2016 International Conference on Information Technology

A Comparative Analysis of Different Modulation Techniques based on Subcarrier Intensity Modulation in Free Space Optics using Log-normal Turbulence Model

Rajat Kumar Giri and Bijayananda Patnaik
Department of ETC Engineering, IIIT Bhubaneswar, India
rajat@iiit-bh.ac.in , bijayananda@iiit-bh.ac.in

Abstract –**In this paper, the error rate performance of free space optics (FSO) is analyzed by employing different subcarrier-intensity modulation (SIM) based techniques like binary phase shift keying(BPSK-SIM), quadrature amplitude modulation(QAM-SIM), differential phase shift keying (DPSK-SIM). So a comparative study is presented based on bit error rate (BER) plots with respect to signal-to-noise ratio (SNR), average irradiance, scintillation index etc. The analysis has been performed by considering log-normal channel model. The simulation results are verified in Matlab with the mathematical analysis. In our work we have used Gauss-Hermite integration approximation for the BER analysis. The simulation results show that BPSK-SIM is superior to other techniques but QAM-SIM and DPSK-SIM have other advantages. So from this comparative analysis, the appropriate technique can be chosen according to the desired applications.**

Index Terms - **Free space optics (FSO), subcarrier-intensity modulation (SIM), bit-error-rate (BER), on–off keying (OOK), scintillation index (SI), atmospheric turbulence.**

I. INTRODUCTION

Free space optics (FSO) technology is exclusively used for faster data rate transmission over distances up to few kilometers. FSO has much higher bandwidth compare to RF technologies, so allowing much higher data rates. Also, about 300GHz range of frequency is used in FSO which is unlicensed worldwide. That's why, FSO systems are license free [1]. Though there are so many advantages in the FSO communication but it faces lots of challenges. One of the major challenges is atmospheric turbulence, which is caused by variation in pressure and temperature in the atmosphere. This effect causes amplitude and phase variation in the received signal. Due to the atmospheric turbulence, a random intensity fluctuation occurs which is known as scintillation. Especially it happens in a range of distances of 1 km and above of it [2]. Because of this reason signal strength deteriorates at the receiver and bit error rate increases [3]. So the major challenge in FSO is to mitigate scintillation due to atmospheric turbulence.

The FSO technique has been deployed in many commercial applications by employing on–off keying (OOK) modulation due to its simplicity in implementation, where a fixed threshold has to be maintained. But it is very difficult to choose a proper required threshold [4], so it is a complicated task for a receiver design in OOK systems in unknown turbulence level. Pulse position modulation (PPM) is another modulation technique is mostly used in FSO. PPM has excellent power efficiency but it is not bandwidth efficient. So to overcome those problems, subcarrier-intensity modulation (SIM) has been used. SIM technique can use higher level of RF modulation technique and also it needs low bandwidth. Phase-shift keying subcarrier-intensity modulation (PSK-SIM) scheme was proposed in [5] as an alternative approach, where it has been shown that PSK-SIM has better performance compare to OOK in the presence of atmospheric turbulence.

In our work, we have proposed different modulation techniques based on SIM like BPSK-SIM, QAM-SIM and DPSK-SIM schemes with their comparisons to mitigate the scintillation effects up to some extent. Since the performance of FSO systems is very much sensitive to the atmospheric turbulence and the parameters associated with the channel such as the optical wavelength, the length of the channel and turbulence level, thus proper modulation technique has to be chosen for implementation.

The noise occurs in FSO which includes background noise and thermal noise. Background noises occur because of the radiations from both the sky and the sun. So the noise variance can be expressed by [6]

$$\sigma_{Bg}^2 = 2qR_b(I_{sun} + I_{sky}) \tag{1}$$

where, q is electron charge, R_b is bit rate, I_{sun} is irradiance due to sun , I_{sky} is irradiance due to sky.
Thermal noise caused by the thermal fluctuations of electrons in the receiver circuit of equivalent resistance R_L and temperature T. Its noise variance is expressed by [6]

$$\sigma_{th}^2 = 4B_kTR_b / R_L \tag{2}$$

where, B_k is Boltzmann's constant. The dark current and the relative intensity noise are normally very small and hence we have neglected here. So the total noise variance can be

$$\sigma_N^2 = \sigma_{Bg}^2 + \sigma_{th}^2 \tag{3}$$

II. CHANNEL MODEL

Normally lognormal and negative exponential, gamma-gamma distribution models are used for the performance analysis of FSO systems. In case of weak turbulence, the log-normal model, for moderate turbulence gamma-gamma model and for beyond the strong turbulence regime the negative-exponential model is used. Log-normal model does not support multiple scattering which happens in strong turbulence level [7]. Still the log-normal model is a common model for the analysis of atmospheric turbulence level. The reason is that this model is mathematically convenient and tractable. Here

