PERFORMANCE OF THE COHERENT OPTICAL BINARY POLARIZATION-SHIFT-KEYING HETERODYNE SYSTEM IN FREE SPACE OPTICAL COMMUNICATIONS USING A LOGNORMAL ATMOSPHERIC TURBULENCE MODEL

X. Tang[1], Z. Ghassemlooy[1], S. Rajbhandari[1], W. O. Popoola[1] and C. G. Lee[2]
1: Optical Communications Research Group, NCRLab, Northumbria University, Newcastle upon Tyne, UK
2: Department of Electronic Engineering, Chosun University, S. Korea

ABSTRACT

In this paper, simulation results for the bit error rate (BER) performance and fading penalty of a coherent optical binary polarization shift keying (2PolSK) heterodyne system adopted for free space optical (FSO) communication links with a log-normal atmospheric turbulence model is presented. The conditional and unconditional BER expressions are derived, demonstrating the comprehensive similarity between the 2PolSK and binary frequency shift keying (2FSK) schemes with regards to the system sensitivity. The study shows that 2PolSK offers improved performance compared to the binary amplitude shift keying (2ASK).

I. INTRODUCTION

FSO has received momentous attention as one of the ultimate solutions to overcome the bandwidth bottleneck problems in the access networks (i.e. the last mile), and in the mobile base station-to-base station links [1]. FSO offers several advantages compared to the complementary radio frequency (RF) based wireless communications including secure transmission, an unregulated bandwidth in excess of THz, smaller and more compact transceiver modules, low deployment and installation cost and immunity to the electromagnetic interference [2]. However, the FSO system performance depends on the weather conditions. In coherent FSO systems the scintillation induced fading causes optical irradiance fluctuation in the received signal [3-5]. Furthermore, the phase noise of the semiconductor laser source is a major problem in coherent optical communications, which results in an additional power penalty.

Recently, PolSK has been studied extensively because it is less sensitive to the amplitude fluctuation and is highly insensitive to the phase noise [6]. Additionally, PolSK, with a constant envelope, is more resistant to the self-phase modulation (SPM) and cross-phase modulation (XPM) induced crosstalk [7].

In this paper, a novel coherent optical PolSK heterodyne system for FSO communications is proposed. The digital information is encoded in the antipodal states of the polarization (SOP) of the laser source, which can be well maintained over a long distance propagation [3]. At the receiver, influence of the phase noise and the frequency offset can be eliminated thus ensuring reduced power penalty for a given BER performance.

The rest of the paper is arranged as follows: the lognormal turbulence model for the FSO system is presented in section II; the proposed coherent PolSK heterodyne system is analyzed in section III, while conditional and unconditional BER expressions for the system is derived in section IV. The simulation results for the BER performance for the PolSK scheme are discussed in section V. The fading penalty is calculated and the system BER performance is compared with other coherent optical modulation techniques such as 2ASK and 2PSK. Finally, conclusions are presented in section VI.

II. LOGNORMAL TURBULENCE MODEL

In FSO links signal fading is the result of the received signal fluctuation caused by the atmospheric turbulence. The fading strength depends on the link length, the operating wavelength and the channel refractive index structure parameter C_n^2 . The weak atmospheric turbulence regime can be described by the lognormal distribution [8] and is characterized by the Ryotov variance σ_l^2 :

$$\sigma_l^2 = 1.23 C_n^2 \left(\sqrt[6]{k^7 L^{11}} \right); \tag{1}$$

where L is the propagation distance and k is the wave number.

The limitation of the log-normal model is defined by the Ryotov variance rage $0 < \sigma_l^2 < 1.2$ [8].

The probability density function (PDF) of the received irradiance in the log-normal channel is given by [9]:

$$p(I) = \frac{1}{\sqrt{2\pi}\sigma_l} \frac{1}{I} \exp\left\{ -\frac{\ln(I/I_{no}) + \sigma_l^2/2)^2}{2\sigma_l^2} \right\} \quad I \geq 0 \;; \tag{2}$$

where I represents the received irradiance at the receiver and I_{no} is the received irradiance without scintillation.

