Error Performance of Coded BPSK OFDM-FSO System under Atmospheric Turbulence

Bukola D. Ajewole[1], Pius A. Owolawi[2], and Viranjay M. Srivastava[1]
[1] University of Kwazulu-Natal, Durban, 4001, South Africa
[2] Tshwane University of Technology, Pretoria ,0001, South Africa
Email: ajewolebukola561@yahoo.com; p.owolawi@gmail.com; viranjay@ieee.org

***Abstract* —**Free Space Optical (FSO) communication system is one of the emerging technologies for use in future broadband networks, due to its high bandwidth efficiency when compared with Radio Frequency (RF) technology. However, atmospheric turbulence is a major factor impairment that degrades the performance of the FSO systems. As a result of this, Orthogonal Frequency Division Multiplexing (OFDM) has been considered as a tool to enhance the performance of the system. In this work, the authors investigate the performance of Binary Phase Shift Keying (BPSK) OFDM-FSO over the Gamma-Gamma turbulence channel. and Forward Error Correcting (FEC) codes are utilized to improve the error performance of the concerned system. The FEC codes used in this work are Convolutional code, Reed-Solomon codes and Turbo code. The results show that the coded BPSK offers a better performance over the uncoded BPSK. It has been shown that Turbo code significantly improve the system error performance compared with other FEC techniques under the same turbulence conditions and link distances considered.

Index Terms—Orthogonal Frequency Division Multiplexing (OFDM), Free Space Optical communication (FSO), Binary Phase Shift keying (BPSK), Forward Error Correction (FEC), Reed Solomon codes (RS).

I. Introduction

In the last few years, the convergence of communication and information technologies have led to phenomenal growth in the communication superhighway. This growth has led to the increased demand for bandwidth and channel capacity expansion by users in order to achieve higher data rate transmission, better quality of service (QoS) and higher efficiency. These demands by users coupled with the high cost of system installation and use of lower bandwidths have led to congestion in the use of Radio Frequency (RF) spectrum at frequencies in the C- and Ku bands. Free space optical (FSO) communication systems have drawn a huge recognition in the research environment due to the numerous benefits it offers when compared with optical fiber and Radio Frequency (RF) based systems. The benefits include higher bandwidth efficiency, license free spectrum, higher speed, high data rate, last-mile connectivity, cost effectiveness, highly secured for data transmission, flexible installation and etc. [1]-[3]. However, with these distinct qualities of the FSO system, its performance is impaired by atmospheric turbulence which occurs as a result of weather effects (such as rain, fog and haze). The resulting impairments may include signal attenuation losses, random fluctuation of the received signal notably over a distance of 1 km or more [4] among others. Other challenges associated with the use of FSO systems may include physical obstruction which appears in the Line of Sight (LOS) of transmission which is due to shadowing and blocking. Scintillation is also a notable limitation in FSO as the variation of temperature from the earth or artificial devices would cause fluctuations in the amplitude of the signal [5]. Several mitigation techniques such as OFDM, adaptive optics, diversity techniques and channel coding have been addressed and proposed by various researchers to comprehensively boost the performance of FSO link [6].

Various channel distribution techniques are available in literature to model the atmospheric turbulence over the FSO channel. These includes, log-normal distribution which describes the scintillation and signal fading for weak turbulence over short distance of approximately 1 km [7]. The negative exponential and K-distribution are also generally recognized for modelling saturated turbulence strength over longer distance [8]. In this study, the Gamma-Gamma channel distribution was considered as the most suitable distribution model to adopt due to its inherent characteristics to describe and model the weak to strong turbulence for the FSO channel [9].

Over the last decade, On/Off keying (OOK) modulation has been largely used to enhance the performance of FSO link as a result of its cost effectiveness and simplicity in practical implementation [10]. The shortcomings for this modulation scheme is that adaptive threshold is required for optimum performance and it is liable to channel estimation error [9]. Preferably, Pulse Position Modulation (PPM) have been considered for FSO system impairment because it offers good power efficiency, but its performance is limited by poor bandwidth efficiency and it also requires a tight symbol synchronization [11]-[13]. In order to overcome the impediments of OOK and PPM, Orthogonal Frequency Division Multiplexing (OFDM) scheme have been proposed using higher modulation schemes such as Binary Phase Shift keying (BPSK),

Manuscript received March 12, 2019; revised September 5, 2016.
doi:10.12720/jcm.14.10.936-944

Quadrature Phase Shift Keying (QPSK) and M-ary Quadrature Amplitude Modulation (QAM). BPSK has been notably used due to its zero threshold value against OOK and lower bandwidth requirement as compared to PPM [8] and its performance over atmospheric turbulence channel has been widely researched. OFDM is a modulation technique used in wireless communication systems. It is an effective solution to address the Inter-Symbol Interference (ISI) caused by a dispersive channel and robust to frequency selective fading [14]. The basic principle of an OFDM is to split a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a sub-carrier. It is applied to FSO due to its high bandwidth efficiency, increased tolerance capacity against frequency selective fading and narrow-band. The combined OFDM based FSO signal is propagated through the atmospheric turbulence channel including scintillation which will ultimately result in aberration effects.

