



PolSK and ASK Modulation Techniques Based BER Analysis of WDM-FSO System for Under Turbulence Conditions

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Abstract

This paper details a novel model of Wavelength Division Multiplexed (WDM) system using Polarization Shift Keying (PolSK) modulation to increase the capacity of a Free-Space Optical System. The proposed system reduces the cross-channel effects and phase related variations of transmitting signal since PolSK transmits signals in two orthogonal polarized directions. A mathematical model for the system is developed and simulated. The closed-form expressions for the PolSK based WDM system is derived. A case study has been done to implement virtual class rooms in JJCET, Trichy to explore the benefit of using WDM using PolSK for different climatic conditions. The parameters like Bit Error Rate (BER) are analyzed for different weather conditions. The BER of 10^{-10} is obtained for a link distance of 15.3 km under gamma–gamma turbulence channel in heavy rain conditions, and 5.8 km link distance is achieved for fog conditions using this novel method. Four separate channels each with a data rate of 2.5 Gbps are multiplexed to increase the capacity of the system to 10 Gbps. The system is compared with WDM employing Amplitude Shift Keying under the same environmental conditions. The simulation results obtained for BER and received power against different atmospheric conditions are compared for both the modulation schemes and proved that PolSK based WDM offers better performance.

Keywords Wavelength Division Multiplexing (WDM) · Polarization shift keying (PolSK) · Free-space optical (FSO) · Bit error rate (BER) · Gamma–Gamma turbulence model

1 Introduction

Free-space optical (FSO) communication system is a growing communication technology, used as an alternate technology where internet service is not a feasible solution. In FSO light signal is sent from transmitter to receiver using the air as a transmission medium. The advantages of FSO systems are bandwidth scalability, low cost, easy and fast deployment and portability, license-free operation, high transmission security, high bit rates, full duplex transmission etc. [1–3]. Though FSO has plenty of advantages, its performance is

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unpropitious affected by the atmospheric turbulences. The major causes of interference are fog, haze, rain, etc. which changes the characteristics of the transmitted light and as a result decreases the power density of the signal transmitted and the effective distance of the FSO link [4]. In order to overcome this WDM were introduced in FSO which provides higher capacity and a wide coverage area to facilitate a more number of users [4]. The effects of turbulence can be reduced by proper adjustments of parameters like modulation techniques, wavelength, and attenuation coefficient of the transmitter, receiver and link sections. In FSO systems, the intensity of the light signal from the laser source is modulated before transmission. The most common digital modulation techniques used are (1) On–Off Keying (OOK) [5–7] which suffers severe amplitude distortion, (2) Binary Phase Shift Keying (PSK) and Differential Phase Shift Keying (DPSK) [8–10] have a drawback of complexity in receiver structure (3) Pulse Position Modulation (PPM) [11, 12] which requires slot and symbol synchronization, etc. Polarization shift keying (PolSK) modulation [13–15] is a new digital modulation technique in free space communication field. PolSK modulation utilizes the vector characteristics of light signal from laser source for binary and multi-level transmission because the polarization state is the most stable parameter for the laser beam propagated in the atmosphere. Compared to other modulation schemes the PolSK have two advantages: (1) the alignment of polarization coordinates of the transmitter and the receiver is not necessary. (2) Light intensity is more uniform when propagating through atmospheric turbulences. PolSK is a technique, which uses SOP of optical signal as information carrying parameter. The reason of using this modulation scheme is that it uses constant envelope and hence provides reduced sensitivity to phase noise of Laser and also the patterning effects of Optical amplifiers used in the receivers. Therefore, PolSK modulation is chosen be a good choice for FSO system.

WDM is a promising technique for increasing the bandwidth and aids in promoting different types of services in the optical access network. WDM is a technique used to send multiple channels (multiple users) independently over the FSO link with reduced deployment costs. There is always a requirement in the current multimedia communications for a large bandwidth communication which leads the choice of WDM [16]. WDM technique is useful in optical communication network for the reason that the capacity of the FSO system can be increased simply by increasing the number of channels and closely placing the channels without using more than one FSO link. WDM in FSO systems is used to maximize bandwidth usage but in cheaper way [17, 18]. WDM is the approach used to enhance the link capacity [19]. Only very few works have been reported in WDM using FSO and none used PolSK as the modulation scheme.

This proposed work is analysed using a case study to implement simultaneous access to four classrooms in a remote building in a college campus. A model has been devised to provide connectivity between the class rooms between two buildings separated 2 km distance. The system is modeled in consideration of the distance and between the buildings, height of the buildings, and wind velocity We analyzed the Performance of WDM systems using two modulation schemes namely ASK and PolSK and compared the results based on BER and received power and different weather conditions. Based on the analysis, we selected WDM-PolSK scheme to illustrate the virtual classrooms.

The paper is formulated as follows: Sect. 2 explains WDM-FSO system and the channel model used. Section 3 details the system model for WDM-PolSK and the transmitter and receiver section. In Sect. 4 the results are discussed for the proposed model and it is compared with the existing ASK WDM model. Section 5 explains a case study on the virtual class room between two blocks; Main Block and PG Block which are 3.2 km apart in JJ College of Engineering & Technology, Tiruchirappalli. Conclusion is given in Sect. 6.

2 WDM-FSO System

The main objective of this work is to evaluate the BER performance of the WDM employing PolSK modulated FSO system operating over the gamma–gamma atmospheric turbulence channel. The noise, including the background radiation and the thermal noise, is formulated as the additive white Gaussian process (AWGN) and PIN photo detector noises (both thermal and shot noise) are considered. The transmitter and the receiver are in line of sight to avoid misalignment errors.