For a strong atmospheric turbulence the gamma-gamma and the negative exponential models [9] should be adopted.

III. System Description

The block diagram of the proposed transmitter is shown in Figure 1 [10]. The operating wavelength of the $LiNbO_3$ modulator is 1550 nm. V_a and V_b are used to controls the amount of light launched in either polarization and the relative phase of the two polarizations, respectively. The third electrode V_{match} applied to the 3 dB coupler is used for wavelength matching . $\hat{x}$ and $\hat{y}$ are the axes of polarization used to represent digital symbol '0' and '1', respectively. To increased power launched into the free space channel one might use an optical amplifier at the output of the PolSK modulator.

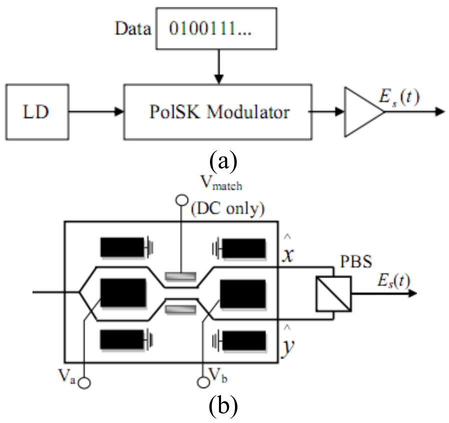

Figure 1: (a) PolSK transmitter block diagram, and (b) $LiNbO_3$ modulator. LD, laser diode; PBS: polarizing beam splitter.

Figure 2 represents the block diagram of the proposed coherent optical PolSK heterodyne receiver. An optical lens is used to focus the received beam into the receiver. The received signal $E_r(t)$ can be viewed in both cases as two orthogonal ASK signals, related to orthogonal components of the transmitted optical field. The local oscillator $E_{lo}(t)$ is linearly polarized at π /4 with respect to the receiver reference axes. Uncorrelated $E_r(t)$ and $E_{lo}(t)$ signals are given by:

$$E_r(t)=\sqrt{P_r}\,e^{i(\omega_r t+\phi_r(t))}\begin{Bmatrix}[1-m(t)]\cdot x\\ +m(t)\cdot y\end{Bmatrix};\qquad (3)$$
$$E_{lo}(t)=\sqrt{P_{lo}}\,e^{i(\omega_{lo} t+\phi_{lo}(t))}\{x+y\}$$

where P_r and P_{lo} are the received signal and local oscillator signal powers, respectively. ω_r , $\phi_r(t)$ and ω_{lo} , $\phi_{lo}(t)$ are the angular frequencies and phase noises for the received and local oscillator fields, respectively and $m(t)$ is the binary information.

$E_r(t)$ and $E_{lo}(t)$ are mixed using an unbalanced directional coupler (DC) with a transfer matrix given by [11]:

$$[S]_{dc}=\begin{bmatrix}\alpha_{dc} & \sqrt{1-\alpha_{dc}^2}\\ -\sqrt{1-\alpha_{dc}^2} & \alpha_{dc}\end{bmatrix};\qquad (4)$$

where α_{dc} is the power splitting ratio.

Therefore, the optical field $E_{dc}(t)$ at the coupler output and consequently at the beam splitter input is given by:

$$\begin{aligned}E_{dc}(t)&=\alpha_{dc}E_r(t)+\sqrt{1-\alpha_{dc}^2}\,E_{lo}(t)\\ &=\alpha_{dc}\sqrt{P_r}\,e^{i(\omega_r t+\phi_r(t))}\{[1-m(t)]\cdot x+m(t)\cdot y\}.\qquad (5)\\ &+\sqrt{\left(1-\alpha_{dc}^2\right)P_{lo}}\,e^{i(\omega_{lo} t+\phi_{lo}(t))}\{x+y\}\end{aligned}$$

