PERFORMANCE INVESTIGATIONS OF SPECTRUM SLICED WAVELENGTH DIVISION MULTIPLEXING FREE SPACE OPTICAL COMMUNICATION

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***Abstract:** In this paper performance investigations are carried out on super continuum generation based spectrum sliced wavelength division multiplexing (WDM) frees pace optical (FSO) communication system by varying link range 1 to 5 km and bit rate 2.5 to 10.0 Gb/s. The link performance is analyzed under clear weather, haze, rain, fog weather turbulences in terms of Q- factor, receiver sensitivity and eye diagrams. The reported performance improvements are optical receiver sensitivity 9 dBm, bit rate 10 Gb/s and link range 5 km in clear weather turbulence. The achieved performance margins are in accordance with [4, 6]. These may be helpful to enhance the FSO link range, bit rate and power affected weather turbulences advanced FSO links.*

***Key Words:** Free space optics (FSO), Highly nonlinear fiber (HNLF), Wavelength division multiplexing (WDM), Bit error rate (BER) Spectrum slicing (SS), Quality factor (Q factor), Receiver sensitivity.*

1. Introduction

Free Space optics (FSO) is an optical communication technology in which data is transmitted by light waves propagation in free space for optical connectivity. Free space can be air, outer space, vacuum etc. [1]. FSO communication system working is similar to optical fiber cable (OFC) communication; however, it is unguided transmission media, free air used for optical propagation [2]. Optical fiber cables are costly for some services where installation and digging to place fiber is also more expensive [3-4]. The problem is also certainly solved with FSO system and networks [5]. Nowadays, FSO systems have sufficient capacity for high speed optical transmission. Additionally, somewhere in optical access networks, it can be employed to bypass local-loop system as a backup network in case of failure of main transmission through fiber link [6-7].

FSO is a line of sight (LOS) communication technology, which nowadays could support voice, video and data full duplex optical communication [8]. Basically, FSO system consists of an optical transceiver at both ends to provide full duplex (bidirectional) capability [9]. To operate reliably to cope up high atmospheric attenuation levels, the FSO system should have the ability to operate at higher power levels for longer distance communication [10]. Moreover, in advanced high speed communication it can support advanced modulation formats. While considered, maintenance point of view, FSO overall system design should have small footprint and low power consumption [11].

The main advantages of FSO links are easy to install, cost effective, flexibility, low power consumption in access networks. However, it has also some challenges like high transmission absorption of optical power, geometrical losses, fading and atmospheric turbulences etc. [12]. First of all, analysis and investigations of outer free space have found that its refractive index continuously varies with atmospheric conditions changes which results in fading of the transmitted signal. These atmospheric turbulences cause degradation in the performance of FSO links which can be generally observed at optical receiver end with its metrics such as bit error rate (BER) increase, SNR deterioration and transmission delays [13-14]. Recent advances in free space optical communications not only increase the capacity of communication system but also improve the system survivability [15]. Moreover, new advancements have been proposed to increase the bandwidth of individual and number of multiplexed wavelength channels [16]. Multiple access technologies have also been developed to support various emerging applications, including real-time, on-demand, high data-rate applications, in a simple, cost effective and energy efficient manner [17]. In spite of these improvements suggested in the literature still there is a scope of improvement in performance of WDM FSO with new and less costly and slightly complex techniques [18].

In this paper, investigations are carried out on free space optical communications with spectrum sliced wavelength division multiplexing (SS WDM) technology by broadening the spectrum of laser light with super continuum (SC) generation with highly nonlinear fiber (HNNF). The results shown here indicate improvement in performance metrics while compared with literature. The paper is organized as follows: after introduction of FSO links in section 1, section 2 discusses super continuum principle and presents an architecture schematic diagram of a proposed system set-up with SS-WDM and HNNF fiber. Section 3 shows the results and discussions carried out while set-up is run under various investigation conditions. At the end section 4 discusses the conclusions drawn from the results and discussions.

2. System Set-Up

Spectrum slicing is the most attractive technique to reduce the cost of multi wavelength FSO system architectures such as wavelength division multiplexing. In WDM, a numbers of coherent intensity sources are used to generate light carriers at different frequencies, which increase the total expenditure of the system. Spectrum slicing is an alternative to WDM, because it can also support same bit rates and similarly parallel optical modulated signal streams can be transmitted.