978-1-5090-3584-7/16 $31.00 © 2016 IEEE
DOI 10.1109/ICIT.2016.45

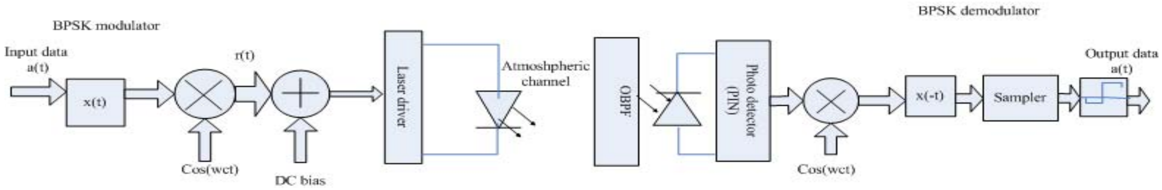

Fig.1. Block diagram of BPSK-SIM based FSO

log-normal model is considered for our analysis. The probability density function (PDF) of this model is given by [8]

$$P(I)=\frac{1}{I\sqrt{2\pi\sigma_R^2}}\exp\left\{-\frac{\left(\ln\left(\frac{I}{I_0}\right)+\frac{\sigma_R^2}{2}\right)^2}{2\sigma_R^2}\right\} \tag{4}$$

and $\sigma_R^2=1.23C_n^2 k^{\frac{7}{6}}L^{\frac{11}{6}}$ (5)

where, I is irradiance(intensity) in turbulent medium, I_0 is irradiance in free space, C_n^2 is turbulence strength, k is wave number, L is link distance.

III. SYSTEM MODEL AND BER PERFORMANCE ANALYSIS

A. BPSK-SIM

BPSK offers high immunity to the intensity fluctuations and it is independent of adaptive thresholding scheme whereas, it is a problem in OOK case. But the optical source is ‘ON’ during the transmission of both digital ‘1’ and ‘0’, makes BPSK-SIM less power efficient [6].

As shown in Fig. 1, a RF subcarrier signal $A\cos(w_c t)$ is pre-modulated by original data a(t) and then the resultant signal r(t) is used to modulate the intensity of the optical carrier signal generated from laser driver. Here before modulating the laser intensity (irradiance), the RF carrier signal is modulated by a(t) using BPSK modulation technique in which the binary data ‘1’ and ‘0’ are symbolized by two different phases. Since the subcarrier signal is sinusoidal having both positive and negative values, a dc level ‘d_o’ is added before applying to laser driver which keeps the bias current above the threshold current value. At the receiver, the optical radiated signal is passed through an optical band pass filter (OBPF) and PIN photo detector is used for the conversion from optical to electrical form. A standard RF coherent demodulator is employed to recover the original data as shown in Fig. 1. The photocurrent is proportional to r(t). The instantaneous photocurrent is thus given by [6],

$$i_p(t)=RI[1+mr(t)]+n(t); \tag{6}$$

where $r(t)=Ax(t)\cos[(w_c t)+\phi]$ and $|mr(t)|<1$ must be maintained to avoid the clipping occurred by over modulation. The received signal is given by [6]

$$i_D(t)=a_i mRIAx(t)\cos(w_c t)+n(t); \tag{7}$$

and the recovery signal after coherent detection is given by

$$i_D(t)=\frac{mRIa_j x(t)}{2}+n_d(t) \tag{8}$$

where A is subcarrier amplitude, m is optical modulation index , R is responsivity, x(t) is rectangular pulse shaping function , a_i[1,-1] is the signal level for i^{th} data symbol, n(t) is the additive white Gaussian noise , $n_d(t)$ is noise after detection. Here we have assumed equiprobable data transmission. For equiprobable data symbols the conditional BER is given by [8]

$$P_c=\int_0^\infty \frac{1}{\sqrt{\pi\sigma_N^2}}\exp\left\{-\left[\frac{(i_d(t)+0.5mRIA)^2}{\sigma_N^2}\right]\right\}di_d(t)$$
$$=0.5erfc\left(\frac{0.5mRIA}{\sigma_N}\right)=Q\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right) \tag{9}$$