In the course of the transmission of data over the free air, it is realized that channel coding plays an imperative role, and makes provision for higher quality performance of data delivery. The different channel coding techniques which are also referred to as Forward Error Correction (FEC) codes have been used in FSO communication systems. The FEC codes are being used due to their distinctive advantages such as the ability to increase the system throughput by adding extra bits to the data bits, error detection or correction and increased transmission [15]-[17]. It also introduces redundancy and frequency diversity into the system with the aim of overcoming signal degradation which causes fading in the FSO's atmospheric channel [18]. Convolution codes, Turbo codes, Low-Density Parity-Check (LDPC) codes, Reed-Solomon codes and so on are various types of FEC codes being used in communication technologies [19]-[20]. Convolution codes have been proved to be robust error-correcting codes because of their good adaptation to decoding complexity [21]. Reed-Solomon (RS) codes were introduced and shown in [22] for having a significant performance over the fading channels.

Considerable studies have been carried out by researchers, which uses FEC codes to improve the OFDM in FSO communication systems. The Low Density Parity Check (LDPD) (define in full)-coded OFDM over the atmospheric turbulence Single Input Single Output (SISO) channel has been studied by [23]. Similarly, [24] studied the performance of OFDM FSO communication system with hybrid channel codes during weak turbulence [24]. In [25], the analysis of Reed-Solomon (RS) codes for OFDM systems over the Rician fading channel has been studied [25]. it was observed that the authors studied the Symbol Error Rate (SER) performance over specified Signal to Noise Ratio (SNR) and it concluded that RS codes performed excellently over the fading channel. It was also observed by Mahdieh *et al*. [26] that the atmospheric turbulence greatly increases the error performance of the transmitted data (10^{-3} to 10^{-2} in BER) with BER < 10^{-10} as the common value in commercial FSO communication system is acceptable for a plausible good performance.

In this paper, we propose the coded OFDM-FSO system under the Gamma-Gamma atmospheric turbulence channel. The aim is to improve the Average Bit Error Rate (ABER) over the Carrier to Noise plus Distortion Ratio (CNDR) for uncoded-BPSK at weak, moderate and strong turbulence regime. The error performance of BPSK with Reed-Solomon, Turbo code and convolutional code would be analyzed under different turbulence and weather conditions. Furthermore, the performance of all FEC codes would be compared to determine the most suitable error correcting scheme for the system. This work has been organized as follows, section II describes the proposed coded OFDM-FSO system and channel model, section III describes the performance analysis, the simulated results are presented and discussed in section IV. Finally, section V concludes the work.

II. Proposed Coded OFDM-FSO System Model

The Orthogonal Frequency Division Multiplexing (OFDM) is a method of encoding digital data on multiple carrier frequencies. It can be referred to as a multicarrier modulation scheme, which splits high data rate into lower rate streams and simultaneously transmits them over a number of subcarriers at different frequencies. It can be divided into three major sections namely, transmitter, channel and the receiver. In this research, the OFDM-FSO system is used with the FEC techniques to reduce the effect of atmospheric turbulence. The RS code is introduced into the system at the transmitter side as shown in Fig. 1. A random input data is processed by RS encoder, the interleaver accepts the set of encoder data and rearrange the data before sending it to the mapper which maps the coded bits to complex symbols. Afterwards**,** the serial to parallel converter divides the data streams into lower data rate. Thereafter, the Inverse Fast Fourier Transforms (IFFT) transforms the coded modulated data from frequency domain to time domain variables:

$$X_j^{\,i} = \frac{1}{\sqrt{N}} \sum_{K=0}^{N-1} X_m \exp\left(\frac{j2\pi km}{N}\right) for\ 0 \le k \le N-1 \qquad (1)$$

where X_j^i is transmitted while the cyclic prefix (CP) is added to ensure orthogonality of the subcarriers. X_j^i represent the complex data symbol of the *j*, *N*, *m*, and *k* denotes the size of the IFFT, the IFFT input at the transmit antenna and OFDM symbol at transmit antenna after the IFFT respectively. The digital to analog conversion is done and the OFDM modulated signal S_{ofdm} obtained just before the Laser Diode (LD) is expressed as [18]:

$$S_{ofdm}(t) = \sum_{j=0}^{N-1} S_j(t) \qquad (2)$$

$$= \sum_{j=0}^{N-1} X_j \exp\left[2\pi i\left(\frac{n}{T_s} + f_c\right)t\right] \quad (3)$$

