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A Space-Time Code Supported Model for free Space Optical Communication Channel with Gamma-Gamma Turbulence

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Abstract: *Free space optical (FSO) communication has been lauded as the state of the art technique for the delivery of high speed last-mile solutions for wireless communication systems, and coherent FSO systems are at the forefront of this development as a result of the ample merits embedded in their detection technique. In this work, the FSO communication channel was modelled for two transmit lasers and any arbitrary number of photodetectors using the closed form expressions for space-time coded FSO system under Gamma-Gamma channel turbulence assumptions. By employing computer aided analytic exploration of different turbulence conditions, this work presents a detailed and extensive understanding of the FSO communication channel in readiness for the deployment of space-time codes (STC).*

Keywords: Space-time codes, Gamma-Gamma channel, Coherent Detection, IM/DD detection, Free Space Optical communication, Diversity.

1. INTRODUCTION

Free space optical (FSO) communication is a wireless point-to-point technology involving the transmission of data from laser sources to photodetectors through free space [1]. By employing optical carrier frequencies, FSO communication promises large bandwidth at ultra-high data rates in addition to excellent security, robustness to electromagnetic interference, cost effectiveness and license free operation [2]-[4]. A unique feature of free space optical communication systems that made it an attractive option for point-to-point wireless communication is excellent data rate. FSO systems have been reported in the range of 300GHz which far overshadows even the best of RF systems. Quiet often, the transmitting segment of FSO systems involve the use of narrow and often invisible optical lasers beams, this narrowness and invisibility afford FSO systems a much desired quality – high data security. FSO has been reported in several quarters as the most secured wireless network technology in the world, a quality which makes it one of the preferred communication techniques in military systems [1], [4]-[6]. This property of FSO systems is partly due to their immunity to detections by RF meters and spectrum analyzers because of their high frequency of operation. Furthermore, in this regard, FSO links are line-of-sight (LOS) links that require perfectly matched transmitters and receivers and as such are extremely difficult to intercept. With improvements in digital signal processing and the development of high switching speed integrated circuits, data encryption over FSO links is now a possibility, this further adds another layer of security to communication over FSO links.

Figure 1: FSO system for terrestrial communication solutions [1].

Owing to these advantages, interests in FSO systems have grown significantly over the past decade for interplanetary communications as well as terrestrial applications. For instance, internet solution providers have leveraged on the massive bandwidth attainable in FSO systems to develop more reliable mobile backhauls connectivity just as wireless cellular and fixed wireless networks are employing FSO systems for the same purpose. Figure 1 shows some of these applications in a metropolitan setup wherein FSO systems are employed for secured and reliable communication between buildings and offices using roof-top to roof-top FSO links, as well as communication between public places and facilities. FSO systems are readily compatible with existing communication infrastructures making it easy to interface them in different levels of hierarchical network infrastructure [7], the impact of FSO systems on modern day communication cannot be over-emphasized.

FSO as a technique has its own inherent challenges as its performance is significantly eroded by turbulence induced fading along the FSO link. This is often as a result of local variations in the refractive index caused by inhomogeneity of atmospheric temperature and pressure, as well as suspended particles and air currents [8]. Mitigating against the effects of this turbulence induced fading remains a major challenge that researchers are continuously tackling. In doing this, several techniques have been devised, including taking the advantage offered by space-time diversity to generate space-time codes for deployment over FSO links. Concerted research efforts have been expended in the aspect of developing coding schemes to reduce the effects of turbulence on the overall system performance of FSO systems [9]-[14], however, clear details of the channels remain sketchy especially in the aspect of design and deployment of space-time trellis codes (STTC) and Space-time block codes (STBC) over FSO links. This work therefore presents a concise technique for modelling the FSO channels under gamma-gamma turbulence condition.

The rest of this paper is organized as follows: A description of coherent FSO systems are first presented including their advantages over other common detection techniques. Several turbulence models reported in literature are also elucidated including the gamma-gamma channel – a theoretical basis for this work. Finally, the theoretical basis for the pairwise error probability of coherent FSO systems is presented, thereafter, the results of this work are presented and their significance and relevance in relation to existing techniques in literature are established.

