Performance analysis of free space optical communication system employing WDM-PolSK under turbulent weather conditions

J. JEYARANI[a,*], D. SRIRAMKUMAR[a], B. E. CAROLINE[b]
[a] *Department of ECE , National Institute of Technology, Tiruchirappalli Tamilnadu , India*
[b] *Department of ECE, IFET College of Engineering, Vilupuram, Tamilnadu, India*

Abstract Wavelength Division Multiplexing (WDM) employing Polarization Shift Keying (PolSK) modulation has been introduced to improve the capacity and efficiency of communication in FSO channel. This paper is to investigate the performance characteristics and quality of each communication link of data rate of 2.5 GB/s. WDM PolSK system is designed and simulated for four channels to increase the performance of communication under various weather conditions. The atmosphere is significantly influenced by different weather conditions. The proposed model is susceptible to system degradation due to turbulences where wind velocity, rain, haze, refractive index and height of buildings have been majorly focused. A case study has been added to implement virtual communication between class rooms in a college building and a school in a village without using internet service.

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1. Introduction

Free-space optical (FSO) communication system is a line of sight technology that provides solution to the emerging multimedia communication and can be used where internet service is not a viable solution. FSO uses air as a medium to transmit signal from one place to other in the form of light. The major advantages of free space optics (FSO) systems when compared with RF are high bandwidth, low cost, easy and fast installation without any major digging operations, redeployment and portability, license-free operation, highly secured transmission , high bit rates, full duplex transmission etc. [1,2]. But, FSO performance is adversely affected by the atmosphere through which it propagates. The interference caused by fog, haze, rain etc modifies the light characteristics and changes the passage of light. This in turn decreases the power density of transmitted beam and the effective distance of the FSO link [3]. In order to increase the capacity of FSO, WDM were introduced. This technique provides the needed range of capacity and a wide coverage area to facilitate more number of users [4]. The major problems faced in FSO due to turbulence can be reduced by choosing parameters like modulation techniques, wavelength, and attenuation coefficient of the transmitter, receiver and link sections. In FSO systems, the signal is transmitted as light intensity which is modulated before transmission. The most common digital modulation techniques used are i) On-Off Keying (OOK) [5,6,7] this technique has the drawback of severe amplitude distortion, ii) Binary Phase Shift Keying (PSK) and Differential Phase Shift Keying (DPSK) [8,9,10] which suffers from the complexity in receiver structure iii)Pulse Position Modulation (PPM) [11,12] which requires slot and symbol synchronization, etc. Polarization shift keying (PolSK) modulation [13, 14, and 15] is a modulation scheme which attracted many researchers in the free space communication field. PolSK modulation utilizes the vector characteristics of light signal from laser source for binary and multilevel transmission because the polarization state is the most stable parameter for the laser beam propagated in the atmosphere. PolSK have the many advantages such as: the alignment of polarization coordinates of the transmitter and the receiver is not necessary since depolarizing nature of atmosphere is not prominent under different weather conditions. Also the intensity of Light is more uniform when propagating through atmospheric turbulences. Therefore, PolSK modulation is chosen be a good choice for FSO system. To satisfy the needs of growing multimedia and internet capacity in wireless networks, WDM yields a promising solution. WDM is used to simultaneously transmit the different channels independently over the FSO link with reduced deployment costs [3, 4].

This proposed work is implemented to provide access to a classroom virtually from a building in a college campus to the classrooms in a nearby village to provide awareness in skill development programs. India is still a developing country where the technical skills for all the people in villages are under progress. A simulated model has been proposed to provide communication between the class rooms separated by 4.8Km distance. The system is modeled considering the wind velocity, refractive index and height of buildings. We analyzed the Performance of BPSK WDM system and PolSK WDM system and compared the results based on BER and received power under turbulent weather conditions. Based on the analysis, we proposed WDM-PolSK scheme to provide the virtual communication. The paper is organized as follows: Section 2 discusses WDM with FSO system model. Section 3 depicts the experimental setup which is implemented to analyze the performance of the system for various weather conditions. In Sections 4 and 5, the results and discussions for the entire setup have been inferred and the required graphs have been plotted as per the analysis.

