I \geq 0 \tag{4}$$

From the above expression, the Rytov variance is represented as σ_I^2, the field irradiance in a turbulent medium is represented as I, the free space intensity is denoted as I_0, and the mean log intensity is expressed as $L(I)$.

3.3.2 Negative Exponential

The quantity of autonomous scattering is too large, which can guide for saturation in this model. Hence for the irradiance, the fluctuation pursues Rayleigh distribution involving negative exponential statistics. The PDF of negative exponential is expressed as,

$$F(I) = \frac{I}{I_0}\exp\left(-\frac{I}{I_0}\right), \quad I_0 \geq 0 \tag{5}$$

The mean established irradiance can be expressed as $L(I) = I_0$.

3.3.3 Gamma-Gamma Distribution

Through the Gamma-Gamma distribution considering scintillation constituents β and γ, that is represented as the functions of geometry factor and Rytov variance. The PDF of the gamma-gamma channel approach is indicated by,

$$F_{I_g}(I_g) = \frac{a(\beta\gamma)^{(\beta+\gamma)/2}}{\Gamma(\beta)\Gamma(\gamma)}I_g^{(\beta+\gamma)/2-1}k_{(\beta-\gamma)}\left(2\sqrt{\beta\gamma I_g}\right) \tag{6}$$

From the above expression, the actual quantity of huge and minor scale turbulent are represented as β and γ. The modified Bessel function of second order kind $(\beta - \gamma)$ is denoted as $k_{(\beta-\gamma)}$ and $\Gamma(.)$ is the gamma function.

The attenuation noises at varying wind speeds, like light rain, heavy rain, medium rain and light fog, are added to the FSO channel. The attenuation values in different weather conditions are described in Table 2.

In the receiver portion, a polarization splitter separates the obtained optical signal into odd and even signals based on polarization states. Each channel is divided by the optical demultiplexer when transmitted from the WDM transmitter by adopting a triangular optical filter, which is achieved by the independent optical network unit on the receiver side. A photodetector is used at the receiver portion to analyze and convert the optical into an electrical signal. To visualize the simulation results, a Bit error rate (BER) analyzer and optical power meter are used as evaluation tools.

Table 2 Values of attenuation under the different weather conditions	Weather conditions	Attenuation values (dB/km)
	Light rain	2.97
	Medium rain	6.55
	Heavy rain	23.12
	Light fog	12.47

4 Results and Discussion

The performance of the SS–WDM–PDM transmission system is analyzed through the MATLAB simulation tool in this section holding the channel space setting of 0.1 and 0.08 nm under various atmospheric conditions. The laser source is divided into four wavelengths, including 1571 nm, 1551 nm, 1531 nm and 1511 nm. The performance metrics involved in evaluating the transmission performance are described as follows:

- The OSNR measures the degree of optical noise disturbances on the optical signals. It is called the ratio of service signal to noise power within an appropriate bandwidth. The OSNR can be mathematically expressed as follows;

$$OSNR = 10\log_{10}(S_p/S_n) = dB(S) - dB(N) \tag{7}$$

where S_p denotes the signal power and S_n represents the signal noise.
- BER is defined as the percentage of bits with error values regarding the overall number of bits established in a data broadcast normally articulated as ten to a negative power.

$$BER = \frac{N\,ERR}{N\,BITS} \tag{8}$$

- The Quality factor or Q factor is a wide-ranging evaluation of the signal superiority over an optical channel by considering the noise effects and linear or non-linear distortions regarding the pulse shapes. The mathematical expression of the Q factor is given as;

$$QF = \frac{(M_1 - M_0)}{(\sigma_1 + \sigma_0)} \tag{9}$$

The above expression $M_1 - M_0$ denotes the mean value difference between two signals and $\sigma_1 + \sigma_0$ represents the addition of noise standard deviations of two signals.

The strategy parameters for the hybridized SS–WDM–PDM system in the simulation setup are listed in Table 3, and the system conformation of the proposed work is described in Table 4.

