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Two-by-two user grouping for enhanced multipoint-to-multipoint Free-Space Optical communications with Pulse Position Modulation

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ABSTRACT

In this paper, we consider the scenario of N collocated users communicating over Free-Space Optical (FSO) channels. We propose a novel cooperation scheme where the users are grouped together in groups of two for the sake of achieving enhanced diversity orders in a simple manner. In this context, instead of communicating independent binary Pulse Position Modulation (PPM) symbols over each of the N available links in a non-cooperative manner, the information from the different users will be combined and encoded in a joint manner. We propose a method for performing the joint encoding and we propose the structure of the 4-ary augmented constellation to be associated with the proposed cooperation scheme. A performance analysis is conducted over gamma-gamma channels reflecting the capability of the proposed scheme in enhancing the diversity order for all levels of background radiation. In particular, we prove that the diversity order is enhanced by the factor $\lfloor \frac{N}{2} \rfloor + 1$.

1. Introduction

Recently, there has been a growing interest in the Free-Space Optical (FSO) communication technology. The license-free FSO transmissions can deliver high data rates over few kilometers and the FSO solution is particularly appealing in situations where it is hard to install optical fibers. While FSO is a promising technology, it is particularly vulnerable to weather conditions that can have a detrimental effect on the link availability. Weather conditions manifest particularly in turbulence-induced scintillation or fading where the received optical power fluctuates in a significant manner severely degrading the system performance. This motivates the investigation of fading mitigation techniques as a means of boosting the reliability of FSO communications.

The literature on FSO fading mitigation techniques is very rich. The investigated solution include the well known multiple-input–multiple-output (MIMO) techniques where several optical apertures are placed at the transmitter and/or receiver sides for the sake of realizing enhanced diversity gains [1–7]. Space-time coding techniques [3], repetition coding with diversity combining [4,5], transmit laser selection [6] all constitute feasible options for exploiting the spatial diversity of the underlying optical channel is a collocated manner. The bit-error-rate performance of MIMO FSO links was carried out in [7] for gamma-gamma fading channels with pointing errors.

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In addition to the collocated MIMO diversity methods, relaying techniques were extensively investigated in the context of FSO communications as a means of exploiting the channel spatial diversity in a distributed manner owing to the presence of multiple users in the wireless network. Several types of FSO relaying, or FSO user-cooperation, were studied in the literature. Serial relaying constitutes a viable solution for extending the coverage of the FSO network [8,9]. In this context, the signal is retransmitted sequentially from one relay to another until it reaches the destination. On the other hand, FSO parallel relaying was also extensively considered for the sake of achieving enhanced diversity gains [10–15]. For such systems, the information message is first transmitted from the source to the relays and, in a second time slot, the relays retransmit this message to the destination node. Both Decode-and-Forward (DF) [10] and Amplify-and-Forward (AF) [11] cooperation can be envisaged. Moreover, all-active relaying constitutes a simple and efficient solution in the absence of channel state information (CSI) [12] while selective relaying is known to achieve enhanced coding gains in the presence of full CSI [13]. While for all-active relaying the power is evenly split among all available FSO links, only the best end-to-end link is selected in the case of selective-relaying thus making a better use of the available transmit power. The performance of selective-relaying over lognormal fading channels was evaluated in [14] while the MIMO and the relaying techniques were compared in [15] under gamma-gamma turbulence induced fading. In addition to the two-phase parallel-relaying protocols, inter-relay cooperation was proposed and analyzed in [16]. This constitutes a three-phase communications protocol comprising the source-relay, relay-relay and relay-destination phases. In this context, the relay-relay phase was added for the sake of enhancing the chances of correct packet detection at the relays prior to the retransmission toward the destination node. Two variants of the inter-relay cooperation protocols were envisaged; namely the forward and forward-backward cooperation. It was also proven in [16] that inter-relay cooperation is not useful for all networks. Moreover, hybrid parallel-serial relaying where each one of the parallel links compromises a certain number of hops was considered in [17]. Finally, the problem of two-way FSO relaying was considered in [18] where iterative multiuser detection was implemented at the receiver. In addition to the numerous theoretical and numerical studies on relay-assisted FSO systems, experimental evaluations of all-optical AF relay-assisted dual-hop and triple-hop FSO systems were carried out in [19,20], respectively.

While [8–17,19,20] considered the problem of one source node communicating with one destination node, multiuser FSO transmissions were studied in [21–23]. For such point-to-multipoint systems, a central node communicates with N distinct users along N parallel FSO channels. This is also referred to as opportunistic scheduling where the user with the best channel is selected for reception [21–23]. In case where the best channel is unavailable for numerous network conditions, the nth best channel is selected as an alternative option. On the other hand, multipoint-to-multipoint FSO communications were proposed and analyzed in [24,25]. These references considered the scenario of communications between two buildings where multiple FSO transceivers are installed for establishing the wireless connectivity between different users. N-user multipoint-to-multipoint FSO systems where studied in [24] in the case of pulse amplitude modulation (PAM) for non-coherent systems corrupted by additive Gaussian noise. On the other hand, two-user multipoint-to-multipoint communications were studied in [25] for binary Pulse Position Modulation (PPM) in systems that are corrupted by the Poisson shot noise. In this case, an augmented 4-ary PPM constellation is designed where the generated symbols are transmitted along the best channel (out of the two available channels).

In this paper, we consider the problem of multipoint to multipoint FSO communications with any number of users. Unlike Abou-Rjeily [24] that considers PAM with Gaussian noise, this work targets PPM with shot Poisson noise. A similar system model was considered in [25] for two users and this work extends the results of Abou-Rjeily [25] to the case of N users. Moreover, while only Selection Combining (SC) was analyzed in [25], this work compares SC with Equal Gain Combining (EGC). The solution that we propose in this paper is based on a simple and efficient two-by-two user grouping where the nth weakest channel is associated with the nth strongest channel for the sake of more reliable communications. In this context, a 4-ary symbol that is carved from an extended PPM constellation is simultaneously transmitted along the above pair of channels where the detection of only one of the two available replicas at the receiver is sufficient for extracting the two information bits of the two involved users.

We provide an asymptotic analysis of the average bit error rate (BER) over gamma-gamma fading channels and we derive the achievable diversity orders under different levels of background noise. The main challenges in the proposed analysis are twofold. (i) The two combined channels are dependent based on the performed channel ordering. This complicates the analysis with EGC that calls for evaluating the pdf of the summation of the involved channel irradiances. (ii) The exact BER expression (with the proposed augmented PPM constellation) takes a very complicated form that is not suitable for a subsequent asymptotic analysis. In this context, an additional contribution of the paper resides in proposing upper and lower bounds that have the same asymptotic slope as the exact BER curve. This is a critical calculation steps that relates the achievable diversity gain to the gain that is derived from the proposed bounds.

2. Preliminaries: single-user communications

First, we consider the single-user scenario where communications occur between one pair of FSO transceivers. These transceivers are separated by a distance d and the corresponding optical channel is subject to fading/scintillation. We adopt

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