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# IMPROVING PERFORMANCE IN FREE SPACE OPTICAL COMMUNICATION (FSOC) CHANNEL THROUGH THE DUAL DIFFUSER MODULATION (DDM) DUE TO ATMOSPHERIC TURBULENCE

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**ABSTRACT**

This paper focus on reduction of atmospheric turbulence effect on free space optical communication using robust modulation that is dual diffuser modulation (DDM) technique. This technique uses two transmitter and differential mode detection at the receiver. The combination of dual diffuser with a differential detection mode at receiver produce the superior modulation against the turbulence especially reducing the scintillation index, overcome the signal detection with fix zero threshold and improve the power received. These three element factors are important in order to improve the overall performance of free space optical system. The analysis result show that for receiving power DDM at 3km distance propagation is 4.59dBm compare with conventional OOK that using diffuser only -7.6dB which equal to 3dBm improvement or around 40 percent. Meanwhile in term of BER performance, the DDM can further the distance propagation with approximately 42 percent improvement.

**Keywords:** *Phase Screen Diffuser, Atmospheric Turbulence, Differential Mode Detection, Dual Diffuser Modulation, Free Space Optic*

## 1. INTRODUCTION

Free space optical communication is an attractive alternative over fiber optical communication where provides high bandwidth, fast-installation and high security [1]. However FSOC is suffering with the atmospheric turbulence which can lead the laser beam (a) index oddities. Meanwhile beam spreading refers to conditions where the beam spread more than diffraction estimated predict. Lastly, for scintillation it affected the phase front of the beam can vary and resulting fluctuation irradiance or well know as intensity signal. The combination of all these effect will cause both the spatial and temporal experience random distortion, beam broadening, beam wander and redistribution of the intensity within the beam. The temporary redistribution of the intensity, known as scintillation, results from the chaotic flow changes of air and from thermal gradients within of FSO.

In order to mitigate this effect, partially coherent beam can be used by using the phase screen diffuser. It creates a 'new' Gaussian beam characteristic which effectively propagates through fluctuations in refractive index of the variability of element factor such as temperature, pressure and wind variations along the optical propagation path through the channel [2-9].

Phase screen diffuser which well known as partially coherent beam improve the laser performance in communication system has taken an interest recently [10-13]. The conventional FSO using the perfect coherence beam suffers from the various weather in the atmosphere. A number of phenomena in the atmosphere such as scattering, absorption and turbulence affect laser beam propagation. In this paper we focus on turbulence effect. The most important effects of atmospheric turbulence on the laser beam are such as phase-front

the optical path caused by the variation in air temperature and density. Subsequently, this condition can lead to the signal fading and reduce the performance

atmospheric turbulence. To enhance more the performance FSO using partially beam, at the transmitter part the system we employ two transmitters and at receiver part the reception in differential mode detection. In section II we

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explained the partial coherent beam characteristic. The model of system in section III and result in section IV. Finally, section V is for conclusion.

## 2. PARTIALLY COHERENCE BEAM

### 2.1 Basic model and parameter

The partially coherent beam is formed when the laser through the diffuser [14], the phase and amplitude between two random points in an optical beam wanders by significant amount such that the correlation between them partially decreases. In this section we calculate the scintillation index caused by the combination of diffuser and atmospheric turbulence under weak and moderate to strong conditions. In the presence of atmospheric effect, we need to take into account some scattering properties caused by the diffuser. Now speckle cells associated with diffuser acts as scattering center with the spatial correlation radius '$l_c$' (cell size) of the diffuser surface produces a separate beam coherence center within the original beam source diameter. Hence, the diffuser acts as an array of independent scattering centers. The number of scattering centers is given by,

$$N_S = 1 + \frac{2w_0^2}{l_c^2} \qquad (1)$$

The value of $w_0^2$ = 0.025m and $l_c$ =0.001 for all calculation in this paper. The effect of diffuser on an optical beam at the receiver is characterized by replacing the standard beam parameter $\Theta_1, \Lambda_1$ by effective beam parameter $\Theta_{ed}, \Lambda_{ed}$ define in term of $N_s$ as follows

$$\Lambda_{ed} = \frac{\Lambda_0 N_S}{\Theta_0^2 + \Lambda_0^2 N_S} \quad (2) \text{ and } \quad \Theta_{ed} = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2 N_S} \quad (3)$$

$$\Lambda_1 = \frac{\Lambda_0(L)}{\Theta_0^2(L) + \Lambda_0^2(L)} \quad (4) \text{ and } \quad \Theta(L) = \frac{\Theta_0(L)}{\Theta_0^2(L) + \Lambda_0^2(L)} \quad (5)$$

