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Free-space Optical Communication Employing Polarization Shift Keying Coherent Modulation in Atmospheric Turbulence Channel


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Abstract— A binary polarization shift keying (2PolSK) scheme with a coherent heterodyne receiver for a free space optical (FSO) link through atmospheric turbulence channel is proposed and discussed. The maximum ratio combining (MRC) and equal gain combining (EGC) spatial diversity techniques have been applied to mitigate the turbulence induced irradiance fluctuation with bit error rate (BER) expressions derived for each. The communication channel is modelled as a gamma-gamma channel. The analysis of the 2PolSK characteristics is based on the error performance in turbulence regimes from weak to strong. Simulation results show that using the proposed system with MRC offers the best performance but at the cost of high system complexity.

I. INTRODUCTION

FSO communications is a complementary technology to the radio frequency (RF) technology and optical fibre networks. It has been proposed as a ‘last mile’ solution for broadband wireless links in certain applications and scenarios [1, 2]. Other advantages of FSO consist of THz license-free bandwidth, secure transmission, smaller transceiver architecture, low development and installation cost and immunity to electromagnetic interference [3].

However, the performance of FSO systems is limited by varying atmospheric conditions. one such a scenario is the turbulence induced fading experienced by the received optical signal, which is better known as the scintillation [4]. Scintillation is due to inhomogeneities in temperature and pressure of the atmospheric, which results in the attenuation and phase fluctuation of the optical signal [5]. It can be circumvented through error control coding, aperture averaging, spatial diversity and modulation techniques [5]. However, error control coding introduces vast processing delays and efficiency degradation. Increments in the aperture size to an optimum value results in improved signal-to-noise ratio (SNR) performance. Beyond this very little improvement in the SNR performance can be achieved [6]. Spatial diversity reduces the aperture size of each detector, which avoids the single aperture size that needs to be far greater than the irradiance spatial coherence distance $\rho_0$ and also eliminates the possibility of all detectors suffering from the deep fade simultaneously at any instant [7].

An important factor on the selection of modulation technique for FSO systems is the receiver sensitivity as there is always a trade-off between the receiver sensitivity and complexity. Though amplitude shift keying (ASK) is the simplest and widely reported, it doesn’t offer immunity to the turbulence induced fading [5]. Differential phase shift keying (DPSK) with coherent phase-diversity system offers the best sensitivity in optical fibre systems. However, there is an additional power penalty caused by the frequency offset because of delayed and undelayed bits not being in phase. Furthermore, there is a further power penalty due to the phase noise of the semiconductor lasers sources. Recently, PolSK has been proposed to achieve high immunity to the phase noise of lasers [8, 9] and the states of polarization (SOPs) can be well maintained over a long distance FSO link [9]. In [10] it is shown that at higher SNR values, the coherent optical PolSK system offers much lower BER than the DPSK system.

In this paper, a novel 2PolSK system employing a spatial diversity with $N$ -photodetector is proposed to circumvent the scintillation effect on a FSO link. This scheme offers a number of advantages including: no need for synchronization at the receiver since the optical reference signal is transmitted at a different state of polarization (SOP), the intermediate angular frequency (IF) and the IF phase noise can be eliminated by employing polarization modulation; therefore no error floor and no power penalty in the BER performance, and higher transmission data rates can be achieved by employing the external modulation. Since most FSO links are based on the line-of-sight (LOS), the proposed PolSK modulation scheme is based on a linear polarization scheme. For FSO systems used in moving objects a circle polarization shift keying should be used.

The turbulence channel is modeled as a gamma-gamma distribution, which is valid from weak to strong turbulence scenarios [11]. Only background noise is considered in this paper and it is modeled as an additive white Gaussian [4]. The intersymbol interference (ISI)
due to multipath propagation is not considered because of
LOS link. The paper is organized as follows: the 2PolSK
FSO system with a single detector and error probability
analysis for a coherent optical heterodyne receiver are
presented in section II. The receiver with spatial diversity
techniques such as the equal gain combining (EGC) and
the maximum ratio combining (MRC) and the error
probability for each technique are presented in section III
followed by simulation results in Section V. Finally,
concluding remarks are presented in section VI.