2.1 Gamma–Gamma Turbulence Model

The atmospheric turbulence has been analyzed and different channel models have been proposed by researchers. The major models are (1) Log normal model (weak turbulence) [20, 21] (2) Gamma–Gamma (weak to strong turbulence [22] (3) Negative exponential model (strong turbulence) [22]. Gamma–Gamma model is used in this paper as the channel model to analyse the effects of turbulence. According to this model, the fluctuation of the laser beam propagating through the turbulence medium consists of the refraction and scattering effects. The normalized received irradiance I is defined as the product of two statistically independent random processes I_x and I_y defined [6] by the Eq. (1)

$$I = I_x I_y \tag{1}$$

I_x and I_y are the large-scale and small-scale turbulent eddies, respectively.

Their probability density function [6] is given by the Eqs. (2) and (3)

$$p(I_x) = \frac{\alpha(\alpha I_x)^{\alpha-1}}{\Gamma(\alpha)} \exp(-\alpha I_x) \tag{2}$$

$$p(I_y) = \frac{\beta(\beta I_y)^{\beta-1}}{\Gamma(\beta)} \exp(-\beta I_y) \tag{3}$$

Gamma–gamma irradiance fluctuation [6] is given by Eqs. (4) and (5)

$$p(I) = \int_0^\infty p\left(\frac{I}{I_x}\right) p(I_x) dI_x \tag{4}$$

where $I > 0$;

$$p(I) = \frac{2\alpha\beta^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\frac{\beta}{2})-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{5}$$

where α and β represents small scale and large scale eddies of the scattering process. $K(\cdot)$ is modified bessel function of second kind of order n . $\Gamma(\cdot)$ represents gamma function. α and β values are given by the Eqs. (6) and (7) as

$$\alpha = \left[\exp\left(\frac{0.49\sigma_I^2}{(1 + 1.11\sigma_I^{\frac{2}{3}})^{\frac{7}{6}}}\right) - 1 \right]^{-1} \tag{6}$$

$$\beta = \left[\exp \left(\frac{0.51\sigma_l^2}{\left(1 + 0.69\sigma_l^{\frac{12}{5}}\right)^{\frac{5}{6}}} \right) - 1 \right]^{-1} \tag{7}$$

2.2 PolSK Modulation

The proposed system employs PolSK which is a form of digital optical modulation. Information is transmitted using the state of polarization of a fully polarized light wave. In this scheme the received signal is demodulated and detected using stokes parameters. A detailed theoretical treatment is presented in [1]. Let us assume a fully polarized light wave, which propagates in the z direction. The electric field E can be decomposed into two orthogonal components, E_x and E_y as defined by the Eqs. (8) and (9) as

$$\text{Where } E_x = a_x(t)e^{j(\omega t + \phi_x(t))}\hat{x} = E_x\hat{x} \tag{8}$$

$$E_y = a_y(t)e^{j(\omega t + \phi_y(t))}\hat{y} = E_y\hat{y} \tag{9}$$

where ω is the angular frequency and a_x, a_y are the magnitudes and ϕ_x, ϕ_y are the phase of x and y components respectively.

The stokes parameters are given as the Eqs. (10)–(13)

$$s_1 = a_x^2 - a_y^2 \tag{10}$$

$$s_2 = 2a_x a_y \cos(\delta) \tag{11}$$

$$s_3 = 2a_x a_y \sin(\delta) \tag{12}$$

$$\delta = \phi_x - \phi_y \tag{13}$$

The block diagram of the proposed PolSK system is given in the Fig. 1. E(t) is the signal from the laser source which is split into E_{x(t)} and E_{y(t)} using a Polarization beam splitter.

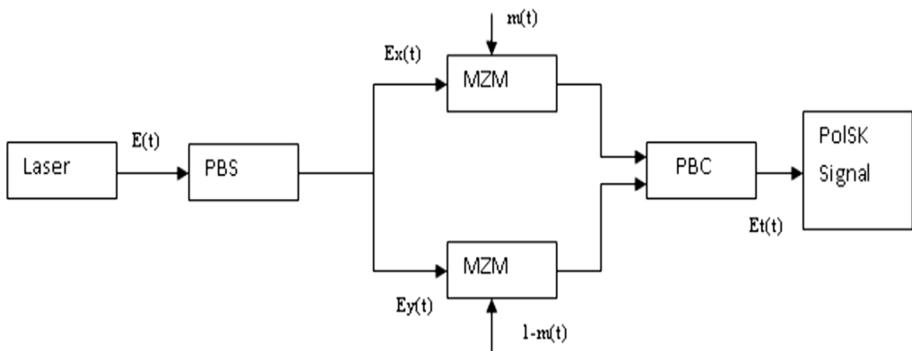


Fig. 1 Block diagram of PolSK transmitter

$E_{x(t)}$ acts as a carrier which modulates the message signal $m(t)$ using a MZM modulator. Similarly $E_{y(t)}$ act as another carrier signal which is orthogonal to $E_{x(t)}$ and modulates the message signal using another MZM modulator. The ‘0’ is transmitted using X polarization and ‘1’ is transmitted using Y polarization. Both are combined using a polarization beam combiner which forms $E_{t(t)}$, the PolSK signal before transmission.

The receiver section of PolSK is shown in the Fig. 2. The received signal is split into the E_x and E_y components before photo detection. Each channel is decoded using a separate PolSK receiver with a single polarization beam splitter, two photo detectors (PIN), and one subtractor and a data recovery block.