The outputs of the polarization beam splitter are defined as:

$$E_1(t)=\begin{Bmatrix}\alpha_{dc}\sqrt{\frac{P_r}{2}}[1-m(t)]e^{i(\omega_r t+\phi_r(t))}\\ +\sqrt{\left(1-\alpha_{dc}^2\right)\frac{P_{lo}}{2}}e^{i(\omega_{lo} t+\phi_{lo}(t))}\end{Bmatrix}x;\qquad (6a)$$

$$E_2(t)=\begin{Bmatrix}\alpha_{dc}\sqrt{\frac{P_r}{2}}m(t)e^{i(\omega_r t+\phi_r(t))}\\ +\sqrt{\left(1-\alpha_{dc}^2\right)\frac{P_{lo}}{2}}e^{i(\omega_{lo} t+\phi_{lo}(t))}\end{Bmatrix}y.\qquad (6b)$$

Assuming an electron is generated by each detected photon. The outputs of two identical PDs are passed through ideal BPFs (of bandwidth $W = 2R_b$, where R_b is the data rate) with outputs defined as:

$$c_1(t)=R\alpha_{dc}\sqrt{\left(1-\alpha_{dc}^2\right)P_rP_{lo}}[1-m(t)]\cos(\omega_{IF}+\phi_t(t))+n_x(t);\ (7a)$$

$$c_2(t)=R\alpha_{dc}\sqrt{\left(1-\alpha_{dc}^2\right)P_rP_{lo}}m(t)\cos(\omega_{IF}+\phi_t(t))+n_y(t);\ (7b)$$

where R is the photodiode responsivity,

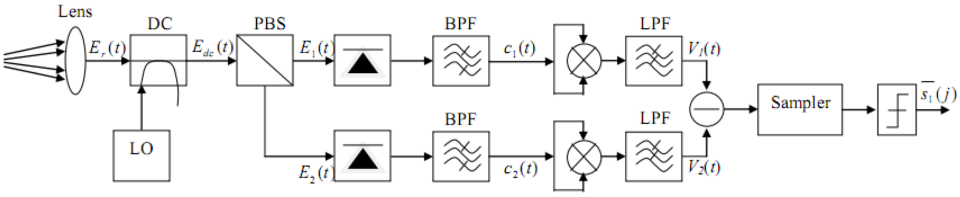

Figure 2: A block diagram of the coherent optical PolSK heterodyne receiver. LO: local oscillator; DC: directional coupler; BPF: bandpass filter; LPF: lowpass filter.

$\omega_{IF} = \omega_r - \omega_{lo}$ and $\phi_t(t) = \phi_r(t) - \phi_{lo}(t)$ are the intermediate angular frequency (IF) and the IF phase noise, respectively. The system noises $\{n_x(t), n_y(t)\}$ is modeled as independent, uncorrelated additive white Gaussian (AWGN) noise with a zero mean and a variance $\sigma_n^2 = WN_0$, where N_0 is the double sideband noise power spectral density.

An ideal square-law demodulator composed of electrical mixers, a low-pass filter, a sampler and a threshold detector are used to recover the information signal. Note that because of the square-law demodulation the phase noise contribution is not included [12].

The 2PolSK modulation is based on the definition of the Stokes parameters [13], and since the optical field is linearly polarized and its power is unchanged, the Stokes parameters are expressed as:

$$S_0 = |c_1(t)|^2 + |c_2(t)|^2 = \frac{R^2\alpha_{dc}^2\left(1-\alpha_{dc}^2\right)P_r P_{lo}}{8} + n_0(t); \quad (8a)$$

$$S_1 = |c_1(t)|^2 - |c_2(t)|^2 = \frac{R^2\alpha_{dc}^2\left(1-\alpha_{dc}^2\right)P_r P_{lo}\left[1-2m(t)\right]}{8} + n_1(t); \quad (8b)$$

$$S_2 = 2|c_1(t)| \times |c_2(t)|\cos(0) = 0 + n_2(t); \quad (8c)$$

$$S_3 = 2|c_1(t)| \times |c_2(t)|\sin(0) = 0 + n_3(t); \quad (8d)$$

where S_0, S_1, S_2 and S_3 are the estimation Stokes parameters; and $\{n_i(t)\}_{i=0,1,2,3}$ are the noise contribution which are independent of the received SOP and have the same variance.