II. 2POLSK MODULATION PRINCIPLES (NO SPATIAL
DIVERSITY)

A. Transmitter

Fig. 1(a) illustrates the block diagram of the proposed
2PolSK transmitter. The continuous wave (CW) light
beam with wavelength $\lambda_1$ is controlled by a polarization
controller (PC) before it is fed into the PS. The CW light
beam is linearly polarized and has a $\pi/4$ polarization with
respect to the principle axes of the phase modulator (PM).
The $\pi/4$ polarization of the input carrier is decomposed by
the PS into two equal components - $x$ and $y$ polarizations,
while only the $x$-component is phase-modulated between
0 and $\pi$ depending on the input data stream. For a binary
input data of ‘0’, no voltage is applied to the PM.
Therefore, no phase shift induced on the optical carrier,
as shown by ‘0’ polarization in Fig. 1(a). Whereas, for the
input data of ‘1’, a voltage of 1.5$V_e$ (for the electro-optic
coefficient ratio of 1/3) is applied to the PM. The applied
voltage induces a $\pi$ phase shift in the $x$-component and
zero phase shifts in the $y$-component. This leads to $\pi/2$
rotation of the polarization of the optical carrier, as
shown by ‘1’ polarization. Under these conditions, the
binary data stream is encoded into two linear orthogonal
SOPs with a constant envelope.

Fig. 1(b) shows operation principles of PM based on
the LiNbO3 device [12]. The amount of light launched in
both polarizations and their relative phases are controlled
by electro voltages $V_a$ and $V_b$, respectively. $V_{match}$ is used
for wavelength matching.

At the PM output, the transmitted optical signal $E_s(t)$
is be expressed as:

$$E_s(t) = e^{i(\omega t)} \left[ P_x \frac{\sqrt{2}}{2} e^{\theta(t)} \cdot x + P_y \frac{\sqrt{2}}{2} \cdot y \right]; \quad (1)$$

![Figure 1. Block diagrams of (a) PolSK transmitter, and (b) phase modulator based on LiNbO3. LD (laser diode), PC (polarization controller), PM (phase modulator), PS (polarizing beam splitter).](image)

![Figure 2. The block diagram of the coherent optical 2PolSK heterodyne receiver. LO (local oscillator), PD (photodiode), BPF (band-pass filter), LPF (low-pass filter).](image)
where $P_t$ is the transmitted optical power, $\omega_0$ is the optical angular frequency, and $\Theta(t)$ is the phase difference between the two field components. $x$ and $y$ are the reference axes unitary vectors.

### B. Receiver

Fig. 2 illustrates the block diagram of the proposed optical 2PolSK coherent heterodyne receiver. The LO field $E_0(t)$ is linearly polarized at $\pi/4$ with respect to the receiver reference axes. The received optical field $E_r(t)$ and $E_0(t)$ are uncorrelated and can be expressed as:

\[
E_r(t) = e^{i(\omega t + \phi(t))} \left\{ \frac{P_r}{2} e^{i\Theta(t)} \cdot x + \sqrt{\frac{P_r}{2}} \cdot y \right\}; \quad (2a)
\]

\[
E_0(t) = e^{i(\omega_0 t + \phi_0(t))} \left\{ \sqrt{\frac{P_0}{2}} \cdot x + \sqrt{\frac{P_0}{2}} \cdot y \right\}; \quad (2b)
\]

