High capacity performance using new dual diffuser modulation technique to reduce the scintillation effect in free space optical communication

A.K Rahman, S.A Aljunid, Anuar M.S
School of Computer and Communication Engineering
University Malaysia Perlis (UNIMAP)
01000 Kangar, Perlis, MALAYSIA
Corresponding email: huuu_kr3@yahoo.com

***Abstract*—This paper analyze the capacity performance in term of bit rate for free space optical (FSO) communication between the conventional intensity modulation-direct detection on off keying (IM/DD OOK) and new dual diffuser modulation (DDM) technique. This technique employs two transmitters and two receivers with differential mode detection at the receiver. This technique can improve the threshold decision process and expand the diffuser effect. As a result, the bit rate of FSO can be increased with 6 magnitude of BER or equal to 100% improvement percentage with considering at 2.5Gbps bit rate. Meanwhile at the effective power transmit for the comparison between 0dBm and 5dBm, the result of BER is at 3.45×10^{-9} and 2.26×10^{-12} respectively. This indicate that the DDM technique can performance better than conventional modulation technique with able to operate at low power transmit under the acceptable error floor BER 10^{-9}.**

Keywords—turbulence; free space optic; scintillation; intensity modulation, on-off keying; bit error rate

I. INTRODUCTION

Nodaway most of the commercial FSO communication employ the conventional IM/DD OOK for the modulation technique. Basically this technique use bit ‘1’ to represent sending data which indicate in ‘ON’ condition and bit ‘0’ represents no sending data indicate in ‘OFF’ condition. However the major drawback of this technique is threshold decision process. In normal condition, the threshold is set to 0.5 which is half of the signal between bit ‘1’ and ‘0’. So if the incoming signals exceed the 0.5 threshold it will be assume to be bit’1’ and vice versa. However when FSO experiencing fluctuation signal due to scintillation effect at 0.5 threshold decision become not accurate condition. Thus cause the burst error to increase which directly affected the BER performance.

In order to improve this problem, the new DDM technique can be employed. It is a combination technique between modulation and phase screen diffuser [1,6-9]. As a result improved the threshold decision processes which will explained detail in section III and also reduce the scintillation index. The phase screen diffuser creates a 'new' Gaussian beam characteristic which effectively propagates through scintillation effect. The rest of paper, Section II explained detail on diffuser effect and Section III discuss the system model of proposed DDM technique. Meanwhile Section IV and V discuss the result and summary of paper.

II. PARTIALLY COHERENT BEAM

The partially coherent beam is formed when the laser through the diffuser [2], 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,

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

The value of w_0^2 = 0.025m and l_c =0.0001 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 Θ_1, Λ_1 by effective beam parameter $\Theta_{ed}, \Lambda_{ed}$ define in term of N_s as follows

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

$$\Theta_{ed} = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2 N_S} \tag{3}$$

where,

$$\Lambda_1 = \frac{\Lambda_0(L)}{\Theta_0^2(L) + \Lambda_0^2(L)} \tag{4}$$

$$\Theta(L) = \frac{\Theta_0(L)}{\Theta_0^2(L) + \Lambda_0^2(L)} \tag{5}$$

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

$$\Lambda_0(L) = \frac{2L}{kw_0^2} \tag{6}$$

$$\Theta_0(L) = 1 - \frac{L}{F_0} \tag{7}$$

In this paper the value for $F_o = \infty$, collimated beam for all calculation. Expressions for partially coherent beam are derived as same as coherent beam [3] equations except the output beam parameters are change due to diffuser located at the transmitter side with different diffuser correlation length. The typical value for 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= ∞) partially coherent Gaussian-beam is given by.

$$\sigma_B^2 = 3.86\sigma_I^2 \left\{ \begin{array}{l} 0.4\left[(1+2\Theta_{ed})^2 + 4(\Lambda_{ed})^2\right]^{5/12} \\ X\left(\cos\left[\frac{5}{6}\tan^{-1}\left(\frac{1+2\Theta_{ed}}{2\Lambda_{ed}}\right)\right]\right) \\ -\left(\frac{11}{6}(\Lambda_{ed})^{5/6}\right) \end{array} \right\} \tag{8}$$

where σ_I^2 indicate the strength of irradiance fluctuations and proportional to Rytov variance as