Note that the proposed 2PolSK refers only to the parameter S_1. A digital symbol '0' is assumed to have been received if S_1 is above the threshold zero and '1' otherwise.

IV. Bit Error Probability Analysis

No intersymbol interference is considered since the link under consideration is a direct line of sight with no multipath propagation. Assuming independent and identically distributed (i.i.d.) data transmission, the total BER P_{ec} conditioned on the received irradiance is given by:

$$P_{ec} = \frac{1}{2}P(e\,|\,0) + \frac{1}{2}P(e\,|\,1) = P(e\,|\,0); \quad (9)$$

where $P(e|0)$ is the conditional bit error probability for receiving a '1' provided a '0' was sent.

The noise signal $\{n_x(t), n_y(t)\}$, including background noise and quantum noise can be expressed as:

$$n_x(t) = n_{xi}(t)\cos(\omega_{IF}t + \phi_t(t)) - n_{xq}(t)\sin(\omega_{IF}t + \phi_t(t)); \quad (10a)$$

$$n_y(t) = n_{yi}(t)\cos(\omega_{IF}t + \phi_t(t)) - n_{yq}(t)\sin(\omega_{IF}t + \phi_t(t)); \quad (10b)$$

where $\{n_{xi}(t), n_{xq}(t)\}$ and $\{n_{yi}(t), n_{yq}(t)\}$ are the phase and quadrature components, respectively, having a normal distribution with a zero-mean and a variance of σ_n^2.

Given $m(t) = 0$ and $K = R\alpha_{dc}\sqrt{\left(1-\alpha_{dc}^2\right)P_r P_{lo}}$, (7) is given by:

$$< c_1(t) > = \{K + n_{xi}(t)\}\cos(\omega_{IF}t + \phi_t(t)) - n_{xq}(t)\sin(\omega_{IF}t + \phi_t(t)); \quad (11a)$$

$$< c_2(t) > = n_{yi}(t)\cos(\omega_{IF}t + \phi_t(t)) - n_{yq}(t)\sin(\omega_{IF}t + \phi_t(t)). \quad (11b)$$

The baseband outputs $V_1(t)$ and $V_2(t)$ for upper and lower arms (Figure 2), respectively are given as:

$$V_1(t) = \sqrt{\left[K + n_{xi}(t)\right]^2 + n_{xq}^2(t)}; \quad (12a)$$

$$V_2(t) = \sqrt{n_{yi}^2(t) + n_{yq}^2(t)}. \quad (12b)$$

$V_1(t)$ and $V_2(t)$ have fixed mean values and the same variance given by:

$$\mathrm{E}\left[V_1(t)\right] = K, \quad \mathrm{E}\left[V_2(t)\right] = 0, \quad \sigma_1^2 = \sigma_2^2 = \sigma_n^2. \quad (13)$$

With $\omega_{IF} << \omega_r$, the PDF of $V_1(t)$ and $V_2(t)$ can be described by the Rice and the Rayleigh probability functions, respectively [12]:

$$p(V_1) = \left\{\frac{V_1}{\sigma_n^2} I_0\left(\frac{KV_1}{\sigma_n^2}\right)\exp\left[-\frac{\left(V_1^2 + K^2\right)}{2\sigma_n^2}\right]\right\}; \quad (14a)$$

$$p(V_2) = \frac{V_2}{\sigma_n^2}\exp\left(-\frac{V_2^2}{2\sigma_n^2}\right); \quad (14b)$$

where I_0 is the zero order modified Bessel function of the first kind [11].