The transmitted PolSK signal from a single channel is given as the Eq. (14)

$$E_x(t) = P_t e^{j\omega t} \{m(t)\hat{x} + [1 - m(t)]\hat{y}\} \tag{14}$$

where P_t is the transmitted power, ω is the angular frequency and $m(t)$ is the input binary data. The multiplexed data are written in Eq. (15) as

$$E_t(t) = \sum_{i=1}^n E_x(t) \tag{15}$$

where n is the number of channels used.

The received signal after demultiplexing from channel 1 is modeled as the following Eq. (16)

$$E_r(t) = \sqrt{\frac{P_r}{2}} e^{j(\omega t + \phi(t))} \{m(t)\hat{x} + [1 - m(t)]\hat{y}\} \tag{16}$$

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 as $E_x(t)$ and $E_y(t)$ and expressed as (17) and (18) as

$$p_1(t) = RA_r \cos(\omega t)[1 - m(t)] + n_x(t) \tag{17}$$

$$p_2(t) = RA_r \cos(\omega t)m(t) + n_y(t) \tag{18}$$

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.

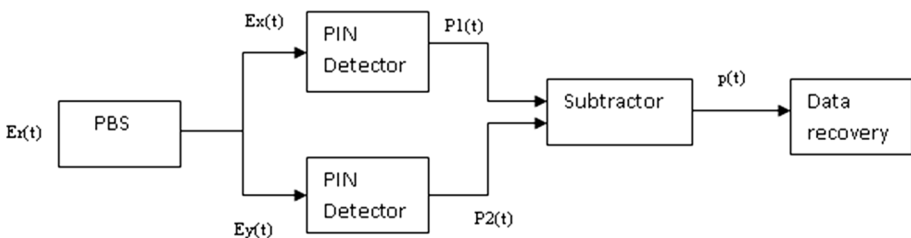


Fig. 2 Block diagram of PolSK receiver

3 System Model for PoISK-WDM FSO Configuration

The WDM for FSO have been analyzed by many researchers. But they have considered OOK as the modulation scheme for transmission for simplicity. Inter channel crosstalk have also been analyzed in [23]. The model for the WDM employing PoISK for FSO link is developed first time in this work and analyzed as follows. The proposed system as shown in Fig. 3, combines signals from four transmitters using WDM and it comprises of three modules (1) transmitter section, (2) FSO link, (3) receiver section. Each channel is having a separate PoISK transmitter as shown in Fig. 1 and a receiver as shown in Fig. 2.

In the proposed system, the four PoISK transmitters transmits four channels with wavelengths as 1550.12 nm, 1550.92 nm, 1551.72 nm and 1552.52 nm with a carrier spacing of 0.8 nm. We used four continuous wave Laser sources with power of 4 mW to satisfy the eye standards safety regulations. NRZ coding scheme is used to encode the binary data in the transmitter. PoISK 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. The Light from continuous wave Laser source is linearly polarized with the angle of (+45°). The stokes parameter values of the designed system are $(s_1, s_2, s_3) = (0, 1, 0)$ which defines a linearly polarized light beam with (+45°) polarization. The four channels are multiplexed using a WDM multiplexer and multiplexed signal is transmitted in free space.

The multiplexed signal travelling through the atmosphere is encountered by various atmospheric turbulences. The received signal is demultiplexed using a DEMUX as shown in Fig. 3 and the channels are split.

The receiver demodulates and decodes 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.

In the simulation, we consider an FSO system link with a transmitter aperture diameter 5 cm and receiver aperture diameter 20 cm at a link length of 1 km with a beam divergence of 2 mrad and for attenuation of 2 dB/Km under normal conditions. Four

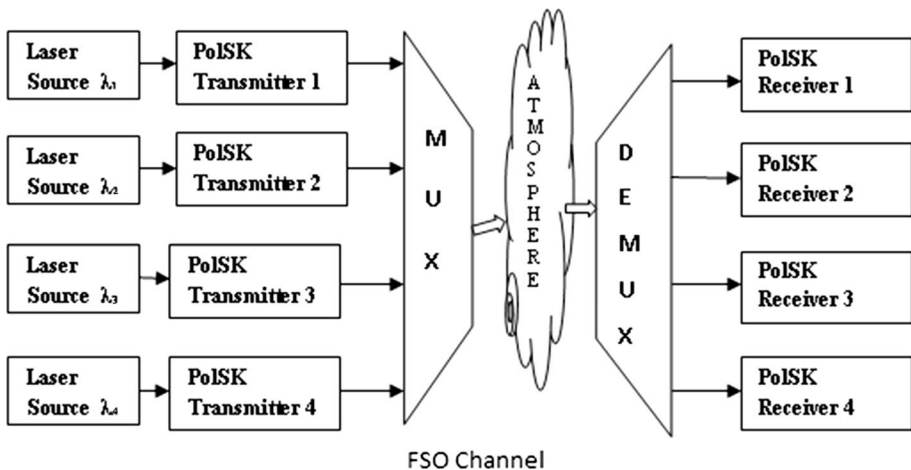


Fig. 3 Block diagram of WDM-FSO system employing PoISK modulation

PoLSK channels, each with a data rate of 2.5 Gbits/s are designed with 0.8 nm channel spacing. The various specifications used for simulation are listed in Table 1.