2. COHERENT FSO SYSTEMS

Earlier works in the domain of FSO involve the detection technique commonly called intensity modulation/direct detection (IM/DD). In this detection technique, the transmitted information is contained in the intensity of the transmitted light such that the receiver directly obtains the transmitted information from the intensity of the arriving light intensity. Although there have been successful works in the area IM/DD FSO systems, there remains more opportunities to be explored in coherent FSO systems as they have been reported to possess enormous potential than the IM/DD FSO systems, albeit, at an expense of receiver and computation complexity.

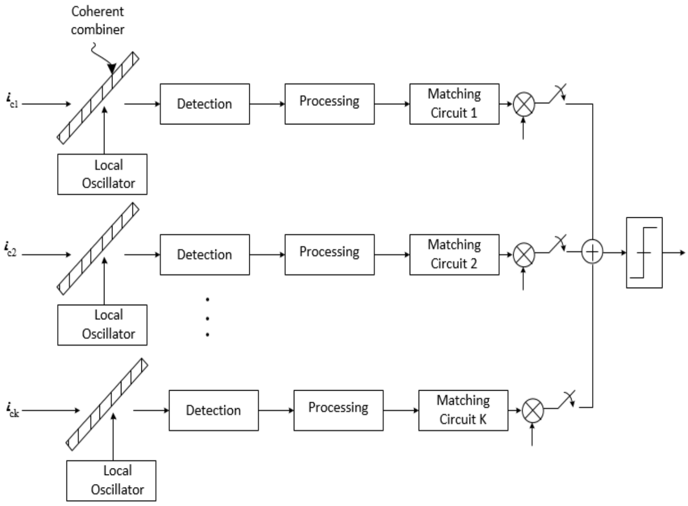


Figure 2: Coherent FSO system with equal gain combining

In coherent FSO systems (depicted in Figure 2), the incoming signal field is firstly combined coherently with a local oscillator before it is routed to the photodetector. Coherent FSO systems offer several advantages over the much simpler and widely researched IM/DD FSO systems. These include excellent background noise rejection, better robustness in terms of combating turbulence induced fading and improved receiver sensitivity.

2.1 Free Space Channel Turbulence

The turbulence induced fading earlier described in the introductory section of this work is most often described using statistical probability density models with turbulence parameters which depict the underlying turbulent conditions of the communication channel. For instance, the lognormal distribution $f_A(a)$, quite often used to describe weak turbulence condition in wireless communication systems, is given as [14]:

$$f_A(a) = \frac{1}{(2\pi\sigma_x^2)^{\frac{1}{2}}a} exp\left(-\frac{\ln a - \mu_x}{2\sigma_x^2}\right), \qquad a > 0 \qquad (1)$$

where the entity μ_x is the mean value of fading and σ_x^2 represents the covariance of fading. While the Gamma-gamma distribution is often employed to describe a wider range of turbulence. This distribution is important in general wireless communication channel modeling because it is applicable to strong turbulence condition as well as weak turbulence condition. So named because it involves double gamma functions of two parameters, the Gamma-Gamma probability density function (PDF) is written as [15]:

$$f_{\tilde{H}}^{GG}(h) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h^{\frac{\alpha-\beta}{2}} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h}\right) \qquad (2)$$

where $K_v(x)$ is the modified Bessel function of the second kind and α and β are the turbulence parameters which can be selected by fitting empirical data in form of approximate analytical expressions [1]. Some other turbulence PDFs for evaluation of different atmospheric turbulence include the K-distribution and the negative distribution.

2.2 Analysis of Pairwise Error Probability for Coherent FSO Systems

The In this work, the properties and performance of the channel is evaluated firstly by the pairwise error probability (PEP). This performance index, for any given pair of transmitters, is regarded as a measure of the number of bits in error which have occurred when the receiver decides erroneously that the first instead of the second has transmitted. Thus, the pairwise error probability proposed in [16] was modified to evaluate the performance of the FSO channel.

