Improving the performance of free space optical systems: a space-time orthogonal frequency division modulation approach

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ABSTRACT

Free space optical (FSO) communication systems are known for high-level capacity and information security. The overall system performances of FSO systems are however significantly affected by atmospheric turbulence induced fading. This paper, therefore, proposes a space-time code (STC) technique to mitigate this effect through the introduction of an additional degree of error correction capacity by exploiting the spectral dimension in the coding space. A space-time trellis coded orthogonal frequency division modulation (OFDM) scheme was developed, simulated and evaluated for free space optical communication through a gamma-gamma channel. The evaluation of the coding gain obtained from the simulation results, the mathematical analysis and the truncation error analysis shows that the proposed technique is a promising and viable technique for improving the error correction performance on optical communication links.

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1. INTRODUCTION

Performance expectations for new generational communication systems are always increasing. This is partly a consequence of users' demand for high bandwidth, information security as well as high capacity. These demands have thus far served as the impetus for the design of communication systems that more efficiently meet users' expectations [1]. In recent years, the radio frequency (RF) spectrum has come under heavy bandwidth, data security, power and licensing constraints, so much that communication systems designers are now looking to deploy optical communication solutions for high-speed communication links.

Optical fiber communication is one of the first solutions that became widely accepted for backbone connectivity and other high-capacity point-to-point connections. However, its need for laborious cabling and layout is shifting attention to free space optical (FSO) in an attempt to establish wireless transmission of information in some applications. Free space optical communication entails the modulation of user information onto optical carriers, and the onward transmission of same over unguided free space channel to photoreceptors. FSO communication systems have proven to be up to this task by offering ultra-high data rates, enormous bandwidth, high data security, high immunity to interference and jamming, and avoidance of regulatory issues and spectrum licensing [2].

Broadly, FSO systems are often categorized based on their reception mechanisms. The most widely reported type of FSO system is the intensity modulation/direct detection (IM/DD) [3]. In this type of FSO communication system, the data to be transmitted is encoded by mapping the data signal to the intensity of the optical signal. At the receiving end, the variation in the irradiance intensity of the received optical signal is simply used to represent the transmitted data [4] such that the converted AC photocurrent is proportional to the optical signal power.

Even though FSO communication systems boast several advantages over their RF-based counterparts, a significant drawback is that the performances of FSO-based communication systems are quite easily reduced by turbulent conditions in the atmosphere [5]. The main culprit for this reduction in performance is the inhomogeneity of the atmosphere as optical signals pass through, owing to varying thermal and pressure gradients of the free space between optical lasers and the photoreceptors. Suspended particles, fog and droplets are also factors that contribute to this reduction in the performance of FSO systems [6]. It has therefore become necessary that solutions to this problem be devised. And one of such turbulence-mitigation solutions is the adaptation of efficient coding schemes that have hitherto been quite successful in RF systems like transmit antenna selection multiple-input multiple-output (MIMO) systems [7], turbo coded RF system [8], super-orthogonal codes for Nakagami fading channels [9], binary phase-shift keying (BPSK) trellis coded orthogonal frequency division modulation (OFDM) MIMO system [10], MIMO OFDM RF systems [11] and hybrid concatenated codes with iterative decoding RF systems [12], for FSO systems. Other similar adaptable RF error mitigating techniques include concatenated low-density parity-check (LDPC) space-time codes [13], codeword diversity technique [14], and interleaving technique for high-speed OFDM systems [15], for FSO systems as reported in space-time coded FSO system as reported in [16] and space-time coded OFDM FSO system reported in [17]. Other turbulence mitigation schemes proposed so far include the exploitation of some diversity properties to enhance the quality of communication by reducing the overall error on FSO links. Some of these diversity schemes include temporal diversity, spatial diversity and spectral diversity [18]. By implementing mechanisms to guarantee the delivery of multiple identical copies of a message to the receiver through different paths and subchannels, these schemes have shown to significantly improve reliability of communication over FSO links.

