Polarization Shift Keying Modulation: A Novel Modulation Technique for FSO Systems

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***Abstract* - A brief review of Polarization Shift Keying Modulation is presented in which binary bits are encoded as orthogonal states of polarization. Circle Polarization Shift Keying Modulation is discussed which reduces the system complexity by cancelling the requirement of polarization coordinate alignment at transmitter and receiver. In contrast to binary Polarization Shift Keying Modulation scheme, multilevel Polarization Shift Keying Modulation scheme supports higher data rates as multiple bits are encoded in one symbol. To combat the effect of atmospheric turbulence, Spatial Diversity proves to be an effective tecnique in FSO systems.**
***IndexTerms* - Free-space optical communication (FSO), Polarization Shift Keying (PolSK) Modulation, State of Polarization (SOP), Circular PolSK (CPolSK), Multilevel PolSk (MPolSK), Spatial Diversity.**

I. INTRODUCTION

Free-space optical communication (FSO) refers to communication of optical data over unguided propagation medium. FSO is a Line of Sight (LOS) technology which operates at 850, 1300 and 1550 nm [1]. FSO based links have been developed for establishing communication links between satellites, ground stations, unmanned aerial vehicles (UAVs), high altitude platforms (HAPs), aircrafts, etc. Such links have proven to be of great advantage for both military and civilians. As bandwidth, spectrum and security issues favour the adoption of FSO as compared to radio frequency (RF) communication, FSO is considered to be a good option for net-centric connectivity [2]. Besides having many advantages like unlimited bandwidth, high data rate, large capacity, unlicensed spectrum, etc., the performance of FSO links is highly affected by atmospheric turbulence, scintillation and pointing errors. In FSO based links, atmospheric turbulence leads to the intensity and the phase fluctuations of the received light signal, negatively effecting the FSO link performance. Temperature and pressure inhomogeneities of the atmosphere also causes variations of the refractive index along the transmission path which leads to deterioration of the quality of the received signal. This finally results in an increase in the link error probability, limiting the performance of communication systems. Aerosol scattering effects caused by rain, snow and fog can also degrade the performance of free-space optical communication systems High degree of attenuation provided by haze, rain, snow and fog degrades the quality of the FSO link because of absorption, scattering and reflection [3]. Many modulation techniques have been proposed to be used in FSO based communication systems based on intensity, frequency and phase modulation such as On-Off Keying, Binary Phase Shift Keying-Subcarrier Intensity Modulation (BPSK-SIM), Differential Phase Shift Keying (DPSK), Differential Phase Shift Keying-Subcarrier Intensity Modulation (DPSK-SIM), M-ary Pulse Position Modulation (M-PPM), etc. [4]. To improve the reliability of the FSO system, various techniques such as adaptive optical technology, time or spatial diversity have been proposed but they also increase the cost and complexity of the system. The solution to achieve a reliable communication link at low cost and less system complexity is to use a novel modulation scheme. As concerning the FSO domain polarization is a more stable property as compared to intensity, frequency and phase. So, Polarization Shift Keying Modulation Technique has proven to be a good option for FSO systems because depolarizing property of atmosphere is very weak.

II. POLARIZATION SHIFT KEYING (POLSK) MODULATION

FSO systems are generally implemented using intensity modulation/direct detection (IM/DD) scheme such as On–Off Keying (OOK), in which digital bit '1' is coded as as a pulse and bit 'zero' as no pulse. PolSK Modulation codes digital bits as different states of polarization (SOPs) where digital bit '1' is coded as +45 Linear Polarized (LP) signal and bit 'zero' as -45 Linear Polarized (LP) signal [5]. In optical communication systems based on a guided propagation medium like optical fiber, State of Polarization (SOP) fluctuates because of the intrinsic birefringence of optical fibers and becomes difficult to detect at the receiver. So, PolSK modulation is not a good option for Optical fiber based communication. But in FSO domain, where the propagation medium is atmosphere, it has been established that the depolarizing property of the atmospheric channel is very weak and the SOP can be maintained easily even after long-distance propagation. So, PolSK modulation can prove to be an excellent technique to improve the reliability of the FSO system. Linear PolSK modulation (LPolSK) has shown a 3.4 dB performance improvement over OOK modulation [6].

