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Performance analysis of M-ary QAM modulated FSO links over turbulent AWGN channel

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Abstract
Free space optical communication is line of sight based fibre-less optical communication over atmosphere as medium of propagation. Due to inherent nature of optical carrier, FSO can support huge data rates and being unlicensed part of EM spectrum, FSO has massive potential to replace existing RF networks. However turbulence associated with atmosphere coupled with conditions like rain, fog, haze etc. can reduce the efficiency and reliability of system. It has been previously seen that use of appropriate modulation techniques can limit the impact of atmospheric turbulences. In this paper, performance of FSO links over adverse atmospheric conditions using Mary-QAM (Quadrature amplitude modulation) schemes has been experimentally studied. The analysis revealed that for increasing values of *M*, the data rates improved considerably at cost of degraded bit error rate performance. Therefore, trade-off must be maintained between acceptable system error performance and required data rate.

Keywords—Gamma gamma channel, AWGN channel, Bandwidth efficeiny, M-ary QAM (Quadrature amplitude shift), BER (Bit error rate) and SNR (Signal to noise ratio).

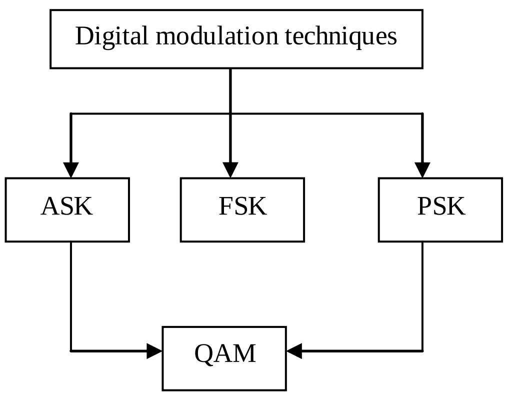
I. INTRODUCTION

In recent couple of decades, the wireless communication has penetrated deep inside our daily lives and this trend will raise manifold over the next coming years [1]. However the potential RF bandwidth available to cater to this ever increasing number of wireless devices is not only in-sufficient but also costly leading to situation of bandwidth starvation. In contrast, Free space optical communication which involves transmission of modulated optical carriers over un-guided medium i.e. atmosphere, offers huge bandwidth and improved data rates along with low power consumption. Being line of sight based communication; FSO is inherently immune to interference and eavesdropping thus making it highly secure. Miscellaneous advantages like FSO utilize unlicensed part of spectrum i.e. visible and infrared bands, thus no fee has to paid in comparison to RF bands which are paid, also optical wireless communication can be used as physical layer application, which means that FSO systems can be used as plug and play devices [2],[3]. These benefits allow shifting and installation of hardware not only easy but also very cost efficient. However in spite of these array of advantages, FSO still has long way to go before it becomes commercially viable and popular like RF regime. The biggest challenge in success of FSO links is the unguided channel itself. Since the channel is prone to atmosphere uncertainties like rain, snow, fog, variation of temperatures and wind speed etc., providing consistent and reliable performance remains a major challenge [4].

On off keying is one of the simplest techniques used for data modulation in FSO, but the performance of OOK systems typically degrades with increase in turbulence leading to non-reducible errors in the data [5]. Since atmospheric turbulence, which is basically random fluctuation in refractive index of the atmosphere caused due to variations in pressure, winds and temperature, it primarily leads to random fluctuations in amplitude and phase of the optically modulated data.

To overcome this challenge, the choice of appropriate modulation technique becomes very important so that effect of fluctuations on the signal can be limited along with maintaining desired data rate and throughput.

Various modulation techniques to improve performance efficiency of FSO system have been recently proposed [6]. Basic modulation techniques include ASK (Amplitude shift keying), FSK (Frequency shift keying) and PSK (Phase shift keying). ASK, FSK, PSK are low cost circuit design, easy to implement but they also are low speed techniques due to modulate one bit per symbol thus huge compromise on data rates in spite of high potential bandwidth [7].