The performance results of a proposed SS–WDM–PDM are validated through Monte Carlo simulations. From the simulation outcomes, it can be analyzed that the proposed model performs better compared to several existing approaches. The MATLAB language provides various higher-level mathematical functions employed to construct a model for

Table 3 Simulation setup parameters

S. no.	Parameter	Values
1	Operating wavelength	1550 (nm)
2	Receiver Aperture diameter	0.005 (cm)
3	Photodetector efficiency	0.5
4	Transmitter efficiency	0.5
5	Transmitter Optical power	5 (mW)
6	Data bit rate	1 and 5 (Gbps)
7	Channel spacing	0.1 and 0.08 (nm)
8	Receiver Noise temperature	1–12 (K)
9	Electron charge	1.60217662 (C)
10	Receiver Load resistor	50 (ohm)
11	Transmitter Divergence angle	10 (mrad)

Table 4 System configuration for the proposed work

Configuration	Parameters
SSM107.smg.local	Full device name
No pen or touch input is available for the display	Pen and touch
64-bit operating system	System type
8.00 GB	Installed RAM
Intel(R) Core (TM) i5-4570S CPU @ 2.90 GHz	Processor

Table 5 OSNR performance in terms of link distance

Techniques used	OSNR (dB)				
	1	2	3	4	5
Traditional PDM–WDM-Light Rain	28.398	27.145	26.17	25.127	23.94
Proposed hybrid SS–WDM–PDM-Light Rain	**59.77621**	**58.34089**	**56.94573**	**54.56066**	**43.65589**
Traditional PDM–WDM-Moderate Rain	26.519	24.987	23.804	21.992	20.182
Proposed hybrid SS–WDM–PDM-Moderate Rain	**54.56906**	**53.14196**	**51.75544**	**49.38681**	**38.59847**
Traditional PDM–WDM-Light Fog	23.316	22.062	20.948	19.209	17.468
Proposed hybrid SS–WDM–PDM-Light Fog	**49.17407**	**47.75851**	**46.3842**	**44.03907**	**33.42552**
Traditional PDM–WDM-Heavy Rain	14.478	12.042	10.439	6.402	0.555
Proposed hybrid SS–WDM–PDM-Heavy Rain	**42.61674**	**41.22186**	**39.86966**	**37.56771**	**27.29857**

The bold values inidicated enhanced OSNR performance outcomes obtained by the proposed model compared to the existing models. The results are analysed by varying the attenuation noises like light rain, heavy rain, moderate rain and light fog

Monte Carlo simulations. The analytical results of a proposed model are verified through numerical and Monte Carlo simulations. Table 5 describes the corresponding values of Traditional PDM–WDM-Light Rain, Traditional PDM–WDM-Moderate Rain, Traditional PDM–WDM-Heavy Rain and Traditional PDM–WDM-Light Fog [26] and the proposed SS–WDM–PDM values to the attenuations like heavy rain, moderate rain, light rain and

light fog. It is clearly described in the table that the proposed technique has provided better performance with higher OSNR values.

Figure 4 depicts the performance of OSNR to the link distance. As the link distance is increased, the OSNR performance of the proposed, as well as the traditional technique, gets decreases. A higher OSNR value insists that the signal strength is high about the noise levels that permit increased data rates. When the proposed and traditional techniques under different atmospheric conditions are compared, the proposed technique has attained better OSNR results, proving that the proposed technique paves a better way for data transmission.

The respective outcomes of Traditional PDM–WDM-Light Rain, Traditional PDM–WDM-Moderate Rain, Traditional PDM–WDM-Heavy Rain and Traditional PDM–WDM-Light Fog [26] and the proposed SS–WDM–PDM technique are listed in Table 6. It is described from the table that the projected technique has provided better performance in terms of BERs.