where $\left(w_n = n/T_s\right)$ is the frequency for each OFDM, N represents the total number of the subcarriers and f_c denotes the carrier frequency. The optical power transmitted $P_o(t)$ is expressed as:

$$P_o(t) = P_{avg}\left[1 + \sum_{j^i=0}^{N-1} m_{j^i} S_{j^i}(t) + \beta_3\left(\sum_{j^i=0}^{N-1} m_{j^i} S_{j^i}(t)\right)^3\right] \quad (4)$$

where β_3, m_n, and P_{avg} are third order non-linear coefficients and the optical modulation index (OMI) for each OFDM frequency and average transmitted optical power [27].

S_{ofdm} is transmitted over the Gamma-Gamma channel, the probability density function can be expressed as [28]:

$$F_h(h) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h^{\frac{\alpha+\beta}{2}} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h}\right), h > 0 \quad (5)$$

α and β are the parameters for small and large scale eddies of the scattering environment. I is the irradiance which can also be described as path loss. $\Gamma(.)$ and $K_{(.)}$ are defined as gamma function and V^{th} order modified Bessel function off the 2^{nd} respectively [29].

$$\alpha = \left[\exp\left(\frac{0.49\sigma_l^2}{\left(1 + 1.1\sigma_l^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right) - 1\right]^{-1} \quad (6)$$

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

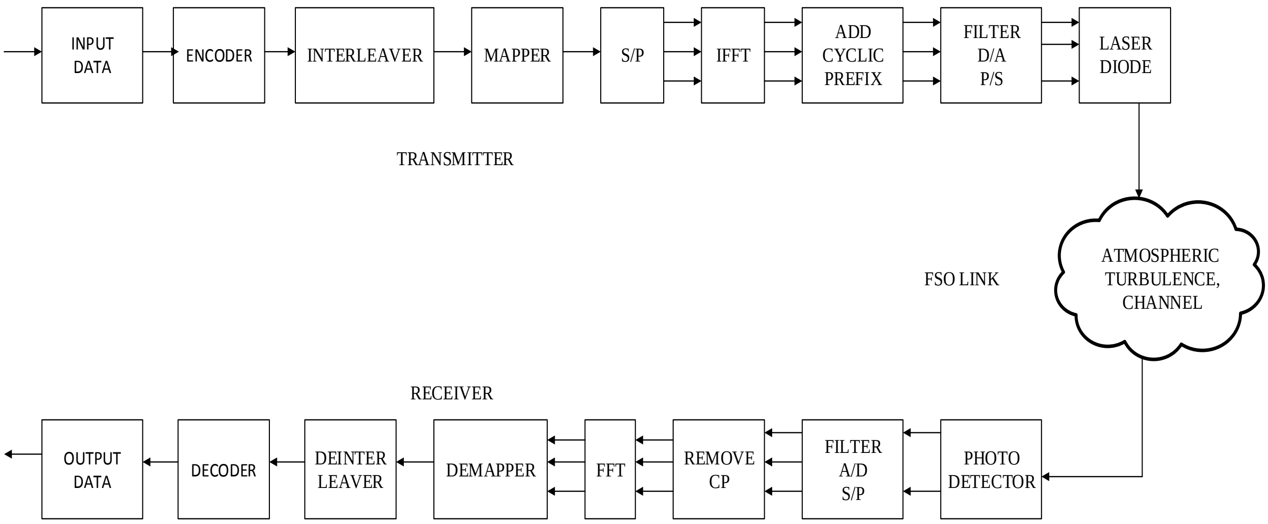

Fig. 1. Block diagram of coded OFDM-FSO

where, $\sigma_l^2 = 0.5\, C_n^2 K^{7/6} L^{11/6}$ is the Rytov variance $K = \left(2\pi/\lambda\right)$. λ and L are the optical wavelength and the link distance between the transmitter and receiver. $C_n^2\left(m^{-2/3}\right)$ is the scintillation index. The OFDM signal is converted into optical signal through the Laser Diode (LD) and transmitted over the atmospheric turbulence channel through the FSO link. The PhotoDetector (PD) converts the optical signal into electrical signal and the optical power can be expressed as

$$P_r(t) = P_0(t)T_{tot} + W(t) \quad (8)$$

where W is the Additive White Gaussian Noise (AWGN) and T_{tot} is the total losses of the optical signals due to atmospheric turbulence. Subsequently, analog to digital conversion, Parallel to serial conversion are performed, Fast Fourier Transform (FFT) transforms signal into complex symbols, the deinterleaver rearrange the complex signal and it is demapped and decoded by the RS decoder and the output data is obtained at the receiver. The carrier to noise plus distortion *($CNDR_j$)* at the receiver is given as [30]

$$CNDR_J(I) = \frac{\left(M_{J^i}\rho L_{tot} P_t I\right)^2}{2\left(N_0/T_S + \sigma_{J,IMD}^2\right)} \quad (9)$$