The unconditional BER is given by [8]

$$P_e=\int_0^\infty P_c P(I)dI$$

$$=\int_0^\infty Q\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right).\frac{1}{I\sqrt{2\pi\sigma_R^2}}\exp\left\{-\frac{\left(\ln\left(\frac{I}{I_0}\right)+\frac{\sigma_R^2}{2}\right)^2}{\sigma_R^2}\right\}dI$$

By putting the variable, $y=\frac{\left[\ln\left(\frac{I}{I_0}\right)+\frac{\sigma_R^2}{2}\right]}{\sqrt{2}\sigma_R}$, so P_e will be as

$$P_e=\int_0^\infty\left[Q\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right).I_0.\exp\left(\sqrt{2}\sigma_R y-\frac{\sigma_R^2}{2}\right)\right]\left[\frac{1}{\sqrt{\pi}}\exp\left(-y^2\right)dy\right]$$

$$= \frac{1}{\sqrt{\pi}} \int_0^{\infty} Q\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right) . I_0 . \exp\left(\sqrt{2}\sigma_R y - \frac{\sigma_R^2}{2}\right) \exp\left(-y^2\right) dy \tag{10}$$

A closed-form solution doesn't exist in (10) and numerical integration could result in truncating its upper limit. So the analytical difficulty involved in (10) can be resolved by Gauss-Hermite quadrature integration approximation. Due its simplicity and compactness, it gives good approximation result. The Gauss-Hermite integration approximation expression is given by [8]

$$\int_0^{\infty} g(y) \exp\left(-y^2\right) dy \simeq \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N} w_i g(y_i)$$

Now $P_e = \frac{1}{\sqrt{\pi}} \sum_{i=1}^{N} w_i Q\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right) . I_0 . \exp\left(\sqrt{2}\sigma_R y_i - \frac{\sigma_R^2}{2}\right)$ (11)

Where the total noise variance from (3) is given by,

$$\begin{aligned} \sigma_N^2 &= \sigma_{sh}^2 + \sigma_{th}^2 \\ &= 2qR_b(I_{sun} + I_{sky}) + 4B_k TR_b / R_L \end{aligned}$$

B. QAM-SIM

QAM is a promising modulation technique which increases the power efficiency and also data rate which are the merits of this modulation technique [9]. But noise is more effective in this technique. Here M-ary QAM based on SIM is considered where M=16 ,which gives better result. Similar to the above system the received optical signal of M-ary QAM system can be expressed as [9]

$$R\left(t\right) = IA\left\{1 + m[g_i(t)\cos\left(w_c t\right) - g_q(t)\sin\left(w_c t\right)]\right\} \tag{12}$$

Where $g_i(t)$ and $g_q(t)$ are in phase component and quadrature phase component respectively. So these components can be defined as,

$$g_i(t) = \sum_i x(t - iTs)\cos\phi_i$$

$$g_q(t) = \sum_q x(t - iTs)\sin\phi_q$$

After coherent detection, the recovered signals are

$$r_i(i) = mAs_i(t) + n_i(t)$$

$$r_q(i) = mAs_q(t) + n_q(t)$$

In the same way as described in BPSK-SIM scheme, the BER of the M-ary-QAM-SIM can be calculated [10] as given below.

$$P_c = \frac{2\left[1 - \frac{1}{\sqrt{M}}\right]}{\log_2 M} Q\left[\sqrt{\frac{3\log_2 M}{2\left(M-1\right)}} . \left(\frac{mRIA}{\sqrt{2}\sigma_N}\right)\right] \tag{13}$$

So the unconditional BER is obtained as

$$P_e = \frac{2\left[1 - \frac{1}{\sqrt{M}}\right]}{\log_2 M} \sum_{i=1}^{N} w_i \left[Q\sqrt{\frac{3\log_2 M}{2\left(M-1\right)}}\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right) . I_0 .\right] \exp\left(\sqrt{2}\sigma_R y_i - \frac{\sigma_R^2}{2}\right) \tag{14}$$

C. DPSK-SIM

The change in DPSK system compare to BPSK is that it uses non-coherent detection which avoids the synchronization circuitry. Here the output of sampler is maintained with a delay of one bit and is compared with the next signal. In DPSK system there is no absolute carrier phase estimation, so it avoids phase ambiguity, which is a problem in BPSK coherent detection system [11].

