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Influence of strong anisotropic turbulent atmosphere on single photons carrying orbital angular momentum states

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ABSTRACT

We model the effective spectrum of anisotropic and weak to strong turbulence of terrene-atmosphere based on the modified Rytov approximation. The normalized probability of the orbital angular momentum (OAM) states and channel capacity of the communication link are established by this effective spectrum. Our results reveal that the effects of anisotropic turbulence on the normalized probability of the OAM states and the channel capacity of link are less than the isotropic turbulence. This result provides additional support for anisotropic turbulence having less influence on beam propagation than the isotropic turbulence, especially in the strong fluctuation region. The effect of the turbulent anisotropy on the channel capacity in low dimension number of Hilbert space is larger than that in high dimension number of Hilbert space.

1. Introduction

Recently, photons carrying orbital angular momentum (OAM) have raised interest for their use in free-space optical communication, because of OAM offering the higher capacity in optical communication. However, the turbulent aberration caused by the atmosphere has a considerable effect on the spatial structure nature of OAM states [1]. Many research results have reported on the impact of isotropic turbulence on the OAM state of photons in the atmospheric optical communication channel by employing the encoding of Laguerre-Gaussian (LG) models [1–9]. In weak turbulent fluctuation region, some authors [1–3] investigated the effects of the Kolmogorov spectrum, non-Kolmogorov spectrum and pump spectrum on the OAM states of single photons propagation in atmospheric turbulence and the channel capacity of OAM-based free-space optical (FSO) communication link. Paterson [1] showed that the effects of the turbulence-aberration are significant, and the key parameter determining the magnitude of the effect is the beam width relative to the coherence scale of the aberrations. Sheng et al. [2] established the probability models of the OAM states for single photon propagation in the slant channel with the non-Kolmogorov turbulence and found that the crosstalk probabilities among neighbor orbits are approximately the same as non-Kolmogorov parameter approaches 4. Li et al. [3] revealed that the use of Kolmogorov turbulence model underestimates the channel capacity of OAM-based FSO link. Zhang et al. [4,5] analyzed the influences of Zernike aberrations of the tilt, coma, and astigmatism and defocus caused by the weak non-Kolmogorov [4] or Kolmogorov [5] turbulence on the

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OAM states of single photons propagation in a slant atmospheric turbulence channel. They indicated that the turbulent tilt is the dominant aberration which causes the orbital angular momentum crosstalk, the coma is second, and the astigmatism is third. But the defocus aberration has no impact on OAM. Anguita et al. [6] numerically analyzed the effects of atmospheric turbulence on the system and found that turbulence induces attenuation and OAM crosstalk among channels. Alonso et al. [7] and Wang et al. [8] numerically simulated OAM states propagation through a turbulent atmosphere, and indicated that even with quantum error [7] and Zernike tilt aberration correction, the range over which we can use OAM for effective quantum communications is limited. By numerically simulation, Sun and Djordjevic [9] showed that, under certain conditions, the OAM multiplexing technique provides a higher security over a single-mode transmission channel in terms of the total secrecy capacity and the probability of achieving a secure communication. Based on the study of the BER performance of low-density parity-check coded OAM modulation over 1 km FSO communication link subjects to OAM modal crosstalk induced by atmospheric turbulence, Djordjevic et al. [10] indicated that OAM modulation is more sensitive to atmospheric turbulence as the number of dimensions increases and this shortcoming can be efficiently mitigated by an error-correction code. Recently, from the study of the transmission characteristic of the OAM modes of partially coherent LG beams in weak horizontal oceanic turbulence, Cheng et al. [11] indicated that optical turbulence in an oceanic environment causes a much stronger effect on the OAM states than that in an atmospheric environment.

On the other hand, we know that anisotropy in stratospheric turbulent inhomogeneities had been experimentally investigated, and laboratory results have shown that turbulence can be anisotropic [12,13]. Therefore, many researchers have concentrated on the effects of anisotropic turbulence [14–17].

