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Performance analysis of decode-and-forward dual-hop optical spatial modulation with diversity combiner over atmospheric turbulence

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ABSTRACT

Dual-hops transmission is a growing interest technique that can be used to mitigate against atmospheric turbulence along the Free Space Optical (FSO) communication links. This paper analyzes the performance of Decode-and-Forward (DF) dual-hops FSO systems in-conjunction with spatial modulation and diversity combiners over a Gamma–Gamma atmospheric turbulence channel using heterodyne detection. Maximum Ratio Combiner (MRC), Equal Gain Combiner (EGC) and Selection Combiner (SC) are considered at the relay and destination as mitigation tools to improve the system error performance. Power series expansion of modified Bessel function is used to derive the closed form expression for the end-to-end Average Pairwise Error Probability (APEP) expressions for each of the combiners under study and a tight upper bound on the Average Bit Error Rate (ABER) per hop is given. Thus, the overall end-to-end ABER for the dual-hops FSO system is then evaluated. The numerical results depicted that dual-hops transmission systems outperformed the direct link systems. Moreover, the impact of having the same and different combiners at the relay and destination are also presented. The results also confirm that the combination of dual hops transmission with spatial modulation and diversity combiner significantly improves the systems error rate with the MRC combiner offering an optimal performance with respect to variation in atmospheric turbulence, change in links average received SNR and link range of the system.

1. Introduction

Free Space Optical (FSO) communication systems are significantly gaining interest in the research community in recent times due to its various characteristics. These include less power consumption, cheap installation and operational cost, license-free spectrum, large bandwidth in the capacity of order of Terabytes/sec, high level of security and immunity to interference compare to Radio Frequency (RF) systems counterpart [1]. These great features make the system efficiently found applications in many areas such as backhaul services, fiber back-up, last mile access, high definition videos transmission, disaster recovery/temporary link among others [2,3]. However, with these great attributes, the performance of FSO system is highly vulnerable to adverse atmospheric turbulence which in turn induces fading. This is caused by the fluctuation in the refraction index as a result of inhomogeneous variation in temperature and pressure along the system link. This impairment becomes more pronounced especially over a distance of 1 km or more and degrades performance and availability of the link [4,5]. Several statistical models have been presented in the literatures to characterize the atmospheric turbulence on the FSO channel and these include lognormal distribution which is considered to give accurate results for weak turbulence conditions over a distance less than 1 km in range [6]. Also, negative exponential and K-distribution are usually used to model a very strong turbulence over several kilometers [7,8]. Gamma–Gamma distribution which was proposed by Al-Haban et al. as a multiplicative random process is usually employed to model turbulence ranging from weak to strong conditions [9,10].

To mitigate the degrading effect of atmospheric turbulence conditions on the FSO systems and to increase the link reliability, conventional On/Off Key (OOK) modulation is mostly adopted owing to its low cost and simplicity in practical implementation [11]. The drawback in this type of modulation is that it requires adaptive thresholds for optimal performance and usually prone to channel estimation errors [12]. Alternatively, Pulse Position Modulation (PPM) has been investigated for FSO link impairments in [13] but with poor bandwidth efficiency. To

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$$H_{mk}(t) = \left[h_1, h_2, \ldots, h_{N_t}\right] \triangleq \begin{bmatrix} h_{11}(t)\exp(j\phi_{11}) & h_{12}(t)\exp(j\phi_{12}) & \cdots & h_{1N_t}(t)\exp(j\phi_{1N_t}) \\ h_{21}(t)\exp(j\phi_{21}) & h_{22}(t)\exp(j\phi_{22}) & \cdots & h_{2N_t}(t)\exp(j\phi_{2N_t}) \\ \vdots & \vdots & & \vdots \\ h_{N_r1}(t)\exp(j\phi_{N_r1}) & h_{N_r2}(t)\exp(j\phi_{N_r2}) & \cdots & h_{N_rN_t}(t)\exp(j\phi_{N_rN_t}) \end{bmatrix} \quad (1)$$

Box I.

overcome this challenge, most of the recent studies proposed Subcarrier Intensity Modulation (SIM) as the best modulation scheme which can permit the use of other modulation techniques [14]. The idea of SIM is drawn from the well-known Orthogonal Frequency Division Multiplexing (OFDM) system where several data streams are modulated onto different RF subcarrier frequencies and the composite RF is used to modulate the laser irradiance [15]. However, this modulation yields a significantly higher transceiver complexity as the number of subcarrier increases and also causes poor optical average power efficiency due to the increase in the number of required DC biases [12,16].