4 Results and Discussions

4.1 BER Calculation

The virtue of digital signal transmission is graded using the Bit Error Rate (BER) pattern of the digital communication system. The BER is assessed by correlating the transmitted bits with the received bits. The bit error rate is defined as

$$BER = \frac{1}{2} * erfc\left(\frac{Q}{\text{sqrt}(2)}\right) \tag{19}$$

The transmitted optical signal in a free space channel is responsive to the different atmospheric conditions such as fog, rain, haze and many environmental conditions. The photons and the molecular constituent of the atmosphere interact and cause scattering and attenuation. Attenuation due to atmosphere reduce the performance of the FSO systems since it varies with respect to the atmospheric conditions is given by Beers–Lambert law [12, 14, 24] given in the Eq. (20)

$$P_R = P_T \exp(-\alpha_{\text{absorption}} + \alpha_{\text{scattering}})z \tag{20}$$

where P_T and P_R represents power transmitted and power received respectively, $\alpha_{\text{scattering}}$, $\alpha_{\text{absorption}}$ are absorption and scattering coefficients.

Optical beam transmitted in rain is less attenuated when compared with that in fog. The scattering coefficient varies with the size of the raindrops, and that of the wavelength of the optical signal. The table gives the value BER for different atmospheric conditions from heavy to light rain. Rain attenuation in dB/km is given by

$$\alpha_{\text{rain}} = 1.076R^{0.67} \tag{21}$$

where α_{rain} is attenuation due to rain and R is rainfall rate in mm/h.

Table 1 Specific values used in simulation

Parameters	Values
Data transmission rate	10 Gbits/s
No. of carriers	4
Wavelengths used (nm) ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$)	1550.12, 1550.92, 1551.72, 1552.52
Carrier spacing	0.800 nm
Laser power	4 mW
Responsivity of PD	1 A/W
Link distance	2 km

4.2 BER Analysis Under Different Weather Conditions

In Fig. 4, FSO link has been analyzed by varying the distance between the transmitter and receiver. Signal can be recovered up to the distance of 350 km for very clear conditions with BER of 10^{-5} using PolSK modulation whereas the distance is reduced to 300 km for WDM-ASK systems. For the same BER value, when we consider the atmosphere as clear, the signal is attenuated by mist and drizzle and the link distance is reduced to 275 km for WDM-PolSK and 224 km for ASK-WDM systems where we can get an additional 51 km using PolSK based systems.

In Fig. 5 we compare the BER value is compared for heavy rain conditions. Under heavy rain conditions the BER of 10^{-10} is obtained for a link distance of 15.3 km for PolSK WDM and 14.7 km for ASK WDM systems. FSO works better in rain conditions than in fog weather conditions. In Figs. 6 and 7, the same BER is obtained for 21.4 km, 25.9 km for moderate and light rainfall conditions. For the same BER value the link distance is reduced to 18.4 km and 19.5 km for ASK WDM system under moderate and light rain conditions.

The fog conditions are shown in Figs. 8 and 9. Under heavy fog condition the link distance of 5.8 km is achieved for a BER of 10^{-10} for PolSK WDM and 2.3 km for ASK WDM systems. The system has an improved performance under light fog for the same BER with a link distance of 7.1 km and 3.7 km for PolSK and ASK systems.

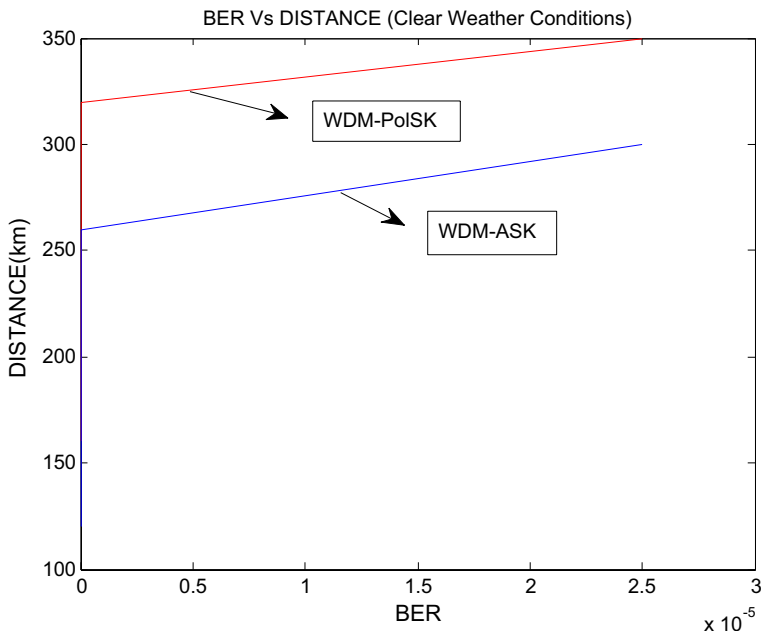


Fig. 4 Performance under clear weather conditions (BER vs Distance)