The conditional BER for $m(t) = 0$ can be derived as [14]:

$$P_{ec} = \int_0^\infty p(V_1)\left[\int_{V_1}^\infty p(V_2)dV_2\right]dV_1 = \int_0^\infty \left\{ \frac{V_1}{\sigma_n^2} I_0\left(\frac{KV_1}{\sigma_n^2}\right) \exp\left[\frac{-2V_1^2 - K^2}{2\sigma_n^2}\right]\right\} dV_1 \quad . \qquad (15)$$

By invoking changes of variables $m = \sqrt{2}V_1/\sigma_n$ and $n = K/\left(\sqrt{2}\sigma_n\right)$ and substituting into (14), P_{ec} now becomes:

$$P_{ec} = \frac{1}{2}e^{-n^2/2}\int_0^\infty mI_0(mn)e^{-\left(m^2+n^2\right)/2}dm \quad . \qquad (16)$$

Defining the Q-function as [14]:

$$Q(n,0) = \int_0^\infty mI_0(mn)e^{-\left(m^2+n^2\right)/2}dm = 1 . \qquad (17)$$

P_{ec} is represented as:

$$P_{ec} = \frac{1}{2}\exp\left(-n^2/2\right) = \frac{1}{2}\exp\left(-K^2/4\sigma_n^2\right). \qquad (18)$$

The electrical signal-to-noise ratio (SNR) at the output of the BPF is defined as:

$$SNR(P_r) = \left(R\alpha_{dc}\sqrt{\left(1-\alpha_{dc}^2\right)P_r P_{lo}} / \sqrt{2}\sigma_n\right)^2 . \qquad (19)$$

P_{ec} can be expressed in terms of the SNR by substituting (18) into (17):

$$P_{ec}(P_r) = \frac{1}{2}\exp(-SNR(P_r)/2) . \qquad (20)$$

This result is same as the BER expression of FSK. As regards the system sensitivity, PolSK and FSK techniques have complete equivalence [15].

Adopting the approach given in [16], the unconditional probability P_e is obtained by averaging (20) over the log normal irradiance fluctuation statistics given as:

$$P_e = \int_0^\infty P_{ec}(P_r)\cdot p(P_r)dP_r = \int_0^\infty \left\{ \frac{1}{2}\exp\left(-SNR(P_r)/2\right)\frac{1}{P_r\sqrt{2\pi\sigma_l^2}} \cdot \exp\left\{-\frac{\left[\ln\left(P_r/P_{no}\right)+\sigma_l^2/2\right]^2}{2\sigma_l^2}\right\}\right\} dP_r \quad . \qquad (21)$$

V. RESULTS AND DISCUSSIONS

Following the analytical approach outlined above, we have evaluated the BER performance of the coherent optical 2PolSK heterodyne transmission system for an FSO link. For comparison simulation results for 2ASK, 2PSK are also given. To investigate the effects of noise and scintillation on the system performance, the BER metric and fading penalty are shown under different channel conditions.

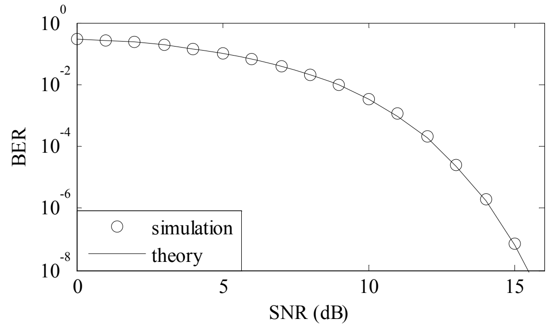

Figure 3: The theoretical and simulated BERs of PolSK against the SNR in an AWGN channel without turbulence.

Figure 3 illustrates the simulated and calculated (using (19)) BERs performance against the SNR in an AWGN channel without turbulence. Both simulated and theoretical curves match very closely which confirms the validity of the simulation.

