Convolutional Coded On-Off Keying Free-Space Optical Links over Fading Channels

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ABSTRACT: **The performance of Free Space Optical (FSO) systems reduces due to the presence of turbulence and misalignment effects. In this paper, we investigate the error control coding schemes as a candidate solution to mitigate turbulence and misalignment induced fadings over free space optical links. we have investigated for first time the error performance for coded on-off keying (OOK) optical wireless communication systems assuming intensity modulation/direct detection(IM/DD) represented by strong turbulence and pointing error effects. Specifically, we consider various combinations of channels assuming the existence of turbulence and/or pointing error effects and derive exact mathematical expressions for the pairwise error probability (PEP). By using this expressions upper bounds on the bit error rate (BER) are obtain using the transfer function technique. Then we calculate the error performance by using the pulse position modulation with different fading channels.**

Keywords - Free space optical communications, atmospheric turbulence channel, pairwise error probability, error performance analysis.

I. INTRODUCTION

Research in the field of FSO communication has grown exponentially since 1970 and a large number of commercial products based on FSO technology are now readily available. FSO is proposed as a complementary technology to the RF technology. It offers an unregulated bandwidth in excess of terahertz technology and very high speeds, which makes this an extremely attractive means of meeting the ever increasing demand for broadband traffic, mostly driven by the last mile access network and high definition television broad casting services [1]. Between the transmitter and receiver the optical wireless signals are attenuated and are subject to atmospheric turbulence. Alignment between transmitter and receiver, is the another issue affecting the performance. Usually FSO systems are installed on high buildings, building sway causes vibrations in the transmitted beam leading to misalignment (pointing error (PE) effects) between the transmitter and receiver [2].

To satisfy the typical bit error rate targets for reliable communications within the practical ranges of signal to noise ratio, error control coding has been employed. In [3], Zhu and Khan studied the performance of coded FSO links assuming a log-normal channel model for atmospheric turbulence. Specifically, they derived an approximate upper bound on the PEP for a coded FSO communication system with intensity modulation/direct detection and provided upper bound on the BER using the transfer function technique. Although log normal distribution is the most widely used model for the probability density function of the irradiance due to its simplicity, this pdf model is only applicable to weak turbulence conditions. Interleaved convolutional coding was also used in [4]. In [5], [6], [7], and [8], Uysal and Li used the same assumptions as in [3], and used this turbulence model to evaluate the performance of coded FSO systems in terms of the PEP with negative exponential(NE), K, I-K, and gamma-gamma channels, respectively. Turbo codes have been used in [9] and [10] as well. In the former, Ohtsuki proposed a turbo- coded atmospheric optical subcarrier phase shift keying system and a turbo-coded atmospheric optical pulse position modulation system and obtained upper bounds on the BER for maximum likelihood decoding. Finally in [11], the authors examined the performance of low density parity check (LDPC) codes for a gamma-gamma FSO channel.

In this paper we propose an error control coding for calculating the performance of the system. The error control coding is also said to be two-folded code. By using this kind of coding we can calculate the error rate performance over a wide range of transmission and also we calculate the performance for various turbulence models. We use K and NE distributions for characterizing the turbulence models and misalignment fading is characterized by a distribution proposed in [12]. We consider several channel types and derive exact mathematical expressions for the pairwise error probability (PEP).These expressions are applied to obtain upper bounds on the bit error rate (BER) performance using the transfer function technique. Finally, analyse the error performance using 4-PPM modulation technique for Lognormal and Rayleigh fading channels.

II. SYSTEM AND CHANNEL MODEL

A. System model

We consider a single- input single-output (SISO) FSO system using IM/DD with OOK, which is widely deployed in commercial systems.FSO system, contains a transmitter with modulator and a light source as laser or LED, telescope, optical beams and receiver with photodiode and demodulator. The receiver SNR is limited by short noise caused by either ambient light or the signal itself. This noise can be modelled as additive white Gaussian noise (AWGN). The statistical channel model is then given as

$$y(t)=\eta I x(t)+n(t) \tag{1}$$

Where I denotes the received normalized irradiance, x(t) is the modulated OOK signal either 0 or 1, n(t) is the AWGN with zero mean and noise power N_0 ; independent of whether the received bit is off or on. In (1), η represents the effective photo current ratio of the receiver and is expressed by

$$\eta = q\frac{e\lambda}{h_p c} \tag{2}$$

Where q is the quantum efficiency of the photo receiver, e the electron charge, λ is the signal wavelength, plank's constant and c is the speed of light.

