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Modelling and Characterization of OFDM Based Subcarrier Intensity Modulation in Free Space Optical Communication

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***Abstract*— The thesis concept focuses on the implementation of an orthogonal frequency division multiplexing based free space optical communication system. OFDM based FSO is a novel technique in the areas of optical wireless communication system. This system is modelled and characterized using MATLAB software. The FSO system analysis for two specific cases of modulation techniques such as M-ary phase shift keying and rectangular quadrature amplitude modulation has been modified by incorporating the adaptive technique. The adaptive schemes offer efficient utilization of optical wireless communication channel capacity by adapting the modulation order according to the received signal-to-noise ratio and a pre-defined target bit-error rate requirement. The improved spectral efficiency can be achieved by the adaptive systems without increasing the transmitter power. To enhance the performance of subcarrier intensity modulation based free space optical communication, OFDM technique is employed under Gamma-Gamma turbulence using M-PSK and R-QAM.**

Index Terms*— Free-space optical communications, atmospheric turbulence, gamma-gamma distribution, intensity modulation

I. INTRODUCTION

FREE Space Optical Communication FSO involves the transfer of data/information between two points using optical radiation as the carrier signal through unguided channels. The data to be transported could be modulated on the intensity, phase or frequency of the optical carrier. An FSO link is essentially based on line-of sight (LOS), thus to ensure a successful exchange of information requires that both the transmitter and the receiver directly “see” one another without any obstruction in their path. The unguided channels could be any, or a combination, of space, sea-water, or atmosphere.

The demand for quality of service offered and the capacity-hungry communication from LAN to internet has driven the innovation of new technology. Free Space Optics (FSO) is one such wireless optical communication that uses the unlicensed band of frequency to transmit the data over free space. Due to the ease of installation along the window, terrace etc. it is preferred for last mile access technology that serves as a solution for the rising demand of high bandwidth for next generation access network. High bandwidth data can be transmitted using point to point link that finds application in the field of inter-satellite communication, from ground-to satellite link and satellite-to ground link and deep space probing. It has the advantage of less Electromagnetic interference, high bandwidth available and low power usage. But at the same time the link availability depends on the climatic condition. It is possible to provide full duplex, usually protocol independent data transmission with this technology. The major requirement for a FSO link is the clear Line Of Sight (LOS) and proper alignment of the transmitter and the receiver.

The FSO can be classified based on the ambient condition as indoor link and outdoor link. The indoor link ranges over short range and the outdoor connectivity range is greater than the indoor link. The outdoor link is established with LOS connectivity that is affected greatly by the atmospheric condition. The fade margin of the FSO system compels the designer to increase the transmitter power. But it is very essential to select the transmitter power within the eye safety requirement. When fade margin is quite high, the link is unavailable and the transmission is interrupted. Meteorological effects like fog, rain, mist, haze, scintillation etc. causes the light to fade. Besides the meteorological effects, the atmospheric phenomena like absorption and scattering attenuates the optical signal in free space. The occurrence of these phenomena depends on the geographical area which in turn limits the availability of the FSO link. OFDM being a parallel transmission system widely applied in the wireless environment that is affected by the multipath propagation effects. FSO being a wireless application, combining OFDM with FSO can provide new hybrid technology that can take the advantage of both OFDM and the FSO systems. The transmission rate can be increased by the OFDM modulation of the signal that can easily be transmitted through FSO link over window panes or terrace to form ubiquitous connectivity.

Solar radiation absorbed by the Earth's surface causes air around the earth surface to be warmer than that at higher altitude. This layer of warmer air becomes less dense and rises to mix turbulently with the surrounding cooler air causing the air temperature to fluctuate randomly. Inhomogeneities caused by turbulence can be viewed as discrete cells, or eddies of different temperature, acting like refractive prisms of different sizes and indices of refraction. The interaction between the laser beam and the turbulent medium results in random phase and amplitude variations (scintillation) of the information-bearing optical beam which ultimately results in performance degradation of FSO links. Atmospheric turbulence is usually categorised in regimes depending on the magnitude of index of refraction variation and inhomogeneities. These regimes are a function of the distance travelled by the optical radiation through the atmosphere and are classified as weak, moderate, strong and saturation. Turbulence is caused by inhomogeneities of both temperature and pressure in the atmosphere, and is responsible for the refractive index variation of the air. Turbulence causes amplitude and phase fluctuations in the received optical beam. Such fluctuations deteriorate signal intensity at the receiver, increase bit error rate (BER), and can break the communication link.