A proposed spectrum sliced WDM FSO system set-up architecture is shown in fig. 1. An optical transmitter consists of a continuous wave laser, which generates a light wave at 193.548 THz frequency and 30 dBm optical powers. A laser generated light carrier wave is shown in fig. 2 (a)

The wave is further launched to single mode highly nonlinear fiber (HNLF) for super continuum generation and shown in Fig. 2 (b). The HNLF is specially prepared for high fiber nonlinearity coefficient called self-phase modulation (SPM) and it generate as broad optical carrier wave spectrum prepared for slicing. The SPM principle for the generation of broad optical spectrum is due to highly nonlinear fiber with very small effective core area (typically 10 μm^2) and propagation through it a coherent high laser pulse. The spectral broadening is improved by high nonlinear index coefficient (n) of the fiber and employing high peak power pulses. Fiber nonlinear coefficient increase by material with high nonlinearity and reduction in its effective core cross sectional area. Molecules of the HNLF vibrate due to highly intense laser wave and subsequently there exists a varying fiber core refractive index [1].

SPM Proportionality constant of HNLF can be expressed as

$$\gamma_{SPM} = \frac{2\pi n^2}{\lambda A_{eff}} \qquad (1)$$

Where γ_{SPM} is SPM fiber nonlinearity ($W^{-1}km^{-1}$), n is refractive index of the fiber core, λ is operating wavelength of light wave (m) and A_{eff} (μm^2) effective core area of HNLF. The super continuum generation in HNLF can be altered, varying fiber length, the time of pulse maximum intensity and wavelength of pump [1]. The HNNF output light wave spectrum is sliced into four wavelength channels having frequency range such as 193.000, 193.075, 193.150 and 193.225 THz by an optical continuous wave division de-multiplexer (DEMUX). A dense channel spacing 100 GHz is kept to make system bandwidth efficient. A data source bank consisting of four individual pseudo random bit sequence (PRBS) generators are used for four independent non-returns to zero (NRZ) pulse generators. The sliced channels are optically modulated by biased at peak point four optical Mach-Zehnder modulators (MZM). These modulated optical waves are now wavelength division multiplexed (WDM) and transmitted into free space by optical antenna. The various component parameters of set-up selected during investigations are shown in Table 1.

At receiver an optical antenna receives the optical WDM FSO transmission. The received waves are de-multiplexed by a WDM DEMUX and route to optical receivers. Where now, the received waves are incident to four individual optical detectors.

Each optical receiver consists of a photo detector that converts the light signal into electric signal. The proposed system has employed PIN photodiodes with dark current 10 nA and 1 A/W responsively and is followed by a low pass electric Bessel filter. LPF is used for removing noises from the received signals. A 3-R regenerator placed after LPF for retiming, re-shaping and re-amplification followed by BER analyzer. Bit error rate analyzer is used a decision component that indicates Q-factor, bit error rate, eye closer penalty etc. OSA (optical spectrum analyzers) is placed to access the spectrum frequencies and power of each slices of wavelength. Optical time domain visualizes represents data bits with respective to time of each bit slot. There are four identical optical receivers employed in the system whereas, due to limitations of the space here, observations only one channel are shown in the results section.

Now, performance of the proposed SS-WDM FSO system is investigated with atmospheric turbulence conditions such as clear weather, haze, mild rain, medium rain and fog.