Section 6 explains a case study on the virtual class room between the village nearby and the college building which are 4.8 km apart(Main Block in the College and Village called InamKulathur) . Finally, concluding remarks are highlighted in Section 7.

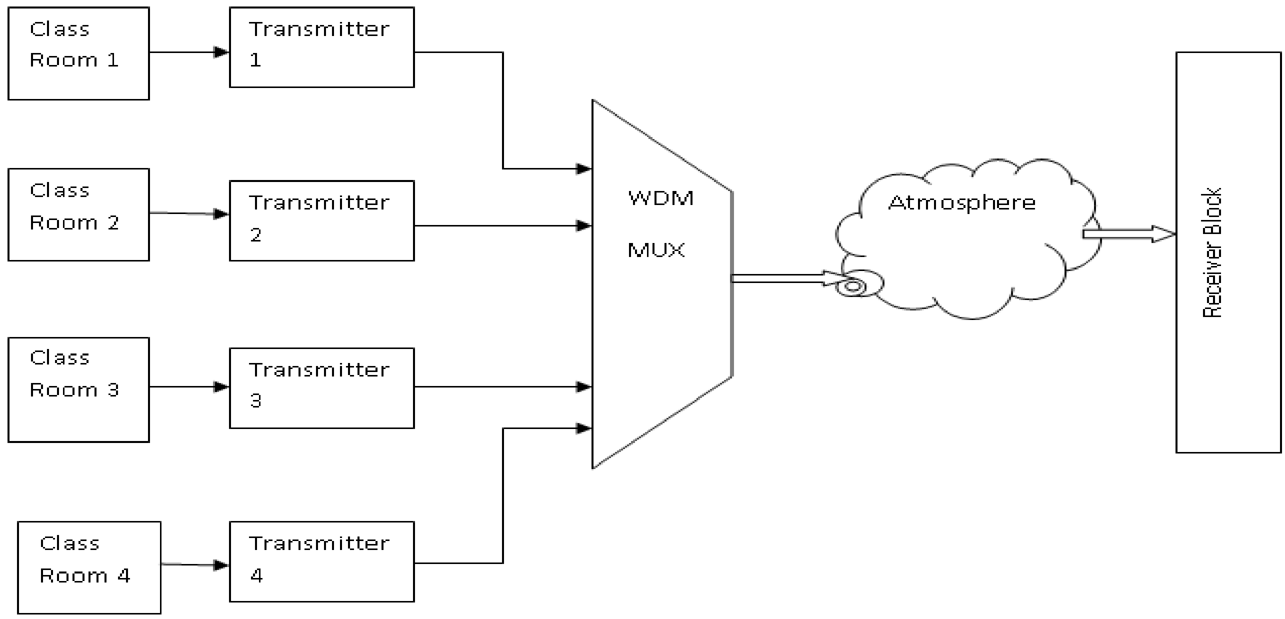

Fig. 1. Block Diagram of WDM Transceiver

2. WDM - FSO system model

WDM is a scalable network which supports higher bandwidth. The capacity of the system can be extended according to the system developed by the user in a particular area [4]. The optical signals transmitted have the potential to attain high speed communication without the need of optical– electrical–optical process. FSO is a point to point wireless communication technology which sends signals through the atmosphere using optical signals as the carrier frequencies. In FSO line of sight communication occurs through air for the video, voice and data transmission considering air as a medium [1]. Using this method of communication a case study has been considered. The block diagram of the proposed system is shown in fig 1.

Four class rooms with separate mike and cameras have been set up. The real time captured voice and video signals from the four class rooms are optically modulated and transmitted separately using two WDM multiplexers from one building to another building. The real time voice and video signal are converted into electrical signals. The electrical signals are used to modulate a continuous wave LASER source for a single voice or video channel. The multiplexed signals are transmitted through atmosphere. FSO offers narrow bandwidth which makes it a secured communication [1].

3. System model for PolSK - WDM FSO Configuration

The model for the WDM employing PolSK [18, 19] for FSO link is developed in the equations as follows.