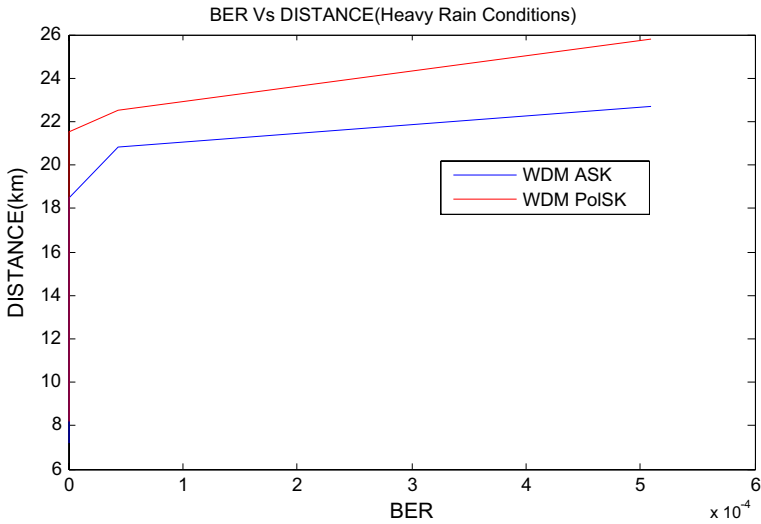


Fig. 5 Performance under heavy rain conditions

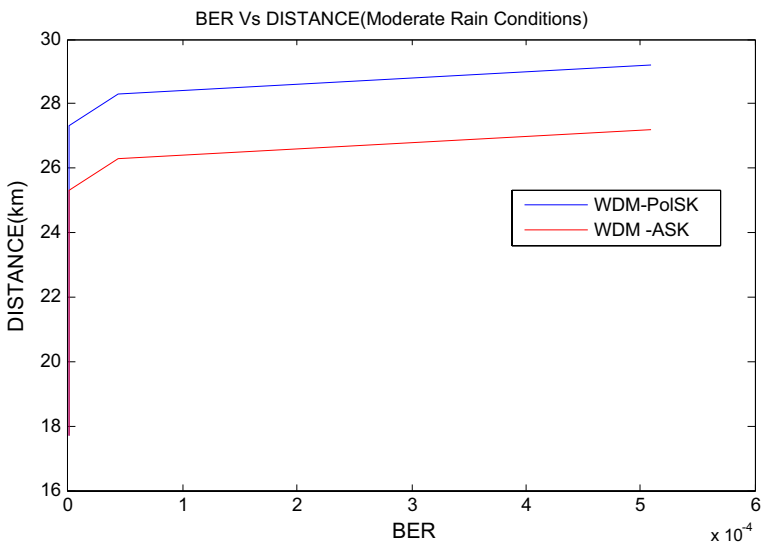


Fig. 6 Performance under moderate rain conditions

4.3 BER Versus Received Power Analysis

The system is analyzed based on the power received during the different weather conditions and the graphs are plotted. Figure 10 illustrates the performance of the system under heavy and light fog conditions. The distance of the link is considered as 55 km and the received power of -72 dBm is obtained for the BER of 10^{-9} in case of PoISK based WDM and for the same received power the BER of 10^{-7} is obtained for the ASK WDM systems

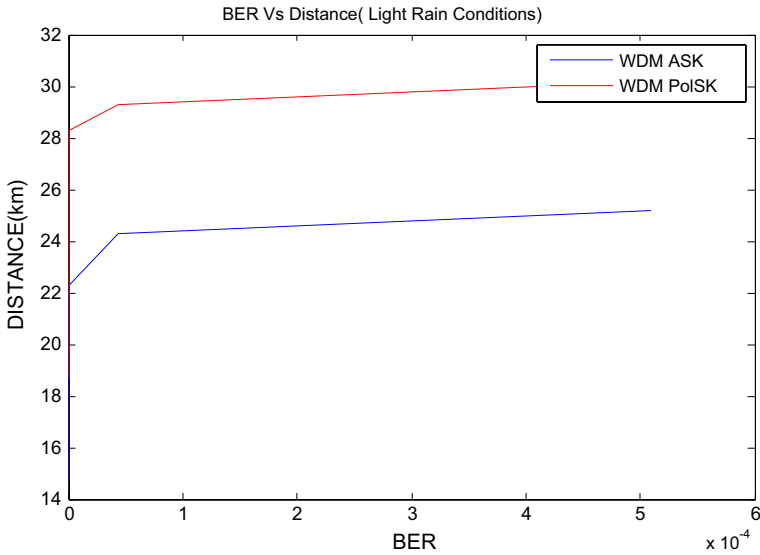


Fig. 7 Performance under light rain conditions

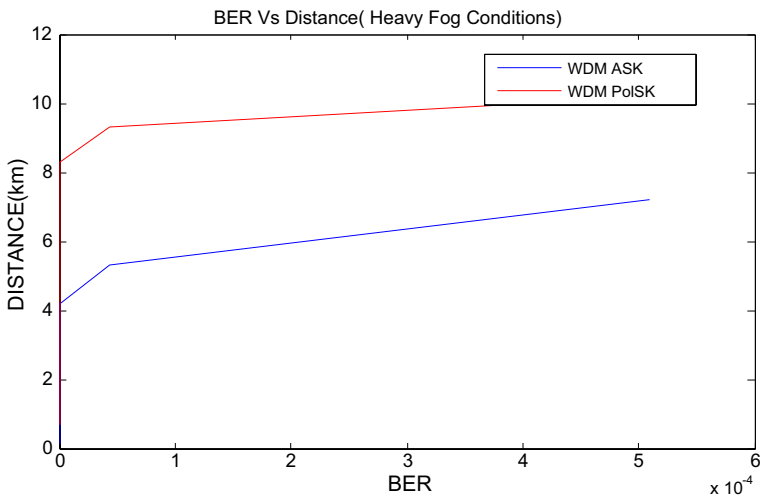


Fig. 8 Performance under heavy fog conditions

under light haze conditions. Whereas the power of -75 dBm is obtained for 10^{-6} and 10^{-4} for PolSK and ASK systems under heavy haze conditions.

In the Fig. 11 the performance of the system under various rain conditions have been analyzed and plotted. The combined plot shows the performance of both the systems in rain conditions.