$$P_e \doteq \frac{\left(\pi a_h^2 \Gamma^2(2\mu) F(\mu,\mu:1;\xi^2)\right)^N}{2\sqrt{\pi}(d_{11}d_{22})\Gamma(2\mu N+1)} \times \frac{\Gamma\left(2\mu N+\frac{1}{2}\right)\gamma_{coh}^{-2\gamma N}}{\Gamma^{2N}\left(\mu+\frac{1}{2}\right)} \quad (3)$$

where $F(\cdot)$ is the Gaussian hypergeometric function and the entity a_h^2 is written in terms of the series representation of the Gamma-Gamma function as:

$$a_h \triangleq \frac{1}{\Gamma(\mu)\Gamma(v)\sin\left(\pi(v-\mu)\right)} \times \frac{2\pi(\mu v)^{\mu}}{\Gamma(\mu-v+1)} \quad (4)$$

where v and μ are the maximum and minimum of the turbulence parameters, respectively. That is, $v = max\{\alpha,\beta\}$ and $\mu = min\{\alpha,\beta\}$.

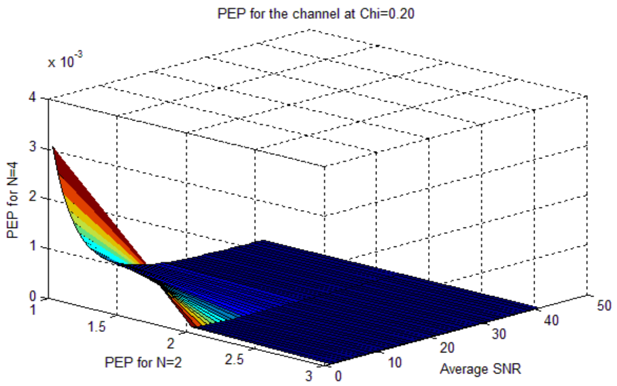
The analytic models and closed form expressions described in the sections above were realized using the computing environment offered by the MATLAB programming tool. The entity a_h was first obtained by computing the gamma values and the powers of appropriate terms in Equation 4. This step however involves a preliminary step of obtaining the maximum and minimum values of Gamma-Gamma turbulence parameters α and β in order to obtain v and μ respectively. Thereafter, the expression in Equation 3 was employed in deriving the pairwise error probability for each data point. This step include the computation of the Gaussian hypergeometric function $F(\mu,\mu:1;\xi^2)$ where the function is generally expressed as:

$$F(a,b;c;z) = \sum_{n=0}^{\infty} \frac{\Gamma(a+n)}{\Gamma(a)} \cdot \frac{\Gamma(b+n)}{\Gamma(b)} \cdot \frac{\Gamma(c)}{\Gamma(c+n)} \cdot \frac{Z^n}{n!} \quad (5)$$

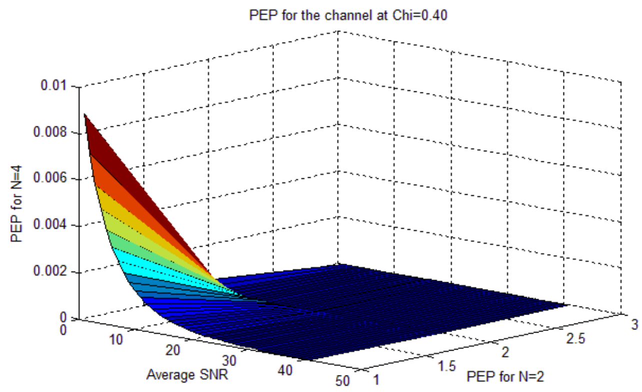
This converges for arbitrary a, b, and c for real $-1 < z < 1$ and for $z = \pm 1$ if $c > a + b$, provided c is not a negative integer. In Equation 3, the entity ξ, bounded by $0 \leq \xi < 1$, is a parameter which is a function of the fraction of the determinants and roots of the elements of matrix $\boldsymbol{D} = \boldsymbol{E}^H\boldsymbol{E}$ where $\boldsymbol{E}$ is the error matrix for a case when a space-time codeword C_1 is incorrectly detected as C_2.