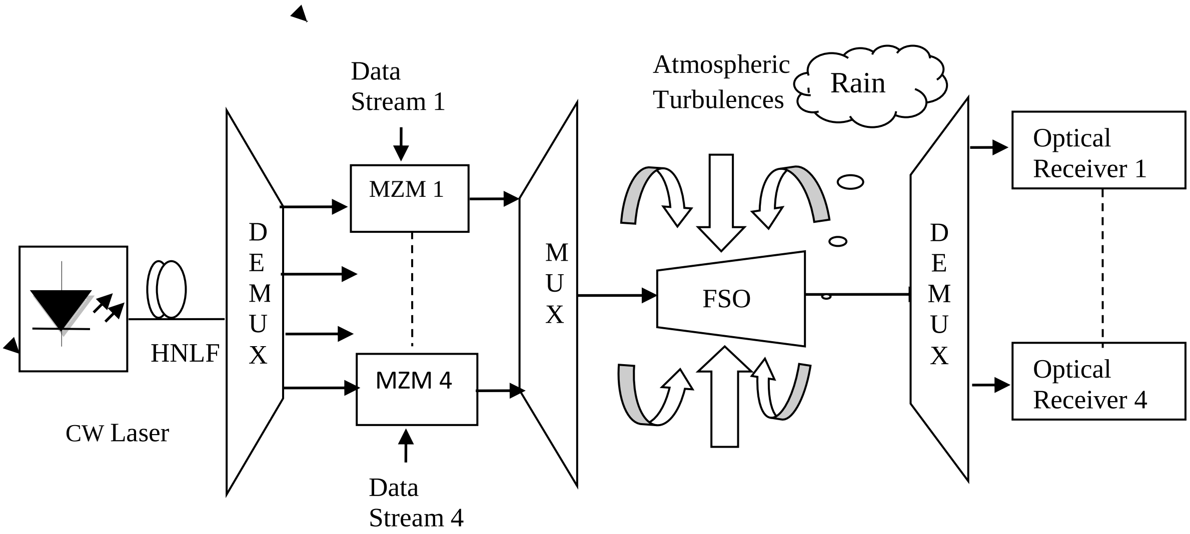
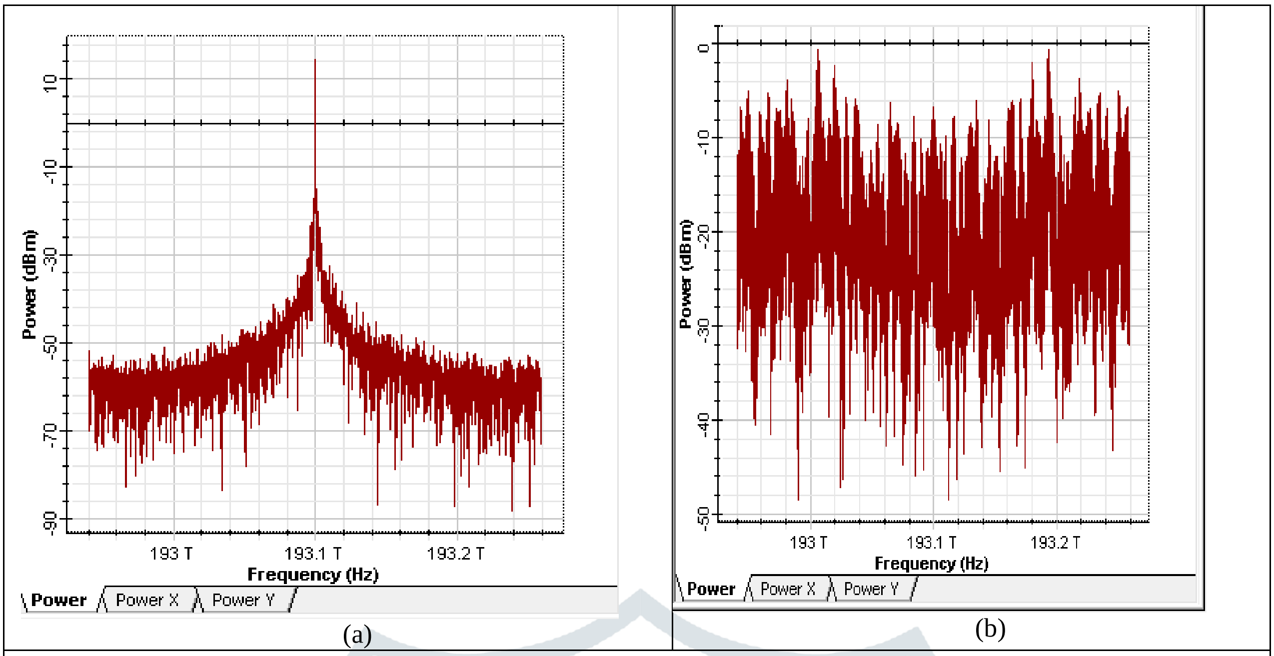


Fig1: SS-WDM-FSO system architecture



(a)

(b)

Fig. 2 CW laser spectrums (a) at laser output (b) with super continuum generation by passing through HNLF.

Table 1: Simulation Parameter selected

S. No.	Name	Value selected
1.	Frequency (THz)	193.54
2.	Laser power (dBm)	30
3.	Numbers of channels	4
4.	Channel frequency range (THz)	193.000-193.225
5.	Channel bandwidth (GHz)	100
6.	HNLF attenuation (dB/km)	0.1
7.	HNLF Beta$_2$(ps^2/km)	191.9
8.	Nonlinear refractive index (m^2/w)	2.35×10^{-20}
9.	HNLF Effective core aperture(μm^2)	10
10.	Transmitter aperture diameter (cm)	5
11.	Receiver aperture diameter (cm)	20
12.	Beam divergence Angle (mrad)	2
13.	Link distance (km)	1 to 5

3. Results and discussion

The performance of system set-up is observed in terms of Q-factor, optical receiver power vs. link distance and eye diagrams by varying bit rates. The system operating bit rate is varied 2.5 to 10 Gb/s up and link distance range 1 to 5 km. The Q- factor and received optical power observations are plotted for the five above mentioned atmospheric conditions. Table 2 shows the typical attenuation coefficient of the indicated five atmospheric turbulences.