The $CNDR_j$ per OFDM subcarrier can be obtained as:

$$CNDR_j(I) \approx \frac{M^2{}_{j^i}\rho^2 L^2{}_{tot} P^2{}_t I^2}{2\left(\left(N_0/T_S\right)_{AV} + \left(\sigma_j{}^2{}_{,IMD}\right)_{AV}\right)} \quad (10)$$

AV, ρ, *T*, δ and *F* are the average over scintillation value, PD responsivity, temperature, electron charge and noise present in the receiver. $N_0 = \left(4K_B T\, F/R_L\right) + 2\delta l_0 + l^2{}_0(RIN)$, K_B, l_o and R_L are the Boltzmann's constant, received photocurrent and resistor load respectively. *IMD* and *RIN* is the inter-modulation distortion and is the relative intensity noise [27], [31]

III. Performance Analysis

In this section authors present the average bit error rate for OFDM-FSO system for BPSK in turbulence channel modeled by Gamma-Gamma distribution model. The BER expression for BPSK OFDM signal is given as [32]

$$B_e = \frac{N^{-1}}{\log_a(2)} \sum_{J=0}^{N-1} erfc\left(\sqrt{CNDR_J(I)}\sin\left(\frac{\pi}{2}\right)\right) \qquad (11)$$

The PDF of Gamma-Gamma channel present in FSO link is given in (5). By expressing the Bessel function in terms of Meijer G function [32], (5) may re-written as:

$$F_I(I) = \frac{(\alpha\,\beta)^{\left(\frac{\alpha+\beta}{2}\right)} I^{\frac{(\alpha+\beta)}{2}-1}}{\Gamma(\alpha)\Gamma(\beta) I_a^{\frac{(\alpha+\beta)}{2}}} G_{0,2}^{2,0}\left(\frac{\alpha\beta I}{I_a}\middle|_{\left(\frac{\alpha+\beta}{2}\right),\left(\frac{\beta-\alpha}{2}\right)}^{-,-}\right) \qquad (12)$$

I_a is the atmospheric attenuation and *I* is the channel state. The ABER of OFDM-FSO over Gamma-Gamma (GG) channel is given as [33, 34]:

$$\text{ABEP} = \int_0^\infty B_e(I) F_I(I)\, dI \qquad (13)$$

Therefore, by substituting BER of BPSK OFDM in (11) and the pdf of GG in (12) into (13), the ABER becomes

$$\frac{N^{-1}}{\log_a(2)} \sum_{j=0}^{N-1} \int_0^\infty \left[erfc\left(\sqrt{CNDR_j(I)}\,\sin\left(\frac{\pi}{2}\right)\right) F_I(I)\, dI\right] \qquad (14)$$

Substituting $F_I(I)$ in (12) into (14), we obtain the expression

$$\cong \frac{(\alpha\,\beta)^{\left(\frac{\alpha+\beta}{2}\right)}}{N\log_2(2)\Gamma(\alpha)\Gamma(\beta) I^{\frac{(\alpha+\beta)}{2}}} \sum_{j=0}^{N-1}\int_0^\infty I^{\frac{(\alpha+\beta)}{2}-1} erfc\left(\sqrt{CNDR_j}(I)\right)\sin\left(\frac{\pi}{2}\right) \times G_{0,2}^{2,0}\left(\frac{\alpha\,\beta\, I}{I_a}\middle|_{\frac{\alpha-\beta}{2}\ \ \frac{\beta-\alpha}{2}}^{-\ \ -}\right) dI \qquad (15)$$

The complementary error function (*erfc*) can be expressed in terms of Meijer G function as [35, 36]:

$$erfc(q) = \frac{1}{\sqrt{\pi}} G_{1,2}^{2,0}\left(q\middle|_{0,\ 1/2}^{1}\right) \qquad (16)$$

q is substituted into the equation as:

$$q = CNDR_j(I) \times \left(\sin\left(\frac{\pi}{2}\right)\right) \qquad (17)$$

The ABER for BPSK OFDM-FSO scheme may be written as:

$$ABER = \frac{(\alpha\,\beta)^{\left(\frac{\alpha+\beta}{2}\right)}}{\sqrt{\pi} N\log_2(2)\Gamma(\alpha)\Gamma(\beta) I^{\frac{(\alpha+\beta)}{2}}} \sum_{j=0}^{N-1}\int_0^\infty I^{\frac{(\alpha+\beta)}{2}-1} \times G_{0,2}^{2,0}\left(\frac{\alpha\beta\, I}{I_a}\middle|_{\frac{\alpha-\beta}{2}\ \ \frac{\beta-\alpha}{2}}^{-\ \ -}\right) G_{1,2}^{2,0}\left(\frac{qI^2}{2}\middle|_{0,\ 1/2}^{1}\right) dI \qquad (18)$$