Figure 5 shows the performance of BER to the link distance. The BER performance is analyzed by varying the link capacity from 1 to 5 km by considering various atmospheric situations in the case of proposed and traditional techniques. For an efficient system, the BER value should be less. When comparing the proposed and traditional techniques, the proposed technique through the atmospheric circumstances of heavy rain, moderate rain, light rain and light fog provided fewer outcomes. The traditional approaches attained increased BERs due to the limited link capacity.

The corresponding values of the Q-factor for proposed and traditional techniques [26] by undergoing different forms of attenuations are listed in Table 7.

Figure 6 illustrates the Q-factor performance to the link distance. When the link distance increases, the performance Q-factor in the case of a proposed and traditional technique decreases. A higher Q-factor outcome indicates that the signal possesses increased spectral efficiency, resulting in better transmission. When the proposed and traditional techniques under different atmospheric conditions are compared, the proposed technique
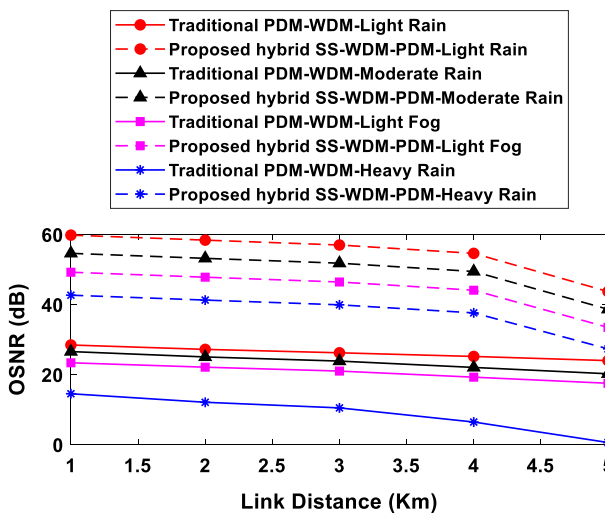

Fig. 4 OSNR versus Link distance

Table 6 BER performance in terms of link distance

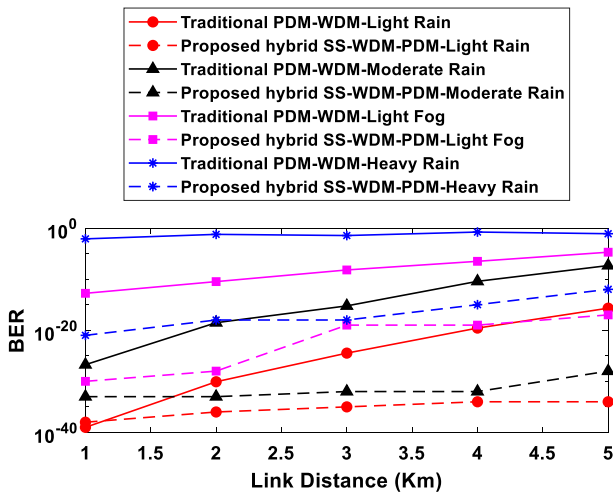| Techniques used	BER				
	1	2	3	4	5
Traditional PDM–WDM-Light Rain	1.01E−39	8.43E−31	3.38E−25	2.70E−20	2.10E−16
Proposed hybrid SS–WDM–PDM-Light Rain	1.02E−38	1.02E−36	1.02E−35	1.02E−34	1.02E−34
Traditional PDM–WDM-Moderate Rain	1.85E−27	3.05E−19	5.94E−16	3.78E−11	4.62E−08
Proposed hybrid SS–WDM–PDM-Moderate Rain	1.02E−33	1.02E−33	1.02E−32	1.02E−32	1.02E−28
Traditional PDM–WDM-Light Fog	1.72E−13	3.35E−11	6.41E−09	3.13E−07	1.90E−05
Proposed hybrid SS–WDM–PDM-Light Fog	1.02E−30	1.02E−28	1.02E−19	1.02E−19	1.02E−17
Traditional PDM–WDM-Heavy Rain	0.007762	0.058884	0.034834	0.166341	0.07925
Proposed hybrid SS–WDM–PDM-Heavy Rain	1.02E−21	1.02E−18	1.02E−18	1.02E−15	1.02E−12