The transmitted PolSK signal from a single channel from a classroom is given as the equation (1)

$$E(t) = P_t e^{j\omega t}\{m(t)\hat{x} + [1 - m(t)]\hat{y}\} \quad (1)$$

where P_t is the transmitted power, ω is the angular frequency and m (t) is the input binary data. The multiplexed data is written in equation (2) as

$$E_t(t) = \sum_{i=1}^{n} E_i(t) \quad (2)$$

where n is the number of channels.

The received signal after demultiplexing from channel 1 is modeled as the following equation (3)

$$E_r(t) = \sqrt{\frac{P_r}{2}} e^{j(\omega t + \varphi(t))} E_t(t) \quad (3)$$

where P_r is the received power and m (t) is the input binary data. The received optical signal E_r (t) is split into two polarized fields by using a beam splitter and detected as $R_1(t)$ and $R_2(t)$ and expressed in (4) and (5) as

$$R_1(t) = RA_r \cos(\omega t)[1-m(t)] + n_x(t) \tag{4}$$

$$R_2(t) = RA_r \cos(\omega t) m(t) + n_y(t) \tag{5}$$

where R is the responsivity of PIN photo detector $n_x(t)$ and $n_y(t)$ represents the noise and A_r is the amplitude of the received signal.

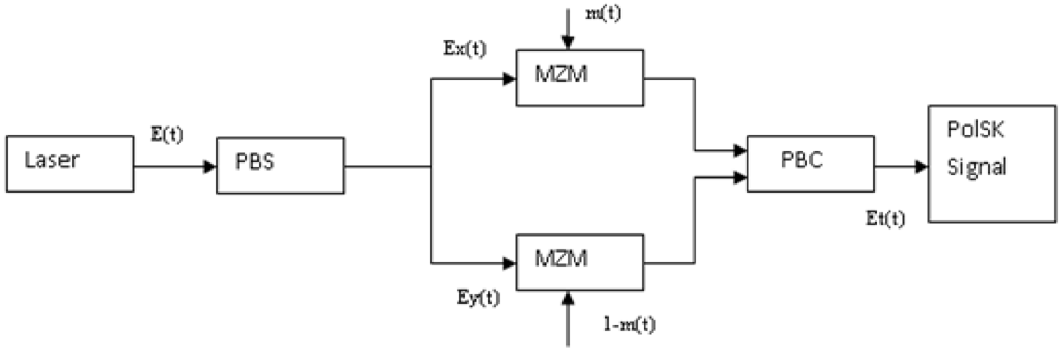

Fig. 2. PolSK transmitter

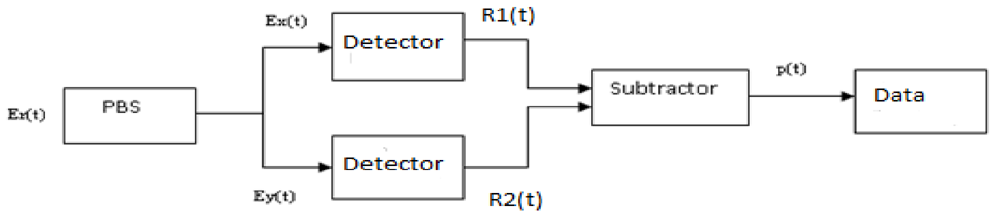

Fig. 3. PolSK receiver

4. Simulation setup

Video signals are electronically digitized into a stream of on/off pulses, and converted into an equivalent electric signal. An optical transmitter takes the incoming electrical signal and converts it into an equivalent light signal. We used four Laser sources for the four class rooms.

The proposed system comprises of three modules 1) transmitter 2) FSO link 3) receiver which is illustrated in Fig. 1. Each PolSK transmitters as shown in Fig. 2 consist of a Laser source, a Polarization Beam Splitter (PBS), two Mach- Zehnder modulators (MZM) and a polarization Beam Combiner (PBC). The light signal from the Laser source is split into two equal components x and y polarizations.

Each polarized signal is modulated with the given binary data using separate MZM modulators and combined using a PBC as a PolSK signal. The four PolSK Transmitters transmit four channels with wavelengths as 1550 nm, 1552nm, 1553nm and 1555 nm with a carrier spacing of 0.9nm. The four channels are multiplexed using WDM multiplexer and transmitted in free space. Four continuous wave Laser sources with power of 4mW are used in the transmitters which produced four different wavelengths which satisfied the eye standards safety regulations. The binary data considered in this proposed work used NRZ coding scheme for encoding.