Table 2: Specific attenuation due to different atmospheric conditions

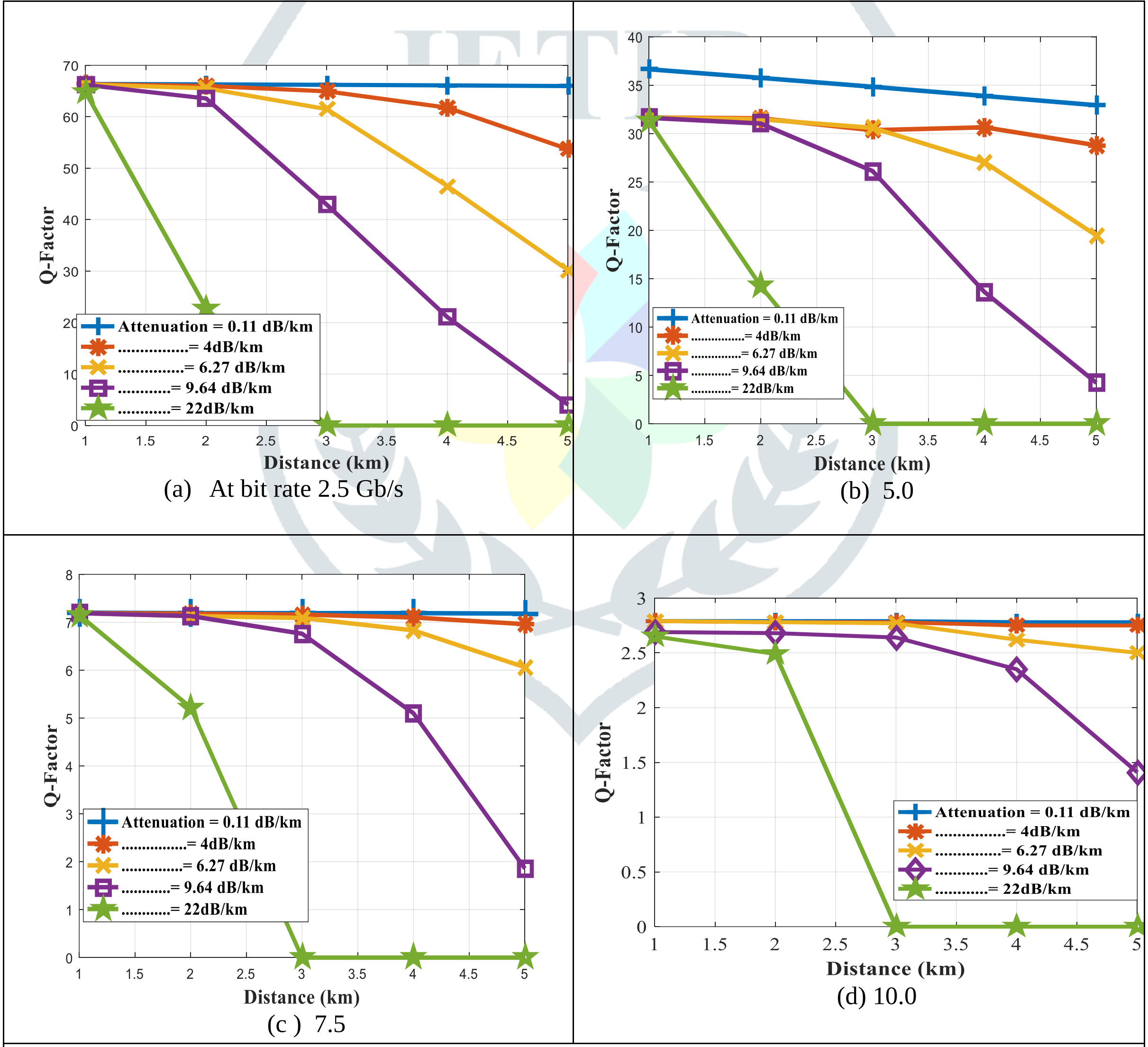
S. No	Atmospheric turbulences	Attenuation(dB/km)
(a)	Clear Weather	0.11
(b)	Haze	4
(c)	Mild Rain	6.27
(d)	Medium Rain	9.64
(e)	Fog	22