where $P_r$ and $\omega_0$ are the power and angular frequency of the LO field, respectively. $P_r$ is the received power irradiance. $\{\phi_0(t), \phi_0(t)\}$ are the phase noises associated with the transmitting laser and the LO, respectively. $E_r(t)$ is decomposed in $x$ and $y$ axes, which are superimposed to the corresponding components of LO. Assuming an electron is generated by each detected photon; the outputs from two identical PDs with a unit detector area are filtered via ideal BPFs with a bandwidth $W \geq 2R_0$, where $R_0$ is the data rate. The electric currents $\{c_x(t), c_y(t)\}$ are expressed by:

\[
c_x(t) = R\left[\sqrt{P_rP_0} \cos(\omega_0 t + \Theta(t) + \phi(t))\right] + n_x(t); \quad (3a)
\]

\[
c_y(t) = R\left[\sqrt{P_rP_0} \cos(\omega_0 t + \phi(t))\right] + n_y(t); \quad (3b)
\]

where $R$ is the photodiode responsivity, $\omega_0 = \omega - \omega_0$ and $\phi(t) = \phi_x(t) - \phi_y(t)$ are the IF angular and the IF phase noise, respectively. $\{n_x(t), n_y(t)\}$ are the x- and y-channel noises sources, respectively, which are assumed to be complex band-limited Gaussian with a zero-mean and a variance of $\sigma_n^2$. $\{n_x(t), n_y(t)\}$ can be assumed to be statistically independent because they are allocated within orthogonal SOPs. The electric currents processed by the square-law device are passed through a LPF (bandwidth of $R_0$) to eliminate the high-frequency components, prior to being sampled at the end of each bit interval. The input to the threshold detector is given by:

\[
V(t) = \left[\sqrt{2}P_rP_0/2\right] \cos \Theta(t) + n_D(t). \quad (4)
\]

LPF also suppresses the noise variance to half of its value at the output of the BPF so $n_D(t) \sim (0, \sigma_n^2/2)$. A binary ‘0’ is assumed to have been received if $V(t)$ is above the threshold level of zero and ‘1’ otherwise. It is noteworthy that, under the consideration of the multiplicative demodulation process, the influence of the IF phase and the IF angular noise in the BER performance can be eliminated.

### C. Bit error rate analysis

The probability density function (pdf) of the decision variable depends on the transmitted bit only through its average value. Assuming independent and identically distributed (i.i.d.) data transmission, the conditional bit error probability for receiving a ‘0’ provided a ‘1’ was sent, $P(V(t) < 0| m(t) = 1)$, is equal to the probability $P(V(t) < 0|m(t) = 0)$. Thus, the BER conditioned on the received power irradiance is expressed as:

\[
P_{ec} = \frac{1}{2} P(V(t) < 0| m(t) = 0) + \frac{1}{2} P(V(t) > 0| m(t) = 1). \quad (5)
\]

The noise $\{n_x(t), n_y(t)\}$ can be expressed as:

\[
n_x(t) = n_{xp}(t) \cos(\omega_0 t + \phi(t)); \quad (6a)
\]

\[
n_y(t) = n_{yp}(t) \cos(\omega_0 t + \phi(t)); \quad (6b)
\]

where $\{n_{xp}(t), n_{yp}(t)\}$ and $\{n_{xp}(t), n_{yp}(t)\}$ are the phase and quadrature components, respectively, which are band-limited Gaussian with a zero mean and a variance of $\sigma_n^2$.

Given $m(t) = 0$ and $\Theta(t) = 0, \{c_x(t), c_y(t)\}$ are expressed as:

\[
\begin{align*}
  c_x(t) &= \left[\sqrt{P_rP_0} + n_{xp}(t)\right] \cos(\omega_0 t + \phi(t)) \quad - n_{xp}(t) \sin(\omega_0 t + \phi(t)); \\
  c_y(t) &= \left[\sqrt{P_rP_0} + n_{yp}(t)\right] \cos(\omega_0 t + \phi(t)) \quad - n_{yp}(t) \sin(\omega_0 t + \phi(t))
\end{align*}
\]

(7a) \quad (7b)

Thus, the output $V(t)$ is given as:

\[
V(t) = \sqrt{\frac{P_rP_0}{2}} \left[\sqrt{P_rP_0} + n_{xp}(t) \cos(\omega_0 t + \phi(t)) \quad - n_{xp}(t) \sin(\omega_0 t + \phi(t))\right]. \quad (8)
\]

Both $n_{xp}(t)$ and $n_{yp}(t)$ are normally distributed Gaussian noise with a zero mean and a variance of $\sigma_n^2/2$.

