Performance of Bit Error Rate (BER) in OOK Modulation Using Orbital Angular Momentum (OAM) Carrying Gaussian Vortex Beam

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***Abstract* - Achieving higher spectral efficiency is an absolute necessity in this era where demand for higher bandwidth is ever increasing. Optical communication emerged as potential solution in this direction to the requirement. A laser light beam carrying an Orbital Angular Momentum (OAM) has opened a new paradigm in the data communications owing to their theoretically infinite and orthogonal modes which can be efficiently multiplexed. In this paper we studied the propagation of Gaussian vortex (GV) beam for different order of topological charge. The data communication system has been modelled with OAM carrying GV beam as a carrier, modulation using ON-OFF keying (OOK) and a channel with additive white Gaussian noise (AWGN) channel. The system model was used to calculate the bit error rates (BER) for various signal to noise ratio (SNR) values and the results are in accordance with the theoretical expectations.**

***Keywords* – Orbital angular momentum, Gaussian vortex, bit error rate, signal to noise ratio.**

I. INTRODUCTION

A tremendous increase in the requirement of higher spectral efficiency has resulted from ever increasing data pouring into the data communication systems [1]. The data transmission speed in any communication system can be enhanced by increasing the bandwidth, using bandwidth efficient modulation schemes and multiplexing [2]. High-rate image, speech, and data transmission using free-space optical (FSO) communication is one amongst appealing and economical solutions. Several factors including unlicensed spectrum, high data rates, and inherent security makes it an interesting solution. Additionally, narrow beam width of lasers offers the capability of the use of multiple connections and spatial multiplexing in a specific place. Spatial structure of light beams in addition to its amplitude, frequency, phase and polarization, contributes an added dimension which is being explored rigorously as a means of obtaining high spectral efficiency. Recently researchers are looking at Space Division Multiplexing (SDM) as a potential alternative and it has sparked interest amongst the research community due to its advantages [3].

A light beam was shown to possess OAM in 1992 by Allen et al [4]. OAM carrying beam exhibit helical phase fronts that twist along the propagation direction which is different from spin angular momentum which indicates polarisation state of the light which can take only two possible states [5]. OAM possess doughnut shaped intensity profile with no intensity in the beam's centre. OAM carrying beam is characterised by the azimuthal phase term $exp(il\varphi)$ φ being the transverse azimuthal angle and l represents topological charge. The twisting rate, l, can theoretically take on an endless number of values. Additionally, OAM beams carrying various l values are also orthogonal to one another, making them a suitable choice for multiplexing to boost spectral efficiency [6-7]. In order to increase spectral efficiency, this OAM multiplexing can be employed in conjunction with other well-known multiplexing techniques including frequency/wavelength division multiplexing [8], polarisation division multiplexing [9], and mode division multiplexing [10]. The OAM beam has huge potential for the next generation communication which promises data transmission speed upto few Petabits/sec [11].

In this paper, we have studied the characteristics of Gaussian vortex (GV) beam. In the first part we have numerically simulated the intensity and phase structures of GV beam. As a preliminary study, we implement a simple OOK based communication system using GV carrying OAM beam as a carrier. The BER was calculated for different values of SNR with AWGN channel. This article is structured as follows: The methodologies are presented in part 2, the results are described in section 3, and the final conclusions are presented in section 4.

II. METHODS

For this study, we consider GV beam equation carrying OAM. A GV beam's electric field can be determined using [12].

$$E(x,y,z,t) = E_0 \frac{w_0}{w(z)} \left(\frac{\sqrt{x^2+y^2}}{w(z)}\right)^l exp\left(-\frac{x^2+y^2}{w(z)^2}\right) \times exp\big(i\phi(x,y,z,t)\big) \quad (1)$$

Where $\phi(x,y,z,t)$ is given by $\phi(x,y,z,t) = -(|l|+1)arctan\frac{2z}{kw_0^2} + k\frac{(x^2+y^2)}{2R(z)} + l.arctan\left(\frac{y}{x}\right) + kz - \omega t$, Where w_0 is the beam waist, $w(z) = w_0\sqrt{\left(1+\left(\frac{z}{Z_R}\right)^2\right)}$ is beam width along z direction, $R(z) = z\left(1+\left(\frac{Z_R}{z}\right)^2\right)$ is the radius of curvature, $\psi(z) = atan(\frac{Z}{Z_R})$ and $Z_R = \frac{1}{2}Kw_0^2$ gives the Rayleigh range, K being the wave number, l the topological charge that determines the quantity of 2π phase shifts along the beam axis's circumference. Figure 1 shows our simulation model block diagram of OOK communication link.