Fig, 2(a)-(d)show Q-factor analysis at receiver output by varying the link length in a range of 1 to 5 km at bit rate 2.5, 5.0, 7.5 and 10.0 Gb/s respectively. It is evidently shown, at clear weather conditions, Q-factor variations are less compared to other considered weather conditions due to its low absorption coefficient. Whereas, Q- factor deteriorations of fog weather are maximum due to its high attenuation factor at this turbulence. First of all, Fig 2 (a) shows at bit rate 2.5 Gb/s, Q-factor deteriorations are 66.37 to 65.96 (clear weather), 66.33 to 53.71 (haze), 66.29 to 30.17 (mild rain), 66.20 to 4.05 (medium rain) and 64.81 to 22.09 (fog) under these indicated weather turbulences by increasing the link length range 1 to 5 km. This Q- factor deterioration indicates link length is highly affected power by absorption, scintillation, fading with turbulences [2-3]. Comparatively, it can be observed that Q- factor performance improvements of the proposed system are better than the results reported in ref. [4] under similar turbulence conditions.

Similarly, Fig 2 (b) shows at 5.0 Gb/s, Q- factor performance transmission under same the above mentioned weather turbulences at link range. The Q-factor deteriorations 36.64 to 32.92 (clear weather), 31.65 to 28.78 (haze), 31.64 to 19.46 (mild rain), 31.62 to 4.23 (medium rain) and 31.31 to 14.24 (fog) are shown varying link length 1-5 km. Fig 2 (c) shows at 7.5 Gb/s bit rate performance in terms of Q-factor variation 7.20 to 7.18 (clear weather), 7.19 to 6.96 (haze), 7.19 to 6.06 (mild rain), 7.19 to 1.86 (medium rain) and 7.15 to 5.22 (fog) with link length. These observations show Q-factor deteriorations due to absorption and geometrical losses of with link distance and bit rate increase due to power loss atmospheric turbulences.

Finally, Fig 2 (d) shows Q-factor effect at higher bit rate, 10 Gb/s varies in range of 2.79 to 2.78 (clear weather), 2.79 to 2.75 (haze), 2.79 to 2.50 (mild rain), 2.69 to 1.41 (medium rain) and 2.65 to 2.49 (fog) by increasing the transmission link length. The Q-factor deteriorations are clearly visible under observed turbulences with link length.

Additionally, Q factor performance analysis is also presented here in tabular form in Table 3 vs. link range and bit rates. A noticeable trend from the Q- factor observations, are performance deteriorations are highly affected with transmitted bit rate and link distance range. Firstly, it evident that, at all considered weather conditions, the purposed set up covers efficiently up to 7.5 Gb/s only and beyond it at higher bit (10.0 Gb/s) link is hardly reliable Similarly, another observation can be seen that the FSO link performance is highly affected by link range extensions. It is shown that maximum link length is 5 km for clear weather, haze, mild rain and medium rain. Whereas under fog weather, link range is working efficiently up to 2.7, 2.5 and 2.0 km at bit rate 2.5, 5.0 and 7.5 Gb/s respectively. The link length deteriorations/limitations by increasing bit rate and link range are very similar and comparatively better the observations given in literature ref. [4].



(a) At bit rate 2.5 Gb/s

(b) 5.0

(c) 7.5

(d) 10.0

Fig. 3. Q-factor at the receiver output by varying range (km) 0 to 5, with different atmospheric turbulences at various bit rates, (a) 2.5, (b) 5.0, (c) 7.5, and (d) 10 (Gb/s).

Table 3: Q- factor vs. range (km) and bit rates (Gb/s) at turbulences of Table 2.

S. No.	Data Rate Gb/s	Distance (km) ↓	→ Atmospheric Turbulences no. as Table 2 (a)	(b)	(c)	(d)	(e)
1.	2.5	1.	66.37	66.33	66.29	66.2	64.81
		2.	66.29	65.99	65.53	63.55	22.81
		3.	66.2	64.94	61.48	42.92	0
		4.	66.09	61.76	46.52	21.05	0
		5.	65.96	53.71	30.17	4.05	0
2.	5	1.	36.64	31.65	31.64	31.62	31.31
		2.	35.75	31.57	31.47	31.03	14.24
		3.	34.83	30.34	30.58	26.12	0
		4.	33.88	30.64	27.03	13.62	0
		5.	32.92	28.78	19.46	4.23	0
3.	7.5	1.	7.2	7.19	7.19	7.19	7.15
		2.	7.19	7.18	7.13	7.13	5.22
		3.	7.19	7.16	7.09	6.76	0
		4.	7.19	7.1	6.83	5.1	0
		5.	7.18	6.96	6.06	1.86	0
4.	10	1.	2.79	2.79	2.79	2.69	2.65
		2.	2.79	2.78	2.78	2.68	2.49
		3.	2.79	2.78	2.77	2.64	0
		4.	2.78	2.75	2.62	2.35	0
		5.	2.78	2.75	2.5	1.41	0