The leading goal of every modulation technique is to transmit data with least error probability on required bandwidth channel with best power efficiency. Quadrature amplitude

modulation (QAM) which is combination of best of simplicity of amplitude modulation and noise immunity of phase modulation is a popular and time tested RF technique. It doubles the transmitted data rate without increasing the transmission bandwidth. Due to high spectral efficiency M-ary QAM is most effective modulation technique for wireless communication. Taking clue from success of QAM technique for RF systems, FSO channel in this paper have been tested for M-ary QAM modulation to analyze noise error performance and available data rates over turbulent channels. As highlighted previously, basic modulation techniques are can modulate one bit per symbol thus the data rate were highly in-sufficient for next generation communication system. M-ary modulation techniques offer high data rates along improved bandwidth efficiency.
In this paper the performance of M-ary QAM is compared for different values of *M*, by determining its probability of error over additive white Gaussian noise (AWGN).The rest of paper is organized as, section II outlines the description about FSO channels and their characteristics, comparison of different FSO modulation are contained in Section III, Section IV contains simulation set up results and outcome results conclusion presented in Section V.

II. FSO CHANNEL MODEL

A. *AWGN channel*

In information theory, additive white Gaussian noise (AWGN) is basic noise model which contain all the effects of natural random processes. The term 'additive' indicates the noise added (not multiply) internally to the information system. 'White' indicates uniform power for information system frequency bands and 'Gaussian' due to normal distribution in time domain. As we know that receiver has superposition property due receiver is always a linear device. Followed by superposition property, receiver has been adding the signal or noise. Probability of noise to be positive always equal to the probability of noise to be negative, this means noise does not contain any polarity so it's kind of white (means constant). As per the limit information theory, the output summation of different atmosphere conditions is Gaussian nature that we mostly used in communication systems [8]. That's why this model is well suited for all real noises in data communication. Gaussian distribution had not accounted for non linearity, frequency selectivity, dispersion and fading. The probability distribution function *P(z)* is given by

$$P(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{z-a}{z}\right)^2\right] \quad (1)$$

Where 'σ' is the variance, 'z' is any random signal and 'a' is mean of 'z'.

B. *Gamma-gamma distribution model*

. Atmospheric conditions also affect the performance of the FSO system. To overcome this drawbacks there are many atmospheric channel models in free space optics. In theses channel models Lognormal, Negative exponential and Gamma-gamma channel models are mostly used. Lognormal model is used for low turbulence and for high turbulence Negative exponential model is used. Gamma-gamma channel model widely used by low to high turbulence [9]. To enhance the performance these models play an important role in FSO communication. Gamma-gamma channel model is widely used.
Through the statistics and probability theory, the gamma-gamma distribution model is a continuous probability distribution. The exponential and chi squared distribution are the main cases of gamma-gamma distribution model. For evaluating BER for FSO communication system gamma-gamma distribution is used. It is given by [10]:

$$P(I) = \frac{2}{\Gamma(\alpha)\Gamma(\beta)I}(\alpha\beta I)^{\frac{\alpha+\beta}{2}} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \text{ for } I \,\square\, 0 \quad (2)$$

Where, 'I' is the normalized irradiance, 'α' and 'β' are parameters of PDF, 'Γ' is the gamma function and $K_{\alpha-\beta}$ is the modified Bessel function of the second kind of order α-β [11]. The parameters 'α' and 'β' are given by their expressions:

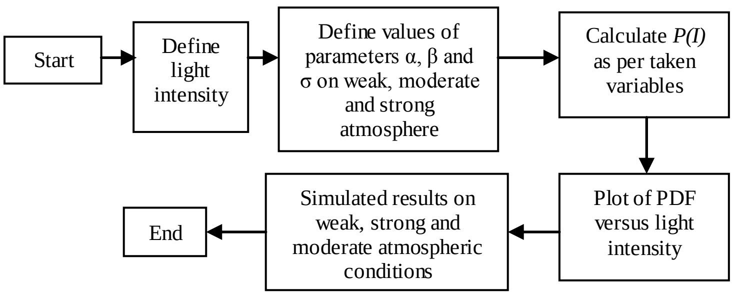
$$\alpha = \{\exp[0.49\sigma^2/(1+1.11\sigma^{12/5})^{7/6}]-1\}^{-1} \quad (3)$$

$$\beta = \{\exp[0.51\sigma^2/(1+0.69\sigma^{12/5})^{5/6}]-1\}^{-1} \quad (4)$$

'α' and 'β' are large scale and small scale log irradiance variances. σ^2 is Rytov variance [12]. In gamma-gamma distributed channel transmitted signal has faced many other parameters that affect its performance such as intensity fading. The received signal that we get represented with the expression as:

$$Y = hx + n = \eta I x + n \quad (5)$$

Where parameter representation as *h*-stands for gamma-gamma channel gain, *x*-stands for transmitted signal, *n*-stands for additive white Gaussian noise with having zero mean and $N_0/2$ variance and η-stands for photo current conversion ratio [13],[14].



As the above block diagram explains about the turbulence model and process followed in creating turbulent conditions for FSO link and accordingly weak, moderate or strong turbulence may be simulated as shown in fig 1. For given region of turbulence, probability density function for light intensity may be calculated which then becomes key basis for determining efficiency of modulated FSO links, which has been elaborated in following section of this paper.

III. FSO MODULATION TECHNIQUES

Digital modulation is technique to modulate carrier wave with the help of digital bits over the nature of the communication channels. As information carried by ASK in amplitude variations it is basically known by its simplicity in implementation manners and it represented two amplitudes for carrier frequency. For binary logic 1, pulse is present and there is no pulse for logic 0 in ASK. So ASK referred by on-off keying (OOK). In PSK, information modulated with the phase of carrier signal where logic 1 represents phase change of 0 and on the other hand logic 0 represents the 180 phase change Quadrature amplitude modulation (QAM) is the well known higher data rate modulation technique that utilizes both amplitude and phase modulation. Presently most used wireless technologies are bandwidth hungry. They require huge amount of transmission rate of bits per symbol. To overcome these limitations M-ary or higher modulation techniques are used.

A. Bit rates and baud rates

Table I Bit rate and baud rate comparison of different modulation

Modulation techniques	Baud rate	Bit rate
ASK,FSK,PSK	N	N
QPSK	N	N
4-PSK	N	2N
8-PSK	N	3N
16-QAM	N	4N
32-QAM	N	5N
64-QAM	N	6N
128-QAM	N	7N
256-QAM	N	8N

Different modulation techniques offer different baud rate which is defined as number of samples per second while bit rates is defined as number of data bits per second. The table I shows comparison between these rates for different modulation techniques. The required bandwidth for the transmission of the signal has stated by baud rate, N is represented as number of bits used and M implies number of bits used per sample.

Higher data transmission rates are possible at required bandwidth with the help of data compression. The relationship between the number of modulated bits, the required minimum bandwidth and how many possible output conditions for ASK, FSK, PSK and QAM for bit rate f_b bare given below. For performance measurement of FSO communication bandwidth efficiency is the best method for evaluation.

Bandwidth efficiency states that how faster in speed bits are transmitted in particular assigned bandwidth. With the help of formula, bandwidth efficiency defined as

$$\text{Bandwidth efficiency} = \frac{bit\ rates\ (R_b)}{required\ bandwidth\ (B_{req})}$$

From the above expression, the unit of bandwidth efficiency is bits per hertz "bps/Hz".