The transmitted multiplexed signal through the atmosphere is faded by atmospheric turbulences. De-multiplexers in the receiving end is used to separate the multi-wavelength optical signal by splitting it back into a series of the original wavelengths.

After leaving de-multiplexers, these single-wavelength optical signals are sent to optical receiver. A receiver, which typically includes a photo detector and electronic circuitry, converts received optical signal into an equivalent electrical signal. This signal is subsequently converted back into its original sound, video or data form. DEMUX shown in Fig.1 dis-aggregates the received signal and the channels are split into four as in the transmitter. The block diagram of the proposed PolSK system is given in the Fig. 2.

The Light from the continuous wave laser is split into Ex and Ey and modulated by MZM modulators. The outputs are combined using a PBC as PolSK signal. The block diagram of receiver is shown in the Fig. 3. The signal is split into Ex and Ey components before photo detection. Each channel is decoded using a PolSK receiver which consists of PBS, PIN photo detectors, and subtractor and a data recovery block.

The receiver has demodulators which demodulates and the received data. Each channel Receiver uses two photo detectors and a subtractor to get the original data transmitted as described by the mathematical model. The results are calculated including the thermal noise, shot noise of PIN photo detectors in the receiver.

PolSK modulation is simulated using Phase Modulator and binary 1 is phase modulated and transmitted in X polarization and binary zero is transmitted without modulation and transmitted in Y polarization.

5. Simulation parameters

The FSO system performance has been inspected for various weather conditions by applying the set of parameters (see Table 1).

Table 1

Simulation Parameters	Values
Data Transmission rate	2.5 Gb/s for single Channel
No .of Carriers	4
Wavelengths used(nm) (λ1,λ2,λ3,λ4)	1552.5244,1553.4244, 1554.3244,1555.2244
Carrier Spacing	0.900nm
Laser Power	10mW
Responsivity of PD	1.11 A/W

The wavelength for simulation is used around 1550nm since it is legally allowed to transmit 50 times more power than other wavelengths and favors penetration through fog for long distances [21]. Central wavelength is assumed from the nominal central wavelengths provided by ITU-TG.694.1 [22]. The transmission rate of 2.5 GB/s is already reported in [23]. Laser type class 1M with the power of 10mW is used as permitted by IEC (International Electro Technical Commission) in [24]. Responsivity is calculated for central wavelength of 1552nm

6. Results and discussions

The performance and characteristics of WDM-BPSK and WDM-PolSK FSO system have been evaluated and compared using BER versus distance and BER versus received power under different weather conditions namely clear, haze, rain and fog for the data rate of 2.5Gb/s. It is perceived that increase in BER, increases transmission distance as well as attenuation factor.

6.1. BER versus transmission distance analysis

FSO link achieved up to 350 km for very clear conditions with BER of 10^{-5} using PolSK modulation whereas the distance is reduced to 312Km for WDM-BPSK systems which is shown in Fig 4. For the same BER when the atmosphere is clear, the transmitted optical signal is mostly attenuated by mist and drizzle and hence the transmitted distance is reduced to 275 Km for WDM-PolSK and 231Km for BPSK-WDM systems. PolSK based WDM systems travel 44km more than BPSK based system. In Fig. 5 we compare the BER value is compared for different rain conditions.

Attenuation of optical beam due to the rain is rather low compared to the fog. For rainfall, the scattering coefficient depends on the size of the raindrops, which is many times larger than the wavelength of the optical signal and Rain imposes a great effect in atmospheric turbulence. Rain attenuation known as "specific attenuation" in dB/km is given by

$$\alpha_{rain} = 1.076R^{0.67} \tag{6}$$

Under heavy rain conditions the BER of 10^{-10} is obtained for a link distance of 16.3Km for PolSK WDM and 12.7Km for BPSK WDM systems. FSO works better in rain conditions than in fog weather conditions. In the same figure, BER value of 10^{-10} is obtained for 22.4Km, 27.9Km for moderate and light rainfall conditions. For the same BER value the link distance is reduced to 17.4Km and 21.5K for BPSK system under moderate and light rain conditions. Fig. 5 shows the rain conditions.