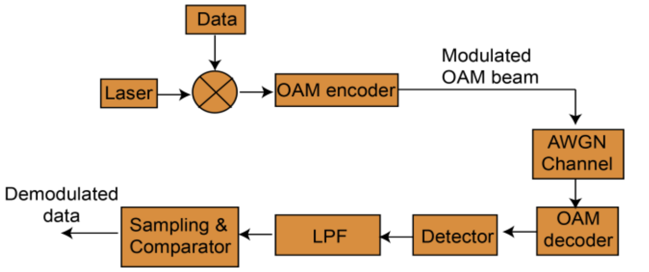

Fig. 1: Simulation model block diagram of an OAM-based OOK communication link.

OAM encoder (Fig. 1) is simulated to have a transfer function for given l value such that the Gaussian beam $G\ (x, y, z)$ at the input of an OAM encoder emerges as an OAM beam given by

$$U_{GV}\ (x, y, z) = G\ (x, y, z) * \exp\ (i\phi_l(x, y, z)) \quad (2)$$

where $G\ (x, y, z) = \frac{-(x^2+y^2)}{w(z)^2}$ is the amplitude of the complex electric field at the centre of the Gaussian beam, and

$$\phi_l\ (x, y, z) = -(|l| + 1)\ \arctan\frac{2Z}{kw_o{}^2} + \frac{k(x^2+y^2)}{2R(z)} + l\ \arctan\left(\frac{y}{x}\right) + kz$$

OAM decoder is simulated with transfer function with topological charge $-l$ such that the OAM beam $U_{GV}\ (x, y, z)$ at its input emerges as Gaussian beam at its output. We employed AWGN channel which represents the noise source andis a linear addition of white noise having constant spectral density and amplitude with Gaussian distribution.

III. RESULTS

In this section, we discuss the simulation results. First, GV beam equation (Eq. 1) is simulated to study the intensity profiles and phase structures for different topological charges. For the numerical simulation we developed a MATLAB program with $\lambda = 1550\ nm$ and $w_0 = 1\ mm$. The Gaussian beam is indicated by $l = 0$ and it is the fundamental mode. The simulated intensity profiles and phase structures are shown in figure 2 and clearly indicate that the intensity profile has a hole in the center which confirms the vortex beam. Generally, the orientation of the phase structure is dependent on the sign of l value. The l can have positive as well as negative value indicating clockwise/anticlockwise rotation of the phase structure. By increasing the l value we see that the beam diameter increases. In addition, the width of the zero intensity ring also increases and is proportional to l. The number of twist in the phase structure is equal to the l value.

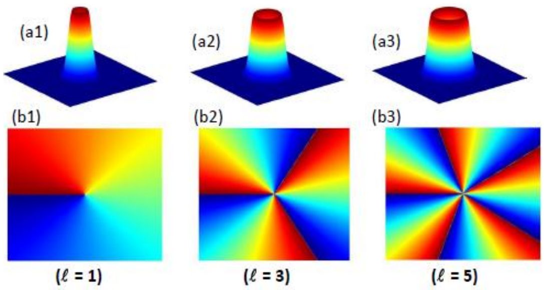

Fig. 2: Simulated intensity profile (a1, a2, a3) and spiral wavefront phase of OAM (b1, b2, b3) for the three different topological charges $l = 1, 2, 3$.

Next, we studied the propagation of GV beam. The propagation of OAM beam is important when designing free-space optical system due to beam divergence. Because of this, placing a detector at the receiving end becomes quite critical in such system [13]. Here we carried out the simulation of the vortex beam for the propagation distance of 10 meter. From the simulation results it is observed that OAM beam starts to diverge after travelling 2 meters (Rayleigh length).