Given $z = \sqrt{\frac{P_rP_0}{2}} \left[\sqrt{P_rP_0} + n_{xp}(t) \cos(\omega_0 t + \phi(t)) \quad - n_{xp}(t) \sin(\omega_0 t + \phi(t))\right]$, the BER becomes:

\[
P(V(t) < 0|m(t) = 0) = P[z < 0]; \quad (9)
\]

where $z \sim N(\sqrt{\frac{P_rP_0}{2}} \sigma_n^2)$, respectively.

The pdf of $z$ is $f(z)$, thus $P_{ec}$ can be derived as:

\[
P_{ec} = \int_{-\infty}^{0} f(z) dz = \frac{1}{\sqrt{2\pi\sigma_n}} \int_{-\infty}^{0} e^{\frac{z^2}{2\sigma_n^2}} dz. \quad (10)
\]

where the electrical SNR $= R^2P_rP_0/\sigma_n^2$.

Using the approach adopted in [13], the link performance is evaluated under weak to strong turbulence regimes. The unconditional probability $P_e$ (without the knowledge of the channel state information) is obtained by averaging (10) over the gamma-gamma irradiance fluctuation statistics $p(P_r)$ to obtain the following:

\[
\begin{align*}
  &P_e = \frac{1}{2} P(V(t) < 0| m(t) = 0) + \frac{1}{2} P(V(t) > 0| m(t) = 1) \\
  &= P(V(t) < 0| m(t) = 0).
\end{align*}
\]
\[ P_e = \int_{0}^{\infty} P_e^r(P_r) \cdot p(P_r) dP_r \]
\[ = \int_{0}^{\infty} \left( \frac{Q(\text{SNR}(P_r)) \cdot 2^{(\alpha \beta)^2/2}}{\Gamma(\alpha) \Gamma(\beta)} \right) \cdot dP_r \quad (11a) \]
\[ = \left\{ \begin{array}{ll}
\frac{\pi^{\alpha-1}}{\Gamma(\alpha) \Gamma(\beta)} \left( \frac{2^{\alpha \beta}}{\sqrt{2\pi}} \right) & \text{for } P_r > 0 \\
0 & \text{otherwise}
\end{array} \right. \]
\[ \alpha = \left( \frac{0.49 \sigma_l^2}{1 + 1.1 \sigma_l^2} \right)^{1/2} \quad (11b) \]
\[ \beta = \left( \frac{0.51 \sigma_l^2}{1 + 0.69 \sigma_l^2} \right)^{1/2} \quad (11c) \]

where \( \sigma_l^2 \) is the modified Bessel function of the 2nd kind of order \( n \) and \( \sigma_l^2 \) is the Ryotov variance. Values for the intensity variance \( \sigma_l^2 \) are 0.2, 1.6 and 3.5, respectively, corresponding to weak, moderate and strong atmospheric turbulence conditions [11].

### III. POLSK MODULATION WITH SPATIAL DIVERSITY

Assuming laser radiation is diffraction-limited and the beam width can sufficiently cover the entire field of view of the \( N \)-detector at the receiver, independent signals can be received in each detector if the separation \( S \) of PDs is longer than the spatial coherence length \( \rho_0 \) of the atmospheric channel. This assumption is realistic because \( \rho_0 \) measures in a few centimetres. However, the price paid is alignment difficulty and tracking complexity. This is because the channel and received irradiance are randomly changing with time. During one symbol duration \( t < \tau_0 \), the received signal can be most probably constant and time invariant since the coherence time \( \tau_0 \) of the irradiance fluctuation is in the order of milliseconds [7].