Popular models for describing atmospheric turbulence are the lognormal distribution (for weak turbulence induced irradiance fluctuation), the K-distribution (for strong turbulence induced irradiance fluctuation), the negative exponential distribution (for irradiance fluctuation in saturated turbulence conditions), and the Gamma-Gamma distribution (for describing irradiance fluctuation over a wide range of turbulence regimes from weak to strong turbulence).

OFDM is a multicarrier transmission technique which divides the available spectrum into many carriers, each one being modulated by a low data rate stream. OFDM is similar to Frequency Division Multiple Access (FDMA) in that the multiple user access is achieved by sub-dividing the available bandwidth into multiple channels, which are then allocated to users. However OFDM uses the spectrum much more efficiently by spacing the channels more closely together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the adjacent carriers.

The remainder of the paper is organized as follows. Section II presents the system and channel models. Section III studies Subcarrier Intensity Modulation systems employing *M*-PSK and R-QAM. Adaptive modulation strategies discussed out in Section IV. Section V describes about performance evaluation. Numerical results and discussions are presented in Section VI. Finally, Section VII makes some concluding remarks.

II. SYSTEM AND CHANNEL MODELS

A. System Model

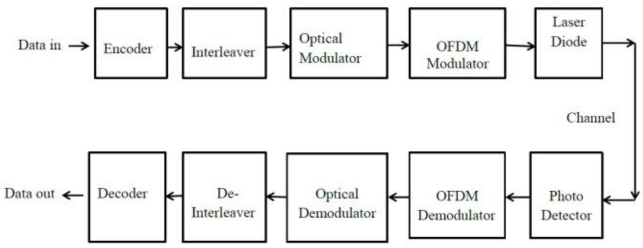

Fig.1. Block diagram of an optical communication system through atmospheric turbulence channels.

Fig. 1 shows the block diagram of an optical communication system through the atmosphere. The information generated by a source is encoded by an encoder, interleaved, and modulated into an electrical waveform by an electrical modulator. In the optical modulator, the intensity of a light source is modulated by the output signal of the electrical modulator. The light source is a laser, characterized by its wavelength, power, and beam divergence angle. There is a collimator or telescope in the transmitter to determine the direction and the size of the laser beam. The receiver consists of an optical front end, a photodetector, a demodulator, a deinterleaver, and a decoder. The optical front end contains lenses focusing the received optical field onto a photodetector. The photodetector converts the received optical field to an electronic signal, which is demodulated. The demodulator output signal is deinterleaved and decoded. The decoded bits are fed into an information sink.

B. Atmospheric Turbulence Models

Statistical model of atmospheric turbulence is well investigated in the literature. Popular models for describing atmospheric turbulence are the lognormal distribution (for weak turbulence induced irradiance fluctuation), the *K*-distribution (for strong turbulence induced irradiance fluctuation), the negative exponential distribution (for irradiance fluctuation in saturated turbulence conditions), and the Gamma-Gamma distribution (for describing irradiance fluctuation over a wide range of turbulence regimes from weak to strong turbulence).

C .The Gamma-Gamma Turbulence Model

This model is based on the modulation process where the fluctuation of light radiation traversing a turbulent atmosphere is assumed to consist of small scale (scattering) and large scale (refraction) effects. Large scale fluctuations on the other hand are generated by turbulent eddies larger than that of the first Fresnel zone or the scattering disk whichever is larger. The small scale eddies are assumed to be modulated by the large scale eddies. Consequently, the normalised received irradiance I is defined as the product of two statistically independent random processes Ix and Iy:

$$I= IxIy \quad (1)$$

Ix and Iy arise from the large scale and small scale turbulent eddies respectively and are both proposed to obey the gamma distribution by Andrews et al.

III. SUBCARRIER INTENSITY MODULATION

In an OWC SIM link, an RF signal, $s(t)$, pre-modulated with data source, is used to modulate the irradiance of a continuous wave optical beam at the laser transmitter after being properly biased. For an atmospheric turbulence channel, the received photocurrent after direct detection using photodetector can be expressed as

$$ir(t) = RI(t)A[1 + \xi s(t)] + n(t) \quad (2)$$

where ξ is the modulation index satisfying the condition $-1 \leq \xi s(t) \leq 1$ in order to avoid over modulation. In (1), R is the responsivity of phtotodetector, $I(t)$ is assumed to be a stationary random process for the received irradiance fluctuation caused by atmospheric turbulence, A is the area of photodetector, and $n(t)$ is the noise term, which is assumed to be caused by background radiation (i.e., ambient light) and/or thermal noise, and it is modeled as an additive white Gaussian noise (AWGN) process with variance σ_n^2 .