The ABER for uncoded BPSK OFDM-FSO can be solved by applying the integral identity given in [37]:

$$= \frac{2^{\alpha+\beta}}{N\log_2(2)\Gamma(\alpha)\Gamma(\beta)4\pi^{3/4}} \sum_{j=0}^{N-1} G_{5,2}^{2,4} \left(\frac{8qI_a^2}{(\alpha\beta)^2}\middle|_{0,\ 1/2}^{\frac{1-\alpha}{2},\frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2}}\right) \qquad (19)$$

A. Channel Coding

In this section we give a concise description for the coding schemes used to improve the error performance of the uncoded BPSK used in OFDM-FSO system. The FEC codes used are convolutional codes (CC), Reed-Solomon codes (RS) and Turbo code (TC).

a) Convolution Code

The average bit error for convolutional coded BPSK system assuming a perfect interleaving can be written as [38]

$$ABER_{CODED} \le \sum_{x=d_{FREE}}^{\infty} \frac{1}{K} W_x\, B_x \qquad (20)$$

where d_{FREE} is the minimum rate free distance of the convolutional code, *d* is the hamming distance, W_x is the weighting coefficient and B_x is given as:
where

$$B_x = \begin{cases} \displaystyle\sum_{e=\frac{x+1}{2}}^{x} \frac{x!P^e(1-p)^{x-e}}{e!(x-e)!} & ,x\,odd \\ \displaystyle\frac{x!P^{x/2}(1-p)^{x/2}}{2\frac{x}{2}!\left(x-\frac{x}{2}\right)!} + \sum_{c=x/2+1}^{x} \frac{x!P^x(1-p)^{x-e}}{e!(x-e)!} & ,x\,even \end{cases} \qquad (21)$$

b) Reed-Solomon

"The RS *(n,k)* code has a minimum distance $d_{min} = 2t + 1$ and it is able to correct $t = \left(n - k/2\right)$ symbol error. The bit error probability for Reed- Solomon using hard-decision decoding can be approximately by" [39]

$$P_{b,c} \approx \frac{1}{N} \sum_{i=t-1}^{N} \binom{N}{i} p_w{}^i (1-p_w)^{N-i} \qquad (22)$$

"where *n* and *k* is the length of code word and the message bit. P_w is the probability of error of the RS code symbol The RS codes introduces redundancy into the system causing the increase in the transmission rate for the channel symbol and decreasing the CNRD received. Thus, ABER performance of Reed-Solomon codes for BPSK modulation in turbulence channel can be expressed" as

$$P_b = Q\left(\sqrt{2R\frac{E_b}{N_0}}\right) \tag{23}$$

R= k / n.

c) Turbo code

"The BPSK are modulated at the transmitter and are demodulated continuously at the receiver. The Error Probability to evaluate the linear block code for turbo code on AWGN channel can be upper bounded as" [40]:

$$BER \le \sum_{w=1}^{N}\sum_{d=d_f}^{\infty} A(w,d)\frac{w}{N}P_d \tag{24}$$

$$p_d = Q\left(\sqrt{2.d.R\frac{E_b}{N_0}}\right) \tag{25}$$

"where *A(w,d)* is the number of codeword of input weight *w* and the total weight *d*. P_d is the error probability for the codeword, R is the code rate and E_b/N_0 is the Signal to Noise Ratio (SNR). Hence, by changing the summation order we have":

$$\le \sum_{d=d_f}^{\infty} A_d.Q\left(\sqrt{2.d.R.\frac{E_b}{N_o}}\right) \tag{26}$$

$$\le \sum_{d=d_f}^{\infty} A_d.P_d \tag{27}$$

"where A_d is the codeword range which is divided by the *N* total number of information bits/codeword. It can be expressed as":

$$A_d = \sum_{w=1}^{N} A(w,d)\frac{w}{N} \tag{28}$$

"N_d, Wd are the number of codewords of the total weight *d* and average information weight". Thus,

$$N_d.W_d = \sum_{w=1}^{N} A(w,d).w \tag{29}$$

$$A_d = W_d\frac{N_d}{N} \tag{30}$$

$\frac{N_d}{N}$ is referred to as the valid range of codewords of weight *d*. by substituting Eq. (30) into Eq. (26), the expression as

$$BER \le \sum_{d=d_f}^{\infty} W_d\frac{N_d}{N}Q\left(\sqrt{2.d.R.\frac{E_b}{No}}\right) \tag{31}$$