3. RESULTS AND DISCUSSION

The PEP for the coherent FSO channel under different conditions was analyzed and it was observed that the channel model performed impressively under various conditions. The excellent performance of coherent FSO systems even at high average SNR values is once again re-affirmed in this work as the PEP remain significantly low even at SNR values as high as 40. The particular case of two transmit lasers ($N = 2$) and any arbitrary number of photodetectors was considered. For instance, Figure 3a shows the channel behaviour for two and four transmit lasers at a space-time codeword index ξ value of 0.20. The result shows that at low average SNR, the obtained PEP for the channel was as low as 3×10^{-3} and the PEP values decreases progressively with increasing values of average SNR. It can be observed that, for the two instances of space-time codeword index considered, the performance improved with increasing number of photodetectors as the PEP values for $N = 4$ out performs that for $N = 2$ for $\xi = 0.20$ (Figure 3a) and for $\xi = 0.40$ (Figure 3b).



(a)



(b)

Figure 3: The behaviour of the coherent FSO channel for different number of photodetectors for (a) Space-time codeword index $\xi = 0.20$ and (b) Space-time codeword index = 0.20 $\xi = 0.40$.

Different degrees of atmospheric turbulence were analyzed for SNR values ranging between 1 and 40. These turbulence conditions were realized by varying the values of the turbulence parameters α and β for the Gamma-Gamma PDF. For the purpose of cross evaluation, the values of turbulence parameters α and β analyzed in this work are some values often reported in literature. Figure 4 shows the logarithmic scale results obtained for different situations. First, it can be observed that the channel model is robust enough to accommodate a wide range of turbulence parameters α and β. Secondly, the PEP for the case of $\alpha = 2.30$ and $\beta = 1.4$ outperforms that for $\alpha = 2.711$ and $\beta = 2.319$. For the sake of clarity, the symbols "a" and "b" in Figure 4 represent α and β, respectively.

The patterns observed from the analysis of this model indicate that system planners and designers for coherent FSO systems need to do a careful analysis of their systems and obtain the best network and system parameters in order to attain the optimum set for better quality of service.

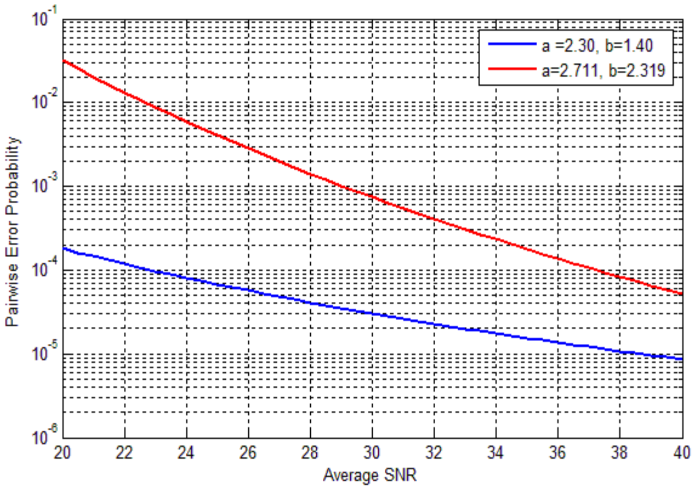


Figure 4: Performance under different turbulence conditions

The discrepancies between the performance over the coherent FSO channel, for different sets of $\{\alpha, \beta\}$, appear to wane as the average signal-to-noise ratio increases. This implies that, at lower average SNRs, stringent scrutiny should be done at design and simulation levels in order to ascertain that the optimal values of parameters have been chosen.

It should be noted that one of the highlights of this work it that the codeword C is not subjected to any stringent condition like orthogonality as are the case in reported similar previous models. It should be interesting to know the overall performance of this model under diverse STC schemes and concatenated codes.

4. CONCLUSION AND FUTURE WORKS

In this work, a Gamma-Gamma free space optical (FSO) communication channel has been modelled using the comprehensive closed form relation for the pairwise error probability of coherent FSO systems with full capability for space-time codes (STC). Based on this, a computer assisted analytic simulation was implemented and the corresponding results have been discussed. Again, the different results and observations made in this paper serves as handy tools in the quest for better understanding of the free space optical communication channel for the purpose of teaching and further research, especially for space-time coded MIMO FSO system, and, even more importantly, coherent FSO systems. As a form of improvement over this work and to develop better models for better in-depth understanding of the FSO channel under different turbulence conditions, the powerful computing prowess of the much researched artificial neural networks could be harnessed in developing resilient and intelligent neuromodels for space-time coded (STC) FSO systems. This recommendation can be extended to other softcomputing techniques as a means of blending communication systems and softcomputing techniques. Such a hybrid model will harness the impressive potentials of each constituent technique, potentially guaranteeing enhanced overall performance of FSO communication systems.

