OAM Mode Selection and Space-Time Coding for Turbulence Mitigation in FSO Communications

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Abstract—Free space optical (FSO) communications using orbital angular momentum (OAM) modes has recently received a considerable interest. Propagating OAM modes through free space may be subject to atmospheric turbulence (AT) distortions that cause intermodal crosstalk and power disparities between OAM modes. In this article, we are interested in $2 \times 2$ multiple-input multiple-output (MIMO) FSO coherent communication systems using OAM. We propose a selection criterion for OAM modes to minimize the impact of AT. To further improve the obtained performance, we propose a space-time (ST) coding scheme at the transmitter. Through numerical simulations of the error probability, we show that the penalty from AT is completely absorbed for weak AT and considerable coding gains are obtained in the strong AT regime.

Index Terms—Orbital Angular Momentum, Free space Optics, Space-Time Coding, MIMO

I. INTRODUCTION

In analogy to mode division multiplexing (MDM) in optical fibers where several spatial modes are used for multiplexing, orbital angular momentum (OAM) multiplexing is proposed as a versatile technique to transmit multiple signals over free space channels [1], [2]. OAM modes are orthogonal which makes them suitable to co-propagate and carry independent data streams in free space. Laboratory demonstrations have shown beyond 1 Pbit/s free space transmission with a spectral efficiency exceeding 100 bit/s/Hz using 26 modes [3]. Such transmission performances have never been reached with any other communication technique. However, in real-life communication scenarios, transmitted OAM beams are subject to atmospheric turbulence (AT) in which the refractive index of the air experiences spatial variations. The propagation of OAM beams in turbulent atmosphere leads to phase-front distortions as well as beam spread and wandering. Furthermore, the power of a signal carried by a particular OAM mode is spread to other modes which results in modal crosstalk. The latter is mode dependent and engenders the break of orthogonality between OAM modes resulting in loss disparities known as mode-dependent loss (MDL) that causes performance degradations at the system level [4]. Several techniques have been proposed to mitigate turbulence-induced aberrations in free space. Turbulence mitigation can be either performed at the beam level by using adaptive optics (AO), or by digital signal processing (DSP) such as channel coding and channel equalization techniques. AO aims at correcting the deformations of an incoming wavefront by deforming a mirror, or by controlling a liquid crystal array in order to compensate for aberrations. In [5], pre- and post-compensation based on AO allowed to reduce the crosstalk by more than 12 dB. For DSP approaches, MIMO equalization associated with heterodyne detection was shown to mitigate turbulence-induced crosstalk for 4 OAM beams carrying 20 Gbit/s QPSK signals in [6]. In [7], the authors proposed a half-rate Alamouti space-time (ST) code and a vertical Bell labs layered ST (V-BLAST) code along with a sub-optimal zero-forcing channel equalization. The previous AO and DSP solutions were shown to significantly improve the bit-error rate (BER) in the presence of AT. Nonetheless, in all the previous studies, MDL was not taken into consideration. Though even after compensation OAM modes still have different performances.

In this work, we focus on the effect of MDL caused by atmospheric turbulence. We show that the amount of MDL dependents on the OAM modes considered for multiplexing. Therefore, the BER is improved by selecting the OAM modes that minimizes the MDL. At the receiver, a maximum likelihood (ML) detection is used for optimal decoding performance. The proposed selection method completely absorbs the signal to noise ratio (SNR) penalty in weak turbulence conditions. For the strong turbulence regime and to further enhance the obtained performance, a full-rate full-diversity ST coding at the transmitter is proposed. The ST coding scheme brings more than 2.4 dB gain.

This article is organized as follows: First, spatial multiplexing using OAM in free space and the
II. ORBITAL/angular momentum multiplexing

A lightwave carrying an OAM of $\ell h$ per photon is a wave with a helica phase-front induced by an azimuthally varying phase term $\exp(i\ell \phi)$, where $\ell$ is an unbounded integer known as the topological charge, $\phi$ is the azimuth and $h$ is the reduced Planck constant. ‘Orbital’ angular momentum should not be confused with ‘spin’ angular momentum that is associated with circular polarization and could have two possible states ‘right-handed’ and ‘left-handed’ circularly polarized. To realize OAM multiplexing, single and superpositions of orthogonal beams that have a well defined vorticity can be used including Hermite-Gaussian (HG) beams, Ince-Gaussian beams, Bessel-Gaussian beams and Laguerre-Gauss (LG) beams. In this work, we are interested in OAM carrying beams derived from LG modes [8].