Fig. 5 BER Versus Link distance

Table 7 Q-factor performance in terms of link distance

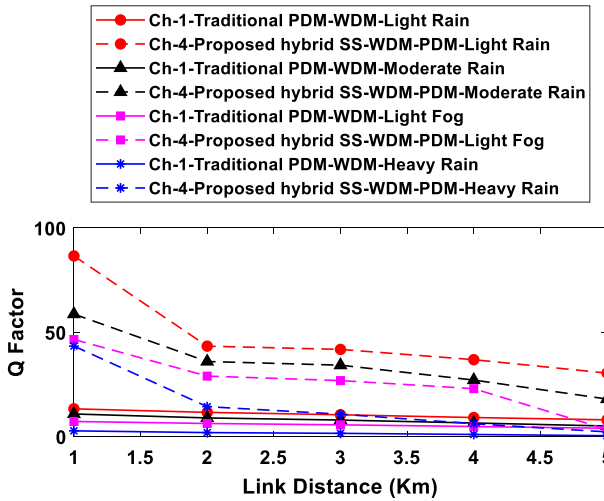| Techniques used	Q-factor				
	1	2	3	4	5
Traditional PDM–WDM-Light Rain	13.251	11.548	10.406	9.077	7.973
Proposed hybrid SS–WDM–PDM-Light Rain	86.54333	43.2976	41.73844	36.81312	30.37818
Traditional PDM–WDM-Moderate Rain	10.781	8.89	7.861	6.457	5.016
Proposed hybrid SS–WDM–PDM-Moderate Rain	58.66779	35.93333	34.17625	27.0462	17.94624
Traditional PDM–WDM-Light Fog	7.187	6.233	5.577	4.773	3.93
Proposed hybrid SS–WDM–PDM-Light Fog	46.5022	28.94191	26.7943	22.92027	3.347589
Traditional PDM–WDM-Heavy Rain	2.695	1.853	1.497	0.954	0.374
Proposed hybrid SS–WDM–PDM-Heavy Rain	43.31619	14.28652	10.67848	6.120889	2.190627

Fig. 6 Q-factor Versus Link distance

has accomplished better Q factor values. The 1-channel traditional techniques produce fewer Q factor outcomes than the proposed 4-channel system.

The modulation-based Q factor outcomes in terms of link distance are demonstrated in Table 8. The performances of existing RZ SS–WDM, NRZ SS–WDM, CSRZ SS–WDM [27] and the proposed SS–WDM–PDM techniques are compared. The table shows that the proposed technique performs better with higher Q factor values.

Figure 7 depicts the Q factor performance of proposed and existing techniques under distinct weather conditions. Existing techniques like RZ SS–WDM, NRZ SS–WDM and CSRZ SS–WDM have attained lower Q factor values by varying the link distance from 1 to 5. The proposed (Mach–Zehnder) MZ SS–WDM–PDM has obtained an increased Q factor outcome. When the link distance varies from 1 to 5 km, the proposed technique has attained 48.208, 22.199, 21.946, 17.422 and 12.221 Q factor values that are comparatively higher than the existing approaches.

The respective values of modulation-based Log (BER) performance in link distance by undergoing different forms of attenuations for existing [27] and proposed techniques are listed in Table 9.