Several distributions have been used to model the free space optical communication channel with different performances for different turbulence strengths. These include the log-normal distribution, K-distribution, negative exponential distribution and gamma-gamma distribution. Of all these, the gamma-gamma distribution possesses the advantage of being applicable for a wider range of turbulence, covering weak turbulence, mild turbulence and strong turbulence [19]. In this paper, an approach for reducing the unwanted results of atmospheric turbulence on the performance of FSO links is presented by exploiting the spectral dimension of the coding space in addition to the coding gain and diversity offered by space-time coding schemes.

2. RESEARCH METHOD

The approach adopted for this study include modelling of the free space optical channel under the adopted distribution assumption and the development of the proposed space-time trellis coded OFDM coding scheme. The conceptual framework for the proposed turbulence mitigation scheme was developed. The developed scheme was thereafter deployed over the channel under the modelled conditions. The effectiveness of the proposed approach at reducing errors was evaluated in relation to similar works. Finally, the performance of the proposed scheme was validated with mathematical analysis. Modelling of communication channels using statistical distributions is one of the approaches that have been deployed in depicting atmospheric turbulence over the years. These distributions attempt to model the channel condition and behavior with the purpose of understanding the impact of the channel on propagating optical signals.

Since interest in FSO systems has gathered pace over the last decade, several other variants of FSO systems have been researched and reported. For example, coherent FSO systems are also gaining vast interest [20] wherein the received signal is firstly coherently merged with a continuous wave local oscillator. Other common forms of FSO systems include differential FSO systems [21], other variants of FSO systems [22]–[25], and even recently, distributed FSO systems [19].

2.1. The system model

The Rayleigh fading model does not satisfactorily cater for the large-scale effect on propagating optical signals, as such, proper modification is therefore required for application for FSO communication. Now, assuming a unit energy signal, and considering that the overall atmospheric turbulence effect on the transmitted signal is a combination of the small-scale effects, I_x, (also known as scattering) and the large-scale effect (refraction), I_y. Such that the received normalized irradiance I is written as (1),

$$I = I_x I_y \tag{1}$$

I_x and I_y being gamma distribution functions themselves allow the gamma-gamma distribution to be modelled as (2) [26]:

$$p(I_x) = \frac{\alpha(\alpha I_x)^{\alpha-1}}{\Gamma(\alpha)} e^{(-\alpha I_x)} \quad I_x > 0;\ \alpha > 0 \tag{2}$$

and,

$$p(I_y) = \frac{\beta(\beta I_y)^{\beta-1}}{\Gamma(\beta)} e^{(-\beta I_y)} \quad I_y > 0;\ \beta > 0. \tag{3}$$

The conditional probability distribution function may consequently be written as seen in (4).

$$p\left(\frac{I}{I_x}\right) = \frac{\beta\left(\frac{\beta I}{I_x}\right)^{\beta-1}}{I_x\Gamma(\beta)} e^{\left(-\frac{\beta I}{I_x}\right)} \quad I > 0 \tag{4}$$

Averaging (4) over the range in order to obtain the unconditional distribution function, the gamma-gamma distribution function for the channel irradiance is therefore obtained by (5):

$$p(I) = \int_0^\infty p\left(\frac{I}{I_x}\right) p(I_x)dx \tag{5}$$

and expressed as (6) [27]:

$$p(I) = \frac{2(\alpha\beta)^{\left(\frac{\alpha+\beta}{2}\right)}}{\Gamma(\alpha)\Gamma(\beta)} \cdot I^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \quad I > 0 \tag{6}$$

where $K_{\alpha-\beta}$ is the modified Bessel function (also known as hyperbolic Bessel function) of the second kind of order $\alpha - \beta$, and I is the irradiance. The variables α and β are the turbulence parameters expressed as functions of the Roytov variance. The selection of the values of α and β is dependent on another entity called the Roytov variance σ_x^2.

$$\sigma_x^2 = 1.33k^{\frac{7}{6}}C_n^2(L)^{\frac{11}{6}} \tag{7}$$

However, the value of α is often greater than β and they both describe the physical effects of large-scale and small-scale scintillations. Also, the gamma-gamma model was adopted in this study because of its accuracy in modeling a wider range of turbulence conditions than other models such as log-normal distribution or K-distribution. For the different turbulence types, the corresponding Roytov ranges are highlighted in Table 1.