The initial Fresnel ratio $\Lambda_0(L)$ and the initial phase curvature $\Theta_0(L)$ are given by

$$\Lambda_0(L) = \frac{2L}{kw_0^2} \quad (6) \text{ and } \quad \Theta_0(L) = 1 - \frac{L}{F_0} \quad (7)$$

In this paper we use value for $F_o = \infty$, collimated beam for all calculation. Expressions for partially coherent beam are derived as same as a coherent beam [15] equations except the output beam parameters are changing due to diffuser located at the transmitter side with a different diffuser correlation length. The typical value for the diffuser correlation length ($l_c^2$) are 0.1,0.01,0.001 and 0.0001 .Using the Kolmogorov spectrum and standard extended Rytov theory the on axis scintillation index for weak turbulence (inner scale l=0, Outer scale L=$\infty$) partially coherent Gaussian-beam is given by.

$$\sigma_B^2 = 3.86\sigma_I^2 \left\{ \begin{array}{l} 0.4\left[(1+2\Theta_{ed})^2 + 4(\Lambda_{ed})^2\right]^{5/12} \\ \mathrm{X}\left(\cos\left[\frac{5}{6}\tan^{-1}\left(\frac{1+2\Theta_{ed}}{2\Lambda_{ed}}\right)\right]\right) \\ -\left(\frac{11}{6}(\Lambda_{ed})^{5/6}\right) \end{array} \right\}$$

(8)

Indicate where the strength of irradiance fluctuations and proportional to Rytov variance as

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \qquad (9)$$

For weak fluctuation, it is less than 1 and for strong fluctuation it is greater than 1. $C_n^2$ is the refractive index structure constant that characterizes the strength of the index of refraction fluctuations. The typical $C_n^2$ value weak turbulence is $10^{-17}$ $m^{-2/3}$ and strong $10^{-12}$ $m^{-2/3}$. For moderate to strong turbulence scintillation index is

$$\sigma_{I,strong}^2 = \exp\left\{ \frac{0.49\sigma_R^2}{\left[1+0.56(1+\Theta_{ed})\sigma_R^{\frac{12}{5}}\right]^{\frac{7}{6}}} + \frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{\frac{5}{6}}} \right\} - 1$$

(10)

If we consider the scintillation index influenced by the size aperture receiver, we have to use the relation normalized receiver aperture ($\Omega$) which is defined as $\Omega = \frac{2L}{kW_G^2}$ where $W_G^2$ is the Gaussian lens radius. The log irradiance due to large scale eddies is given as

$$\sigma_{\ln x}^2(D) = 0.49\sigma_I^2 \left(\frac{\Omega-\Lambda_{ed}}{\Omega+\Lambda_{ed}}\right) x \left(\frac{1}{3} - \frac{1}{2}\bar{\Theta}_{ed} + \frac{1}{5}\bar{\Theta}_{ed}^2\right) x \left(\frac{n_x}{1+\frac{0.4 n_x (1+\Theta_{ed})}{\Lambda_e d + \Omega}}\right)^{7/6}$$

(11)

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where the quantity $n_x$ is the normalize large-scale cutoff frequency determined by the asymptotic behavior of $\sigma^2_{\ln x}$ ion weak turbulence and the saturation regime [16]

$$n_x = \frac{\left(\frac{1}{3} - \frac{1}{2}\overline{\Theta}_{eff} + \frac{1}{5}\overline{\Theta}^2_{eff}\right)^{-6/7}\left(\sigma_B \big/ \sigma_I^2\right)^{12/7}}{1 + 0.56\sigma_B^{12/5}} \quad (12)$$

Meanwhile the log irradiance due to small-scale eddies is given by

$$\sigma^2_{\ln y}(D) = \frac{1.27\sigma_I^2 n_y^{-5/6}}{1 + \frac{0.4 n_y}{\Lambda_1 + \Omega}} \quad (13)$$

where the corresponding cutoff frequency is

$$n_y = 3\left(\frac{\sigma_I}{\sigma_B}\right)^{12/5}\left(1 + 0.69\,\sigma_B^{12/5}\right)$$