Table 8 Modulation-based Q-factor performance in terms of link distance

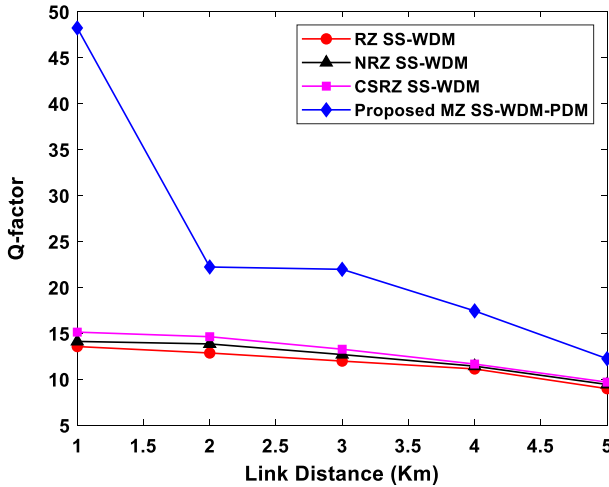| Techniques used	Q-factor				
	1	2	3	4	5
RZ SS–WDM	12.86	12.86	12.01	11.23	9.13
NRZ SS–WDM	14.16	13.91	12.69	11.44	9.44
CSRZ SS–WDM	15.2	14.56	13.34	11.54	9.57
Proposed MZ SS–WDM–PDM	48.20814	22.19933	21.94654	17.42268	12.22199

Fig. 7 Q-factor Versus Link distance

Table 9 Modulation-based Log (BER) performance in terms of link distance

Techniques used	Log (BER)				
	1	2	3	4	5
RZ SS–WDM	− 43.347	− 38.222	− 34.662	− 30.25	− 20.997
NRZ SS–WDM	− 45.91	− 43.914	− 37.796	− 31.389	− 21.854
CSRZ SS–WDM	− 53.028	− 49.04	− 41.351	− 31.818	− 22.563
Proposed MZ SS–WDM–PDM	− 59.7615	− 54	− 54	− 54	− 54

The graphical representation of Log (BER) versus link distance is demonstrated in Fig. 8. To analyze the log (BER) outcomes of the FSO system, the distance between the transmitter and receiver is varied from 1 to 5 km. The advantage of the obtained signal is dependent upon the link distance of the transmitter or receiver. By the characteristics of dispersion tolerance and the constant power supply, the carrier overwhelms the return to zero modulation. The figure shows that the existing techniques possess higher log (BER) values than the proposed technique.

Table 10 describes the corresponding values of received power performance for SOA, Raman [28] and the proposed EDFA amplifier to the link distance.

Figure 9 illustrates the graphical representation of established power by increasing the link distance from 1 to 5. It can be noticed from the figure that when the link length increases, the established power of the signal gets decreases. Compared with various amplifier performances, maximum received power performance is attained with proposed EDFA amplifiers. When the amplifier performance of SOA and Raman are compared with the proposed EDFA, less power is received by the existing amplifiers.

The performance of modulation-based Q-factor to link distance in case of different amplifiers of proposed and existing [28] are listed in Table 11.
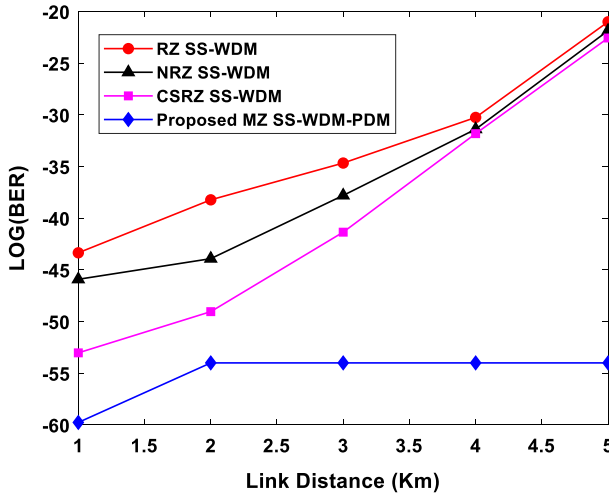
Fig. 8 Log (BER) Versus Link distance