Received power of -67 dBm is obtained for the BER of 10^{-8} for PolSK and 10^{-7} for ASK WDM under heavy rain conditions. The systems perform well in rain conditions

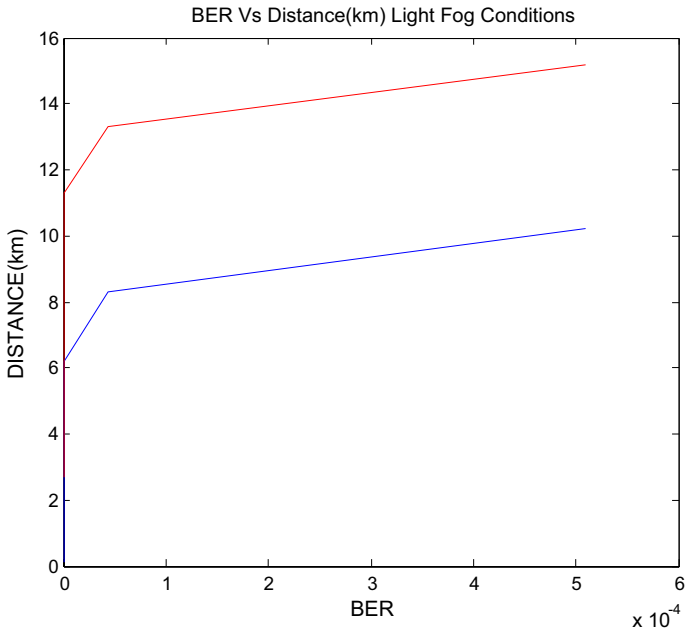


Fig. 9 Performance under light fog conditions

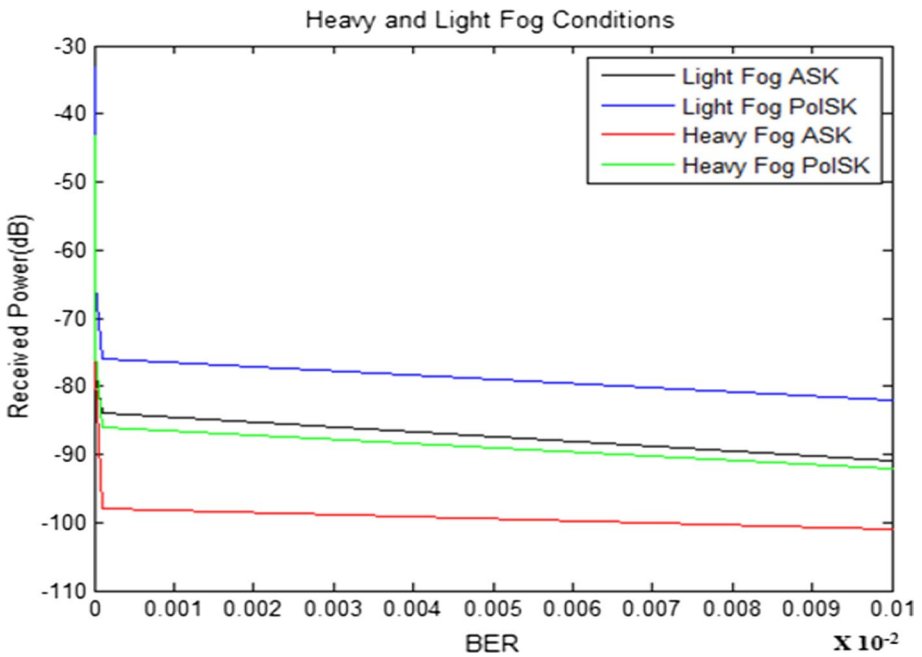


Fig. 10 Fog conditions

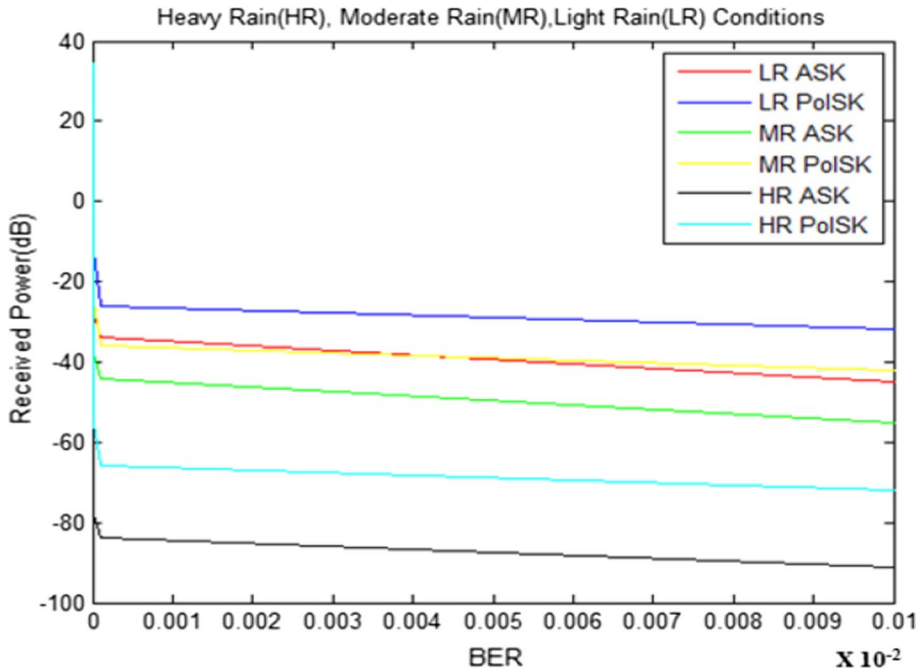


Fig. 11 Rain conditions

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.