Linear PolSK (LPolSK) modulation with Coherent Heterodyne Detection

A binary polarization shift keying (2PolSK) modulation scheme with a coherent heterodyne receiver was proposed in [7] for FSO turbulence channel.

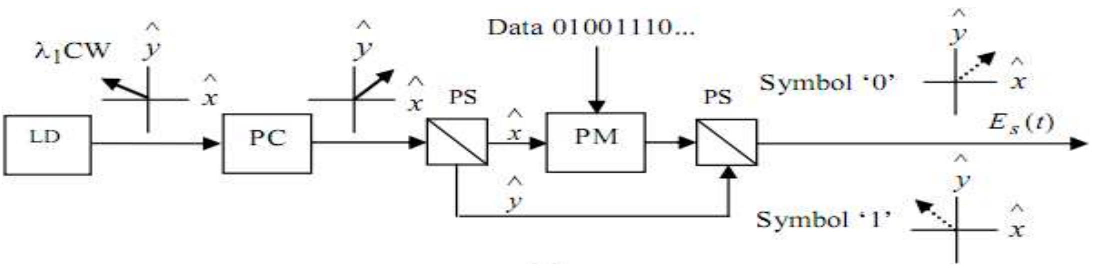

Fig. 1: Transmitter for LPolSK Modulator

Laser Diode (LD) emits light beam which is adjusted to 45 LP by using Polarization Controller (PC). Then 45 LP light is decomposed using Polarization Splitter (PS) into x-component and y-component. The x-component is modulated using Phase Modulator (PM) on the basis of incoming bit streams. The phase modulated x-component and y-component are then combined. For symbol '0' +45 LP and for symbol '1' -45 LP signals are generated as shown in Fig. 1.

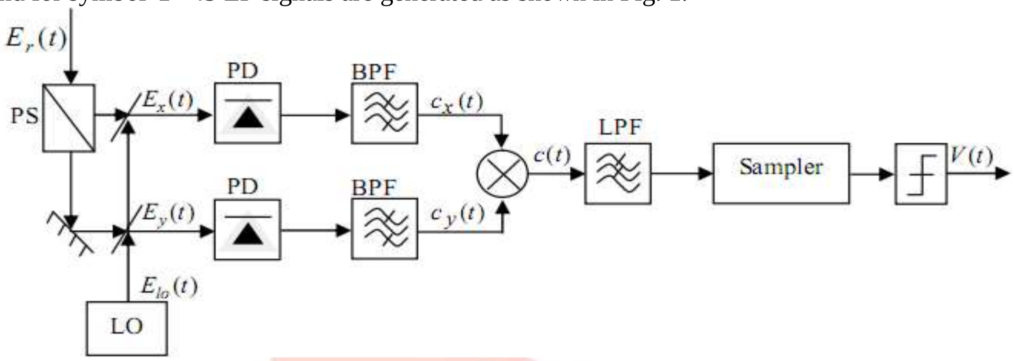

Fig. 2: Coherent Optical LPolSK Heterodyne receiver

Since, it is a coherent detection, Local Oscillator (LO) is used as shown in Fig. 2 and LO field Elo(t) is 45 LP with respect to the receiver reference axes. Er(t) is the received optical field and is decomposed into Ex(t) and Ey(t) which are superimposed on to the corresponding components of LO. The optical to electrical conversion is done using Photodiode and then filtered using Band Pass Filter (BPF). The x and y components are then combined and then fed to Low Pass Filter (LPF) for removal of high frequency noise signals before being sampled at the end of each bit interval. It is assumed that Bit'0' is received if V(t) is above the threshold level of zero, otherwise, Bit'1'is assumed to have been received.