REFERENCES

[1] Khalighi, M. A. & Uysal, M. (2014a). Survey on Free Space Optical Communication : A Communication Theory Perspective. *IEEE Communication Surveys & Tutorials*, *16*(4), 2231–2258.

[2] Layioye, O. A., Afullo, T. J. O. & Owolawi, P. A. (2016). Calculations of the Influence of Diverse Atmospheric Turbulence Conditions on Free Space Optical Communication Systems Using the BPSK-SIM over the Gamma-Gamma Model. *Southern Africa Telecommunication Networks and Applications Conference*, *1*(1), 350–357.

[3] Peppas, K. P. & Mathiopoulos, P. T. (2015). Free-Space Optical Communication With Spatial Modulation and Coherent Detection Over H-K Atmospheric Turbulence Channels. *Journal of Lightwave Technology*, *33*(20), 4221–4232.

[4] Hasan, M. R. & Reza, L. H. (2011). *Performance Analysis on Free space MIMO Optical Wireless link over strong Atmospheric Turbulences*. *The Department of Electronic Electrical Engineering, BRAC University, Dhaka, Bangladesh*.

[5] Mansour, A., Mesleh, R. & Abaza, M. (2017). New challenges in wireless and free space optical communications. *Optics and Lasers in Engineering*, *89*, 95–108.

[6] Tang, X. & Xu, Z. (2013). Outage Probability of Multihop Free Space Optical Communications over Nakagami Fading Channels, *Proceedings of the 2013 18th European Conference on Network and Optical Communications & 2013 18th Conference on Optical Cabling and Infrastructure*, 199–202.

[7] Cao, Q. (2005). *Performance analysis of Communication Systems over MIMO Free Space Optical Channels. Department of Electrical and Computer Engineering, University of Virginia.*

[8] Thakur, A., Nagpal, S. & Gupta, A. (2017). Kerr Effect Based Spectrum Sliced Wavelength Division Multiplexing For Free Space Optical Communication. *Optik - International Journal for Light and Electron Optics*, 1–11.

[9] Abou-rjeily, C. & Fawaz, W. (2008). Space-Time Codes for MIMO Ultra-Wideband Communications and MIMO Free-Space Optical Communications with PPM. *IEEE Journal on Selected Areas in Communications*, *26*(6), 938–947.

[10] Garcia-Zambrana, A., Castillo-vazquez, C. & Castillo-vazquez, B. (2010). Space-time trellis coding with transmit laser selection for FSO links over strong atmospheric turbulence channels. *Optics Express*, *18*(6), 1293–1300.

[11] Naila, C. Ben, Bekkali, A., Kazaura, K. & Matsumoto, M. (2010). BPSK Intensity Modulated Free-Space Optical Communications using Aperture Averaging. In *International Conference on Photonics* (pp. 1–5).

[12] Niu, M., Cheng, J. & Holzman, J. F. (2013). Space-Time Coded MPSK Coherent MIMO FSO Systems in Gamma-Gamma Turbulence. In *IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 4266–4271).

[13] Safari, M. & Uysal, M. (2008). Do We Really Need OSTBCs for Free-Space Optical Communication with Direct Detection? *IEEE Transactions on Wireless Communications*, *7*(11), 4445–4448.

[14] Wang, H., Wang, F. & Cao, M. (2015). A Novel Concatenated Coding Scheme Combined LDPC and VBLAST for FSO Links. In *IEEE International Conference on Communication Software and Networks (ICCSN)* (pp. 192–195).

[15] Bhatnagar, M. R. & Anees, S. (2015). On the Performance of Alamouti Scheme in Gamma-Gamma Fading FSO Links With Pointing Errors. *IEEE WIreless Communications Letters*, *4*(1), 94–97.

[16] Bayaki, E. & Schober, R. (2012). Performance and Design of Coherent and Differential Space-Time Coded FSO Systems. *Journal of Lightwave Technology*, *30*(11), 1569–1577.