Table II Minimum bandwidth requirement of different modulations

Modulation scheme	Modulated bits	Modulated states	Minimum bandwidth
ASK	1 bit	2	f_b
FSK	1 bit	2	f_b
BPSK	1 bit	2	f_b
QPSK	2 bits	4	$\frac{f_b}{2}$
QAM	2 bits	4	$\frac{f_b}{2}$
8-PSK	3 bits	8	$\frac{f_b}{3}$
8-QAM	3 bits	8	$\frac{f_b}{3}$
16-PSK	4 bits	16	$\frac{f_b}{4}$
16-QAM	4 bits	16	$\frac{f_b}{4}$
32-PSK	5 bits	32	$\frac{f_b}{5}$
32-QAM	5 bits	32	$\frac{f_b}{5}$
64-PSK	6 bits	64	$\frac{f_b}{6}$
64-QAM	6 bits	64	$\frac{f_b}{6}$
128-PSK	7 bits	128	$\frac{f_b}{7}$
128-QAM	7 bits	128	$\frac{f_b}{7}$

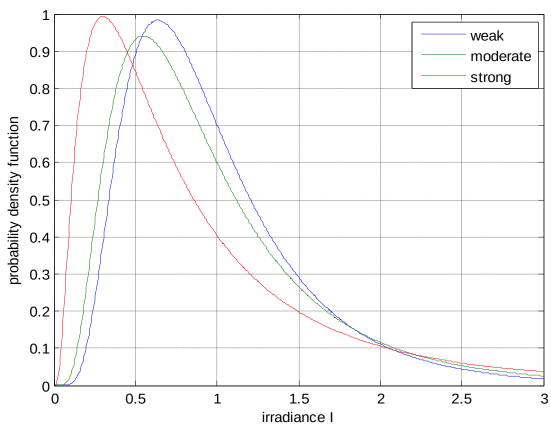


Figure 1 PDF curve

The curve shown in fig 1 has indicates that different turbulence regions have different PDF values on same intensity 'I'. On the value of I=1, PDF value for strong, moderate and weak turbulence has 0.4, 0.6 and 0.7 respectively. It means on the same amount of intensity, we get PDF at 0.7 in weak turbulence conditions and at 0.4 we get same in strong turbulence.

This plot shows the variation of probability density function with respect to the irradiance on different turbulence conditions. Graph given different wave curves for weak, moderate and strong conditions. As the curves state that in strong turbulence conditions, at very small value of irradiance the probability density function becomes high. This is opposite in weak turbulence condition. Curve placed in between on moderate conditions this plot taken with the help of parameters alpha, beta, variance and irradiance of light. These parameters have experimental values for different atmospheric conditions..
In the presence of AWGN noise, when there has been no turbulence the general formula of BER for OOK modulation is given by [15]

$$P_e=\frac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{E_b}{2\sigma^2}}\right) \quad (6)$$

Where E_b is normalized bit energy and σ^2 is the variance. Complementary error function formula is given by

$$\mathrm{erfc}(x)=\frac{2}{\sqrt{}}\int_x^{\infty}\exp\left(-\frac{t^2}{2}\right)dt \quad (7)$$

In decibels, signal to noise ratio (SNR) along relationship with normalized bit energy and variance is defined by [16]

$$\mathrm{SNR(dB)}=10\log\left(\frac{E_b}{\sigma^2}\right) \quad (8)$$

In PSK, BER expression given as [17]

$$P_e=0.5\mathrm{erfc}\left(\sqrt{\frac{E_b}{\sigma^2}}\right) \quad (9)$$

For Mary PSK, BER formula with respect to the normalized bit energy is represented as

$$P_e=\frac{1}{k}\,erfc\left(\sqrt{\frac{kE_b}{No}}\sin\left(\frac{\pi}{k}\right)\right) \quad (10)$$