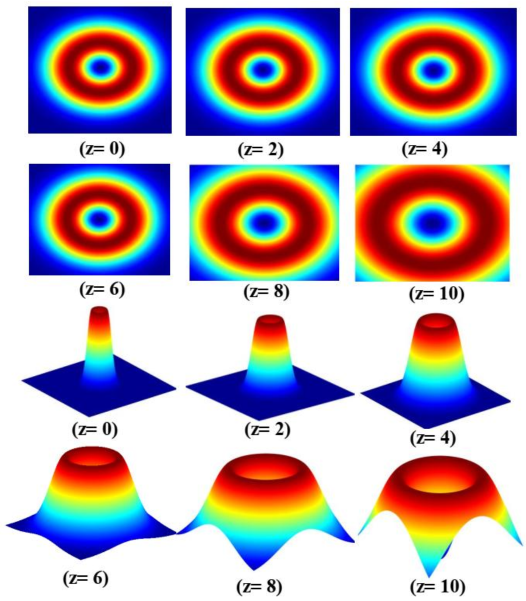

Fig. 3: Simulated intensity profile for different propagation distance in 2D view (top) and 3D view (bottom) for noiseless channel.

Figure 3 shows the intensity profiles for a noiseless channel along the direction of propagation. As demonstrated by figure 4, the intensity of the beam decreases noticeably as we travel along the direction of propagation for SNR = 5. As the SNR is increased from 5 to 20, which indicates more signal strength compared to noise, the beam intensity is quite bright even after propagating longer distance (fig. 5).

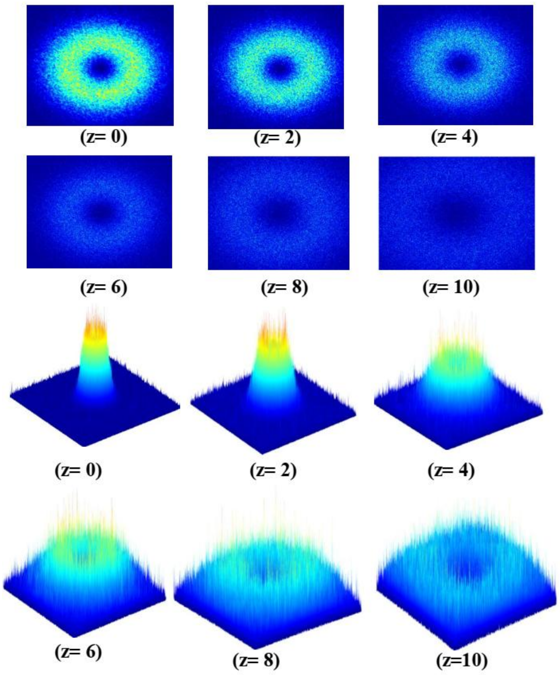

Fig. 4: Simulated intensity profiles for different propagation distance in 2D view (top) and 3D view (bottom) for SNR = 5.

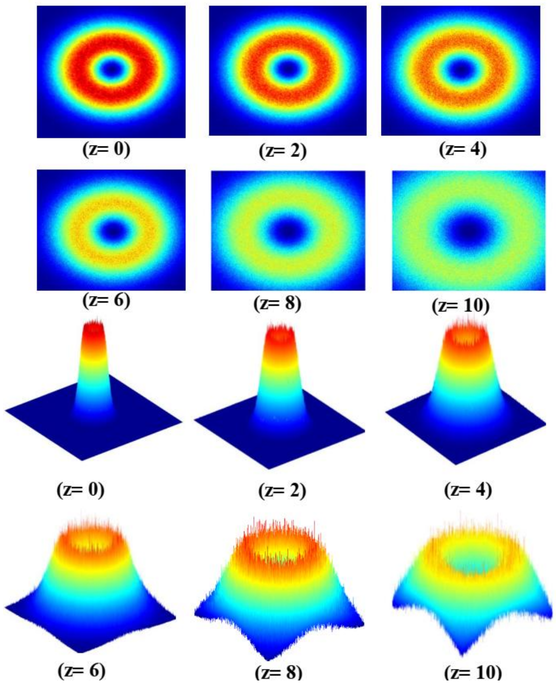

Fig. 5: Simulated intensity profile for different propagation distance in 2D view (top) and 3D view (bottom) for SNR = 20.