"It can be observed from Eq. (31) that the BER of the codeword is dependent on the average weight of the information, its complementary error function and the effective multiplicity of the code. It be assumed that as the weight of the codeword is reduced as the CNRD increases. In gamma-gamma turbulence channel where the CNRD is from weak to strong turbulence, the free distance term in the union bound on the ABER performance of the code is influenced by the free distance ($d=d_{free}$). Hence, for turbo codes performance approaches asymptotic distance, Eq. (31) can be rewritten as" [40]:

$$BER \le \sum_{d=d}^{\infty} A_d P_d \tag{32}$$

Let,

$$P_d = [P_e]^d \sum_{k=0}^{d-1}\binom{d-1+k}{k}(1-P_e)^k \tag{33}$$

$$P_b \approx \frac{N_{free}\dot{W}_{free}}{N}Q\left(d_{free}\frac{2.R.E_b}{N_0}\right) \tag{34}$$

IV. Simulated Results and Discussion

In this section, the bit error probability upper bounds derived in previous section are employed to evaluate the performance of Reed-Solomon and Turbo code. The coding techniques utilized by OFDM-FSO link are subjected to the weak, moderate and strong turbulence in gamma-gamma fading channel. Monte Carlo (MC) simulations are carried out in to validate the accuracy of the analytical expressions. The simulated results illustrate the variation of the average bit error rate of the uncoded BPSK with the carrier to noise plus distortion ratio for the system. The Reed- Solomon codes RS (31, 27), RS (31, 21), RS (31, 17) are used in the simulation for simplicity sake because it would be complex making simple demonstration with the RS (255, 223).

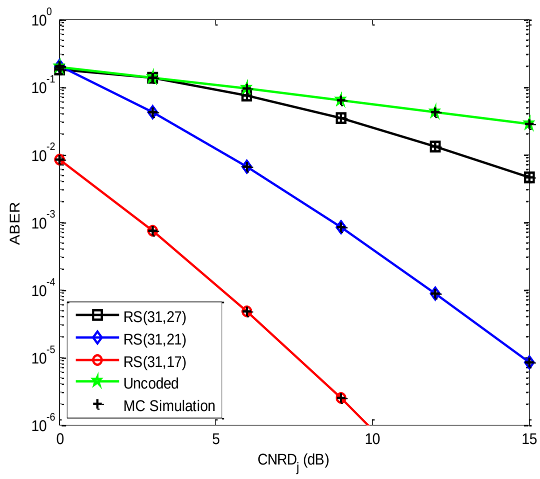

Fig. 2. Comparison between Reed Solomon under strong turbulence.

In Fig. 2, the ABER of uncoded and Reed-Solomon coded OFDM-FSO system are compared under strong turbulence. The simulated result illustrates that the RS (31,17) coded OFDM-FSO improves the error performance significantly than RS (31,21) and RS (31, 27) with ABER of 10^{-6} and a coding gain of 6 dB.

The performance of RS (31,27) was investigated under the three turbulence regime in Gamma-Gamma turbulence channel is presented in Fig. 3. The weak turbulence the ABER recorded is approximately 10^{-5}, ABER of 10^{-4} was obtained at the moderate turbulence and ABER of 10^{-2} for the strong turbulence. As expected, error performance of the system worsens as the strength of the turbulence increases. Similarly, it can be observed that the CNRD remained the same at all turbulence regime.