For comparison, the total aperture area of \( N \) identical PDs is assumed to be equal to a single detector area for the single transmitter-single receiver system. For background noise limited FSO systems, the noise variance on each branch is proportional to the detector area. The variance of the overall Gaussian noise with a zero mean becomes:

\[ \sigma^2 = \sum_{i=1}^{N} a_i^2 \sigma_i^2 = \sum_{i=1}^{N} \frac{a_i^2 \sigma_i^2}{N} \quad (12) \]

where \( i = 1, 2, 3, \ldots, N \).

The individual received power irradiance is given by:

\[ E_{ri}(t) = e^{j(\omega_i t + \phi_i(t)))} \left[ \frac{P_{ri}}{2} e^{j \Theta_i(t)} + \sqrt{P_{ri} / 2} y \right] \quad (13) \]

The current generated from each photodetector is scaled by a gain factor, \( \{a_{ci}\}_{i=1}^{N} \), before being co-phased and coherently combined. Since separation between photodetector is only a few centimetres and the link length is a few kilometres, then the propagation delay across the receiver array can be neglected. The outputs \( \{c_i(t), c(t)\} \) from combiners are given by:

\[ c_x(t) = \sum_{i=1}^{N} \left[ \frac{R_{a_{ci} \sqrt{P_{ri} P_{lo}}}}{N} \cos(\omega_{iF} t + \Theta(t) + \phi_i(t)) \right] \quad (14a) \]
\[ c_y(t) = \sum_{i=1}^{N} \left[ \frac{R_{a_{ci} \sqrt{P_{ri} P_{lo}}}}{N} \cos(\omega_{iF} t + \phi_i(t)) \right] \quad (14b) \]

The SNR at the output of the combiner following suppression of higher harmonic using BPFs is expressed as:

![Figure 3. Spatial diversity receiver with N-PDs](image-url)
SNR = \left( \sum_{i=1}^{N} \frac{R_d a_i \sqrt{P_{ri} P_{lo}}}{N} \right)^2 \sigma^2 . \quad (15)

To calculate the BER with the spatial diversity, two combination techniques namely EGC and MRC are considered in this study.

### A. Equal gain combining

Here, all received signals of x- and y- channels are combined coherently with equal weights of \( a_{ci} \). The SNR for EGC is given by:

\[
\text{SNR}_{\text{EGC}} = \frac{R^2 P_{lo}}{N^2 \sigma_n^2} \left( \sum_{i=1}^{N} \sqrt{P_{ri}} \right)^2 ; \quad (16)
\]

The unconditional BER is obtained by averaging the conditional error rate over the statistics of the intensity fluctuation on each diversity branch, which is given as:

\[
P_e(\text{EGC}) = \int_0^\infty \left\{ \frac{Q\left[\sqrt{\text{SNR}_{\text{EGC}}} \right]}{2(\alpha+\beta)/2} \Gamma(\alpha) \Gamma(\beta) \right\} P_r \, dP_r > 0 . \quad (17)
\]

### B. Maximum ratio combining

The weights \( a_{ci} \) of MRC combiner are proportional to the received intensity which results in a maximum-likelihood receiver [7]. Regardless of the fading statistics, MRC is the optimal in the absence of interference. However, this leads to higher system complexity since both the received power level and the phase on every branch has to be estimated prior before to coherent summation. The SNR for MRC are derived as:

\[
\text{SNR}_{\text{MRC}} = \left[ \sum_{i=1}^{N} \frac{R_d a_i \sqrt{P_{ri} P_{lo}}}{N} \right]^2 ; \quad (18)
\]