The power of electromagnetic radiation per unit area incident on a surface is called irradiance. It is subject to either strong atmospheric turbulence conditions and/or pointing error effects. Here we consider irradiance is a product of two random variables i.e., $I=I_a I_p$, where I_a is the attenuation due to atmospheric turbulence and I_p is the attenuation due to pointing errors.

B. Channel models

1) Turbulence Channel Models: Understanding of the statistical distribution of the received irradiance in the atmospheric turbulence is necessary to predict the reliability of an optical system operating in such an environment. Several mathematical models for the random fading irradiance signals have been developed. Log-normal distribution is the most widely used channel model, however its applicability is mainly restricted to weak turbulence conditions. As the strength of the turbulence increases, K or NE distributions are used. The pdf of the K distribution is given by [1]

$$f_{I_a}(I_a) = \frac{2\alpha^{\frac{\alpha+1}{2}}}{\Gamma(\alpha)} I_a^{\frac{\alpha-1}{2}} k_{\alpha-1}(2\sqrt{\alpha I_a}), I_a > 0 \tag{3}$$

Where α is a channel parameter related to the effective number of discrete scatters, Γ(·) is the well known Gamma function [14, eq. (8.310.1)], and $k_v(\cdot)$ is the νth order modified Bessel function of the second kind defined in [14, eq. (8.432)]. The pdf of NE distribution is derived from (3) when $\alpha \to \infty$.NE model is the limiting case of K distribution [1].The pdf of irradiance is given by

$$f_{I_a}(I_a) = \exp(-I_a), I_a > 0 \tag{4}$$

In the Lognormal model the pdf of the path gain is

$$f_{I_a}(I_a) = \frac{1}{\sqrt{2\pi}\sigma I_a}\exp\left(-\frac{(\ln I_a-\mu)^2}{2\sigma^2}\right) \tag{5}$$

Where the parameter μ and σ satisfy the relation $\mu = -\sigma^2$.The pdf for Rayleigh fading channel is given below

$$f_{I_a}(I_a) = 2I_a \exp(-I_a^{\,2}) \tag{6}$$

2) Misalignment Fading Model: In line-of-sight communication links, pointing accuracy is an important issue in determining link performance and reliability. However, wind loads and thermal expansions result in random building sways, which, in turn, cause misalignment errors and signal fadings at the receiver [12]. In this section, we derive a new

statistical model for pointing errors loss due to misalignment, which considers the beam waist radius, w_z, distance between the transmitter and receiver is z, circular aperture of radius r and jitter variance σ_s^2. Then the pdf of I_p is given by

$$f_{I_p}(I_p) = \frac{\gamma^2}{A_0^{\gamma^2}} I_p^{\gamma^2-1}, \quad 0 \le I_p \le A_0 \qquad (7)$$

Where $\gamma = \frac{w_{z_{eq}}}{2\sigma_s}$ is the ratio between the equivalent beam radius at the receiver and jitter at the receiver, $w_{z_{eq}}{}^2 = \frac{w_z{}^2\sqrt{\pi}\,\mathrm{erf}(\upsilon)}{2\upsilon\exp(-\upsilon^2)}$, $\upsilon = \frac{\sqrt{\pi}r}{\sqrt{2}w_z}$, $A_0 = [\mathrm{erf}(\upsilon)]^2$ and $\mathrm{erf}(\cdot)$ is the error function [14,eq.(8.250.1)]. From now on, we refer to (7) as the PE model.

3) Combined Fading Models: The combined pdf of irradiance I, is derived using the formula [12]

$$f_{I(I)} = \int f_{\frac{I}{I_a}}\left(\frac{I}{I_a}\right) f_{I_a}(I_a)\, dI_a \qquad (8)$$

Where $f_{\frac{I}{I_a}}(I/I_a)$ is the conditional probability given I_a state and is expressed by

$$f_{\frac{I}{I_a}}\left(\frac{I}{I_a}\right) = \frac{\gamma^2}{A_0^{\gamma^2} I_a}\left(\frac{I}{I_a}\right)^{\gamma^2-1}, 0 \le I \le A_0 I_a \qquad (9)$$

A closed form expression of the combined pdf when I_a follows K distribution was derived in [16] as

$$f_I(I) = \frac{\alpha\gamma^2}{A_0\Gamma(\alpha)} G_{1,3}^{3,0}\left[\frac{\alpha}{A_0} I \Big|_{-1+\gamma^2,\alpha-1,0}^{\gamma^2}\right] \qquad (10)$$

Where $G_{p,q}^{m,n}[\cdot]$ is the Meijer's G-function, defined in [14, eq. (9.301)].