Table 4: Received power (dBm) at different Atmospheric conditions

Sr. No.	Link Range (km)	Received Optical Power (dBm)				
		Clear weather	Haze	Mild Rain	Medium Rain	Fog
1	1	-8.59	-12.46	-14.73	-18.18	-30.46
2	2	-14.66	-22.44	-26.98	-33.72	-58.44
3	3	-18.28	-29.95	-36.76	-46.87	-83.95
4	4	-20.88	-36.44	-45.52	-59.00	-100
5	5	-22.92	-42.37	-53.72	-70.57	-100

Further, theoretical optical receiver sensitivity for a SS WDM FSO system can be calculated by equation (2), as per reference [18].

$$p_{receiver} = p_{transmitter}\frac{D^2}{\theta_{div}^2}10^{-\gamma L/10}\tau_{transmitter}\tau_{receiver}(2)$$

Where $P_{transmitter}$ is FSO optical transmitted power, D is the receiver diameter, θ_{div} is the full transmitting beam divergence angle, γ is the atmospheric attenuation factor dB/km, $\tau_{transmitter}$ is the transmitter optical efficiency, $\tau_{receiver}$ and is receiver optical efficiency and L link range distance. One can find out, receiver sensitivity by the proposed system parameters indicted in Table 1. We have calculated the system sensitivity -29.16 dBm. If receiver power decreases beyond -29.16 dBm the system may not work with good reliability.

The proposed system performance also has been explored in terms of received optical power at detector for link range under atmospheric turbulences: clear weather, haze, mild rain, medium rain and fog with 2.5 Gb/s bit rate. The analysis is shown in fig. 4, plotting of received power with link length. It can be elaborated that, at clear weather condition the received optical power is decreased -8.59 to -22.92 dBm by varying link range 1 to 5 km which is comparatively less deteriorations to other here considered weather conditions. This is due to less attenuation abortion coefficient (typically 0.11dB/km, Table 2) and geometric loses of the link. The received power deteriorations can be seen -

12.46 to -42.37, -14.73 to - 53.72, -18.10 to -70.57 and -30.46 to -100 dBm at haze, mild rain and medium rain and fog turbulences respectively. As per the optical received power data indicated in Table 4 and fig. 4 the proposed system will work full range up to 1to 5 km under clear weather condition but link range is limited to 2.7, 2.0 and 1.0 km for haze, mild rain and medium turbulences respectively. Whereas at fog weather conditions the link performance highly affected with power absorption by suspended water droplets in air.

Moreover, the system performance in terms eye-diagrams are investigated after optical detection at optical receiver output under different turbulences. Fig. 5 (a)-(b) and Table 5 show the eye opening analysis at various turbulences (as given in Table 2) by varying range length 1 to 5 and at bit rate 2.5 and 5.0 Gb/s. The laser input optical power 30 dBm is launched in the HNNF fiber for super continuum generation.