5 Analysis of Virtual Class Rooms: A Case Study

Figure 12 shows the block diagram of the proposed virtual class rooms with four separate channels using four different wavelengths, considered each class room as a separate optical channel which uses PolSK modulation for transmission.

Each classroom is provided with a separate digital camera which captures video signal and a mike for audio signal. Along with the data, these signals are multiplexed using H.264 video compression format. And the multiplexed video is modulated using a separate optical signal from a laser source and sent as a channel for transmission. Four such channels are multiplexed using a MUX and sent into the atmosphere using a single FSO Link using an optical antenna. The Fig. 13 shows the block diagram of the transmitter setup in the class room.

Figure 14 shows the receiver block diagram. The demux at the receiver receives optical multiplexed signal from the atmosphere using an optical antenna. The demux separates the four wavelengths and each wavelength is given to a separate receiving class room where the signal is demodulated and detected.

Figure 15 shows the receiver block diagram in the virtual classroom. Each classroom is provided with a demodulator and data deformatter and the output is given to a demux

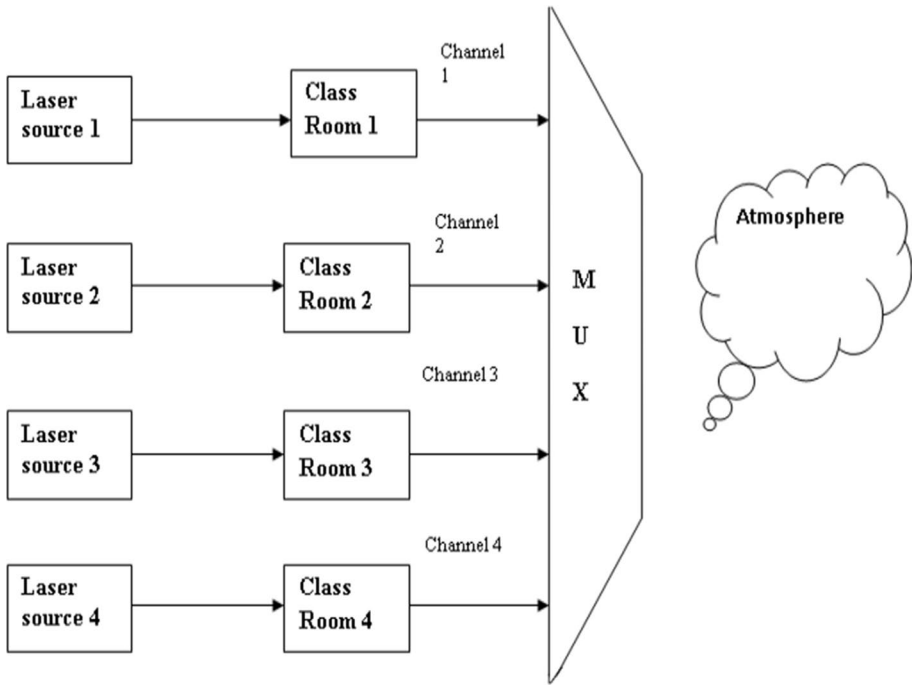


Fig. 12 Block diagram for virtual class rooms

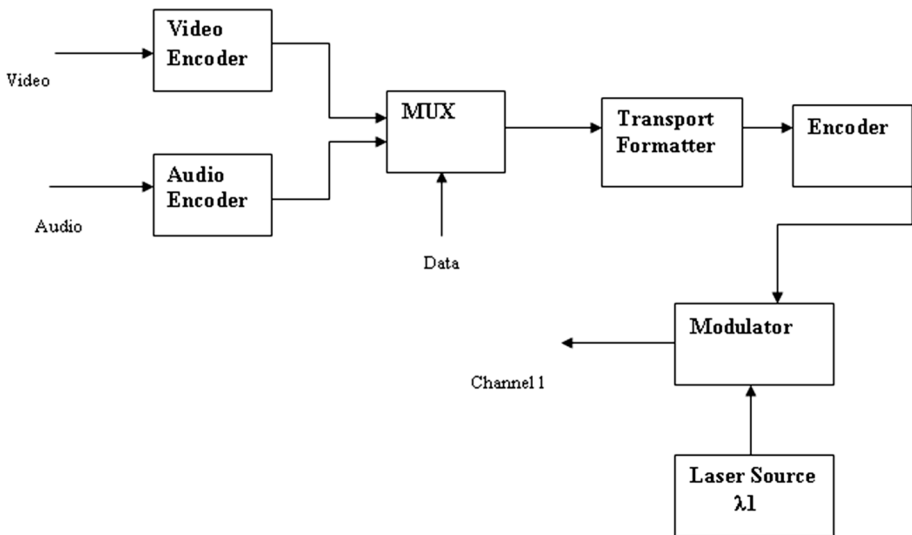


Fig. 13 Transmitter setup in the class room

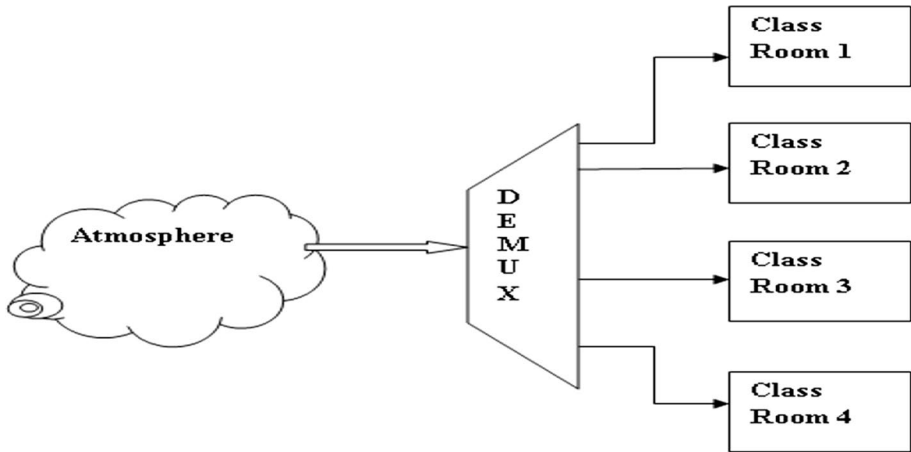


Fig. 14 Block diagram for receiver

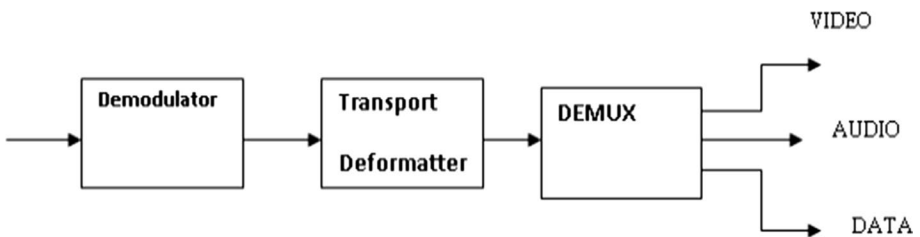


Fig. 15 Receiver at virtual classroom

which separates audio, video and data outputs. They are displayed using a LCD Screen and also with an audio system.

As proposed in [3, 11–14] the wind power has been considered to analyze the performance of the systems since it attenuate the transmitted optical signal in the free space environment. The wind influence on FSO are taken into account due to optical energy redistribution [3, 13]. The wind flows in every direction and releases turbulent energy which can determine the intensity of the velocity. This can be calculated as referenced in [3, 20]