A representation of a $2 \times 2$ MIMO OAM FSO transmission system is shown in Fig. 1. Generation of OAM beams in practice can be realized through different techniques including spiral phase plates (SPPs), q-plates, metamaterial structures, compact devices and computer generated holograms (CGHs) programmed on a spatial light modulator (SLMs). A SPP is an optical element having the form of spiral staircases that shapes an incident Gaussian beam into a twisted beam with a helical phase front. One SPP allow the generation of a single OAM mode with a particular topological charge in a stable and efficient manner. An SLM can be dynamically addressed to change a digital hologram printed on an LCD screen to generate single and superposition of OAM beams in a wide wavelength range from an incident Gaussian beam. At the receiver side, the inverse operation can be performed using the same device to transform an incoming OAM mode back to a Gaussian like beam. The idea is to apply an optical scalar product measurement between the incident OAM beam and a CGH with the conjugate phase at the image plan of a Fourier transforming lens. The produced beam can be coupled to a single mode fiber of a coherent detector or to a conventional photodiode in an intensity modulation and direct detection (IM/DD) scheme to recover the originally encoded signal. The vorticity of OAM beams propagating in a FSO media without atmospheric turbulence is preserved and OAM beams maintain orthogonality as they propagate and thus OAM multiplexing can be considered as a degree of freedom to increase the capacity of FSO systems. Consequently, it is possible to filter and decode each orthogonal channel at the receiver.

OAM propagation in turbulence

The propagation of OAM modes can be affected by atmospheric turbulence induced distortions [4]–[7]. Atmospheric turbulence is related to the weather conditions, and is mainly caused by snow, rain, fog and wind loads. Pressure and temperature fluctuations in the atmosphere result in an additional random behavior in the atmospheric refractive index. Due to AT, the power of an initially OAM mode leaks to other modes including the ones unused for multiplexing. This phenomenon causes signal overlapping as well as different losses experienced by OAM modes.

To emulate atmospheric turbulence, random phase screens can be placed along the FSO channel (see Fig. 1). These phase screens are generated based on the modified Von Karman spectrum. The strength of the turbulence in a FSO channel is given by the Rytov variance defined as $\sigma_R^2 = 1.23C_n^2(2\pi/\lambda)^{7/6}z^{11/6}$, where $C_n^2$ represents the refractive index structure parameter, $\lambda$ is the carrier wavelength and $z$ the propagation distance. We note that for $\sigma_R^2 < 1$ ($\sigma_R^2 > 1$), the system is operating under a weak (strong) turbulence regime. The phase of an OAM beam with a topological charge $\ell = +1$ and the corresponding mode purity...
Fig. 2: Phase distortion for OAM mode $\ell = +1$: (a): AT-free, (b): weak AT, (c): strong AT. Received optical power per OAM mode: (d): AT-free, (e): weak AT, (f): strong AT.

In Figs. 2(b) and 2(c), we show the phase distortions of OAM state $\ell = +1$ at different turbulence regimes after 1 km of propagation. For a weak turbulence regime (see Fig. 2(b)), the phase of the OAM is affected but can still be recognizable. In this case, the spread of optical power to other OAM modes is low (Fig. 2(e)). However, for a strong turbulence regime (Fig. 2(c)), we can clearly see that the phase of the electromagnetic field is severely impacted. This results in a wide spread and a considerable power leakage to other OAM modes (Fig. 2(f)).

In addition to crosstalk, the break of the orthogonality between OAM states due to AT causes transmitted modes to have different losses. This phenomenon is known as mode-dependent loss and can be measured by the ratio of the maximum received power to the minimum received power. MDL was intensively studied for few-mode fibers and multi-core fibers optical communications [10] and was shown to be the main capacity and performance limiting factor. In OAM FSO communications, MDL was only investigated in the case of laterally displaced OAM beams [11]. In the next section, we show that MDL also reduces the performance of OAM FSO systems. Moreover, the selected OAM modes for multiplexing determines the level of MDL of the MIMO system.

III. OAM MODE SELECTION

Given that $M$ OAM modes are available for multiplexing, we aim to select the set of OAM modes $M_T < M$ that gives the best performance in term of the error probability. At the receiver side, we only detect the transmitted modes, so $M_R = M_T$. Spatial diversity can be obtained by detecting more OAM modes (i.e. $M_R > M_T$) by using a maximum ratio combining technique but at the cost of more hardware complexity [9]. In this work, we set $M_R = M_T = 2$ and we aim to find the set of OAM modes $(p, q)$ that makes the $2 \times 2$ MIMO channel have the lowest mode-dependent loss.