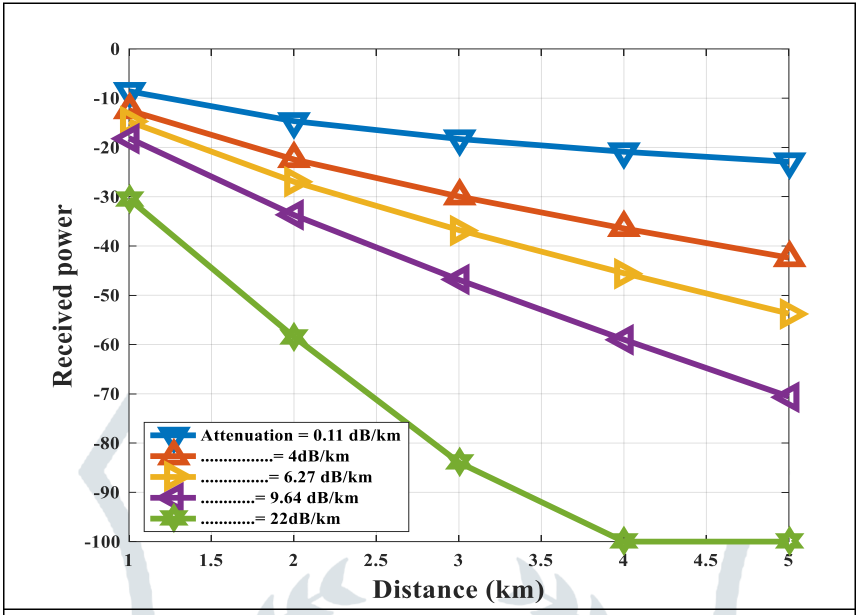


Fig.4 Received optical power (dBm) vs. Link range (km)

Firstly, Fig. 5 (a) shows, eye –diagrams analysis at 2.5 Gb/s bit rate varying link range. It can be observed that maximum variations in eye opening are (32.4 to1.1)× 10^{-3} by varying link range 1 to 5 km with clear weather, which is due to less effect of scintillation noise. Whereas, in haze condition, signal is more fluctuating due to fast winds and diversions. Comparatively less eye is opened (13.2to 0.13) $\times 10^{-4}$ at haze condition due to the power fluctuations, effect of greater power absorption coefficient and more scintillation noise. Similarly, at other weather turbulences comparatively less eye openings are observed such as (78.6 to 0.09) $\times 10^{-5}$, (36.14 to 0.01) $\times 10^{-6}$ and (21.53 to 0) $\times 10^{-7}$ at mild rain, medium rain and fog weather conditions respectively by varying link range 1 to 5 km. This due to the heavy rainy seasons the signal is more scattered due to the large size of water droplets. It has been observed that main feature of the spectrum sliced WDM system; one can obtain better performance at medium rain weather (attenuation 9.64 dB/km in Table 2).

Secondly, Fig. 5 (b) indicates eye diagrams analysis at 5.0 Gb/s bit rate. The maximum eye opening is shown at clear weather due to less absorption coefficient and effect of scintillation noise. The eye opening observed are at different turbulences such as (29.32 to 1.08) $\times 10^{-3}$, (11.95 to 1.12) $\times 10^{-4}$, (7.11 to 0.08) $\times 10^{-5}$, (3.27 to 0.01) $\times 10^{-6}$ and (1.90 to 0.00) $\times 10^{-7}$ at clear weather, haze, mild rain, medium rain and fog conditions respectively. It can be notice that the proposed system works effectively up to 5 km with all weather conditions but its performance in fog satisfactory up to 2 km only. The reason for this can be attributed such as at winter season with fog weather there is frozen droplets present in free air atmosphere having same size of wavelength of optical wave results in maximum power absorption. This limits link range of the system at this fog weather condition.

Table 5: Eye opening vs. distance (km) at 2.5 and 5.0 Gb/s bit rate

Range Distance (km)	**Eye height (a.u.) with range (km) with turbulences of Table 2, at 2.5 Gb/s bit rate**				
	(a) $\times 10^{-3}$	**(b)** $\times 10^{-4}$	**(c)** $\times 10^{-5}$	**(d)** $\times 10^{-6}$	**(e)** $\times 10^{-7}$
1	32.4	32.1	78.66	36.14	21.53
2	7.9	13.0	46.8	99.13	03.02
3	3.4	2.3	4.92	4.7	0
4	1.9	0.53	0.06	0.26	0
5	1.1	0.13	0.09	0.01	0

Range Distance (km)	**at 5.0 Gb/s bit rate**				
1	29.3	19.45	71.14	327.4	19.75
2	7.23	12.57	4.28	8.97	2.68
3	3.14	2.13	0.45	4.2743	0
4	1.72	0.48	0.06	0.23	0
5	1.08	0.12	0.08	0.01	0