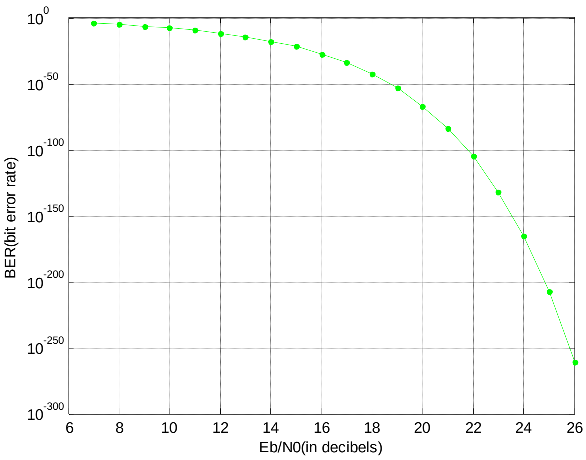


Figure 2 BER performance of QAM

In this paper, we used to estimate probability of error for different values of M in QAM. The generalized formula for calculation bit error rate for M-QAM is derived from the signal to noise ratio E_b/N_0 and number of bits per symbol M.
For Mary QAM, BER is represented as

$$P_e=\frac{2}{k}\left(1-\frac{1}{\sqrt{M}}\right)erfc\left(\frac{x}{\sqrt{2}}\right) \quad (11)$$

Where k is the number of bits used and

$$x=\sqrt{\frac{3kE_b}{(M-1)N_0}} \quad (12)$$

IV. SIMULATION RESULTS DISCUSSION

Using channel and link parameters as described in section II, FSO link was simulated. The equation (11), (12) were used to calculate the probability of error for the experimental set up as described above. The QAM was tested/analyzed for its error performance for given range of derived SNR such that M=8, 16, 32, 64, 256.
The mathematical analysis and simulation states that BER performance for M-ary QAM digital modulation schemes degrades with increasing signal to noise ratio (E_b/N_0). Practically, 8-QAM occupies one third bandwidth of binary QAM as shown in table II. The transmission of information with 8-QAM contained thrice the bit error rate as compare to the binary QAM contained thrice the bit error rate as compare to the binary QAM.
From simulation results and mathematical analysis, we find that increasing the value of M reduces the error performance of the system thus increasing the probability of error. This happens mainly because the increase in M reduces the Euclidian distance between the constellation points.

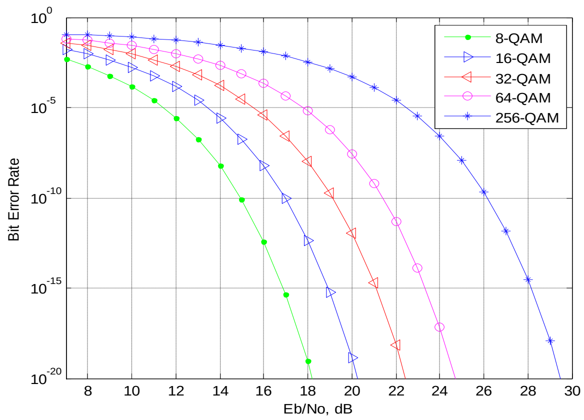


Figure 2 BER performance of M-QAM over AWGN

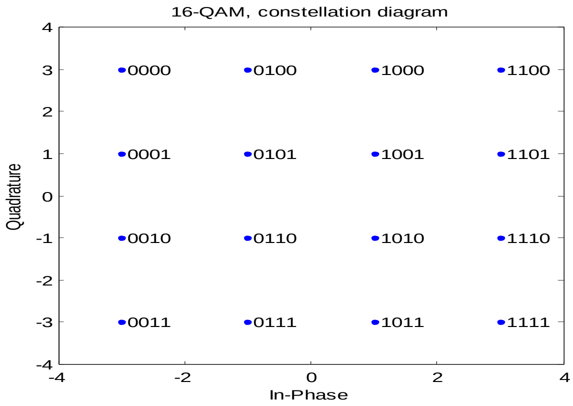


Figure 3 16-QAM constellation mapping points

Results indicate that the higher order modulation, offers higher data rate along with higher error rate. With increase in data rate, SNR also improves but then it also introduces more erroneous bits causing an irreparable damage to data because noise floors rise as more transmitted bits are packed closer. That's why the goodness earned by increase in SNR gets negated thus we may conclude that improvement in SNR levels is limited we cannot increase it at certain level due BER rate also increases.