If I_a follows NE distribution, a closed form expression is obtained by substituting (9) and (4) in (8). Then equation (8) becomes

$$f_I(I) = \frac{\gamma^2}{A_0^{\gamma^2}} I^{\gamma^2-1} \int_{I/A_0}^{\infty} I_a{}^{-\gamma^2} \exp(-I_a)\, dI_a$$

(11)

And a solution can be found using [14, eq. (3.351.2)] as

$$f_I(I) = \frac{\gamma^2}{A_0^{\gamma^2}} I^{\gamma^2-1}\Gamma(1-\gamma^2, I/A_0) \qquad (12)$$

Where $\Gamma(.,.)$ is the upper incomplete Gamma function defined in [14,eq.(8.350.2)].An equivalent expression can be found if we express the exponential integrand of (11) in terms of the Meijer's G-function [17,eq. (11)] and use [14,eq. (9.31.2)] and [14, eq. (7.811.3)] as

$$f_I(I) = \frac{\gamma^2}{A_0} G_{1,2}^{2,0}\left[\frac{I}{A_0}\Big|_{\gamma^2-1,0}^{\gamma^2}\right] \qquad (13)$$

III.ERROR PERFORMANCE

A.PEP derivation

For code design, PEP used as the main criterion and is the basic method for compute union bounds for coded systems [13]. This represents the probability of choosing the coded sequence $\hat{X} = (\widehat{x_1}, \dots, \widehat{x_N})$ when $X=(x_1, \dots, x_N)$is transmitted [5]. Assuming the assumptions in [3], i.e., OOK transmission and ML soft decoding, the conditional PEP subject to fading coefficients $I = (I_1, \dots I_M)$ is given by

$$P(X, \hat{X}/I) = Q\left(\sqrt{\frac{E_s}{2N_0}\sum_{k\in\Omega} I_k^2}\right) \qquad (14)$$

Where $Q(\cdot)$ is the Gaussian Q function, E_s is the total transmitted energy and Ω is the error event.From Uysal and Li methodology [8], we define SNR as $\mu = E_s/N_0$ and using the alternative form for Gaussian Q function [13], then

$$P(X, \hat{X}/I) = \frac{1}{\pi}\int_0^{\pi/2} \prod_{k\in\Omega} \exp\left(-\frac{\mu}{4}\frac{I_k^2}{(\sin\theta)^2}\right) d\theta \qquad (15)$$

To obtain unconditional PEP, we need to take an expectation of (15) with respect to I_k.Using independency among fading coefficientsI_k, we write

$$P(X, \hat{X}) = \frac{1}{\pi}\int_0^{\pi/2} \prod_{k\in\Omega} E_{I_k}\left[\exp\left(-\frac{\mu}{4}\frac{I_k^2}{(\sin\theta)^2}\right)\right] d\theta$$

(16)

Where E $(\cdot)$ is the expectation operation. If we use the Meijer-G function in the exponential integrand of (16), then the Equation becomes

$$P(X, \hat{X}) = \frac{1}{\pi}\int_0^{\pi/2}\left[\int_0^{\infty} G_{0,1}^{1,0}\left[\frac{\mu}{4}\frac{I^2}{(\sin\theta)^2}\Big|_0^{-}\right] f_I(I)\, dI\right]^{|\Omega|} d\theta$$

(17)

We particularly examine the following cases

K channel: In this case, we consider only turbulence fading effects i.e., I= I_a.Hence the pdf of the irradiance for K channel is given by (3) and (17) takes the form of (18) by expressing the exponential and $k_v(\cdot)$ integrands in terms of the Meijer-G function[17, eq. (14)] and using inner integral in

[17,eq. (21)].This exact expression is more accurate than that of approximate one given by [5, eq. (12)].

$$P(X,\hat{X}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[\frac{2^{\alpha-1}}{\pi\Gamma(\alpha)}G_{4,1}^{1,4}\left[\frac{4\mu}{(\sin\theta)^2\alpha^2}\Big|_0^{\frac{1-\alpha}{2},\ \frac{2-\alpha}{2},\ 0,\ \frac{1}{2}}\right]\right]^{|\Omega|}d\theta \quad (18)$$