The fog conditions are shown in Fig. 6. Under heavy fog condition the link distance of 6.8Km is achieved for a BER of 10^{-10} for PolSK WDM and 3.3Km for BPSK WDM systems. The system has an improved performance under light fog for the same BER with a link distance of 7.1Km and 3.7Km for PolSK and BPSK systems.

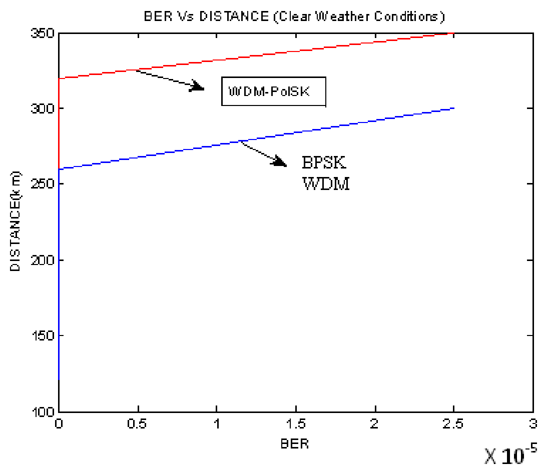

Fig. 4. BER Vs distance under clear weather conditions

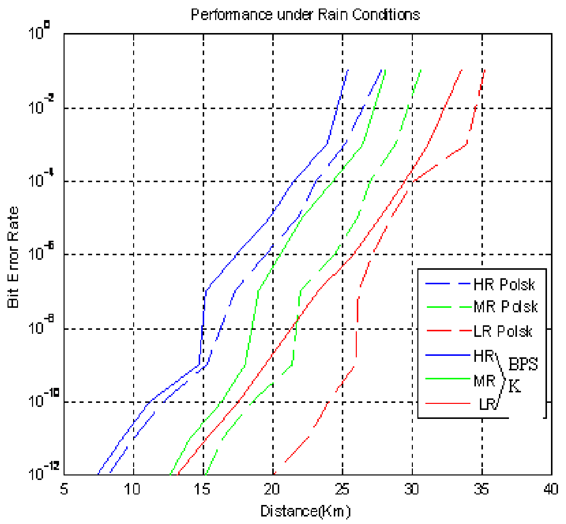

Fig. 5. BER Vs distance under rain conditions

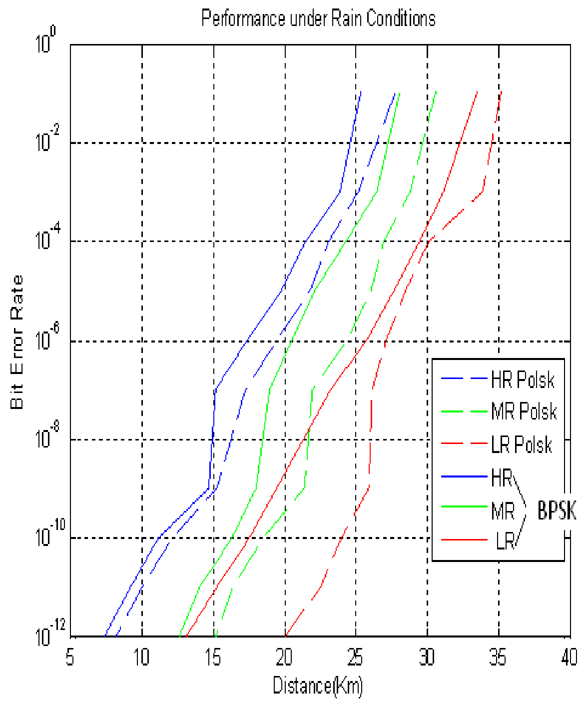

Fig. 6. BER Vs Distance (km) under fog conditions

6.2. BER versus received power analysis

The system is analyzed based on the power received during the different weather conditions and the graphs are plotted. Fig. 7 and Fig. 8 illustrates the performance of the system under heavy and light fog conditions. The distance of the link is considered as 50 Km and the received power of -70 dBm is obtained for the BER of 10^{-9} in case of PolSK based WDM and for the same received power the BER of 10^{-7} is obtained for the BPSK WDM systems under light haze conditions. Whereas the power of -78dBm is obtained for 10^{-6} and 10^{-4} for PolSK and BPSK systems under heavy haze conditions.