To have an insight on the proposed selection strategy, we compute the average MDL for different $2 \times 2$ channels. We simulate the propagation of OAM beams at a wavelength $\lambda = 850$ nm for a propagation distance $z = 1$ km. Propagation through the turbulent atmosphere is simulated using the commonly used split-step Fourier method, where turbulence is emulated by random phase screens placed every 50 m along the propagation path. For weak and strong turbulence regimes, we consider two values of the refractive index structure $C_n^2 = 10^{-14}$ and $C_n^2 = 10^{-13}$, respectively.

In Fig. 3(a) and 3(b), the average MDL is shown for all possible combinations of $p$ and $q$ in the
range \{-10, -9, \ldots, +9, +10\}. For both the weak and strong AT regimes, the minimum values of the average MDL were found for OAM modes having opposite topological charges \((p = -q)\) (see anti-diagonal elements in Fig. 3). Moreover, for OAM modes satisfying the previous condition, the MDL decreases as the topological charge increases. Hence, the lowest MDL corresponds to the set \((-10, +10)\).

To examine the efficiency of the proposed mode selection approach on the error probability performance, we consider a \(2 \times 2\) transmission with different OAM sets where in each set modes have opposite topological charges \((p = -q)\). At the transmitter, bits are modulated to form QPSK symbols that are sent on the two co-propagating modes. At the receiver, an ML decoder is implemented. In Fig. 4 and Fig. 5, we plot the BER as a function of SNR for different sets of OAMs in the weak and strong turbulence regimes. The atmospheric turbulence-free case is also plotted as a reference. For both figures, we notice that the BER decreases as the topological charge \(p\) increases and the optimal performance is reached for the set \((-10, +10)\). For weak atmospheric turbulence, as depicted in Fig. 4, the same set completely absorbs the AT penalty. The obtained results, show that the choice of the OAM modes based on the minimization of the MDL is an accurate criterion to obtain the best error probability performance. However, as can be seen from Fig. 5, in the strong turbulence regime, the optimal OAM set could not completely compensate for AT. To further enhance the obtained performance, we propose to add a space time-coding scheme at the transmitter.

IV. SPACE-TIME CODING

Space-time codes were originally designed for MIMO wireless communications to bring coding gain and achieve a full diversity at the transmitter side. Recently, ST coding was also investigated for optical communications and was demonstrated to be efficient in mitigating non-unitary effects in polarization multiplexed systems [12] and also in few-mode fibers [13]. The principle of ST coding consists in sending a coded linear combination of modulated symbols during several channel uses. At the receiver side, the same signal is received on all modes, this allows the ML detector to retrieve the data from different copies attenuated differently by AT and hence gives a better estimate. Different ST code families have been designed for wireless MIMO channels. We particularly focus here on the space time block codes (STBC). A STBC is characterized by its generator matrix \(G\) and the transmitted codeword matrix \(X_{M_T \times T}\).

The latter is obtained by the multiplication of \(G\) by the symbols vector \(S_{M_T \times 1}\) followed by an arrangement operation. For a \(2 \times 2\) MIMO channel, and during two channel uses \((T = 2)\), a ST codeword matrix uses 4 modulated symbols to achieve a full-rate transmission. In our analysis, we use the Golden code [14] and the Silver code [15] which are the two best ST codes satisfying a full-rate, full diversity and optimal coding gain.

To have an insight on the performance of ST coding on OAM FSO-based transmission over a turbulent channel, we compare ST coded transmissions using the Golden and Silver codes and the uncoded transmission. A QPSK constellation was used to construct the codewords of the ST codes. In Fig. 6, we plotted the BER curves versus the SNR for the strong AT regime. We notice that the Golden code outperforms the Silver code. The coding gain
brought by the Golden code is 2.2 dB comparing to the uncoded scheme and hence the SNR gap to the turbulence free channel is reduced to 2.6 dB.

Fig. 4: BER versus SNR for different OAM sets in the weak AT regime.

Fig. 5: BER versus SNR for different OAM sets in the strong AT regime.

V. CONCLUSION

In this article, we have shown that an optimal selection of OAM modes is relevant to improve the performance of OAM FSO systems over turbulent atmosphere. The selection criterion is based on the minimization of the average MDL and no algorithm is required to update the set of optimal OAM modes. Hence, it is a low cost complexity solution that can be integrated to real time systems. In our simulations, we have considered an ML decoding strategy to obtain the optimal performance. Nonetheless, sub-optimal decoders with lower complexity can also be used. To further mitigate the atmospheric turbulence effect on FSO transmission, we proposed a ST coding scheme at the transmitter. We showed that AT was completely mitigated in the weak turbulence regime and important coding gains were obtained in the strong turbulence regime. Future works will extend higher dimensional MIMO systems as well as experimental validation of the proposed techniques.

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