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

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

$$\sigma_{I,strong}^2 = \exp\left\{ \frac{0.49\sigma_R^2}{\left[1+0.56(1+\Theta_{ed})\sigma_R^{\frac{12}{5}}\right]^{\frac{7}{6}}} + \frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{\frac{5}{6}}} \right\} - 1 \tag{9}$$

Now, let us define scintillation index for receiver detector having lens diameter 'D'. For that we assume Ω is the normalized receiver aperture 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

$$\sigma_{\ln x}^2(D) = 0.49\sigma_I^2 \left(\frac{\Omega - \Lambda_{ed}}{\Omega + \Lambda_{ed}}\right) x \left(\frac{1}{3} - \frac{1}{2}\overline{\Theta}_{ed} + \frac{1}{5}\overline{\Theta}_{ed}^2\right) x \left(\frac{n_x}{1 + \frac{0.4 n_x (1+\Theta_{ed})}{\Lambda_e d + \Omega}}\right)^{7/6} \tag{10}$$

where the quantity n_x is the normalize large-scale cutoff frequency determined by asymptotic behavior of $\sigma_{\ln x}^2$ in weak turbulence and saturation regime[4].

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

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

$$\sigma_{\ln y}^2(D) = \frac{1.27\sigma_I^2 n_y^{-5/6}}{1 + \frac{0.4 n_y}{\Lambda_1 + \Omega}} \tag{11}$$

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

$$\sigma_I^2(D) = \exp\left[\sigma_{\ln x}^2(D) + \sigma_{\ln y}^2(D)\right] - 1 \tag{12}$$

A. Effective Spot Beam

The effective spot beam $W_{eff,\zeta}(L)$ and global coherent parameter ζ of partially coherent beam can be denoted as [10]

$$W_{eff\zeta}(L) = w_o \sqrt{\left(\Theta_o^2 + \zeta\left(\frac{2L}{kw_o}\right)^2\right)} \quad (13)$$

$$\zeta = \zeta_s + \frac{2w_o^2}{\rho_o} \quad (14)$$

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 σ_μ^2 is the variance of the Gaussian describing the ensemble average of the random phases. If ζ_s equal to 1 , the beam is fully coherent and the beam is partially coherent beam if the ζ_s above value 1.

B. Mean Intensity

The unit amplitude of partially coherent beam for average intensity given as [10]

$$\langle I(\rho, L)\rangle = \frac{w_o^2}{w_{eff.\zeta}^2}\exp\left[\frac{-2\rho^2}{w_{eff.\zeta}^2}\right] \quad (15)$$

III. SYSTEM MODEL

The system employs two transmitter and on-off keying (OOK) modulation as reference for conventional system. When the first transmitter send binary '1', the second transmitter in inverted condition send binary '0' in simultaneously and vice versa. Meanwhile at the receiver part, the signal will through the subtractor for differential detection process. Here we assume the ideal subtractor condition where no losses signals occur during subtraction. Therefore, the signal output will become '1' for sending binary '1' and bit '-1' for sending binary '0'. This condition lead to modification on conventional OOK modulation particularly in improves signal threshold detection and reduces power loss.

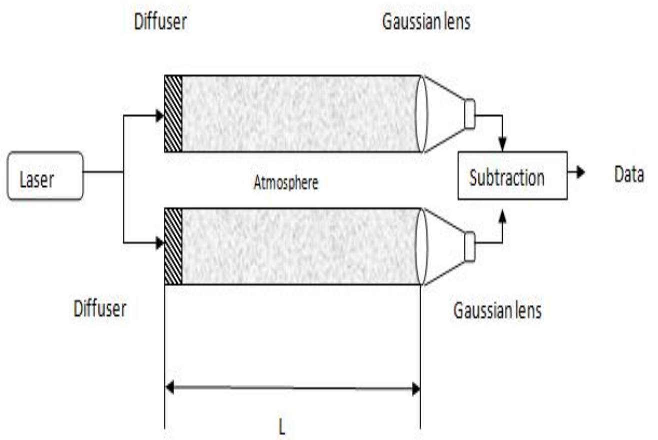

Figure 1: Dual Diffuser Modulation setup

A. Signal to noise ratio (SNR)

First, we define the output SNR in the absence of optical turbulence by the ratio of the detector signal current i_s to the root-mean-square (rms) noise current- σ_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 [5]

$$SNR_0 = \frac{SNR_o}{\sqrt{PP_o / P_o}}$$

where PP_o is the received power partially coherent beam and P_o is the power of coherent beam

$$SNR_0 = \frac{SNR_o}{\sqrt{1 + q_c\Lambda_1}}$$

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

(16)