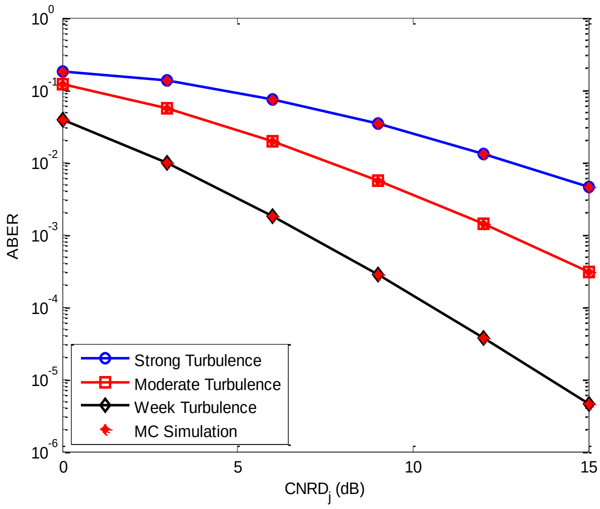

Fig. 3. Performance of RS (31,27) under different turbulence conditions

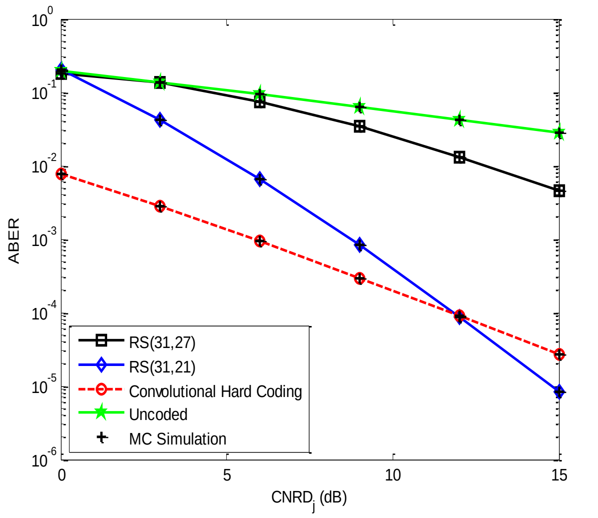

Fig. 4. Comparison between Reed-Solomon and Convolutional Hard Coding under strong turbulence.

In Fig. 4, the performance of Reed-Solomon is compared to convolutional hard coding under strong turbulence. Expected, the uncoded BPSK OFDM-FSO has the highest rate of error of ~10^{-1}. It is observed that the ABER of the system is decreasing as the coding techniques is introduced into the system. RS (31, 21) provided the lowest error rate with ABER of ~10^{-5} while the convolutional hard coding has an ABER of ~10^{-4}. It can be observed that the RS (31,21) provides a better performance under strong turbulence.

The performance of uncoded and Coded BPSK OFDM-FSO (Reed-Solomon, convolutional and turbo code) are compared under strong turbulence condition in Fig. 5. At this turbulence regime, the uncoded BPSK had the highest error performance with ABER of 10^{-1} when RS (31, 27) is been applied to the system, its ABER reduces to 10^{-2}. Convolutional code reduces the ABER to 10^{-5}, the system was further improved by employing RS (31, 21) and the error performance decreases to 10^{-8}. However, with the introduction of turbo code the error performance considerably decreased and the CNRD was improved from 15dB to ~12 dB, thereby giving a coding gain of 3 dB. It can be seen that turbo code performed better than other coding techniques employed in the system.

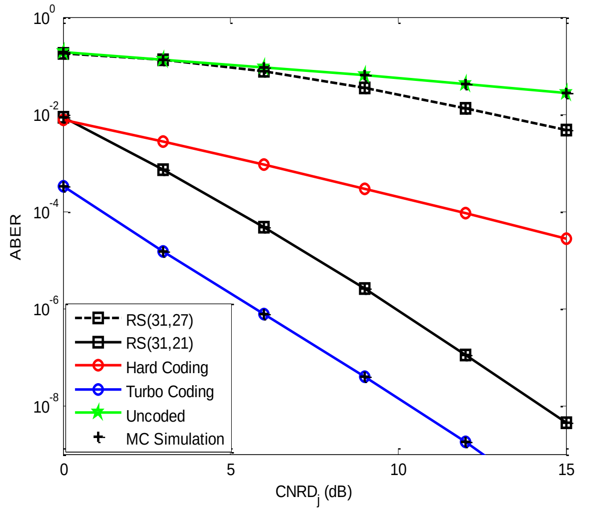

Fig. 5. Performance comparison between different coding techniques under strong turbulence conditions.

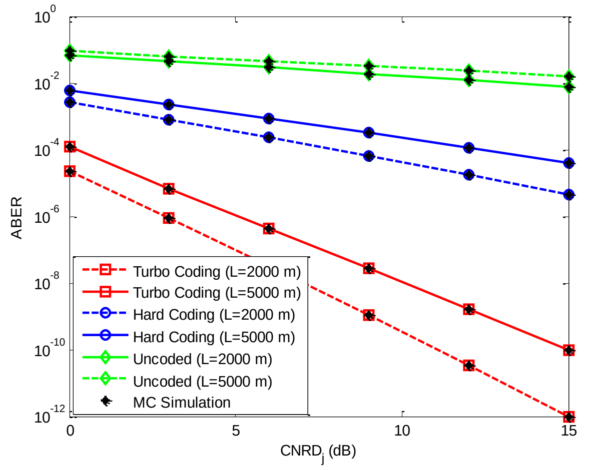

Fig. 6. Performance comparison between Turbo coding and Convolutional Hard coding under different link distance.

Fig. 6 illustrates the performance comparison between the turbo coding and convolutional coding under different link distance. Here, two different link distances L= 2000 m and 5000 m are used for the considered coding techniques. It is observed that the level of the distortion reduces as the coding techniques was integrated. However, a better performance was achieved by the turbo code over a longer distance through which the reducing the ABER from ~10^{-2} to 10^{-12}.