The information data sequence is converted into an electrical signal

$$z(u,t) = \sum_{i=-\infty}^{\infty} d_i\, g(t - iT_s) \quad (3)$$

where $di \in \{1, -1\}$ is the signal level for the ith data symbol, $g(t)$ is the shaping pulse, and Ts is the symbol time. This electrical signal drives a laser. The intensity of the transmitted laser beam can be written as

$$s(t) = 1 + \sum_{i=-\infty}^{\infty} d_i\, g(t - iT_s) \quad (4)$$

The received intensity of the optical beam can be written as

$$P(t) = \frac{P}{2}A(u,t) + \sum_{i=-\infty}^{\infty} \frac{P}{2}\, A(u,t)\, d_i\, g(t - iT_s) \quad (5)$$

where P is the maximum received intensity when there is no turbulence. Hence, the received electrical signal is

$$r(t) = K\{A(u,t) + \sum_{i=-\infty}^{\infty} A(u,t) d_i\, g(t - iT_s)\} + n(t) \quad (6)$$

where K is a constant determined by the received optical intensity and the photoelectric conversion efficiency, $n(t)$ is additive white Gaussian noise (AWGN)

IV. ADAPTIVE MODULATION

Adaptive modulation strategy improves the spectral efficiency of FSO systems, without increasing the transmitted average optical power. The main objective of a constant power, variable-rate adaptive transmission technique is to maximize the number of transmitted bits per symbol interval by using the largest possible modulation order while maintaining a pre-defined target BER P_0. In practice, the receiver selects a modulation order from N available choices $\{ M_1, M_2, \ldots M_N \}$, depending on the values of receiver estimated SNR² $\tilde{\gamma}$ and the target BER requirement P_0. Specifically, the range of SNR is divided into N+1 regions, and each region is associated with a modulation order, M_n, according to the following rule for R-QAM based adaptive SIM

$$M = M_n = I_n J_n = 2^n \quad (7)$$
$$\text{if } \gamma_n \leq \tilde{\gamma} < \gamma_{n+1}, \; n = 1, 2, \cdots N.$$

If n is even $I_n = J_n = 2^{n/2}$,

If n is odd $I_n = 2^{(n+1)/2}$ and $J_n = 2^{(n-1)/2}$

For M-PSK based adaptive SIM system, the rule in (7) is modified to

$$M = M_n = 2^n \quad (8)$$
$$\text{if } \mu_n \leq \tilde{\gamma} < \mu_{n+1}, \; n = 1, 2, \ldots N.$$

V. PERFORMANCE EVALUATION

A. Achievable Spectral Efficiency

ASE is the information rate that can be transmitted per unit bandwidth. For a constant-power, adaptive discrete rate SIM assuming ideal Nyquist data pulses for each constellation, the ASE is defined as

$$S = \frac{R}{W} = \sum_{n=1}^{N} \log_2 M_n \quad (9)$$

where R and W represent the transmitted data rate and bandwidth measured in bits/s and in Hz, respectively.

B. Bit Error Rate

The BER of a constant-power, adaptive discrete rate system can be calculated as the ratio of the average number of erroneous bits to the total average number of transmitted bits.

At the transmitter end, the RF subcarrier signal is modulated by the data sequence using PSK or QAM. The optical intensity must satisfy the non-negativity constraint, a proper DC bias must be added to the RF electrical signal in order to prevent clipping and distortion in the optical domain. The laser operates in its linear region to avoids over modulation induced clipping. This functional element has the primary duty of modulating the source data onto the optical carrier which is then propagated through the atmospheric to the receiver. The most widely used modulation type is the intensity modulation (IM) in which the source data is modulated. This is achieved by varying the driving current of the optical source directly in sympathy with the data to be transmitted or via an external modulator such as electro absorption modulator The use of an modulator guarantees a higher data rates than what is obtainable with direct modulation but an external modulator has a non-linear response. Other properties of the radiated optical field such as its phase, frequency and state of polarization can also be modulated with data/information through the use of an external modulator.

At the receiver's end, the optical power which is incident on the photodetector is converted into an electrical signal through direct detection. After removing the DC bias and demodulating through an electrical PSK demodulator, the sampled electrical signal obtained at the output of the receiver. Atmospheric turbulence is a major performance degrading factor in FSO systems, which leads to intensity variations of the received optical signals. For its statistical description, various statistical models have been proposed depending on the turbulence strength. In weak turbulence conditions the most widely accepted fading model is the lognormal (LN) one. In this case, the logarithm of the intensity variations is normally distributed. In moderate to strong turbulence conditions, the recently proposed Gamma Gamma (GG) model can be used for the statistical description of turbulence-induced fading. According to this model, intensity fluctuations are considered to be derived from the product of small-scale and large-scale fluctuations, both statistically defined by the Gamma distribution.