In equation (16), the noises consider are shot noise, background noise and thermal noise. D is diameter receiver, W (*L*) is beam spot size at receiver, N (λ) = spectral radiance of sky, W(λ) = spectral radiant emmittance of sun, Δλ = bandwidth of optical bandpass filter (OBPF), = photodetector field of view angle (FOV) in radians, kb is the Bolztman's constant, T_n is the temperature of receiver noise, B is the electrical equivalent noise bandwidth of the receiver and RL 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

$$\langle SNRP\rangle = \frac{SNR_o}{\sqrt{1 + q_c\Lambda_1 + 1.63\sigma_I^{\frac{12}{5}}\Lambda_1 + \sigma_I^2 SNR_o^2}}$$

where SNR_o is obtain from equation (13), 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

$\frac{Pso}{\langle Ps \rangle}$ provides a measure of SNR deterioration caused by atmospheric induced beam spreading given by

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

B. Probability of Error

The two conditional PDFs for DDM can be written as:

$$P(Y_n|1) = \frac{1}{\sqrt{2\pi}\,2\sqrt{\frac{N_o}{2}}} e^{-\left(\frac{(Y_n - \sqrt{E_b})^2}{2\left(\frac{N_o}{4}\right)}\right)} \tag{18}$$

$$P(Y_n|0) = \frac{1}{\sqrt{2\pi}\,2\sqrt{\frac{N_o}{2}}} e^{-\left(\frac{(Y_n + \sqrt{E_b})^2}{2\left(\frac{N_o}{4}\right)}\right)} \tag{19}$$

where $N_o/4$ is a variance (σ^2) with zero mean obtained from involving two random variable by using chi-square random variable approximation and Y_n is the received signal. Here we use the $\sqrt{E_b}$ as signal energy representative and $N_o/2$ variance of noise. By considering equally likely condition, we obtain the probability error in absence atmospheric turbulence.

$$P(Y_n|1) = P(Y_n 0) = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \cong \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{20}$$

where Q(x) is Gaussian Q-function with

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

In the presence of atmospheric turbulence, the probability of error is given by [11]

$$\Pr(E) = \langle BER \rangle = \frac{1}{2}\int_0^\infty p_I(u) erfc\left(\sqrt{\left\langle \frac{E_b}{N_o} \right\rangle u}\right) du \tag{21}$$

where $p_I(u)$ is a gamma-gamma distribution with unit mean $p_I(u) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} u^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta u}\right)$ for u>0 and $\left\langle \frac{E_b}{N_o} \right\rangle = \langle SNRP \rangle$. When aperture averaging effects are consider, parameters α and β for the gamma-gamma PDF are define as $\alpha = \frac{1}{\exp\left[\sigma^2_{\ln X}(D)\right] - 1}$ and $\beta = \frac{1}{\exp\left[\sigma^2_{\ln Y}(D)\right] - 1}$ where $\sigma^2_{\ln X}$ (D) and $\sigma^2_{\ln Y}$ (D) can be calculate using equation (10) and (11) respectively.

IV. Result And Discussion

The data bit rates are evaluated from 0.622Gbps up to 10Gbps. The Figure 2 shows the performance of DDM compare with conventional IM/DD-OOK for receiving power set fix at -10dBm under strong turbulence condition. Clearly the DDM shows the superior performance where at data bit rate 2.5Gbps, the BER of DDM is $4.48\text{x}10^{-12}$ and BER for conventional IM/DD-OOK is only at $1.09\ \text{x}10^{-6}$. This shows that the margin changing magnitude of BER is 6 with 100% improvement percentage.