Circular PolSK (CPolSK) modulation with Direct Detection

To improve the performance of the FSO communication system, Circular PolSK (CPolSK) modulation was proposed in [8]. Since, polarization coordinate alignment is required at the transmitter and receiver in case of LPolSK Modulation, complexity of the system is increased. Also this requirement is difficult to be maintained under those scenarios where FSO link has to be established on moving objects. In CPolSK modulation, the data is encoded as two rotation states of Circle Polarization. So, coordinate alignment requirement is cancelled in CPolSK modulation. Hence, CPolSK scheme has a great potential to be used in biomedical telemetry which generally does not involve LOS links owing to the patient's unpredictable body movements.

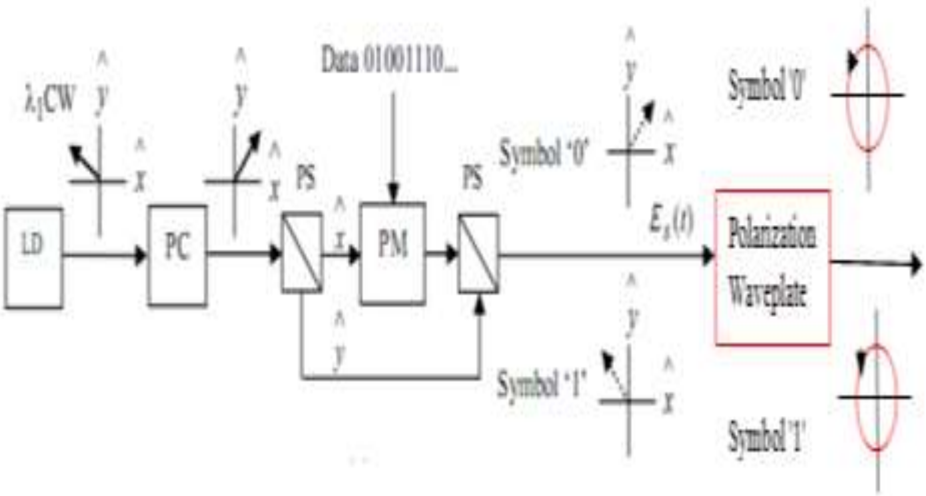

Fig. 3: Transmitter for CPolSK Modulation

In addition to the system explained in Fig. 1 for transmitter of LPolSK Modulator, Polarization Waveplate with phase deviation of 90º is added which can convert LP into Circular Polarization (CP) as shown in Fig. 3. For symbol '0' Left CP (LCP) and for symbol '1' Right CP (RCP) signals are generated.

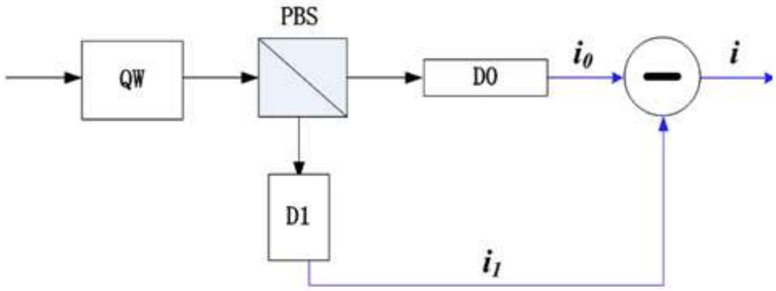

Fig. 4: Direct Detection Receiver for CPolSK Modulation

Since, CPolSK is being used, so polarization coordinate alignment is not required. Even if there is some mismatch in the angle between the polarization axis of the transmitter and the receiver, after the Quarter Waveplate, the RCP is converted into -45 LP and LCP is converted into +45 LP. After being decomposed by PBS , detection is done by D0 and D1. If i=i1-i0 >0, Bit 1 is assumed to be transmitted and if i=i1-i0 < 0, Bit 0 is assumed to be transmitted.

The reliability of the CPolSK system can be further improved if the polarization properties of optical signals remain uniform from the transmitter to the receiver [9].