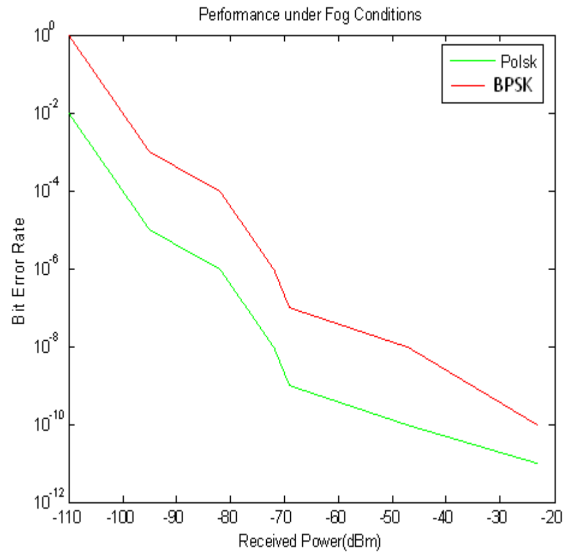

Fig. 7. Fog conditions (heavy fog)

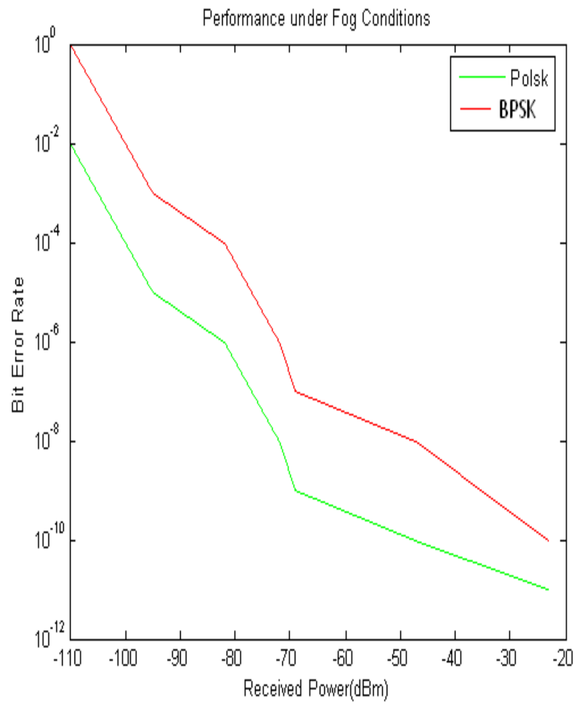

Fig. 8. Fog conditions (light fog)

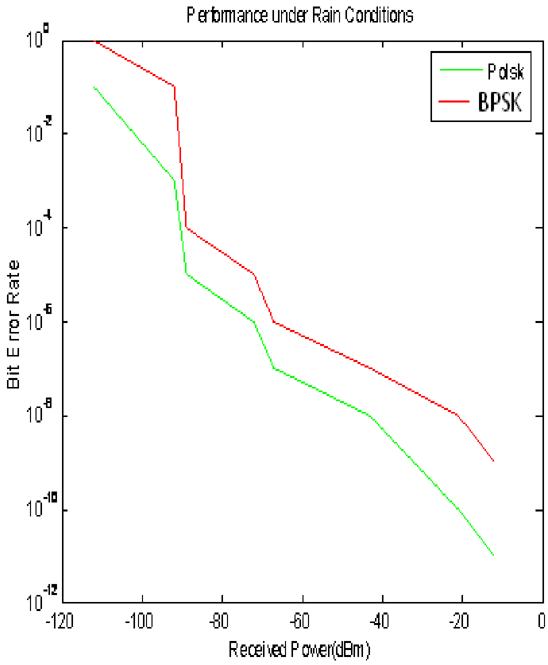

Fig. 9. Rain conditions (Heavy)

In the Fig. 9 the performance of the system under heavy rain conditions have been analyzed and plotted. The combined plot shows the performance of both the systems in rain conditions.