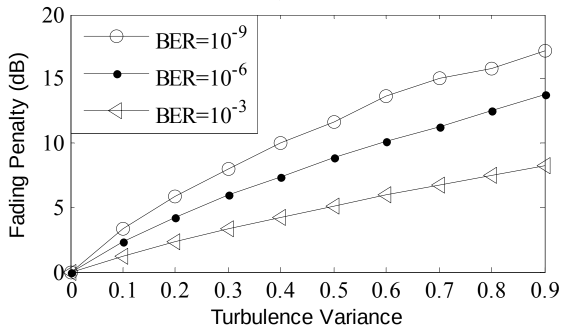

Figure 4: The fading penalty against the log intensity for the PolSK heterodyne system in a weak atmospheric turbulence under different BER conditions.

Figure 4 shows the fading penalty against turbulence variances for a range of BERs. For a fixed BER, the fading penalty increases with the turbulence variance. To achieve a BER of 10^{-3}, the fading penalties are ~ 3.3 dB and ~ 6.7 dB for $\sigma_l^2 = 0.3$ and $\sigma_l^2 = 0.7$, respectively. Fading penalty is higher for lower values of BER at the same turbulence level. For example, for a turbulence variance of 0.5 the fading penalties are ~ 5.1 dB, ~ 8.8 dB and ~ 11.6 dB corresponding to BERs of 10^{-3}, 10^{-6} and 10^{-9}, respectively. A much higher fading penalty of ~ 17.2 dB at scintillation levels close to 0.9 is observed for a BER of 10^{-9}, thus demonstrating the vulnerability of the system under extreme turbulence conditions.

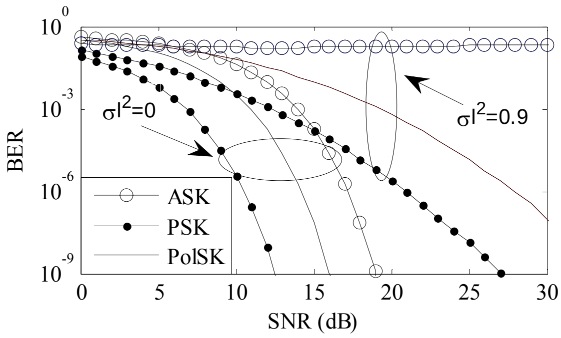

Figure 5: The BER performances of 2ASK, 2PolSK and 2PSK against the SNR in the AWGN channel with turbulence variances of $\sigma_l^2 = \{0, 0.9\}$

The BER perfromance of 2ASK, 2PolSK and 2PSK in the AWGN channel for turbulence values of 0 and 0.9 are depicted in Figure 5. For a given BER, 2PolSK outperforms and under-performs 2ASK and 2PSK by 3 dB, respectively in the AWGN channel without turbulences. For example, for a BER of 10^{-9} without turbulence the additional SNRs are ~ 13 dB, ~ 16 dB and ~ 19 dB for 2PSK, 2PolSK and 2ASK, respectively. For channels with a turbulence variance of 0.9 to achieve a BER of 10^{-6}, the required SNR for 2PSK and 2PolSK are ~ 20.9 dB and ~ 28 dB, respectively. Additional the SNR is required for the 2ASK system. The turbulence induced fading penalty is much higher for the 2ASK scheme compared to the 2PolSK even in a weak turbulence channel, thus illustrating the superior performance of 2PolSK in fading channels.

The difference in the performance of different modulations is attributable to how the information is embeded in the optical carrier signal. Compared to the intensity modulation / direct detection schemes, the phase detection scheme can improve the receiver sensitivity. This is because the distance between symbols, expressed as phasors on a complex plane, is extended by the use of the phase information. 2ASK is more prone to the intensity fluctuations compare to 2PolSK and 2PSK where information is embeded in the SOP and phase, respectively.

VI. CONCLUSION

The analytical conditional and unconditional error probabilities for a coherent optical 2PolSK heterodyne system adopted for an FSO communication link through the weak atmospheric turbulence channel was calculated and verified using computer simulations. Results show the susceptibility of 2PolSK scheme when operated in a turbulence environment. A fading penalty of ~ 8.1 dB is observed at a turbulence variance of 0.3 at a BER of 10^{-9}; increasing to ~ 17.2 dB at a turbulence variance of 0.9. The comparative study of 2PolSK, 2ASK and 2PSK showed that PSK offers the highest immunity to the turbulence followed by 2PolSK.