III. MULTILEVEL POLSK MODULATION

In the literature, various multilevel modulation formats have been proposed for optical communication. The advantage of using Multilevel modulation schemes is that they offer higher data rates than binary modulation formats. In optical communication, Multilevel modulation scheme has been widely used with Phase-Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) to encode multiple bits per symbol [10]. PolSK modulation can be combined with ASK and PSK and demodulated without polarization control requirement at the receiver. Multilevel Polarization Shift Keying (MPolSK) can be realized using a specifically designed LiNbO3 device as proposed in [11]. This LiNbO3 deice was able to generate any SOP for transmission of MPolSK constellation.

Multilevel Polarization Shift Keying (MPolSK) in FSO turbulence channel was studies for first time in [12].

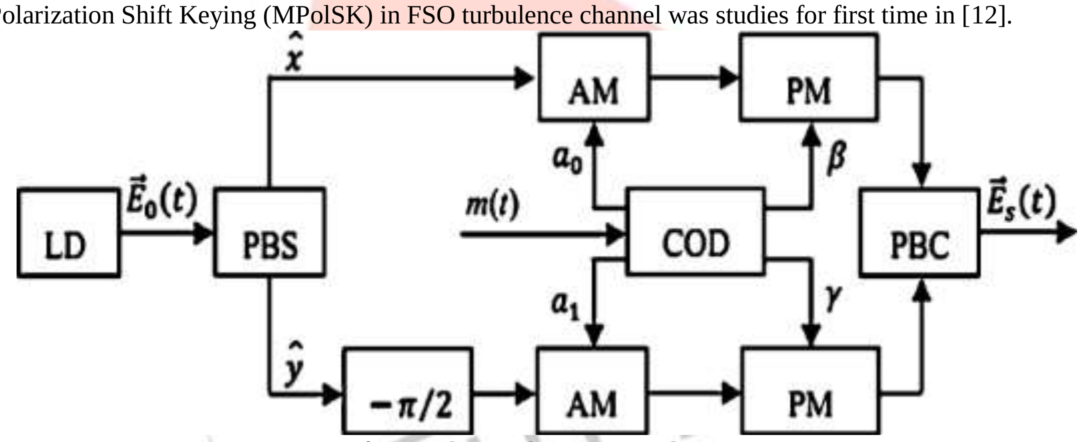

Fig. 5: Transmitter for MPolSK Coherent Optical Communication System

Laser Diode (LD) emits light beam which is decomposed using Polarization Beam Splitter (PBS) into x-component and y-component. These orthogonally polarized components are then amplitude and phase modulated synchronously and then fed into the PBC as shown in Fig. 5.