Received power of -64 dBm is obtained for the BER of 10^{-8} for PolSK and 10^{-7} for BPSK WDM under heavy rain conditions. The systems perform well in rain conditions when compared to fog and haze atmosphere. Since PolSK WDM performs better in all turbulence conditions we consider this scheme of modulation in our case study experiment.

7. Analysis of proposed system for wind Conditions

As already mentioned in the literature [11, 12] the wind power has been considered as a powerful tool to analyze the performance of the systems since it attenuate the transmitted optical signal in the free space environment. The wind influence on FSO is taken into account due to optical energy re-distribution [13]. The wind flows in every direction and releases turbulent energy which can determines the intensity of the velocity. which can be calculated as mentioned in [20]

$$E_t = 0.5 * 1/N \sum (u-\bar{u})^2 + (v-\bar{v})^2 + (w-\bar{w})^2 \quad (6)$$

where u, v, w are the wind speed in a particular direction. $\bar{u}, \bar{v}, \bar{w}$ are the cumulative wind speed in any one direction. N is the total number of samples and Et is the turbulent energy of the wind.

The attenuation due to wind speed is written as [13]

$$A = 70 - 73e^{-0.2867} E_t \quad (7)$$

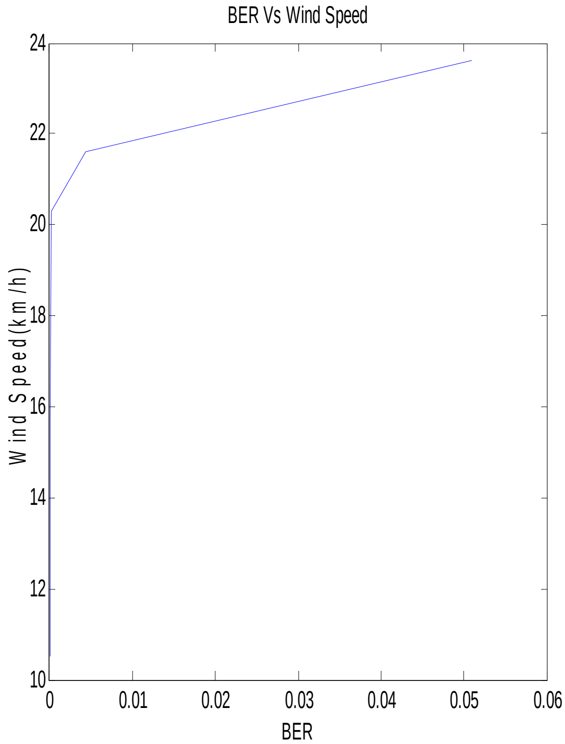

Fig. 10 . BER Vs wind speed for 12 months (tricky weather conditions)

Along with the wind speed, the height of the building is another main factor to be considered for FSO propagation. The wind speeds in the college building and the nearby village where the virtual communication have to be setup are calculated. The proposed setup is established in the Main Block the College and classrooms in the village school building named InamKulathur, a small village in Tamilnadu, India. They are separated by 4.8 Km distance with the height of the building from where signal is to be sent is 12.972m. The wind speed for 12 months is collected for the last 10 years from January 2006 to January 2017 using the meteorological data. From the data collected, it is observed that wind speed is very high during the months of June and July compared to other months. Fig. 10 is plotted for BER for the various wind speeds. Minimum BER of 10^{-3} is obtained for the month of July where the average wind speed is 23.6Km/h and maximum BER of 10^{-12} is obtained during the month of April and December where the wind speed is 10.2Km/h.

The results of the proposed system are compared with the existing works in Table 2, the works by MA. Esmail et al. [24-29]. The existing works investigated the performance of FSO system under fog conditions. The proposed work considered the performance of the system in rain conditions also.

The modulation schemes used in this paper proved better provided better link distance when compared with the existing works.