Table 1. Different turbulence types and their corresponding Roytov variance values

S/N	Roytov range	Turbulence type
1	$\sigma \leq 0.3$	Weak turbulence
2	$0.3 < \sigma \leq 5$	Moderate turbulence
3	$\sigma > 5$	Strong turbulence

Modifying the Bessel equations originally presented by [28], the modified Bessel function of the second kind, $K_{\alpha-\beta}$, in the gamma-gamma relation in (6) is written in terms of the modified Bessel function of the first kind $I_{(\alpha-\beta)}(x)$ as (8),

$$K_{(\alpha-\beta)}(x) = \frac{\pi}{2}\frac{I_{-(\alpha-\beta)}(x) - I_{(\alpha-\beta)}(x)}{\sin(\alpha-\beta)\pi} \tag{8}$$

where $I_{(\alpha-\beta)}(x)$ is expressed as (9).

$$I_{(\alpha-\beta)}(x) = \sum_{m=0}^{\infty} \frac{1}{m!\Gamma(m+(\alpha-\beta)+1)}\left(\frac{x}{2}\right)^{2m+(\alpha-\beta)} \tag{9}$$

In order to simulate the effects of multipath fading in the channel, the simulation employs a tap model approach with delay lines and different tap points. In the process, the total fading effect on the transmitted signal was estimated. This estimation involves the computation of the total fading effect as a summation of the total powers in the individual taps. Thereafter, space-time coded signals are transmitted into the channel and the effect thereof is estimated upon arriving at the receiving end.

2.2. Space-time trellis code for free space optical communication link

Space-time trellis code (STTC) attempts to combine digital modulation schemes with trellis structures in order to attain full rate, full diversity as well as coding gain. The possibility of adopting STTC for multiple antennas is of particular interest to this work. This enables the transmission of information over multiple laser diodes through free space. In other words, space-time trellis codes are STCs adapted for multiple transmit laser diodes.

The fundamental purpose of a space-time trellis encoder is to utilize mapping functions that serve as representations of their corresponding trellis diagrams for mapping binary data to modulation symbols. In this study, we employ the specific space-time trellis code depicted in Efendi [29]. To ensure simplicity while preserving the desired MIMO configuration, two laser diodes were utilized. Consequently, the input bit stream $\boldsymbol{c}$ for the space-time trellis code, taking into account the presence of the two laser diodes, is expressed as (10).

$$c = (c_0, c_1, c_2, \dots, c_t, \dots) \tag{10}$$

The variable c_t represents a pair of information bits at a specific time instant, as defined in (11). By utilizing feedforward shift registers, the encoder converts the input bit array into a sequence of QPSK modulated signals, denoted as x_0, x_1, x_2, …, and so on. Each element in this array corresponds to the space-time symbol at a particular time *t*.

$$c_1 = (c_t^1, c_t^2) \tag{11}$$

The output x_t^i of the encoder for the i-th transmitter at time *t* is expressed, as introduced in [30], in (12). Thus, the STTC encoder translates the input bit stream into quadrature phase shift keying (QPSK) modulated symbols.

$$x_t^i = \sum_{k=1}^{m} \sum_{j=0}^{v_k} g_{j,i}^k c_{t-j}^k \text{ Mod } 2, \quad i = 1, 2 \tag{12}$$

The encoding structure and the decoding structure are illustrated in Figure 1. At the transmit end, the input bits are encoded according to the specified trellis structure and the generator matrix, the codewords are then transmitted into free space through the transmit lasers onto the receivers. At the other end of the system, the optical signal being received is combined and detected, and is forwarded for onward decoding using Viterbi algorithm. The original transmitted bit is thereby recovered and the error therein is evaluated.