$$E_t = 0.5 * 1/N \sum (x - \bar{x})^2 + (y - \bar{y})^2 + (z - \bar{z})^2 \tag{22}$$

where x, y, z are defining the wind speed in the three directions. \bar{x} , \bar{y} , \bar{z} defines the cumulative wind speed in one particular direction. N denotes the samples used for calculation and E_t is the turbulent energy of the wind.

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

$$A = 70 - 73e^{-0.2867 E_t} \tag{23}$$

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 buildings where the virtuals have to be setup are calculated.

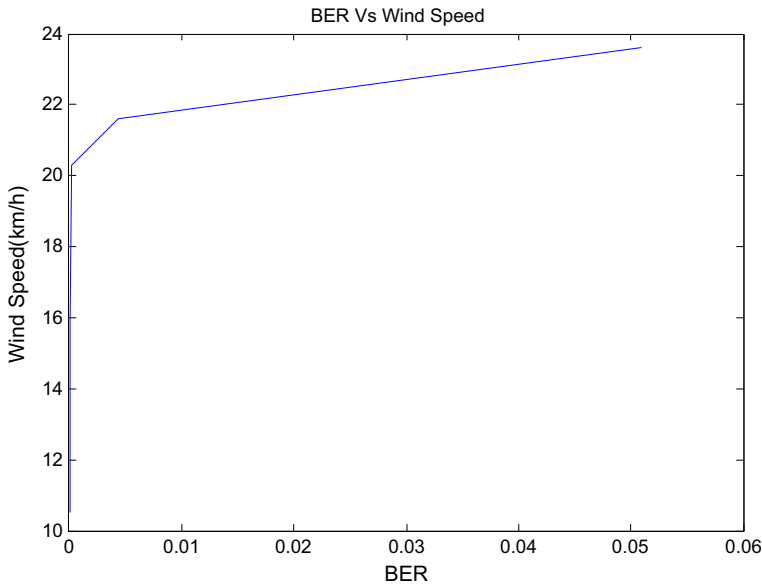


Fig. 16 Performance for Trichy weather conditions (BER vs Wind Speed for 12 months)

The proposed setup is established in the Main Block and PG block of JJ College of Engineering and Technology, Trichy, Tamilnadu in India. The two blocks are separated by 3.2 km distance with the height of 10.972 m. The wind speeds for 12 months are 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. Figure 16 is plotted for BER for the various wind speeds. Minimum BER of 10^{-3} is obtained in the month of July where the average wind speed is 23.6 km/h and maximum BER of 10^{-12} is obtained during the month of April and December where the wind speed is 10.2 km/h.

6 Conclusions

In this paper, the mathematical model for WDM-FSO is developed and the model is simulated for different weather conditions. The performance of the system is analyzed using the network parameter such as BER for varying distance and power received for different distances. The system improves the capacity of an FSO link by using WDM as 10 Gbits/s. The proposed system supports the link distance up to 10 km under heavy fog conditions. The proposed system is compared with the ASK WDM system and from the analysis, it is shown that the PoISK WDM system works well in all the turbulence conditions. The proposed system is useful to implement virtual class rooms in hilly areas where the wired connections are not possible to be established. Since WDM is useful to transfer multiple channels simultaneously, this report will be useful to find applications in broadcasting in terrestrial areas.

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