REFERENCES

[1] J. C. Brandenburg and J. Q. Liu, "Optical signal detection in the turbulent atmosphere using p-i-n photodiodes," *IEEE Journal on Selected Areas in Communications,* vol. 27, pp. 1564-1571, December 2009.

[2] S. S. Muhammad, T. Plank, E. Leitgeb, A. Friedl, K. Zettl, T. Javornik, and N. Schmitt, "Challenges in establishing free space optical communications between flying vehicles " in *CNSDSP 2008* Graz, Austria, 25 July 2008, pp. 82-86.

[3] X. Zhao, Y. Yao, Y. Sun, and C. Liu, "Circle polarization shift keying with direct detection for free-space optical communication " *Optical Communications and Networking, ,* vol. 1, pp. 307-312, September 2009.

[4] C. Liu, Y. Sun, Y. Yao, and X. Zhao, "Analysis of direct detection and coherent detection in wireless optical communication with polarization shift keying " *CLEO/PACIFIC RIM '09,* pp. 1-2, August 2009.

[5] R. R. Iniguez, S. M. Idrus, and Z. Sun, "Atmospheric transmission limitations," in *Optical Wireless Communications - IR for Wireless Connectivity* London: Taylor & Francis Group, LLC, 2008, p. 40.

[6] M. Nazarathy and E. Simony, "Error probability performance of equi-energy combined transmission of differential phase, amplitude, and polarization," *Lightwave Technology,* vol. 25, pp. 249-260, Janauary 2007.

[7] M. N.-A.-S. Bhuiyan, M. Matsuura, H. N. Tan, and N. Kishi, "Polarization insensitive wavelength conversion for polarization shift keying signal based on four wave mixing in highly non-linear fiber " *14th OECC 2009,* pp. 1-2, 13-17 July 2009.

[8] W. O. Popoola and Z. Ghassemlooy, "BPSK subcarrier intensity modulated free-space optical communications in atmospheric turbulence," *Journal of Lightwave Technology,* vol. 27, pp. 967 - 973, April 2009.

[9] G. R. Osche, *Optical detection theory for laser applications*: Wiley, New Jersey, 2002.

[10] S. Benedetto, A. Djupsjobacka, B. Lagerstrom, R. Paoletti, P. Poggiolini, and G. Mijic, "Multilevel polarization

modulation using a specifically designed LiNbO3 device," *IEEE Photonics Technology Letters,* vol. 6, pp. 949-951, August 1994.

[11] I. Seto, T. Ohtsuki, H. Yshima, I. Sasase, and S. Mori, "Coherent optical polarization-shift-keying (PolSK) homodyne system using phase-diversity receivers," *GLOBECOM '91,* vol. 3, pp. 1601-1605, 2-5 December 1991.

[12] R. Calvani, R. Caponi, F. Delpiano, and G. Marone, "An experiment of optical heterodyne transmission with polarizationmodulation at 140 Mbit/s bitrate and 1550 nm wavelength," *GLOBECOM '91,* vol. 3, pp. 1587-1591, 2-5 December 1991.

[13] E. Collett, "The stokes polarization parameters," in *Polarized light: fundamentals and applications* New York: Marcel Dekker, Inc., 1993, pp. 33-66.

[14] J. G. Proakis, *Digital communications*. New York: McGraw-Hill, Inc., 1995.

[15] R. Calvani, R. Caponi, F. Delpiano, and G. Marone, "An experiment of optical heterodyne transmission with polarization modulation at 140 Mbit/s bitrate and 1550 nm wavelength " *GLOBECOM '91,* vol. 3, pp. 1587-1591, 2-5 December 1991

[16] A. Jurado-Navas, A. Garcia-Zambrana, and A. Puerta-Notario, "Efficient lognormal channel model for turbulent FSO communications," *Electronics Letters,* vol. 43, pp. 178-179, February 2007.