Optical wireless systems are severely limited by power and error correcting coding is desired. The atmospheric turbulence is relatively slow compared with the data rates in optical wireless systems. This means the scintillation is almost the same over successive bits, the channel has memory. The decoding algorithms for convolutional codes cannot exploit the channel memory and are not optimum for atmospheric turbulence channels. Having low complexity, convolutional codes and the Viterbi decoding algorithm are efficient to correct random errors. When the instantaneous scintillation is severe, it can cause burst errors and severely degrade decoder performance. Interleaving can be employed to change the bit sequence in coded information blocks. Although there might be successive bit errors in the received bit stream, a deinterleaver changes the bit sequence of the received information block back, and makes the occurrences of errors random. Block interleaving is assumed to improve the performance of the Viterbi decoder in the presence of atmospheric turbulence. When interleaving is employed, the bound calculation is simplified and the decoding algorithm is simplified and optimum. Interleaving can help improve system performance in optical communications through relatively slow scintillation channels. Interleaving can help reduce decoder complexity significantly and simplify the performance analysis for decoding. Convolutional codes can be employed in optical communications through atmospheric turbulence channels to improve performance and to reduce the transmission power.

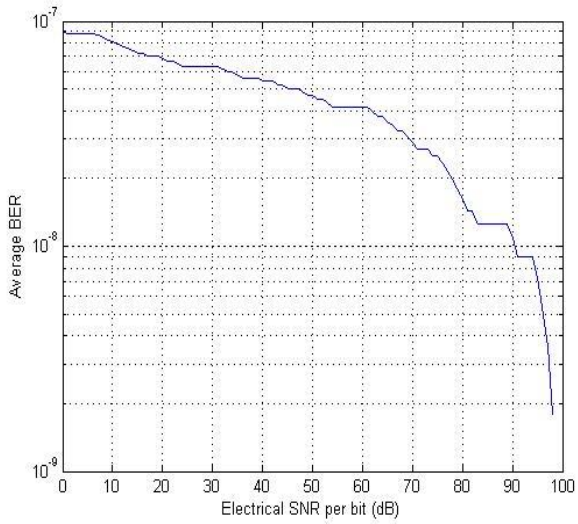

Fig.2. BER of 32-PSK based adaptive SIM over the Gamma-Gamma turbulence channels.

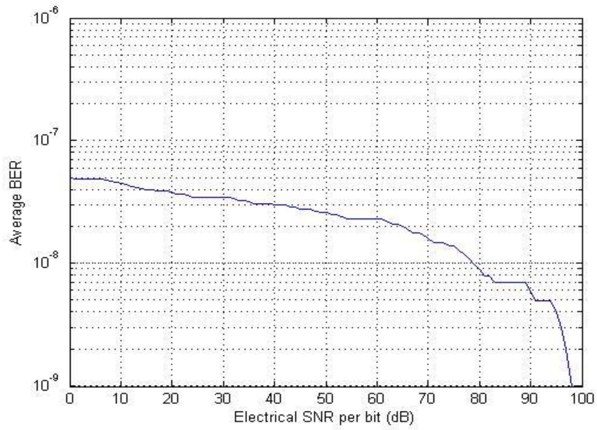

Fig.3. BER of 16-QAM based adaptive SIM over the Gamma-Gamma turbulence channels.

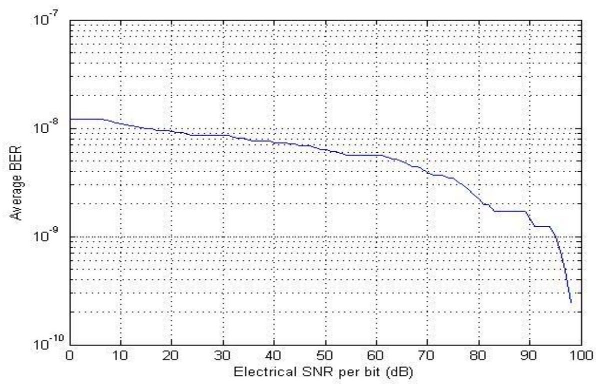

Fig.4. BER of 64-QAM based adaptive SIM over the Gamma-Gamma turbulence channels.

