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Turbulence mitigation scheme based on spatial diversity in orbital-angular-momentum multiplexed system

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ABSTRACT

Atmospheric turbulence (AT) induced crosstalk can significantly impair the performance of free-space optical (FSO) communication link using orbital angular momentum (OAM) multiplexing. In this paper, we propose a spatial diversity (SD) turbulence mitigation scheme in an OAM-multiplexed FSO communication link. First, we present a SD mitigation model for the OAM-multiplexed FSO communication link under AT. Then we present a SD combining technique based on equal gain to enhance AT tolerance of the OAM-multiplexed FSO communication link. The numerical results show that performance of the OAM-multiplexed communication link has greatly improved by the proposed scheme. When the turbulence strength C_n^2 is 5×10^{-15} m$^{-2/3}$, the transmission distance is 1000 m and the channel signal-to-noise ratio (SNR) is 20 dB, the bit-error-rate (BER) performance of four spatial multiplexed OAM modes $l_m = +1, +2, +3, +4$ are 3 fold increase in comparison with those results without the proposed scheme. The proposed scheme is a promising direction for compensating the interference caused by AT in the OAM-multiplexed FSO communication link.

1. Introduction

Orbital angular momentum (OAM) can increases both channel capacity and spectral efficiency effectively by exploiting the orthogonality phenomenon among different OAM modes [1–3]. However, one limitation of free-space optical (FSO) communication link is known as the atmospheric turbulence(AT) induced signal degradation. The purity of an OAM mode is susceptible to spatial aberrations caused by AT [4–7]. Consequently, AT causes errors for crosstalk among different OAM modes [8–10]. Subsequently, several methods have been presented to mitigate the crosstalk caused by atmospheric turbulence in the OAM-multiplexed FSO communication link [11–15]. In addition, we also proposed a multiple-user detection (MUD) mitigation to increase the performance of OAM-multiplexed FSO communication link through AT [16].

However, optical links with the gigabit transmission rate exhibit high temporal correlation [17] and the performance of FSO communication link severely suffers from turbulence-induced fading [18]. Spatial diversity (SD) [19–21] technique provides an effective receiving method for the signals transmitting through different fading channels. SD is the best method to overcome multipath fading in mobile communication. In addition, SD compensate for fading channel loss. Without increasing the transmission power and bandwidth, the performance of the mobile communication system can be significantly improved. It has been verified that it is an effective way to mitigate multipath interference and fading effect in wireless communication systems [22]. At the receiving end, diversity gain can be obtained by combining techniques. Currently, a lot of combining techniques have been designed to obtain the optimum sending information, such as the selective diversity combining [23], switched diversity combining [24], maximum ratio combining [25], and equal gain diversity combining [26].

The OAM-multiplexed FSO communication link also suffers from turbulence-induced fading. In this paper, we present a turbulence fading mitigation scheme based on SD idea in the OAM-multiplexed FSO communication link. Here, the OAM-multiplexed FSO communication link with AT is similar to the multipath fading channel in multiaerial system. The authors proposed the spatial diversity combined with MIMO equalization turbulence mitigation [27]. Different to [27], our spatial diversity is based on equal gain strategy which theoretically provides better performance.

Since that, it is possible to provide the better performance of the spatial diversity by employing the equal gain strategy. Therefore, in

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our proposed scheme, an SD mitigation scheme model for the OAM-multiplexed FSO communication link disturbed by AT is considered. In order to characterize the superiority of our proposed scheme, the theoretical analysis is given in the following. Last the performance of the OAM-multiplexed communication link is discussed with and without the proposed SD mitigation scheme.

The rest of this paper is organized as follows. In Section 2, the theoretical analysis of the SD mitigation scheme model for the OAM-multiplexed FSO communication link disturbed by AT is described in which, the objective problem can be efficiently solved by using the equal gain diversity combining method. In Section 3, after introducing the simulation environment of the turbulence model and the SD mitigation scheme, the performance of the OAM-multiplexed FSO communication link is discussed with and without the proposed turbulence mitigation scheme. Finally, Section 4 concludes this paper.

2. A turbulence mitigation scheme based on SD in the OAM-multiplexed FSO communication link

In this section, an SD mitigation model for the OAM-multiplexed FSO communication link disturbed by AT is presented. Subsequently, the equal gain diversity combining method is used at the receiver to obtain the sending signals transmitted through AT.