Table 2

S.No with Title	**Journal**	**Parameters discussed**	**Comparison**		
			Existing System	**Proposed System With BER 10^{-10}**	
				BPSK WDM	**PolSK WDM**
1.OutageProbabilit Analysis of FSO Links Over Foggy Channel ***Ref [24]***	*IEEE Photonics Journal*, 2017	Outage Probability 10^{-3} **Modulation** : IM/DD **Multihop Transmission** **Relays used :** 1(Light Fog) 2(Moderate Fog) >3(Heavy Fog) **Direct Transmission** Light Fog Moderate Fog Heavy Fog	Link Distance Achieved 500m 450m 350m 150m	3.7Km 2.9Km 2.3 km	7.1Km 6.4Km 5.8Km
			BER with Distance		
2. On the Performance of Optical Wireless Links Over Random Foggy Channels ***Ref [25]***	*IEEE Access*, 2017	Light Fog Moderate Fog Heavy Fog Transmitted Power(dBm)	500m (4.6×10^{-4} to 7×10^{-10}) 200m (1.2×10^{-2} to 7.7×10^{-8}) 100m (more power used13.5dBm) 22dBm	BER of the orders of 10^{-10} With the distance as above. 10 dBm	
3. Investigation and Demonstration of High Speed Full-Optical Hybrid FSO/Fiber Communication System Under Light Sand Storm Condition ***Ref [26]***	IEEE Photonics Journal, 2017	BER vs. Received Power For QAM systems	**Under Clear weather conditions** -5dBm for BER 10^{-6} -9dBm for BER 10^{-5} -15dBm for BER 10^{-3} **16QAM with 100m FSO** -7dBm for 10^{-6} -9dBm for 10^{-5} -15dBm for 10^{-2}	-72dBm for BER 10^{-7} -75dBm for BER 10^{-4} -67dBm for 10^{-6} (heavy haze)	72dBm for BER10^{-9} -75 dBm for BER 10^{-6} -67dBm for BER 10^{-7} (heavy haze)
4. An Experimental Study of FSO Link Performance in Desert Environment. ***Ref [27]***	IEEE Communications Letters, 2016	Signal attenuation is calculated for desert environments	Max attenuation is 7dB. RIYADH City is Considered. Received power is calculated for different visibility ranges	Trichy city is considered which is not a desert region hence wind velocity is Considered. **Max BER of 10^{-12} is obtained with wind speed of 23.6Kmph**	

S.No with Title	Journal	Parameters discussed	Comparison		
			Existing System	Proposed System With BER 10^{-10}	
				BPSK WDM	PolSK WDM
5.Experimental demonstration of outdoor 2.2 Tbps super-channel FSO transmission System. ***Ref [28]***	ICCW. 2016	Multi format transmitter is considered	12 equal gain subcarriers are generated and modulated by a DP-16QAM signal with different symbol rates. Data rate of 2.2 Tb/s is Achieved.	4 carriers are generated using different wavelength source and multiplexed, 2.5Gb/s is Achieved.	
6. Analysis of fog effects on terrestrial Free Space optical communication links ***Ref [29]***	*IEEE (ICC)*, , 2016	FSO with RF backup is considered	Transmitted power- 22dBm BER 10^{-3} 1 Km (Light Fog) 200m(Light Fog)	Transmitted power 10dBm **(Light Fog)** BER 10^{-9} 7.1Km for PolSK and 5.3Km for BPSK **(Heavy Fog)** BER 10^{-6} 5.8Km for PolSK 2.3Km for BPSK	

8. Conclusion

This paper infers that WDM - PolSK has been subjected to various weather conditions and the performance is evaluated. The performance of the system is analyzed for various atmospheric conditions like haze, fog and rain. The recordings are tabulated and compared with that of BPSK WDM system. It is observed that the link distance is inversely proportional to the BER value under turbulence and clear weather conditions. The capacity of communication in FSO channel is increased using WDM as 10 GB/s. The heights of buildings have been majorly focused for the virtual classroom. A case study has been reported to implement four virtual class rooms in two widely separated buildings in the college campus to provide communication without using internet service.

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*Corresponding author: jeyaranijeyaseelan@gmail.com