Applying the Cauchy inequality [14] to (18):

\[
\text{SNR}_{\text{MRC}} \leq \frac{R^2 P_{lo}}{N^2} \sum_{i=1}^{N} a_{ci}^2 \sum_{i=1}^{N} P_{ri} \left( \frac{\sigma_n^2}{N} \sum_{i=1}^{N} a_{ci}^2 \right) ; \quad (19)
\]

The unconditional BER for MRC are expressed as:

\[
P_e(\text{MRC}) = \int_0^\infty \left\{ \frac{Q\left[\sqrt{\text{SNR}_{\text{MRC}}} \right]}{2(\alpha+\beta)/2} \Gamma(\alpha) \Gamma(\beta) \right\} P_r \, dP_r > 0 . \quad (20)
\]

### IV. SIMULATION RESULTS AND DISCUSSION

Following the analytical approach outlined above, the BER performance of the proposed coherent optical heterodyne system employing 2PolSK in gamma-gamma turbulence channel across all turbulence regimes is simulated using Matlab. BER performances against the SNR for 2PolSK employing a single photodetector compared with EGC and MRC spatial diversities using two photodetectors for weak, moderate and strong turbulence regimes are shown in Fig. 4. The performance superiority of 2PolSK with the MRC spatial diversity in mitigating the effect of turbulence induced fading is evident from Fig. 4. At a BER of 10\(^{-9}\), SNR gains are \( \sim 0.92 \) dB and \( \sim 3.9 \) dB for EGC and MRC, respectively compared to the case with no spatial diversity under weak turbulence regime. However, in moderate regime, SNR gains are \( \sim 5.94 \) dB and \( \sim 8.94 \) dB for EGC and MRC, respectively. This plot also shows that the optimum MRC outperforms the EGC by \( \sim 3 \) dB of SNR at a BER of 10\(^{-9}\).

Fig. 5 illustrates the SNR requirement to achieve a BER of 10\(^{-9}\) against the number of photodetectors \( N \) with MRC for weak, moderate and strong turbulence regimes at a BER of 10\(^{-6}\).
photodetectors for weak, moderate and strong turbulence regimes. For $N = 2$ and at a BER of $10^{-6}$ the SNR drops by $\sim 2.37$ dB, $\sim 11.55$ dB and $\sim 10.77$ dB for weak, moderate and strong turbulence regimes, respectively. The diversity gain ($\text{SNR}_{\text{div},N-1} - \text{SNR}_{\text{div},N}$) is less in the strong turbulence regime than in the moderate regime. This is because of the deep fades resulting from a loss of spatial coherence of the laser radiation. It is noted that for $N \geq 4$, the diversity gain increment is reducing as $N$ increases. For example, increasing $N$ from 3 to 4 for the case with MRC in weak to strong turbulence regimes diversity gains are $\sim 0.74$ dB, $\sim 2.11$ dB and $\sim 2.64$ dB, respectively. Thus, the optimum number of photodetectors is $2 \leq N \leq 4$ to ensure reduced turbulence effects.

V. CONCLUSION

This paper has outlined the BER analysis for an FSO link employing 2PolSK with a spatial diversity in the gamma-gamma atmospheric turbulence. We have shown that spatial diversity can reduce the scintillation effects and thus reduced SNR requirement. For a single detector, to achieve a BER of $10^{-9}$ in a weak turbulence regime ($\sigma_l^2 = 0.2$), the SNR requirement is $\sim 22.4$ dB while applying two photodetectors, the SNR is reduced by $\sim 0.92$ dB and $\sim 3.9$ dB for EGC and MRC schemes, respectively. At strong turbulence regime ($\sigma_l^2 = 3.5$), the effect of deep fading results a reduced spatial diversity gain of $\sim 10.77$ dB for MRC with two photodetectors at a BER of $10^{-6}$. We have also showed that the spatial diversity offers increased link margin as the scintillation level rises.

REFERENCES