Therefore the total log irradiance due to large-scale and small-scale is

$$\sigma_I^2(D) = \exp\left[\sigma^2_{\ln x}(D) + \sigma^2_{\ln y}(D)\right] - 1 \quad (14)$$

### 2.2 Effective Spot Beam

The effective spot beam $W_{eff.\zeta}(L)$ and global coherent parameter $\zeta$ of partially coherent beam can be denoted as [20]

$$w_{eff.\zeta}(L) = w_o\sqrt{\left(\theta_o^2 + \zeta\left(\frac{2L}{kw_o}\right)^2\right)} \quad (15)$$

$$\zeta = \zeta_s + \frac{2w_o^2}{\rho_o} \quad (16)$$

where $\zeta_s = 1 + \frac{w_o^2}{\sigma_\mu^2}$ is the source coherence parameter of the laser beam emitted by the transmitter and $\sigma_\mu^2$ is the variance of the Gaussian describing the ensemble average of the random phases. If $\zeta_s$ equal to 1, the beam is fully coherent and the beam is partially coherent beam if the $\zeta_s$ above value 1.

### 2.3 Mean Intensity

The unit amplitude of partially coherent beam for average intensity given as [20]

$$\langle I(\rho, L)\rangle = \frac{w_o^2}{w^2_{eff.\zeta}}\exp\left[\frac{-2\rho^2}{w^2_{eff.\zeta}}\right] \quad (17)$$

## 3. SYSTEM MODEL

The system employs two transmitters and on off keying (OOK) modulation as reference for conventional system. When the first transmitter sends a bit '1', the second transmitter which is set in compliment condition will send the bit '0' in simultaneously and vice versa. Meanwhile at the receiver part, the signal will go through the subtractor for the differential detection process as shown in Figure 1.

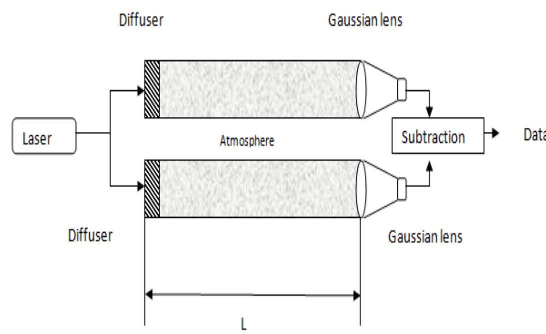


*Figure 1: Dual Diffuser Modulation Setup*

Here we assume the ideal subtractor condition where no losses signal occurs during subtraction. Therefore, the signal output will become bit '1' for sending binary '1' and bit '-1' for sending binary '0'. This condition can be illustrated in Table 1. Here we can see that, this modulation approach eliminated the need of adaptive threshold where the conventional OOK modulation dependable on threshold detection to recognize the incoming signal received whether the bit '1' or '0'. Generally, the conventional detection technique always misinterpretation by receiver where the noise alone capable to trigger as signal bit '1' (sending pulse) which also well known as 'false alarm' and sometimes the signal sending which contain the data is recognize as bit '0' (no pulse condition) when the signal is not reach the threshold value [17]. This condition is well known as 'miss detection' condition. Therefore to overcome this problem, the complex adaptive threshold has been suggested. However with dual diffuser modulation the detection signal is becoming easier with fix threshold at zero. The incoming signal can be referenced to determine the signal sending bit '1' or '0'. In order to maximize the performance, we placed the low cost material phase screen diffuser at transmitter to combat more efficient the

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atmospheric turbulence effect. This combination creates the superior robust modulation in FSOC. According Table 1, let say *Yn* is the received signal with zero threshold detection,

$$\left.\begin{array}{l} Yn > 1 \\ Yn < -1 \end{array}\right\} \quad \begin{array}{l} \text{bit '1'} \\ \text{bit '0'} \end{array}$$

The received signal can be written as:

$$Y_n = 2\sqrt{E_b} + \frac{(n_1 + n_2)}{2} \quad (18)$$

where $\sqrt{E_b}$ is represent the average energy signal and $n_1$ and $n_2$ are representing the noise of photo detector 1 and 2 respectively where n can be denoted as Additive White Gaussian Noise (AWGN) with zero mean and variance σ.