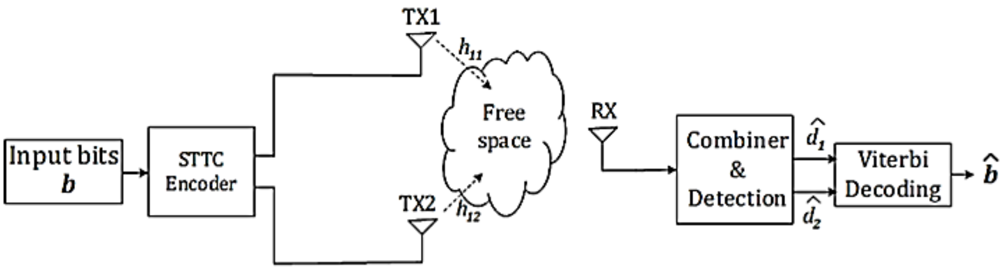


Figure 1. The encoding and decoding structure of the STTC FSO communication system

The parameters involved in the simulation of the space-time trellis coded free space optical communication system were as specified. The effect of different trellis structures of different states was investigated for this proposed turbulence mitigating scheme. These include the 16-state trellis structure and the 32-state trellis structure. The QPSK modulation scheme was integrated with the trellis structure. The parameters involved in the simulation of the space-time trellis coded free space optical communication system include a frame size of 10,000, a modulation type of QPSK at full rate, two laser diodes and one photoreceptor.

2.3. Truncation error analysis

Owing to the use of different mathematical series (binomial expansion and Taylors series) in the mathematical error rate analysis, a certain approximation error is introduced as a result of the truncations taken at various terms in other to make the solutions finite. This section attempts to estimate this error. If we represent the truncation error resulting from discarding all terms after the first J+1 terms as (13).

$$\varepsilon_{J,M} = \sum_{i=0}^{2L} \binom{2L}{i} \sum_{p=J+1}^{\infty} u_p(\alpha, \beta, i, M) \left(\frac{1}{\mu_M \bar{\gamma}}\right)^p \tag{13}$$

The function $u_p(.,.,.,.)$ is expounded into (14). The Taylor series expansion was combined with the identity expressed in (20). The limit analysis on the truncations error, the upper bound for the truncation error can therefore be expressed using (14) to (17).

$$u_p(x, y, i, M) = \frac{\varphi\left(p+2y+i(x-y), \frac{M-1}{M}\right)}{\pi} \times b_p(2L-i, i, x, y) \left(\frac{1}{\mu_M \bar{\gamma}}\right)^{2y+i(x-y)} \tag{14}$$

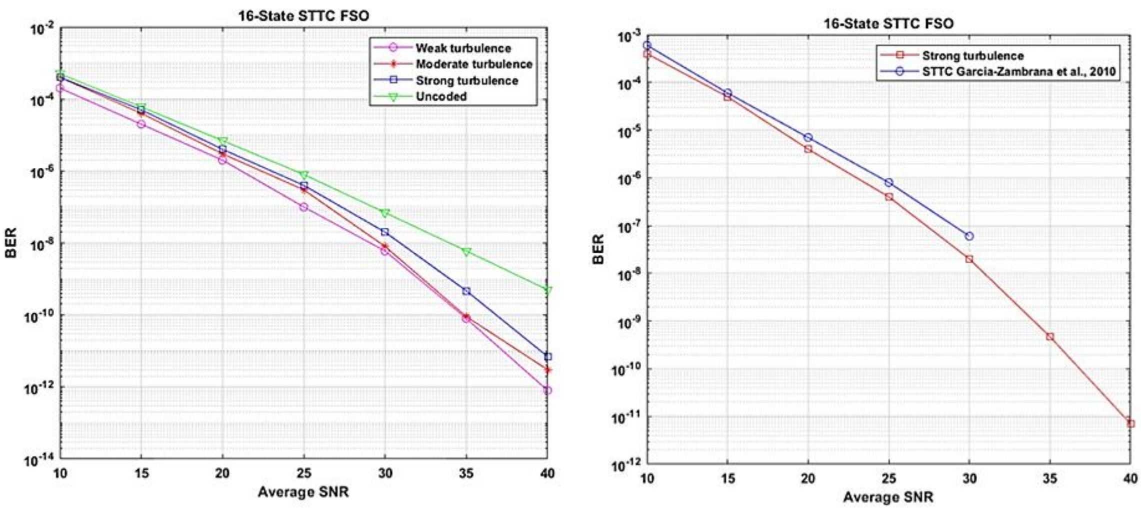
$$\frac{x^{J+1}}{(1-x)} = x^{J+1} + x^{J+2} + x^{J+3} + \cdots + x^{J+n+1} + \cdots, \tag{15}$$