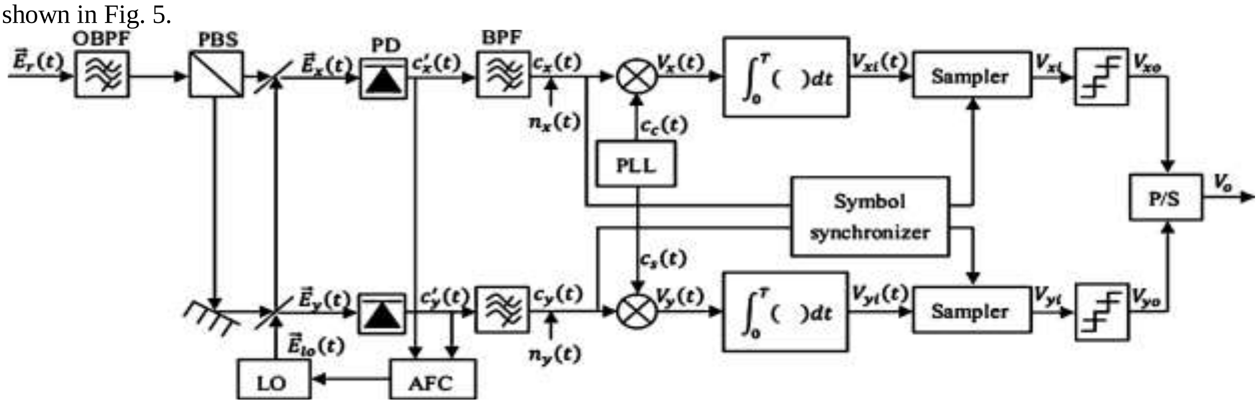

Fig. 6: Coherent Detection based receiver for MPolSK Communication System

The received optical signal, Er(t) is passed through Optical Band Pass Filter (OBPF) and then decomposed into Ex(t) and Ey(t). The LO output, Elo ¬(t) is 45 LP with respect to the receiver reference axis. Ex(t) and Ey(t) are then mixed with x and y components of the Elo ¬(t) and the optical fields (E_x)¯(t) and (E_y)¯(t) are generated which are then fed to photodiodes for optical to electrical conversion followed by a BPF. The output of BPF, cx(t) and cy(t) is then mixed with local carrier signals, cc(t) and cs(t) generated by Phase Locked Loop (PLL). The mixer output, Vx(t) and Vy(t) is passed through matched filters to remove higher frequency noise components. Vxi(t) and Vyi(t) is generated at the output of filters which is then fed to sampler based on whose output, a decision is made about the received bit being 0 or 1.

IV. POLSK MODULATION WITH SPATIAL DIVERSITY

Diversity techniques are used to mitigate the distortions induced by thee channel and improve the transmission link performance. Several diversity techniques have been proposed, such as wavelength diversity, temporal diversity and space diversity. Wavelength diversity is not of much use for FSO communication systems because atmospheric turbulence effects all wavelengths in same way and Temporal diversity requires longer signal processing time. Hence, space diversity becomes an attractive option for FSO links [13].

LPolSK Modulation with Spatial Diversity

The maximum ratio combining (MRC) and equal gain combining (EGC) spatial diversity techniques have been applied to mitigate the fluctuations caused by atmospheric turbulence.

N detectors are used at the receiver as shown in Fig. 7 and it is assumed that the Laser beam can cover the entire field of view of N detectors at the receiver. If the separation of the photodiodes is larger than the spatial coherence length of the atmospheric channel, independent signals can be received in each detector.