NE channel: In this case, we also consider only turbulence fading effects i.e., I= I_a and the pdf of NE channel takes the form of (19) using [14, eq. (2.33.1)]. An equivalent expression is also given by [5, eq. (7)].

$$P(X,\hat{X}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[\sqrt{\frac{\pi(\sin\theta)^2}{\mu}}\exp\left(\frac{(\sin\theta)^2}{\mu}\right)\operatorname{erfc}\left(\sqrt{\frac{(\sin\theta)^2}{\mu}}\right)\right]^{|\Omega|}d\theta \quad (19)$$

PE channel: Here, we assume channel has only pointing error effects i.e., I=I_p.The pdf for PE channel is obtained by substituting [17, eq. (26)] in (17).

$$P(X,\hat{X}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[\frac{\gamma^2}{2}G_{1,2}^{1,1}\left[\frac{\mu A_0{}^2}{4(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2}}\right]\right]^{|\Omega|}d\theta \quad (20)$$

K+PE channel: In this merged case we consider turbulence i.e., K channel and misalignment fading effects. The pdf for this channel is derived by using [17, eq. (21)] and simplified using [14, eq. (9.31.1)] in (17).

$$P(X,\hat{X}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[\frac{2^{\alpha-2}\gamma^2}{\pi\Gamma(\alpha)}G_{5,2}^{1,5}\left[\frac{4\mu\left(\frac{\alpha}{A_0}\right)^{-2}}{(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2},\ \frac{1-\alpha}{2},\ \frac{2-\alpha}{2},\ 0,\ \frac{1}{2}}\right]\right]^{|\Omega|}d\theta \quad (21)$$

NE+PE channel: Finally, we consider NE channel with pointing errors. The pdf is obtained by using [17, eq. (21)] from (17).

$$P(X,\hat{X}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left[\frac{\gamma^2}{2\sqrt{\pi}}G_{3,2}^{1,3}\left[\frac{A_0{}^2}{(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2},\ 0,\ \frac{1}{2}}\right]\right]^{|\Omega|}d\theta \quad (22)$$

Lognormal channel: This channel is mainly suited for low fading conditions. The closed form solution for calculating the error performance is written as

$$P_e = \frac{Q-1}{Q}\left[P_{e,0}P_{e,2} + P_{e,0}P_{e,1} - P_{e,0}P_{e,1}P_{e,2}\right] \quad (23)$$

Where$P_{e,0} \triangleq Fr\left(\frac{\lambda_s}{3},0,\sigma\right)$, $P_{e,1} \triangleq Fr\left(\beta_1\frac{\lambda_s}{3},0,\sigma\right)$ and $P_{e,2} \triangleq Fr\left(\beta_2\frac{\lambda_s}{3},0,\sigma\right)$ where Fr(a,0,b) is the Lognormal density frustration function.

Rayleigh channel: This channel is mainly suited for severe fading conditions. The closed form solution for calculating the error performance is written as

$$P_e = \frac{Q-1}{Q}\left[\frac{1}{\left(1+\frac{\lambda_s}{3}\right)\left(1+\beta_2\frac{\lambda_s}{3}\right)} + \frac{1}{\left(1+\frac{\lambda_s}{3}\right)\left(1+\beta_1\frac{\lambda_s}{3}\right)} - \frac{1}{\left(1+\frac{\lambda_s}{3}\right)\left(1+\beta_1\frac{\lambda_s}{3}+\beta_2\frac{\lambda_s}{3}\right)}\right] \quad (24)$$

B.BER performance

PEP expressions are the basic tool for the calculation of upper bounds on the error probability of a coded communication system. For example, a union upper bound on the average BER assuming uniform error probability codes is given in [13] as

$$P_b(E) \le \frac{1}{\pi}\int_0^{\pi/2}\left[\frac{1}{n}\frac{\partial}{\partial N}T(D(\theta),N)|_{N=1}\right]d\theta \quad (25)$$

Where n the number of information bits per transmission, N is an indicator depends on the number of bits in error, $T(D(\theta),N)$ is the transfer function associated with the state diagram of a particular trellis coded modulation scheme and $D(\theta)$ is based on the derived PEP. Here we are considering convolutional code with rate 1/3 and length as 3, and then the transfer function for this code is [18, eq. (8.2.6)]

$$T(D(\theta),N) = \frac{D^6(\theta)N}{1-2N\,D^2(\theta)} \quad (26)$$

Substituting (26) in (25), we get

$$P_b(E) \le \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\frac{D^6(\theta)N}{1-2D^2(\theta)}d\theta \quad (27)$$