$$\binom{2L}{i} = \frac{2L}{i!(2L-1)!} \tag{16}$$

$$\varepsilon_{J,M} \leq \frac{2}{\pi(\mu_M \bar{\gamma} - 1)} \left(\frac{1}{\mu_M \bar{\gamma}}\right)^J \sum_{i=0}^{2L} \frac{\max\limits_{p>J} \{u_p(\alpha,\beta,i,M)\}}{i!(2L-1)!} 1 \tag{17}$$

3. RESULTS AND ANALYSIS

The effect of space-time trellis code (STTC) in mitigating turbulence induced fading on free space optical communication links was investigated. This was done for weak turbulence, moderate turbulence and for strong turbulence. The performances of the space-time trellis coded FSO system under the above turbulence strength were evaluated against the uncoded FSO system and the results thereof are plotted in Figures 2(a) and 2(b).



(a) (b)

Figure 2. The performance of 16-State STTC for FSO link (a) under different turbulence strengths and (b) in comparison with performance from literature

The 16-state space-time trellis code performed well when compared with the uncoded system throughout the range of SNR. This performance of the space-time trellis coded FSO system becomes evident at higher SNR values where, at bit error rate of 10^{-8} for example, a coding gain of 5 dB was attained over the uncoded system. To further evaluate the performance of the STTC FSO system reported in Figure 2, the performances of the space-time trellis coded FSO system in this study were compared against a similar space-time trellis coded system as reported in [31]. To facilitate logical cross-comparison, this performance comparison was carried out over strong atmospheric turbulence. The STTC FSO code in the study slightly outperforms their reported system. At a bit error rate of 10^{-7} for instance, the STTC FSO in this study attains a coding gain of about 2 dB over the performance reported in [31]. This further underscores the importance of coding schemes such as the one proposed in this work and [32]–[35].

4. CONCLUSION

In this study, a space-time coded OFDM scheme has been developed for free space optical communication under gamma-gamma assumptions. Achieved by exploiting the spectral dimension through the integration of OFDM, the technique was able to mitigate the effect of turbulence-induced fading on transmitted optical signals as they propagate through free space. In addition, the proposed technique represents a way to enable us rapidly evaluate the channel behavior of gamma-gamma FSO links for space-time coded data transmission. The results obtained show easily and rapidly, the behavior of MIMO FSO links under given average SNR and turbulence conditions. This in-depth understanding of the channel response to different parameters affords designers the opportunity to design improved and efficient coding schemes to facilitate low error rates high speed wireless communication with enhanced reliability. All these are tailored towards realizing the full potential of FSO systems as an attractive solution to last-mile problems. In conclusion, free space optical communication offers numerous advantages as a promising technology. However, the presence of atmospheric turbulence poses a significant obstacle that must be overcome to fully harness the potential of this communication method. This article has presented a solution to tackle this challenge. By addressing the issue of atmospheric turbulence, we can pave the way for improved performance and reliability in free space optical communication systems. Through ongoing research and development, we can further refine and enhance this proposed approach, ultimately unlocking the full benefits of free space optical communication in various applications.

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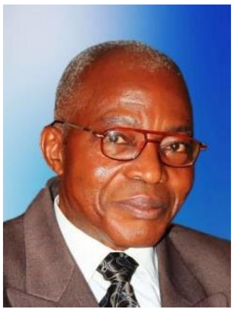

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