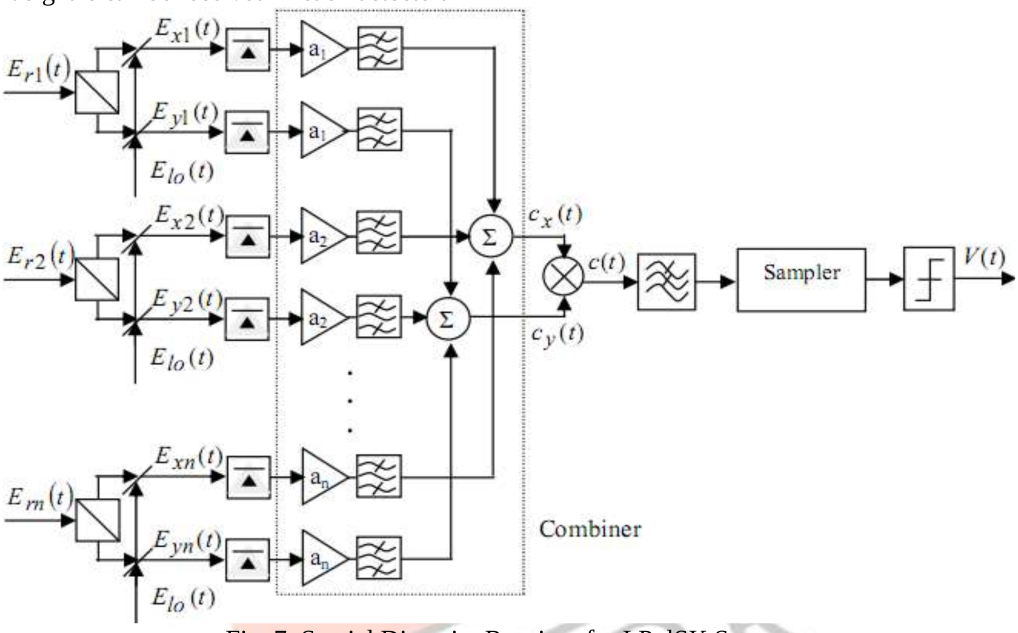

Fig. 7: Spatial Diversity Receiver for LPolSK System

For Bit Error Rate (BER) analysis, MRC and EGC were studied in [7]. In EGC, all received signals of x- and y- channels are combined coherently with equal weights. But, in MRC, the weights are proportional to received intensity resulting in a maximum likelihood receiver.

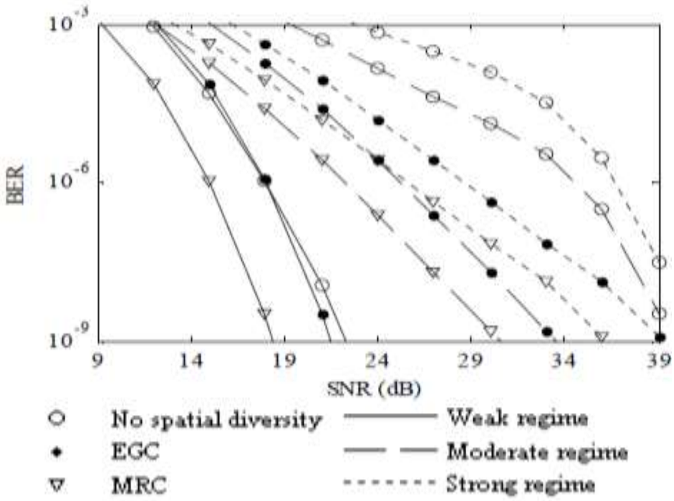

Fig. 8: BER analysis of LPolSK with Spatial Diversity having N=2

Fig. 8 shows a comparative BER analysis of LPolSK without Spatial Diversity and EGC and MRC Spatial Diversity with N=2 over weak, moderate and strong turbulence. It is observed that MRC Spatial Diversity exhibits the best performance. It was

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concluded that to achieve a BER of 10-9 in a weak turbulence, the SNR requirement is 22.4 dB and by employing Spatial Diversity using two photo detectors, SNR is reduced by 0.92 dB and 3.9 dB in EGC and MRC Spatial Diversity, respectively.