Table 10 Received power performance in terms of link distance

Techniques used	Received power (dBm)				
	1	2	3	4	5
SOA	− 36.239	− 40.092	− 43.309	− 53.354	− 56.36
Raman	− 28.783	− 32.955	− 36.905	− 44.743	− 48.906
Proposed-EDFA	− 19.3001	− 20.4519	− 20.493	− 21.7125	− 22.381
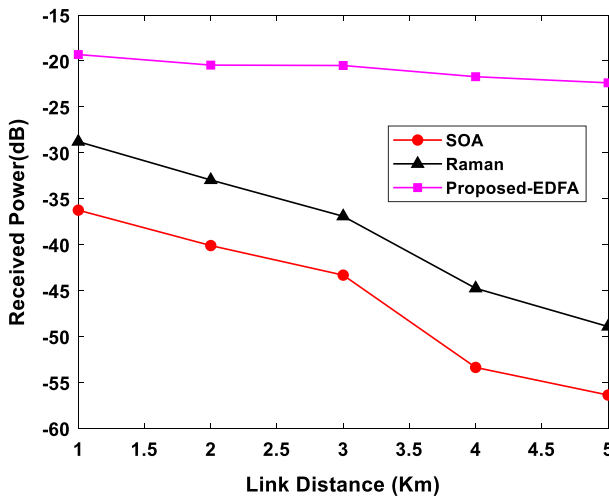
Fig. 9 Received power Versus Link distance

Table 11 Modulation-based Q-factor performance in terms of link distance

Techniques used	Q-factor				
	1	2	3	4	5
SOA	15.422	11.386	9.518	6.265	3.916
Raman	20.241	17.651	15.482	10.602	8.675
Proposed-EDFA	50.13815	24.24452	23.99584	19.59393	14.46008

Figure 10 describes that an increased lengthy distance is attained to the proposed EDFA amplifier, whereas the least outcomes are monitored for SOA and Raman amplifiers. It can be noticed that the established signal quality and the link distance between the transmitter and receiver are enhanced by using an amplifier. From the figure, it is obvious that the supreme Q-factor is attained in the case of the proposed EDFA amplifier. The EDFA amplifier encloses the supreme link distance compared to the existing amplifiers, and EDFA achieves better performance.

Table 12 describes the corresponding values of the existing 16-channel and proposed 4-channel values to link distance. The 16-channel Traditional PDM–WDM-Light Rain, Traditional PDM–WDM-Moderate Rain, Traditional PDM–WDM-Heavy Rain and Traditional PDM–WDM-Light Fog [26] and the proposed 4-channel hybrid SS–WDM–PDM values are compared.

Figure 11 shows the performance of a Q factor to the link distance. The Q factor performance is analyzed by varying the link capacity from 1 to 5 km through various atmospheric circumstances in the proposed channel 4 and traditional channel 16 techniques. For an efficient system, the Q factor value has to be maximized. When comparing the proposed and traditional techniques, the proposed technique under atmospheric conditions like heavy rain, moderate rain, light rain and light fog provided increased outcomes. The traditional approaches attained lower outcomes due to the limited bandwidth. The proposed technique adversely increases the link capacity and spectral efficiency.
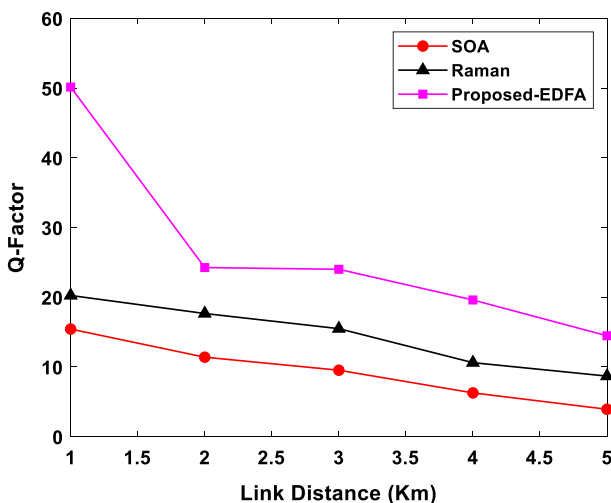