The exact D(θ) formulas for different channels are illustrated in Table 1.

channel	$D(\theta)$
K	$\frac{2^{\alpha-1}}{\pi\Gamma(\alpha)}G_{4,1}^{1,4}\left[\frac{4\mu}{(\sin\theta)^2\alpha^2}\Big|_0^{\frac{1-\alpha}{2},\ \frac{2-\alpha}{2},\ 0,\ \frac{1}{2}}\right]$
NE	$\sqrt{\frac{\pi(\sin\theta)^2}{\mu}}\exp\left(\frac{(\sin\theta)^2}{\mu}\right)erfc\left(\sqrt{\frac{(\sin\theta)^2}{\mu}}\right)$
PE	$\frac{\gamma^2}{2}G_{1,2}^{1,1}\left[\frac{\mu A_0{}^2}{4(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2}}\right]$
K+PE	$\frac{2^{\alpha-2}\gamma^2}{\pi\Gamma(\alpha)}G_{5,2}^{1,5}\left[\frac{4\mu\left(\frac{\alpha}{A_0}\right)^{-2}}{(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2},\ \frac{1-\alpha}{2},\ \frac{2-\alpha}{2},\ 0,\ \frac{1}{2}}\right]$
NE+PE	$\frac{\gamma^2}{2\sqrt{\pi}}G_{3,2}^{1,3}\left[\frac{A_0{}^2}{(\sin\theta)^2}\Big|_{0,-\frac{\gamma^2}{2}}^{\frac{2-\gamma^2}{2},\ 0,\ \frac{1}{2}}\right]$

IV. NUMERICAL RESULTS AND DISCUSSION

In this section several numerical results are provided to study the error performance of different fading channels during turbulence and/or pointing error effects.

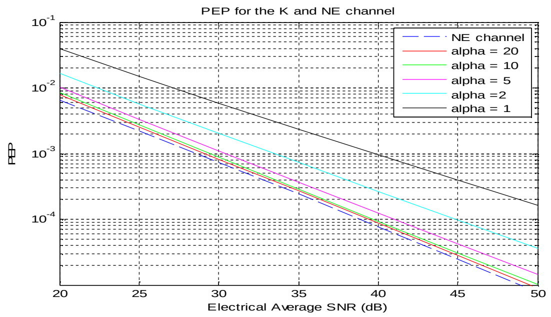

Fig.1. PEP for the K and NE channel.

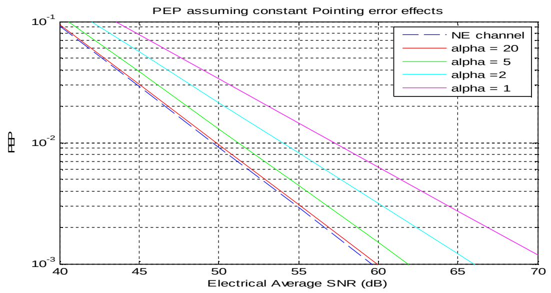

Fig.2. PEP assuming constant pointing error effects.

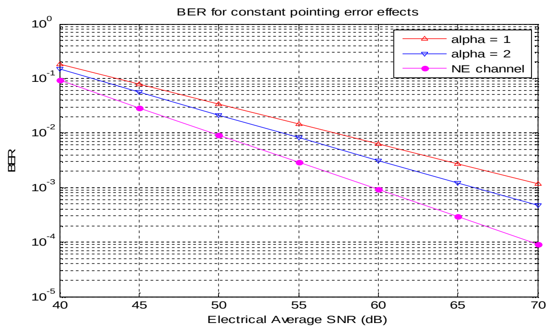

Fig.3. Upper bounds on BER for constant pointing error effects.

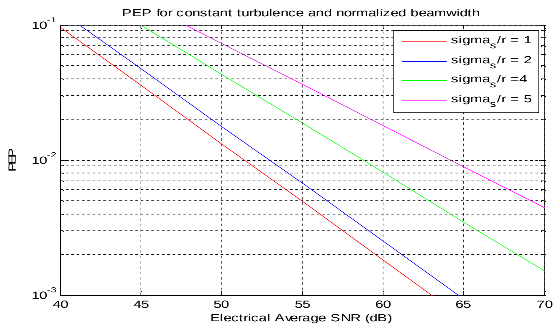

Fig.4. PEP for constant turbulence and beamwidth.