The communication system's performance was first evaluated by implementing an OOK modulation. This modulation is quite robust and depends on the intensity of the signal. The received signal is compared with threshold value and the original data is extracted. The signal above the threshold is considered as bit 1 and below threshold as bit 0. An OOK modulation was implemented using NRZ format. Figure 6 indicate the intensity profile of the OOK modulated GV beam and demodulated data for SNR = 5 and SNR = 20. It is clear from the figure 6 that the intensity of the vortex carrier and modulated carrier for SNR = 20 is brighter than the SNR = 5.

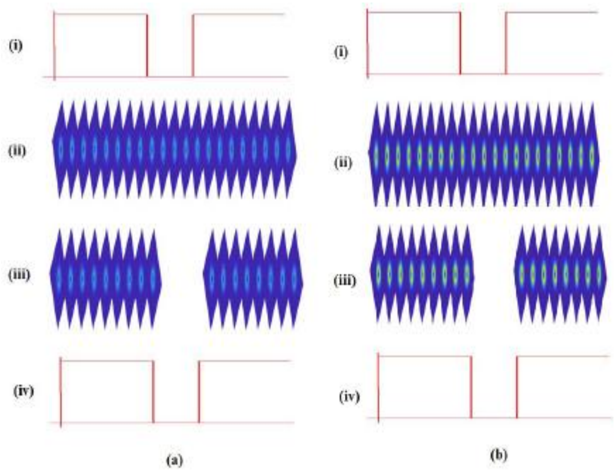

Fig.6: (i) input data (ii) Intensity profile of vortex carrier (iii) Intensity profile of modulated carrier (iv) demodulated data with SNR = 5 (a) and SNR = 20 (b).

Bit Error Rate (BER) is one of the most meaningful metrics in measuring how well a communication system performs. In a digital transmission, BER is defined as the number of error bits received divided by total number of bits transmitted. BER was calculated for different SNR values for OOK modulation system with AWGN channel. When optical data with NRZ-OOK coding is detected using a photodiode, the chance of error can be stated as a function of the Signal-to-Noise Ratio (SNR) as in [14].

$$BER_{NRZ-OOK} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \quad (3)$$

A maximum of 100000 data bits were transmitted at 1 Mbps on a system with Intel Zeon (R) silver 4214R CPU with 64 GB RAM and the number of bits received with error was calculated. The results for BER were obtained different SNR value as shown in figure 7. A lower BER indicates lower number of bits in error detected at the receiver. Initially, the BER is high for lower SNR value and as SNR increases BER decreases in accordance with the well-established theory as per equation 3.

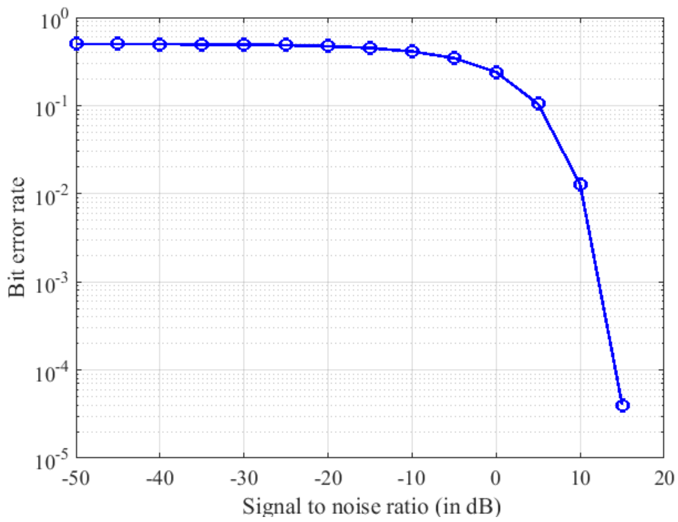

Fig. 7: The BER performance of FSO communication systems employing OOK with Gaussian Vortex beam as a carrier.

IV. CONCLUSIONS

Using OAM carrying beams is definitely a step ahead in the direction of achieving much needed higher spectral efficiency due to its theoretically infinite and orthogonal modes. In this study, the intensity and phase profiles of GV beams for different l were initially simulated. We observed the effect of increasing the l value on the intensity and phase profiles. As an initial step in exploring the communication based on OAM paradigm, we have simulated OOK based communication system using OAM carrying GV beam as a carrier with AWGN channel model. The Gaussian vortex beam was simulated with a λ = 1550 *nm* and w_0 = 1 *mm*. The BER was calculated for different values of SNR and the results shows that the BER decreases with increase in SNR as expected.