The instantaneous photocurrent of DPSK can be expressed as similar to BPSK system, which is given by [11]

$$i_p\left(t\right) = RI[1 + mr\left(t\right)] + n(t) . \tag{15}$$

In the same way as discussed in BPSK-SIM system, the conditional and unconditional BER for DPSK system can be calculated.
The conditional BER is expressed by [10]

$$P_c = \frac{1}{2}\exp\left\{-\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right)^2\right\} \tag{16}$$

The unconditional BER of DPSK-SIM can be obtained as

$$P_e = \int_0^{\infty} P_c P(I) dI$$

$$= \int_0^{\infty} \frac{1}{2}\exp\left\{-\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right)^2\right\} . \frac{1}{I\sqrt{2\pi\sigma_R^2}} \exp\left\{-\frac{\left(\ln\left(\frac{I}{I_0}\right) + \frac{\sigma_R^2}{2}\right)^2}{\sigma_R^2}\right\} dI$$

$$= \frac{1}{2\sqrt{\pi}} \sum_{i=1}^{N} w_i \left\{\exp\left\{-\left(\frac{mRIA}{\sqrt{2}\sigma_N}\right)^2\right\} I_0^2 \exp\left\{2\left(\sqrt{2}\sigma_1 y_i - \frac{\sigma_R^2}{2}\right)\right\}\right\} \tag{17}$$

TABLE I: PARAMETERS USED IN THE PROPOSED SYSTEM

Name	Symbol	Value
Wave length	λ	850nm
Link distance	L	1000 m
Noise temperature	T	300
Responsivity	R	1
Load resistance	R_L	1000 Ω
Bit rate	R_b	1.55Gb/s
Modulation index	m	1
Boltzmann's constant	B_K	1.38×10^{-23}W/K/Hz
Electron charge	q	1.69×10^{-19}C

IV. RESULTS AND DISCUSSION

We have analyzed the BER performance of DPSK-SIM, QAM-SIM and BPSK-SIM schemes in MATLAB environment and also their comparison result is presented. In this paper, the analytical and simulation work is carried out for lognormal channel model and the parameters associated with the corresponding techniques are given in Table I. In each case the turbulence strength taken is $c_n^2=7.5\times10^{-15}\text{m}^{-2/3}$. The BER analysis with respect to SNR of all respective modulations is depicted in fig.2. We observed that the error rate decreases with increase of SNR values. In fig.2, it is found that BPSK-SIM has better BER result compare to the other two techniques. For example for the BER of 10^{-6}, the average SNR required by BPSK is 28 dB which is 4 dB less than DPSK-SIM and 7 dB less than QAM-SIM.

The BER performance with respect to average irradiance is shown in fig.3. Also in BPSK scheme, we get better error rate performance result. As for the BER of 10^{-6}, BPSK-SIM modulation avoids 2.5 dBm power penalty compare to DPSK-SIM and 5.5 dBm penalty compare to QAM-SIM respectively.

Similarly BER with respect to scintillation index is plotted in fig.4. Also in this case, BPSK-SIM shows a good BER result. In fig.4, it can be seen that with the increase in scintillation index (SI), the BER reduces. But there is not much difference between DPSK-SIM and BPSK-SIM. So scintillation index has the negative effects in the error performance.