2.1. The equivalent model of OAM-multiplexed FSO communication link through atmospheric turbulence

The schematic diagram of an SD mitigation model for the OAM-multiplexed FSO communication link disturbed by AT is shown in Fig. 1. In the proposed system model, we assume that each user has an input bit stream while each input is an information-carrying Gaussian beam with planar phase front in a multilevel amplitude/phase modulation format. A coaxially placed spiral phase plate in an *OAM mode converter* transfers the input planar phase front to a helical one which results in the generation of an OAM spatial mode carrying a special azimuthal index l (also calling OAM topological charge) [28]. Different OAM spatial modes are mutually orthogonal in principle and have different aperture radius [29]. Subsequently, N OAM beams each carrying a user's signal $s_i(t)$, for $i \in 1,\ldots,N$, are multiplexed to a superposition OAM mode beam in an *OAM mode multiplexer* and the superposition OAM mode beam is transmitted through M apertures. Here, M aperture pairs should be separated by a distance larger than atmospheric turbulences coherent length (Fried's parameter $r0$). Therefore, the spatial separation between M aperture pairs could ensure not only OAM multiplexed beams experience independent atmospheric turbulence effects, but also the feasibility of the mitigation scheme. Due to the beam transmit through different apertures have inter-crosstalk, the SD mitigation scheme is used. So the superposition OAM mode beam transmit through the *M Atmospheric Turbulence Channel* with additive white Gaussian noise (AWGN). Each atmospheric turbulence channel is with the self-AT due to the random characteristics of atmospheric turbulence. Consequently, for different atmospheric turbulence channels, the received superposition OAM mode beam is different, and the random crosstalk is introduced. It is similar to the multipath fading channel. The signal transmitting through different fading channel has the different influence. Then after each atmospheric turbulence channel, the superposition OAM mode beam is received by M apertures. From each aperture, the received beams are demultiplexed in *OAM Mode Demultiplexer* and N demultiplexed OAM beams are obtained. After that, N demultiplexed OAM beams are changing back to N users' signals $y_{m1}, y_{m2}, \ldots, y_{mN}, m \in 1,\ldots,M$. Here M is the number of atmospheric turbulence channels. Due to different atmospheric turbulence channel has different influence in users' signals, an equal gain diversity combining method is used to mitigate the AT influence on OAM-multiplexed FSO communication link. After *OAM Mode Spatial Diversity Combining Receiver*, the corrected users' signals $\hat{s}_k(t), k \in 1,\ldots,N$ are get.

The theoretical analysis of the SD mitigation scheme model is presented as following.

Laguerre–Gaussian (LG) mode beam is found to have a well-defined orbital angular momentum [30]. Since that LG modes are a complete basis set of orthogonal functions, any beams can be expressed by the combination of LG modes. Consequently, the leakage of OAM mode caused by AT could be expressed by the decomposition of each deformed received OAM mode on its adjacent modes by using LG modes [8] as follows

$$LG_l(r,\theta) = \sqrt{\frac{2p!}{\pi(p+|l|)!}}\frac{1}{w_0}\left[\frac{r\sqrt{2}}{w_0}\right]^{|l|} \times L_p^l\left[\frac{2r^2}{w_0^2}\right]\exp\left[\frac{-r^2}{w_0^2}\right]\exp(-il\theta), \tag{1}$$

where r is the radial distance from the propagation axis, θ is the azimuthal angle, and w_0 is the radius of the zero-order Gaussian beam at the waist, and $L_p^l(\cdot)$ represents the generalized Laguerre polynomial, p refers to the number of radial nodes of the mode in the intensity distribution, and l refers to the topological charge number.

Hence, the multiplexed OAM beams in Fig. 1 which containing N mutually orthogonal OAM modes could be expressed as

$$U_{MUX}(r,\theta,t) = \sum_{i=1}^{N} s_i(t) LG_{l_i}(r,\theta), \tag{2}$$

where $s_i(t)$ is the ith user's information, $LG_{l_i}(r,\theta)$ is the ith user's modulation spatial channel mode with topological charge l_i.

When the multiplexed OAM beams transmit through the free-space optical communication link, the turbulence aberration is occurred. Here, the same multiplexed OAM beams transmit through M different atmospheric turbulence channels. And in each channel, a thin sheet phase screens of Kolmogorov model is used to simulate the aberration. The spatial variation caused by AT can be approximated by several thin sheets with random phase screen $\varphi(r,\theta)$ that modify the phase profile of the propagating beam [31]. Transmitting through each atmospheric turbulence channel, the output of the mth channel, where $m \in 1,\ldots,M$, can be considered as

$$U_{MUX}^{om}(r,\theta,t) = U_{MUX}(r,\theta,t)\cdot e^{i\varphi_m(r,\theta)} + n_m(t), \tag{3}$$

where $\varphi_m(r,\theta)$ is the mth atmospheric turbulence channel's random phase screen, $n_m(t)$ is the mth channel's AWGN noise. Atmospheric turbulence is the inordinance random motion, and the pressure, velocity, temperature and other physical characteristics of turbulence at every point fluctuate randomly. Even though the same multiplexed OAM beams transmit through M atmospheric turbulence channels, the output deformed multiplexed OAM beams of each atmospheric turbulence channel are different. This is similar to the spatial diversity in multipath fading channel, so the SD combining technique has been designed to mitigate the AT influence on the OAM multiplexed system.

Before the SD combining technique, the deformed multiplexed OAM beams should be converted to user's signal $y_{mk}(t)$ by *OAM Mode Demultiplexer* and *OAM Mode Converter*, where $m \in 1,\ldots,M$ and $k \in 1,\ldots,N$. $y_{mk}(t)$ is defined as

$$y_{mk}(t) = \int\int U_{MUX}^{om}(r,\theta,t)\cdot LG_{l_{mk}}^{*}(r,\theta) r dr d\theta, \tag{4}$$

where $LG_{l_{mk}}(r,\theta)$ is the mth AT channel's kth received OAM mode with topological charge l_{mk}, and $LG_{l_{mk}}^{*}(r,\theta)$ is a conjugate of $LG_{l_{mk}}(r,\theta)$. Due to $U_{MUX}^{om}(r,\theta,t)$ are the multiplexed OAM beams $U_{MUX}(r,\theta,t)$ transmitting through atmospheric turbulence channel, $U_{MUX}^{om}(r,\theta,t)$ are the deformed multiplexed OAM beams. So the received signal $y_{mk}(t)$ of kth user in the mth AT channel has interference crosstalk suffers from turbulence-induced fading.

Next the OAM mode spatial diversity combining method is used to mitigated the interference crosstalk suffers from AT. Here the equal gain diversity combining method is used to increase the performance