Fig. 10 Q factor Versus Link distance

Table 12 Q-factor performance for different channels in terms of link distance

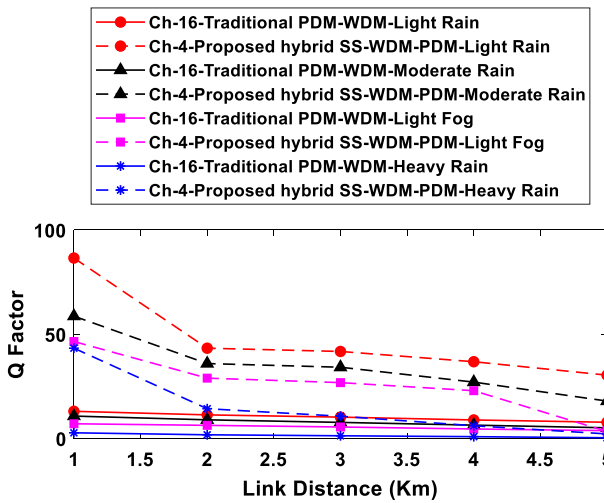| Techniques used	Q-factor				
	1	2	3	4	5
Traditional PDM–WDM-Light Rain	13.037	11.323	10.249	8.895	7.782
Proposed hybrid SS–WDM–PDM-Light Rain	86.54333	43.2976	41.73844	36.81312	30.37818
Traditional PDM–WDM-Moderate Rain	10.751	8.955	7.722	6.409	5.134
Proposed hybrid SS–WDM–PDM-Moderate Rain	58.66779	35.93333	34.17625	27.0462	17.94624
Traditional PDM–WDM-Light Fog	7.061	6.308	5.516	4.563	3.77
Proposed hybrid SS–WDM–PDM-Light Fog	46.5022	28.94191	26.7943	22.92027	3.347589
Traditional PDM–WDM-Heavy Rain	2.727	1.775	1.304	0.872	0.36
Proposed hybrid SS–WDM–PDM-Heavy Rain	43.31619	14.28652	10.67848	6.120889	2.190627

Fig. 11 Q factor Versus Link distance

Table 13 Performance comparison of ASE

Techniques used	ASE (bits/s/Hz)					
	2	4	6	8	10	12
Hybrid MS with PE	35.58	36.1	36.503	36.907	37.48	97.77
Hybrid MS without PE	50.786	51.359	51.819	52.335	52.795	53.367
Proposed SS–WDM–PDM	55.86	56.49	57.00	57.56	58.07	58.70

Table 13 indicates the corresponding values of average spectral efficiency (ASE) in bits/s/Hz [29]. The proposed SS–WDM–PDM approach is compared with certain existing approaches, including hybrid modified pulse-position modulation and spatial pulse-position modulation with pointing error (Hybrid MS with PE) and Hybrid MS without PE. The results were analyzed by varying the receiver aperture diameter from 2 to 12.
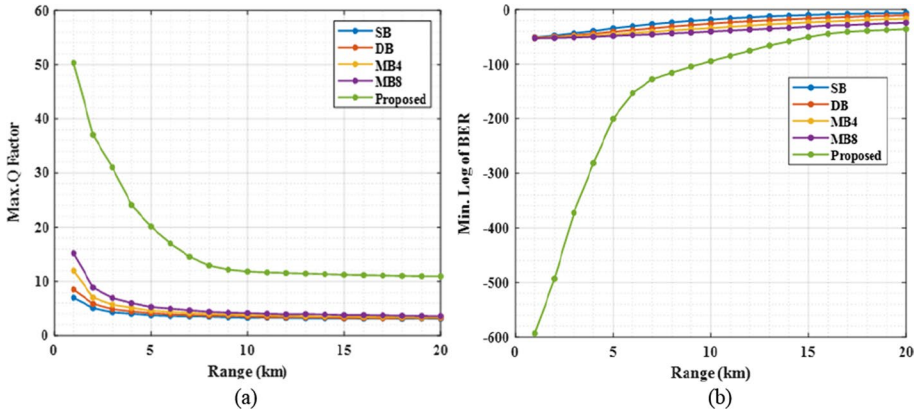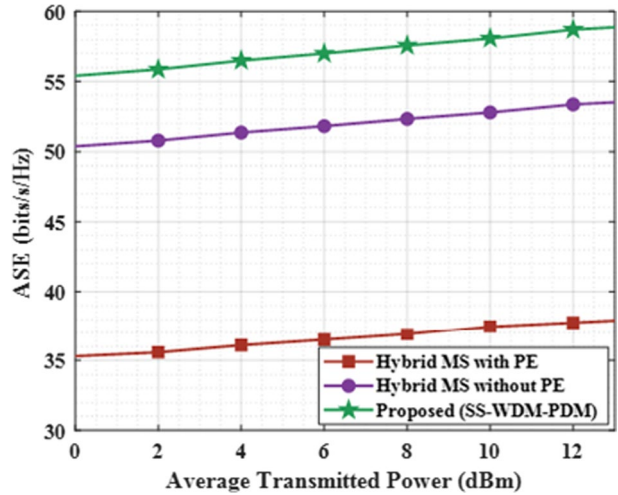
Fig. 12 ASE performance comparison