The Figure 3 shows the performance of BER DDM to investigate the effective bit rate at various powers transmit levels. At 2.5Gbps, the 5dBm powers transmit produce BER $2.26\ \text{x}10^{-12}$. When transmit more lower power at 0dBm, the DDM technique still manage having good quality signal with BER at $3.45\text{x}10^{-9}$. This indicates that the DDM technique able to operate in low power so that reduce the cost in FSO to provide high power laser. In real condition the FSO need high power to support good quality transmission when having various weather condition. However high laser power need a high cost to implementing in FSO. Therefore the DDM technique is cost effectiveness where only require minimum power to operate with optimum performance.

Table 1: Parameters for theoretical analysis

Parameters	Symbols	Value
Wavelength	λ	1550 nm
Distance	L	2000 m
Electron charge	e	$1.6\ \text{x}\ 10^{-19}$ C
Plank constant	h	$6.6\ \text{x}\ 10^{-34}$ J.s
Speed of light	c	$3\ \text{x}\ 10^{8}$ Km/s
Photo detector efficiency	η	0.7
Power transmit	P_o	0 dBm
Diffuser strength	l_c	0.001
Collecting lens	W_G	0.01 m
Radius of curvature	F_o	∞
Spot beam at transmitter (z=0)	W_o	0.025 m

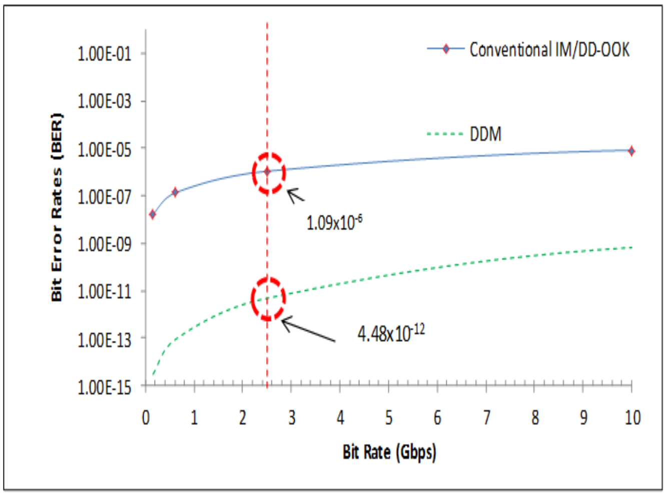

Figure 2: Comparison bit rate under strong turbulence at fix power received -10dBm

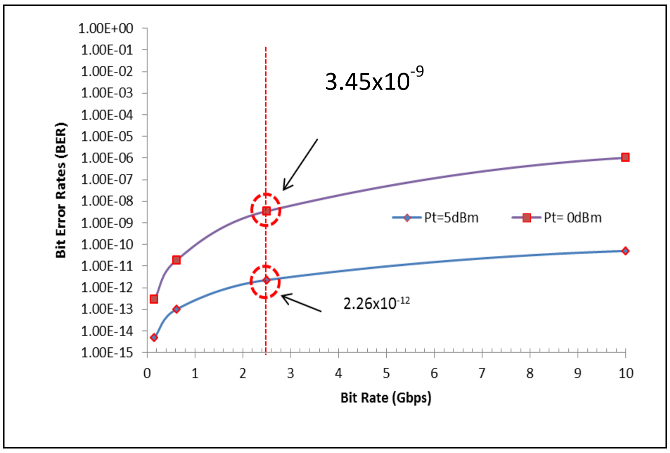

Figure 3: Comparison various power transmit of DDM technique

V. SUMMARY

In this paper we analyze the performance of BER for new DDM technique against the atmospheric turbulence in FSO communication. The result shows that at data bit rate 2.5Gbps, the BER of DDM is $4.48\text{x}10^{-12}$. Meanwhile the BER for conventional IM/DD-OOK only at $1.09\text{x}10^{-6}$. This show that the margin changing magnitude of BER is 6 with 100% improvement percentage. In analysis effective power transmit, at 2.5Gbps the 5dBm power transmit can produce BER $2.26\text{x}10^{-12}$. However when transmit more lower power at 0dBm, the DDM technique still manage having good quality signal with BER at $3.45\text{x}10^{-9}$. Therefore the DDM technique is a cost effectiveness where only require minimum power to operate with optimum performance.

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