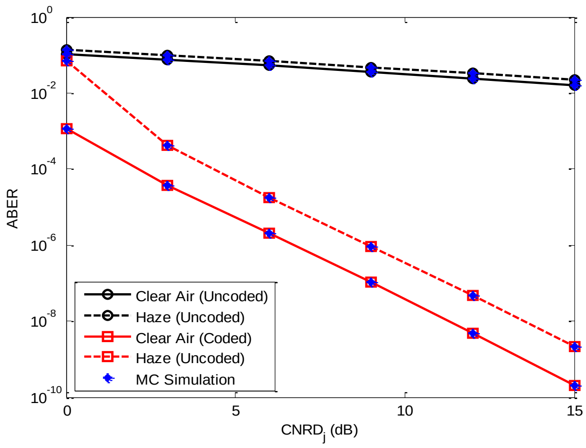

Fig. 7. Performance of turbo coding technique under different weather conditions

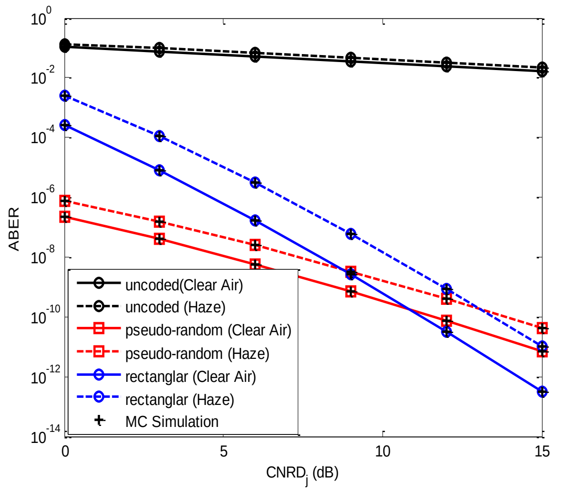

Fig. 8. Free distance asymptotes for turbo codes in BPSK OFDM-FSO system with two different interleavers

The system performance of turbo coding under different weather condition is shown in Fig. 7 There is a significant improvement in the error performance of the system as the turbo was introduced. Hence, reducing the ABER from ~10^{-2} to ~10^{-10}. Here, it is evident that the application of turbo code under clear air and haze offers the system better performance.

Fig. 8 shows the free distance asymptotes for turbo code in BPSK OFDM-FSO system with two different interleavers. It shows that at clear air and haze the rectangular interleavers has a better error performance than the pseudo-random interleaver at the free distance asymptotes. The pseudo-random interleave of length N= 65,536 with information bits per code word N_f =3, d_f = 3, *wf* =2, code rate= ½ and a 120×120 rectangular window *N*= 14,440, N_f = 28,900 , d_f = 12, *wf* =4 with a code rate= ½. Although at about 10 dB the error performance of rectangular interleaver in clear air and pseudo-random interleaver in haze shows the same ABER of 10^{-10}, nevertheless as CNRD increases the rectangular interleaver had a better performance.

V. Conclusions

The mathematical analysis for the bit error rate performance for the uncoded BPSK OFDM-FSO link over the Gamma-Gamma turbulence channel have been derived and validated with the Monte Carlo simulated results in this paper. The atmospheric turbulence over BPSK was analyzed using the derived expression. The Reed-Solomon, Turbo and Convolutional coding techniques were added to the BPSK OFDM-FSO system model in order to enhance its performance and reduce the percentage error. Thereafter, coding techniques were compared under all three turbulence regime of the gamma-gamma channel and different weather conditions. The results obtained showed that the performance of the system under consideration improved significantly with the introduction of FEC codes. Excellent coding gain of 3 dB was achieved by Turbo code over the other two FEC code under the strong turbulence. Finally, there was also a notable improvement in the error performance of the system at the distance of 2000 m and 5000 m with the turbo code.

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Ajewole D. Bukola holds a Bachelor in Engineering degree in Electrical and Electronics Engineering at the Federal University of Technology, Akure, Nigeria. She is currently studying to obtain her Masters of Science degree at the University of KwaZulu-Natal, Durban, South Africa. Her research interest are in optical wireless communication, MIMO systems and OFDM.

Pius A. Owolawi is currently a professor at Tshwane University of Technology, Pretoria, South Africa. His research interests are in the modeling of radio wave propagation at high frequency, fiber optic communication, radio planning and optimization techniques and renewable energy. He has written several research articles and serves as a reviewer for many scientific journals.

Viranjay M. Srivastava is currently a professor in the Department of Electronics Engineering, University of KwaZulu-Natal, Durban, South Africa. He has more than 15 years of teaching and research experience. He is a senior member of IEEE and IEEE HKN, and author of more than 180 scientific contributions including books, chapters and International refereed journals.