Generally, we have to compromise for one between data rate and amount of noise that our receiver can handle. As figure 4 represented constellation points plot on 8-QAM. All points are equally distanced from each other. If we compare 8-QAM with 16-QAm or 32-QAM we can easily get as we increasing the value of M, the distance between the constellation points decreases. The figure 3, 4 and 5 gives the result of Mary-QAM constellation points as binary symbol mapping

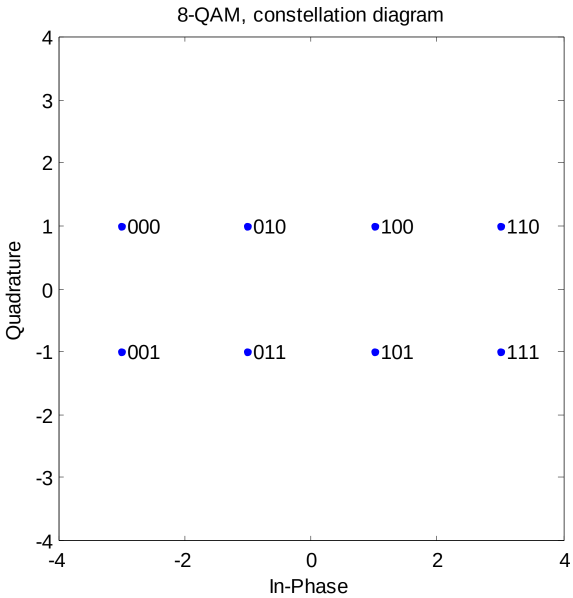


Figure 4 8-QAM constellation mapping points

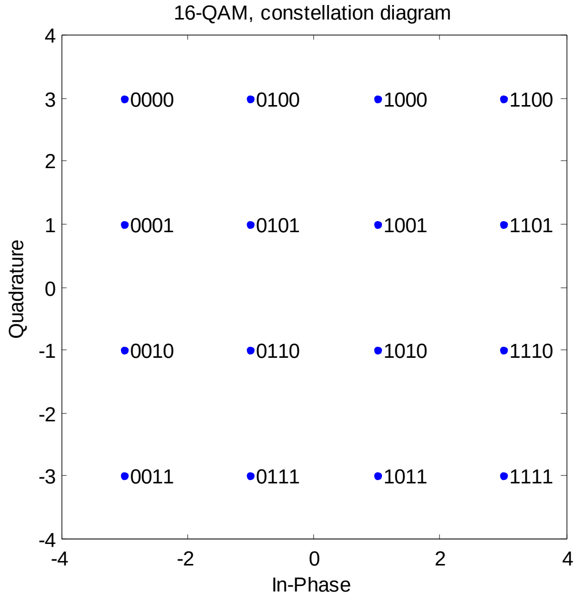


Figure 5 16-QAM constellation mapping points

V. CONCLUSION

In this paper, experimental set up to demonstrate performance of FSO system over turbulent links has been studied using M-ary QAM techniques, so as to assess the noise immunity of FSO links, as number of modulation states are increased. With mathematical and simulation results described here, it can been very well established that as we increase the value of *M*, although increases the data rate but at same time the probability of error of the also increases as the modulation states lie close to each other as shown by binary symbol mapping hence probability of decoding erroneous bits increasing. On the basis of these outcomes, we can say that higher the order of modulation, higher is data rate along with increased probability of error. With increasing SNR value, noise induced is also more for transmitted bits which are packed closer. T0 conclude we can say that trade-off has to be maintained between expected data rates and amount of noise that can be resolved.

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