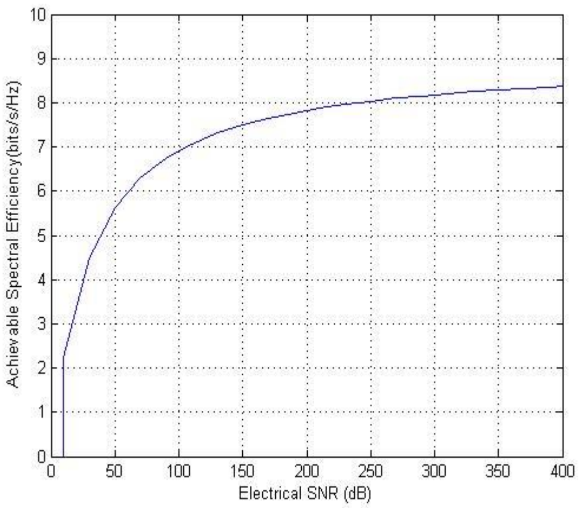

Fig.5. ASE of *M*-PSK based adaptive SIM over the Gamma-Gamma turbulence channels.

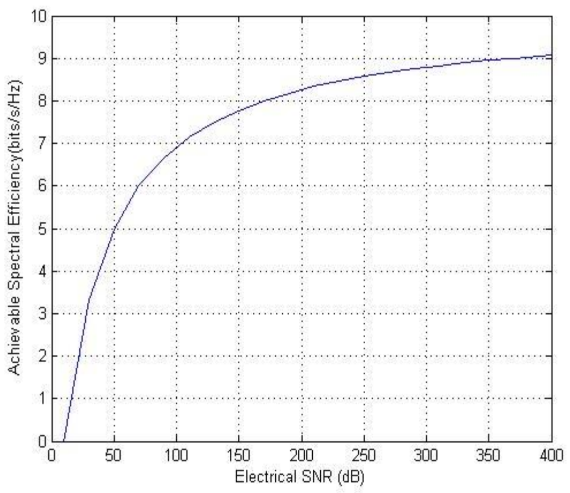

Fig.6. ASE of R-QAM based adaptive SIM over the Gamma-Gamma turbulence channels.

VI. Numerical Results

Fig.2, Fig.3 & Fig 4 presents the BER performance of 32-PSK , 16-QAM, 64-QAM and based adaptive SIM regions over a strong Gamma-Gamma turbulence channel. It is also depicted that the adaptive SIM system always offers a BER less than the target BER, satisfying the basic design goal of the adaptive SIM system. It also see that the R-QAM based adaptive SIM outperforms the *M*-PSK based adaptive SIM in terms of BER performance. This is an expected outcome, because for $M \geq 8$, an R-QAM always offers better BER performance than an *M*-PSK modulation over a fading channel.

From both Fig. 5 and Fig. 6, it is obvious that the adaptive SIM offers large spectral efficiency gain compared to the non -adaptive SIM in the strong turbulence conditions. However, spectral efficiency gain gets reduced as the turbulence strength decreases. This is because at moderate turbulence conditions non-adaptive SIM requires less average SNR to achieve the target BER. Also observed that the adaptive SIM systems can achieve higher ASE in a moderate turbulence condition in the low SNR regimes. This result is expected since for a less faded channel the receiver tends to select a higher order modulation while maintaining the minimum BER requirements. The R-QAM based adaptive SIM provides improved ASE than the *M*-PSK based adaptive SIM for low to moderate SNR values. The SNR thresholds of R-QAM based adaptive SIM are smaller than that of *M*-PSK based adaptive SIM for $M \geq 8$. As a result, receiver of R-QAM based adaptive SIM tends to achieve a larger modulation compared to that of *M*-PSK based modulation. Hence, in low to moderate values of SNR R-QAM based adaptive SIM achieves larger ASE. However, when the SNR is asymptotically large, receivers of both adaptive SIM select the largest available modulation order.

VII. Conclusion

The OFDM based adaptive SIM using R-QAM and M-PSK are modeled and analyzed for free space optical communication over gamma-gamma turbulence channels by using MATLAB software. The simulation results obtained after a series of analysis of OFDM based free space optical communication over the Gamma-Gamma turbulence channels for both non-adaptive and adaptive SIM systems employing R-QAM and M-PSK shows that the R-QAM based adaptive system offers improved ASE and BER performance compared to the M-PSK based adaptive system. The implementation of OFDM technique enhanced the FSO system performance in terms of BER and ASE.

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