First, we reflect on only turbulence effects. Fig. 1 shows the error performance of K and NE channel in terms of SNR by considering error event of length 2 i.e., $|\Omega|$=2 and different values for channel parameter α. The consequential results show that as α increases the turbulence gets weak.

Fig.2 shows the results for constant pointing error effects i.e., beamwidth=10 and jitter=1 in terms of, μ, $|\Omega|$=2 and various values of channel parameter α. Compare with Fig.1 we need high SNR values to achieve the equivalent performance. Fig.3 shows the BER performance in terms of SNR by changing channel parameter. It is possible to achieve low BER targets for SNR values between 60 and 70 dB with the help of convolutional code of rate 1/3 and length of 3.

Next, we calculate the PEP by varying jitter and keeping channel parameter and beamwidth as 10.This results is shown in Fig.4.From this it is clearly shown that the performance degrades as the jitter increases. We study beamwidth variations for constant values of channel parameter and jitter as 3 in Fig.5.From this figure it is evident that overall performance affected by changing values of beam width and jitter.

Fig. 6 and Fig.7 shows the performance of 4-PPM for the Lognormal and Rayleigh fading cases. This results shows the exact match between the simulation results and error probability equations in (23) and (24).Compared with Lognormal fading, Rayleigh fading is more beneficial where performance gain can be realized at smaller error rates. This is because the Rayleigh distribution is used for model the scenario of severe fading while the lognormal model corresponds to the scenario of less severe fading.

V.CONCLUSIONS

We have investigated the error performance for IM/DD Free Space Optical communication systems using convolution coding schemes with OOK and 4-PPM.We have implicit symbol by symbol interleaved channels characterized by strong turbulence and/or pointing error effects. We have derived exact PEP expressions and calculate BER performance using transfer function technique

Numerical results have been also provided to illustrate the error performance for different fading

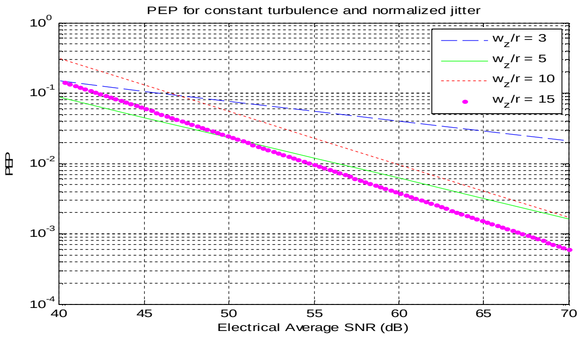

Fig.5. PEP assuming constant turbulence and jitter.

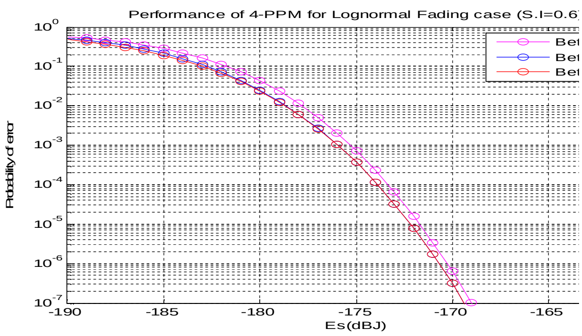

Fig.6. Performance of 4-PPM for Lognormal fading.

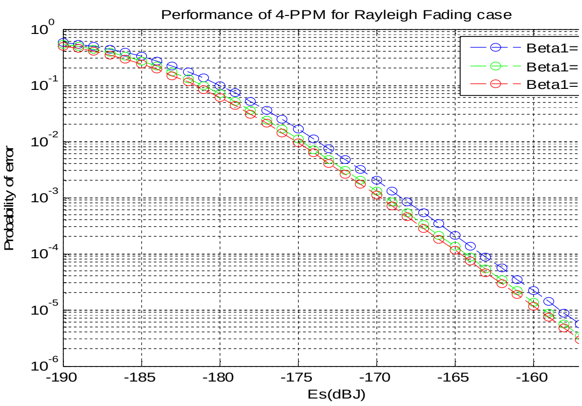

Fig.7. Performance of 4-PPM for Rayleigh fading.

channels by considering turbulence and misalignment fadings. It was shown that, we can attain low BER targets for small SNR values, by using error control coding. This analysis can be easily extended to contain other turbulence models.

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