Further, from the point of the application of the long distance optical communications in the atmospheric environment, the new phenomenon caused by the strong atmospheric turbulence was discovered. Chen et al. [18] pointed out that the normalized average power of the one with an index closer to zero may be greater than that of the other one for two symmetrically-neighboring extrinsic OAM modes. We know the OAM crosstalk is an important factor which affects the performance of the optical communication link [1–9]. However, as our known, there are no reports about the effect of the weak-to-strong turbulence and the anisotropic turbulence on the OAM crosstalk.

In the current study, based on the modified Rytov approximation, we first develop the effective atmospheric spectrum of anisotropic turbulence. Utilizing the effective atmospheric spectrum, the models of the signal-to-noise ratio or equivalent probability of OAM states and the normalized probability of OAM states of photons and channel capacity of links are established. Then, we analyze the effects of the anisotropy of atmospheric turbulence on OAM states and channel capacity in weak to strong fluctuation links.

2. Effective kolmogorov spectrum of anisotropic turbulence

Let us assume that the random fluctuation of refraction index $n_1(\mathbf{r})$ is a statistically homogeneous complex random field with zero mean and Riemann–Stieltjes integral can be represented by [19]

$$n_1(\mathbf{r}) = \int\int\int_{-\infty}^{\infty} \exp(i\boldsymbol{\kappa}\cdot\mathrm{r})dv(\kappa), \tag{1}$$

where $r = |\mathbf{r}|$ and $\mathbf{r} = (\rho, \varphi, z)$ is a vector position; $\boldsymbol{\kappa} = (\kappa_x, \kappa_y, \kappa_z)$ is the spatial wave number of the refractive index fluctuation with units rad/m and $dv(\boldsymbol{\kappa})$ denotes the random amplitude of $n_1(\mathbf{r})$. The covariance function of the random field $n_1(\mathbf{r})$ has the form

$$\begin{aligned} B_n(\mathbf{r}) = \; & \langle n_1(\mathbf{r}_1)n_1^*(\mathbf{r}_2)\rangle = \int\int\int\int\int\int_{-\infty}^{\infty} \exp[i(\boldsymbol{\kappa}\cdot\mathrm{r}_1 - \boldsymbol{\kappa}'\cdot\mathrm{r}_2)] \\ & \times\langle dv(\boldsymbol{\kappa})dv^*(\boldsymbol{\kappa}')\rangle. \end{aligned} \tag{2}$$

For statistical homogeneity $n_1(\mathbf{r})$, it follows that

$$\langle dv(\boldsymbol{\kappa})dv^*(\boldsymbol{\kappa}')\rangle = \delta(\boldsymbol{\kappa} - \boldsymbol{\kappa}')\phi_n(\boldsymbol{\kappa})d^3\kappa d^3\kappa'. \tag{3}$$

In this case, Eq. (2) simplifies to

$$B_n(\mathbf{r}) = \int\int\int_{-\infty}^{\infty} \exp(i\boldsymbol{\kappa}\cdot\mathrm{r})\phi_n(\boldsymbol{\kappa})d^3\kappa. \tag{4}$$

The function $\phi_n(\boldsymbol{\kappa})$ in Eqs. (3) and (4) is the three-dimensional spatial power spectrum of the random field $n_1(\mathbf{r})$. This function can be obtained directly from the covariance function through the inverse Fourier transform relation

$$\phi_n(\boldsymbol{\kappa}) = \int\int\int_{-\infty}^{\infty} B_n(\mathbf{r})\exp(-i\boldsymbol{\kappa}\cdot\mathrm{r})d^3r. \tag{5}$$

As in [20], for a photon beam propagating along a path exhibiting anisotropic turbulence, the wave number $\boldsymbol{\kappa}$ can be expressed by $\kappa_\varsigma = \sqrt{\kappa_z^2 + \varsigma^2(\kappa_x^2 + \kappa_y^2)}$, and the structure function of the refractive index fluctuations is given by [19,20]

$$D_n(\mathbf{r}, \varsigma) = C_n^2(\Delta\rho^2/\varsigma^2 + \Delta z^2)^{1/3}, \tag{6}$$