Fig. 13 Performance comparison (a) Max Q factor (b) Min Log of BER

Figure 12 depicts the performance comparison of ASE, which is analyzed by varying the diameter of average transmitted power from 2 to 12 cm, respectively. For an efficient communication system, the ASE has to possess higher outcomes. When comparing the proposed and traditional techniques, the proposed technique has attained improved outcomes in terms of ASE. The traditional models obtained lower outcomes because of limited efficiency and lower SNR rates. Thus, the proposed technique effectively increases the spectral efficiency compared to the existing models. Figure 13 (a)-(b) depicts the performance of a maximum Q factor and minimum log of BER.

The existing approaches [30], like single-beam (SB), dual-beam (DB), four multiple-beam (MB4) and eight multiple beam (MB8), are compared with the proposed model in terms of maximum Q factor and minimum log of BER values. At the distance of 10 km, the Q factor obtained for SB is 8.66, DB is 10.67, MB4 is 12.22, and MB8 is 13.37, respectively. But the proposed model has attained a max Q factor of 11.01. On considering the min log of BER performance, the min log of BER is -18.4 for SB, -26.19 for DB, -33.93 for MB4 and -40.37 for MB8 correspondingly. Compared to the existing models, the

proposed model has attained the least min of log BER at -96.31. When analyzing the performances of an existing and proposed SS–WDM–PDM technique under different atmospheric attenuations, the proposed hybrid method has obtained improved outcomes to OSNR, BER, Power, ASE and Q-factor. This adversely maximizes the link capacity and improves the proposed approach's spectral efficiency.

5 Conclusion

To extend the presently available resource domains in wireless communications, a hybridized model called SS–WDM–PDM is proposed in this research work. The special merits of this work are increased link capacity and enhanced spectral efficiency. As the FSO communication system is often considered optical wireless communication, better performance outcome is required for effective data transmission. The key features like higher transmission of data rate, improved data security and congestion-free transmission through the atmosphere can be fulfilled in Free space Optic communication systems using SS–WDM–PDM. The ability of effective bandwidth delivery can be attained through FSO links. The atmospheric attenuations like heavy rain, medium rain, light rain and light fog are considered to analyze the performance of the proposed approach. The MATLAB simulation tool analyses the Q factor, OSNR, received power, and BER performance outcomes. Compared to the existing methodologies, better performance is attained in the proposed approach. The performance is evaluated for numerous building heights; wind speeds to distance, and established power. In future work, the applications of a proposed approach will be deeply analyzed under various channel conditions.

Declarations

Conflict of interest Authors declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any authors.

Consent to Participate All authors have agreed to participate in this submitted article.

Consent to Publish All the authors involved in this manuscript give full consent for publication of this submitted article.

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