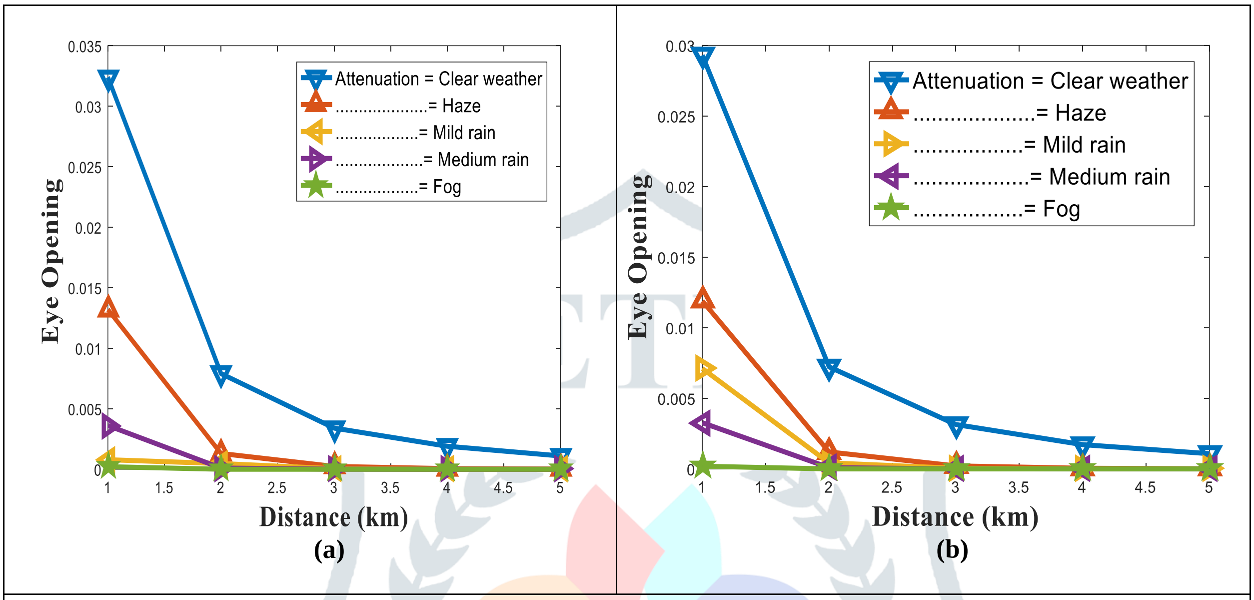


Fig.5 Eye height (a.u.) at the receiver output vs. range (km) 0 to 5, bit rate (a) 2.5, (b) 5.0 Gb/s, with atmospheric turbulences.

Table 6: Comparison of The proposed system with ref. (4) and ref. (6)

S. No.	**Results**	**Ref. (4)**	**Ref. (6)**	**The proposed system**
1.	No of channels and channel spacing	4 channels , 75 GHz	4 channels, 75 GHz	4 Channels, 100 GHz
2.	Optical Power (dBm) Launched in HNNF	30	0 to 15	30
3.	Link range (km)	1 to 5	1 to 2.5	1 to 5
4.	Bit Rate (Gb/s)	2.5	1.56	2.5,5.0,7.5,10
5.	Optical Receiver pow (dBm) varying link range 1 to 5 km.	-17.59 to -31.63	-13.1 to -24.9	-8.59 to -22.92
6.	Q-factor with clear weather for 1 to 5 km	42.57 to 36.24	--	66.37 to 65.96
7.	Eye Opening (a.u.)	------	-----	32.4×10^{-3} to 1.1×10^{-3}

Finally, a comparison of the proposed system performance with referred literature is presented in a tabular form in Table 6. It shows, the system has been investigated at higher transmission bit rates such as 2.5, 5.0, 7.5 and 10.0 Gb/s for range length 1 to 5 km, whereas work in literature [4 and 6] is reported only at 2.5 Gb/s under similar turbulence conditions. Further, optical receiver sensitivity of the investigated system is better about 9, 5 dBm at 1 km range and 9, 2 dBm at 5 km range respectively compare to [4, 6]. This optical power margin can be utilized to enhance the link range and transmission bit rate of the system. Similarly, the system Q-factor improvements are indicated about 22 and 19 for 1 and 5 km range respectively at clear weather, compared to [4]. These indicated improvements are a good contribution to the research work on FSO communication systems.

4. **Conclusion**

The paper has thoroughly investigated of 4 channel SS-WDM-FSO system with super continuum generation HNNF for link range 1 to 5 at bit rates are 2.5, 5, 7.5, and 10Gb/s. The analysis is observed at atmospheric turbulences, clear weather, haze, mild rain, medium rain and fog weathers. The system exhibits better performance in terms of Q-factor, received power and eye height under these atmospheric turbulences. It is shown that, the system has comparatively better performance in terms of Q- factor, optical receiver sensitivity and bit rate to the work reported in literature [4, 6] under similar link range and weather conditions. The improvements reported here, 66.37 Q- factor, 9 optical receiver sensitivity and 10 Gb/s bit rate can be employed to design advanced SS WDM FSO communication systems.

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