References

[1]. Y. A. Mtawa, A. Haque, B. Bitar, the Mammoth Internet: Are We Ready? IEEE Access 7, 132894–132908 (2019).

[2]. Y. Miyamoto, S. Yoshino, A. Okada, Ultrahigh-speed Transmission Technology for Future High-capacity Transport Networks, NTT Technical Review Vol. 17 No. 5 May 2019.

[3]. Guifang Li, Neng Bai, Ningbo Zhao, and Cen Xia, Space-division multiplexing: the next frontier in optical communication, Advances in Optics and Photonics 6, 413–487 (2014).

[4]. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes. Phys. Rev. A 45, 8185–8189 (1992).

[5]. L. Mandel and E. Wolf, Optical Coherence and Quantum Optics (Cambridge University Press, 1995).

[6]. P. Martelli, A. Gatto, P. Boffi, M. Martinelli, Free-space optical transmission with orbital angular momentum division multiplexing. Electronics Letters,47, 972–973.

[7]. J. Wang, J Y. Yang, I. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur & A E. Willner,Terabit free-space data transmission employing orbital angular momentum multiplexing. Nature Photonics, 6, 488–496(2012).

[8]. L. Zhu, G. Zhu, A. Wang, L. Wang, J. Ai, S. Chen, C. Du, J. Liu, S. Yu, J. Wang, 18 km low-crosstalk OAM + WDM transmission with 224 individual channels enabled by a ring-core fiber with large high-order mode group separation, Optics Letters, 2018 Apr 15;43(8):1890-1893.

[9]. J. Wang, J. Liu, X. Lv, L. Zhu, D. Wang, S. Li, A. Wang, Y. Zhao, Y. Long, J. Du, X. Hu, N. Zhou, S. Chen, L. Fang, F. Zhang, Ultra-High 435-bit/s/Hz Spectral Efficiency Using N-Dimentional Multiplexing and Modulation Link with Pol-Muxed 52 Orbital Angular Momentum (OAM) Modes Carrying Nyquist 32-QAM Signals, 2015 European Conference on Optical Communication (ECOC), Valencia, Spain, 2015.

[10]. N. Bozinovic, Y. Yue, Y. Ren, M. Tur, P. Kristensen, A. E. Willner, and S. Ramachandran, Orbital Angular Momentum (OAM) based Mode Division Multiplexing (MDM) over a Km-length Fiber, in European Conference and Exhibition on Optical Communication, OSA Technical Digest (online) (Optica Publishing Group, 2012), paper Th.3.C.6.

[11]. J. Liu, J. Zhang, J. Liu, Z. Lin, Z. Li, Z. Lin, J. Zhang, C. Huang, S. Mo, L. Shen, S. Lin, Y. Chen, R. Gao, L. Zhang, X. Lan, X. Cai, Z. Li and S. Yu, 1-Pbps orbital angular momentum fibre-optic Transmission, Light: Science & Applications, 11 (202) 2022.

[12]. Y. Zhu, W. Lv, J. Zhang, M. Jing, J. Li, X. Guan, Orbital Angular Momentum Density Distribution and Its Simulation Analysis of Gauss Vortex Beam, International Conference on Optical Instruments and Technology: Optical Trapping and Microscopic Imaging, Proceedings of SPIE, vol. 7507 (2009.

[13]. A E. Willner, Z. Zhao, C. Liu, R. Zhang, H. Song, K. Pang, K. Manukyan, H. Song, X. Su, G. Xie, Y. Ren, Y. Yan, M. Tur, A F. Molisch, R W. Boyd, H. Zhou, N. Hu, A. Minoofar, and H. Huang, Perspectives on advances in high-capacity, free-space communications using multiplexing of orbital-angular-momentum beams, APL Photon.6, 030901 (2021).

[14]. Sugianto Trisno. 2006. Design and analysis of advanced free space optical communication systems, Ph.d thesis, University of Maryland.