*Table 1. Dual Diffuser Modulation Approach From Modification Conventional OOK Modulation*

| **Transmitter (TX)** | | **FSO CHALLENGES** | **Receiver (RX)** | | **Subtraction process** | |
|---|---|---|---|---|---|---|
| **Sending bit** | | | **Received bit** | | **RX1-RX2** | |
| **TX1** | **1** | **Atmospheric turbulence** | **RX 1** | **1** | **Bit 1** | **1** |
| | **0** | | | **0** | | |
| **TX2 (Compliment)** | **0** | | **RX 2** | **0** | **Bit 0** | **-1** |
| | **1** | | | **1** | | |

## 4. PERFORMANCE ANALYSIS

### 4.1 Signal to Noise Ratio

The output SNR in the absence of optical turbulence defined by the ratio of the detector signal current $i_s$ to the root-mean-square (rms) noise current- $\sigma_N$ , which yields

$$SNR_0 = \frac{i_s}{\sigma_N}$$

The SNR for partially coherent beam (for dual diffuser), SNRP$_o$ in absence of turbulence as derived in [18]

$$SNRP_0 = \frac{SNR_o}{\sqrt{PP_o / P_o}}$$

where PP$_o$ is the received power partially coherent beam and P$_o$ is the power of coherent beam

$$SNRP_o = \frac{SNR_o}{\sqrt{1 + q_c \Lambda_1}}$$

Thus, the SNR for DDM in absence of atmospheric turbulence can be written as:

$$SNRP_o = \frac{\dfrac{4\Re^2\left(\left(\dfrac{\pi D^2}{8}\right)\left(\dfrac{2P_o}{\pi W^2(L)}\right)\right)^2}{4e\Re\left(\left(\dfrac{\pi D^2}{8}\right)\left(\dfrac{2P_o}{\pi W^2(L)}\right)\right)B + 2e\Re\left(\dfrac{N(\lambda)\Delta\lambda\pi\Omega^2_{FOV}}{4} + W(\lambda)\Delta\lambda\right)B + 2e(i_d)B + \dfrac{4k_bT_nB}{R_L}}}{\sqrt{1+q_c\Lambda_1}}$$

(19)

In equation (19), the noises consider are shot noise, background noise and thermal noise. *D* is diameter receiver, *W(L)* is beam spot size at receiver, $N(\lambda)$ = spectral radiance of sky, $W(\lambda)$ = spectral radiant emmittance of sun, $\Delta\lambda$ = bandwidth of optical bandpass filter (OBPF), $\Omega^2_{FOV}$ = photodetector field of view angle (FOV) in radians, $k_b$ is the Bolztman's constant, $T_n$ is the temperature of receiver noise, *B* is the electrical equivalent noise bandwidth of the receiver and $R_L$ is the load resistant. In the presence of atmospheric turbulence, the received signal exhibits additional power losses (refraction, diffraction) and random irradiance fluctuations. Therefore SNR becomes

$$\langle SNRP \rangle = \frac{SNR_0}{\sqrt{\left(\dfrac{Pso}{\langle Ps \rangle}\right) + \sigma_I^2(D) SNR_0^2}} \quad (20)$$

$$\langle SNRP \rangle = \frac{SNR_0}{\sqrt{1 + q_c\Lambda_1 + 1.63\sigma_I^{12/5}\Lambda_I + \sigma_I^2(D) SNR_0^2}} \quad (21)$$

where SNR$_o$ is obtain from equation (19), $Pso$ is the signal power in the absence of atmospheric effects and $\sigma_I^2(D)$ is the irradiance flux variance on the photo detector. Angle bracket $\langle\ \rangle$ represent mean. The power ratio $\dfrac{Pso}{\langle Ps \rangle}$ provides a measure of SNR deterioration caused by atmospheric induced beam spreading given by

$$\frac{Pso}{\langle Ps \rangle} = 1 + 1.63\sigma_R^{\frac{12}{5}}\Lambda_1$$

### 4.2 Bit Error Rate

The two conditional PDFs for DDM can be written as:

Journal of Theoretical and Applied Information Technology
10th February 2014. Vol. 60 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$P(Y_n|1)=\frac{1}{\sqrt{\frac{2\pi N_o}{4}}}e^{-\left(\frac{Y_n-\sqrt{E_b}^{\,2}}{\left(\frac{2N_o}{4}\right)}\right)} \qquad (22)$$

$$P(Y_n|1)=\frac{1}{\sqrt{\frac{2\pi N_o}{4}}}e^{-\left(\frac{Y_n+\sqrt{E_b}^{\,2}}{\left(\frac{2N_o}{4}\right)}\right)} \qquad (23)$$

where $N_o/4$ is a variance ($\sigma^2$) with zero mean obtained from involving two random variable by using chi-square random variable approximation. By considering equally likely condition, we obtain the probability error in absence atmospheric turbulence.

$$P(Y_n|1)=P(Y_n|0)=Q\left(\sqrt{\frac{2E_b}{N_o}}\right)\cong\frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (24)$$

where Q(x) is Gaussian Q-function with

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}e^{-\left(\frac{t^2}{2}\right)}dt \quad \text{and} \quad \frac{E_b}{N_o}=SNR_o$$

In the presence of atmospheric turbulence, the probability of error is given by [19]

$$\Pr(E)=\langle BER\rangle=\frac{1}{2}\int_0^{\infty}p_I(u)erfc\left(\sqrt{\langle SNRP\rangle}u\right)du \qquad (25)$$

Where $p_I(u)$ is a gamma-gamma distribution with unit mean

$$p_I(u)=\frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}u^{\frac{(\alpha+\beta)}{2}-1}K_{\alpha-\beta}\left(2\sqrt{\alpha\beta u}\right) \text{ for } u>0$$

When aperture averaging effects are considered, parameters $\alpha$ and $\beta$ of the gamma-gamma PDF are defined as

$$\alpha=\frac{1}{\exp\left[\sigma^2_{\ln X}(D)\right]-1} \quad \text{and} \quad \beta=\frac{1}{\exp\left[\sigma^2_{\ln Y}(D)\right]-1}$$

Where $\sigma^2_{\ln X}$ (D) and $\sigma^2_{\ln Y}$ (D) can be calculated using equation (11) and (13) respectively.

Figure 2 shows the degradation of scintillation index when using the diffuser for strong turbulence. As we can see, the scintillation index increase when the distance propagation increase. At a short distance 2km, the scintillation index for coherent beam is 1.5 but with using the diffuser the scintillation index can reduce to 1.2. However the effect of the diffuser is not continuous where from the graph as we can see, above the distance propagation 3km it will turn to flat value. The effect of the diffuser is greater effect on weak turbulence regime [18].

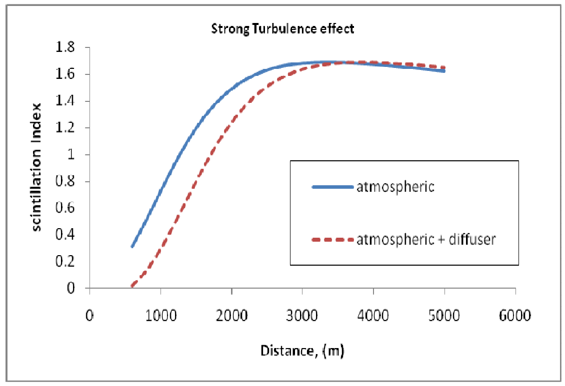

*Figure 2: Scintillation Index Versus Distance For Strong Turbulence*

Figure 3 shows the mean intensity due to diffuser effect. The coherent beam produces the peak amplitude 0.045 at 1.4km but the partially coherent beam at 0.8km. This is because the diffuser will expand the spot size beam and consequently reduction above the mean intensity. As a result it reduces the received power at receiver. However this effect can reduce by using DDM approach where it can double up the magnification power as shown in Figure 4. As an example of 3km distance propagation, the received power for coherent beam is -6.6dBm and for conventional OOK using a diffuser is -7.6dBm but in DDM approach the received power is -4.59dBm. This show the improvement of power received approximately about 40 percent. Meanwhile in Figure 5 shows the comparison mean intensity with various value of the initial curvature beam parameter. As the increasing value for initial curvature beam the small mean intensity will produce. This condition actually relates to various types of laser beam. If $\theta_o < 1$, the laser beam is categorized as collimate beam and if $\theta_o > 1$, is categorized as a divergent beam. Therefore the mean intensity will reduce if the increasing value of initial curvature that is under the divergent beam category.