Relay-assisted technology has recently been proposed as one of the promising powerful techniques in literatures to militate against impairments on FSO links [17]. This technique scales down the distance between the transmitter and receiver into two possibly shorter links through the relay hops and form a system called Dual-hops relay system [15]. The scheme has advantage of increasing the wireless systems coverage area to several kilometers without the needs of large power at the transmitter and relay units. It can also provide high data rate with low bit error at the end-to-end communication [18]. This concept was first explored by Acampora, and Krishnamurthy in [19], and few years later, the effectiveness of the relay system over a large coverage area was later studied in [20,21]. Generally, relay can be categorized into two protocols in order to reduce the problem of a single transmitter to reach its intended target with necessary Signal to Noise Ratio (SNR). This include Amplified-and-Forward (AF) or analog relaying which amplifies any incoming signal from the source and retransmits it to the destination forming a system called non-regenerative relay system. The other type is Decode-and-Forward (DF) or digital relaying that decodes any received signal from the source, re-encodes and then re-transmits the decoded information to the destination and forms a system called regenerative relay system [17,22,23].

Spatial Modulation (SM) has been known to be an efficient low complex Multiple Input Multiple Output (MIMO) technique compared with other conventional MIMO schemes such as spatial multiplexing (Vertical Bell Labs Layered Space-Time Architecture) and repetitive coding. During each time instant, SM makes use of the index of an activated antenna to convey information data while other antennas remain idle [24]. As a result of this, it has advantages of avoiding inter-channel interference, eliminating the needs of inter-antenna synchronization, and provides a robust system against channel estimation errors [24–26]. The concept of SM is recently proposed as migration technique in FSO communication system as it was found useful in [27–29] to improve the system error performance. Thus, based on our study, it shows that this type of modulation scheme has been investigated with relay technology mostly in RF wireless systems [30–34] but has not been taken into consideration in FSO systems. In many FSO research studies, Spatial Diversity (SD) combiner has been extensively used at the receiving end to militate against the effects of atmospheric turbulence induced fading in order to improve the signal strength over a long distance [35]. The most commonly used combiners to combine the signal from diversity branches include Maximum Ratio Combiner (MRC), Equal Gain Combiner (EGC) and Selection Combiner (SC) [36]. Thus, combining these two powerful techniques that is SM and SD with relaying technique can greatly improve the FSO systems BER, capacity and extend its coverage area. Recently, Dang et al. employ combiners at the relay unit and at destination in relay system to enhance the FSO system performance [37]. However, the modulation scheme understudied was PPM modulation with direct detection over gamma–gamma turbulence channel. To the best of our knowledge, the combination of SM and SD in the relay transmission system has not been investigated in FSO systems and even in wireless communication that uses RF. In this paper, we present the performance analysis of DF dual-hop optical spatial modulation with diversity combiner over Gamma–Gamma atmospheric turbulence. Spatial diversity combiner is considered both at the relay and destination terminals. We first derived the end-to-end APEP for each diversity scheme as a power series expression and the ABER per hop is obtained through union bound technique. The end-to-end average error probability for the system is then analyzed.

The remainder of this paper is organized as follows: Section 2 presents the system and channel model. In Section 3, we discuss the performance analysis of End-to-End ABER together with the analysis of APEP over a Gamma–Gamma Channel for each diversity combiner in Sections 3.1–3.3. Numerical and simulation results for the system performance, with their interpretation are presented in Section 4. Finally, the concluding remarks are outlined in Section 5.

2. System and channel models

2.1. System model

In this paper, we consider a dual-hop heterodyne FSO relaying system consisting of a Source (S), Relay (R) and Destination (D) as presented in Fig. 1 and the comprehensive description of each unit is shown in Appendix. Since we are considering spatial modulation (SM), the scheme requires that the transmitter should have more than one laser. In this case, source and relay systems are considered as transmitting node that is $m \in \{S, R\}$ and at the same time provided with N_t^m transmit laser in which only one is active at any transmitting instant to convey SM signal. Also, the relay and the destination are regarded as receiving nodes that is $k \in \{R, D\}$ and equipped with N_r^k received photo-detector diodes ($N_r^k \geq 1$) for heterodyne detection. In this system, the transmission of SM signal occurs in two phases. In the first phase, a block of B bits that is $B = \log_2\left(N_t^s M\right)$ is mapped into a constellation vector $X = \left[x_1, x_2, x_3 \ldots x_{N_t^s}\right]^T$ at the source and M is the constellation size. The first group of these bits $\log_2\left(N_t^s\right)$ is used to identify the active transmit laser index lth while the remaining $\log_2(M)$ bits are employed to indicate the BPSK modulation symbol x_p from the pth signal constellation generated by March–Zehnder Modulator (MZM) for the transmission. At an instant, the information bits are modulated on the electric field of an optical beam as $x_p^s \exp(j\phi_{x_p})$ and are then emitted from the active transmit-laser index l over the $N_r^k \times N_t^m$ MIMO atmospheric turbulence channel defined as [28] Eq. (1) is given in Box I: where $h_{l,n}^m$ and $\phi_{l,n}^m$ are the real positive fading gain and the phase of channel respectively between the lth activated transmit laser and the nth receiver aperture. Thus, the source transmits the SM signal during this phase over the optical channel as [38]:

$$X_{lp}^m = \Big[\, 0\ 0\ \cdots\ \underbrace{x_p^m \exp(j\phi_{x_p})}_{l\text{th laser position}}\ \cdots\ 0\ 0 \,\Big]^T. \quad (2)$$