MPolSK with Spatial Diversity

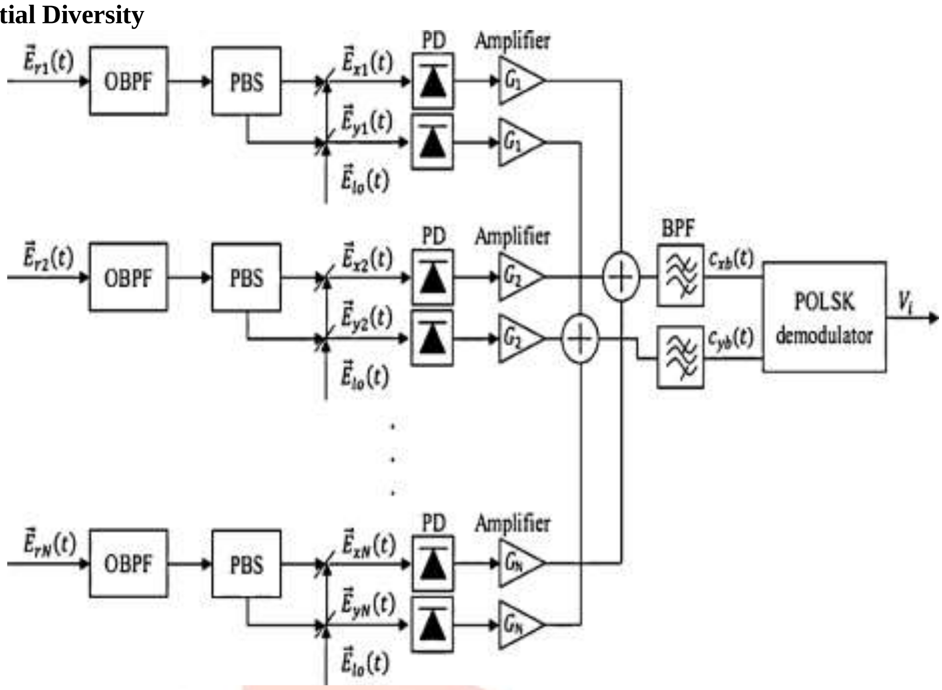

Fig. 9: Spatial Diversity Receiver for MPolSK System

MPolSK with Spatial Diversity was proposed in [12]. The received signal of each branch is weighted by a gain factor, G as shown in Fig. 9. The weighted and co-phased signals are then linearly combined before being fed to the demodulator as explained in Section 3.

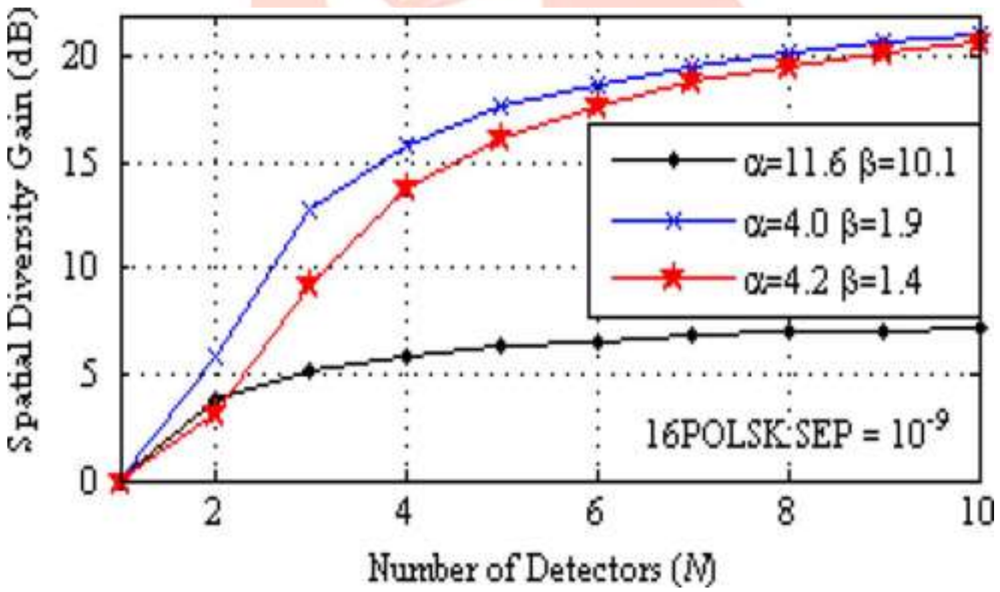

Fig. 10: Spatial Diversity Gain vs number of detectors

Fig. 6 depicts Spatial Diversity Gain vs number of detectors for 16 PolSK using MRC Spatial Diversity to obtain SEP of 10-9. After N=4, the curve starts to flatten out. So, the optimum number of detectors are between 2 and 4. Also with further increase in detectors, system complexity will increase. By using MRC spatial diversity scheme for 16POLSK using four detectors, diversity gain of 5.8, 15.8 and 13.7dB were achieved in weak, moderate, and strong turbulence regimes, respectively.

V. CONCLUSION

PolSK Modulation is a reliable option for FSO systems because depolarizing property of the atmosphere is weakest and polarization is a more stable property as compared to intensity, frequency and phase. The polarization coordinate alignment requirement at transmitter and receiver is difficult to be maintained in LPolSK. CPolSK Modulation removes this requirement and system complexity is reduced. MPolSK Modulation supports higher data rates as compared to Binary PolSK Modulation. Further improvement in the performance has been witnessed using Spatial Diversity.

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