Figure 6 shows the BER versus conventional OOK modulation and dual diffuser modulation for strong atmospheric condition. At standard acceptance BER $10^{-9}$ the conventional OOK only reach distance propagation 1.4km but the superior DDM enhance the distance to 2km where equally 42 percent improvement. The BER of DDM can be increased by using different strength of the diffuser at the transmitter.

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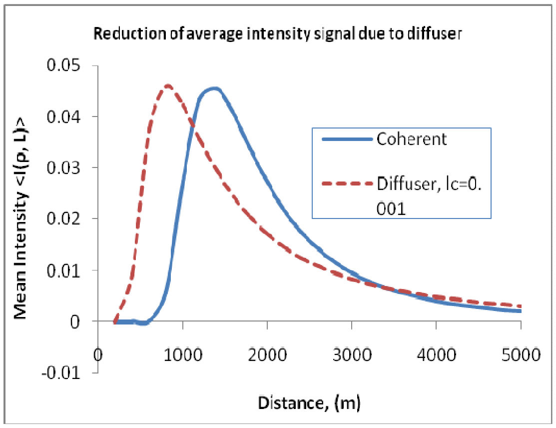


*Figure 3: Mean Intensity Versus Distance For Comparison Coherent Beam And Partially Coherent Beam With Strength Lc =0.001*

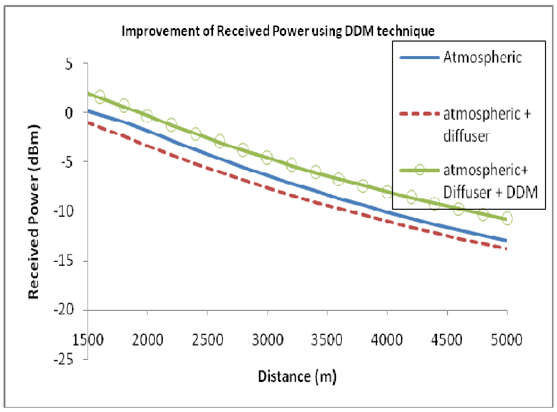


*Figure 4: Improvement Of Receiving Power In DDM* Approach

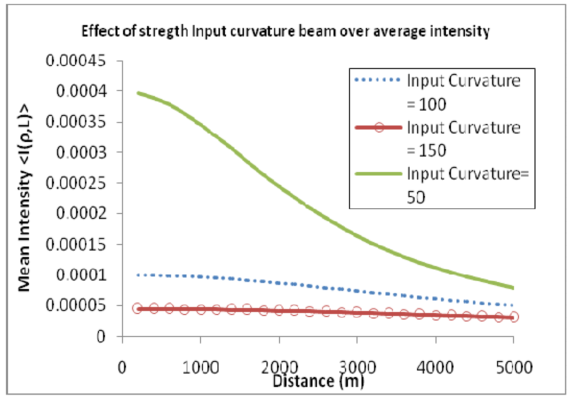


*Figure 5: Mean Intensity Versus Distance For Various Value Of Initial Curvature Parameter*

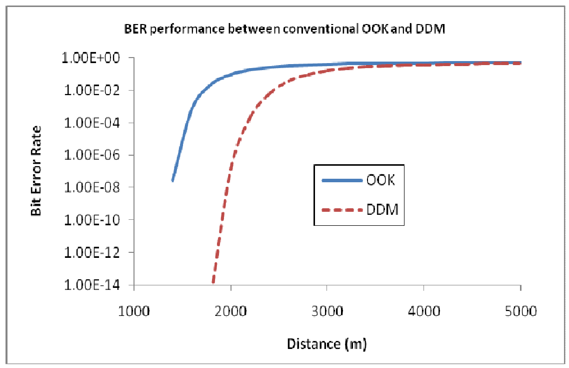


*Figure 6: BER Versus Distance Performance For Conventional OOK And DDM*

## 5. CONCLUSION

In contribution of this paper, the dual diffuser modulation (DDM) improves the performance of the FSOC in atmospheric turbulence channel. The BER in atmospheric are strongly influenced by scintillation index, power received and signal detection (bit '1' or '0'). In our analysis show that the dual diffuser modulations which employ the partially coherent beam improve the power received 40 percent and BER distance 42 percent. As a result, it creates the robust modulation against the turbulence with fix zero threshold value.

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