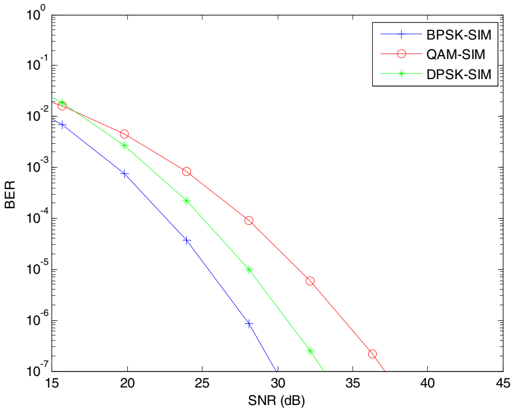

Fig.2: Plot of BER versus SNR

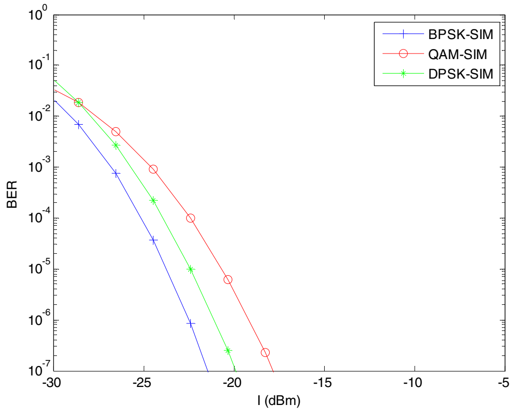

Fig.3: Plot of BER versus Irradiance

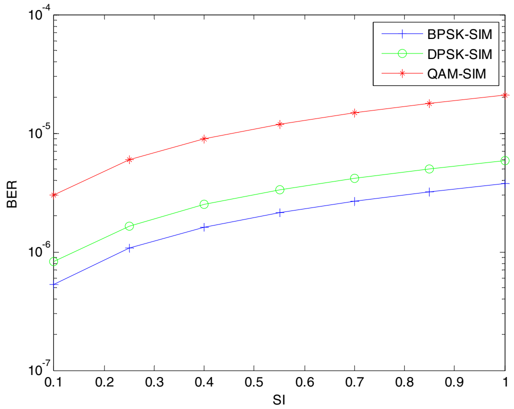

Fig.4: Plot of BER versus SI

V. CONCLUSION

The performance of various modulation techniques have been presented and compared for different parameters like SNR, average irradiance, scintillation index. Among all, BPSK-SIM shows better BER performance compare to the rest two techniques. But for scintillation index, the BER plot of DPSK-SIM is almost similar to BPSK-SIM. Though BPSK-SIM is superior to other techniques in many aspects but QAM-SIM and DPSK-SIM have other advantages as discussed. So the appropriate technique can be chosen according to the desired applications.

REFERENCE

[1] Khalighi, Mohammad Ali, and Murat Uysal,"Survey on Free Space Optical Communication:A Communication Theory Perspective", IEEE Communications Surveys & Tutorials, vol. 2, no. 4, 2014.

[2] Zhang, Jiayi, Linglong Dai, Yanjun Han, YuZhang, and Zhaocheng Wang. "On the Ergodic Capacity of MIMO Free-Space Optical Systems Over Turbulence Channels", IEEE Journal on Selected Areas in Communications, 2015.

[3] I.Kim,E.Woodbridge,V.Chan, and B.R. Strickland, "Scintillation measurements performed during the limited-visiblity lasercom experiment,"*Proc. SPIE*, vol. 3266, pp. 209–220, 1998.

[4] X. Zhu and J. M. Kahn, "Free-space optical communication through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1293–1300, Aug. 2002.

[5] W. Huang, J. Takayanagi, T. Sakanaka, and M. Nakagawa, "Atmospheric optical communication system using subcarrier PSK

modulation," IEICE Trans. Commun., vol. E76–B, no. 9, pp. 1169–1177, Sep. 1993.

[6] W. O. Popoola and Z. Ghassemlooy, "BPSK subcarrier intensity modulated free-space optical communications in atmospheric turbulence," J. Lightwave Technol. Vol.27, no.8 967–973, 2009.

[7] D. Killinger, "Free space optics for laser communication through the air," *Opt. Photon. News*, vol. 13, no. 3, pp. 36–42, Oct. 2002.

[8] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, " Optical Wireless Communications: System and Channel Modelling with MATLAB". New York, NY, USA: CRC, 2012.

[9] M. Nakazawa, M. Yoshida, K. Kasai, and J. Hongou, "20 Msymbol/s, 64 and 128 QAM coherent optical transmission over 525 km using heterodyne detection with frequency estabilised laser," *Electron. Lett.*, vol. 42, no. 12, pp. 710–712, June 2006.

[10] J. G. Proakis, "*Digital Communications"*, New York: McGraw-Hill, 2004.

[11] W.O. Popoola, Z. Ghassemlooy, E. Leitgeb, "BER and outage probability of DPSK subcarrier intensity modulated free space optics in fully developed speckle", J.Commun. vol. 4 , no.8, pp.546–554,2009.