

# Adaptive-optics-based simultaneous pre- and post-turbulence compensation of multiple orbital-angular-momentum beams in a bidirectional free-space optical link: supplementary material

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This document provides supplementary information to "Adaptive-optics-based simultaneous pre- and post-turbulence compensation of multiple orbital-angular-momentum beams in a bidirectional free-space optical link," <http://dx.doi.org/10.1364/optica.1.000376>. The turbulence emulation approach and the detailed implementation of the adaptive optics system used in our experiment are presented. © 2014 Optical Society of America

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## 1. Turbulence Emulation

In our experiment, a phase screen plate with a pseudo-random phase distribution obeying Kolmogorov spectrum statistics and characterized by its effective Fried coherence length  $r_0$  is used to emulate the turbulence. The phase screen plate is mounted onto a rotary stage and placed in the middle of the optical path. The turbulence emulator in our setup represents a thin phase-screen model which is applicable for some cases, particularly if the link distance is not too long or if the turbulent portion of the atmosphere is thin compared to the total link path. The parameters of a practical atmospheric link emulated by the lab link can be calculated from the conditions that the two links have the same  $D/r_0$ , Fresnel number  $F = D^2/\lambda L$  and Rytov variance  $\sigma_R^2$  [1-4]. Here  $\lambda$  denotes the wavelength,  $L$  is the link distance and  $D$  is aperture diameter of the link. In our lab link,  $D$  can be obtained by measuring the beam diameter incident onto the phase plate, and  $\sigma_R^2$  can be estimated as follows. The effective atmospheric structure constant  $\widetilde{C}_n^2$  of the lab link is given by [1, 2]

$$\widetilde{C}_n^2 = C_n^2 d = 2.36(\lambda/2\pi)^2 r_0^{-5/3}$$

where  $C_n^2$  is the actual structure constant, and  $d$  is the thickness of the phase screen. Then the Rytov variance  $\sigma_R^2$  for this link can be expressed as  $\sigma_R^2 = 0.56(2\pi/\lambda)^{7/6} \widetilde{C}_n^2 (L/4)^{5/6}$ . This formula is valid for the case of a spherical wave and also holds in this experiment. With these parameters, a practical link can be adequately represented by the setup. The link emulated in our experiment corresponds to a 1-km atmospheric link with  $F = 11.35$  and  $C_n^2 = 2.2 \times 10^{-14} \text{ m}^{-2/3}$ . We note that our turbulence emulator is based on the thin-screen model and may not adequately represent uniformly distributed turbulence [2, 3].

## 2. Adaptive Optics System

In the experiment, the AO system is placed at the TX-2 side to post-compensate the received beams emitted from TX-1 and pre-compensate the outgoing beams from TX-2. A Gaussian beacon beam co-propagates with the OAM beams from TX-1 through the

turbulence emulator. The multiplexed beams exiting from the turbulence emulator are imaged onto the wavefront corrector (i.e., SLM-3 in Fig. 3) using a 4-f lens system. In the AO compensation system, the Gaussian beacon beam is separated from the distorted OAM beams using a PBS and then directed to a Shack-Hartmann wavefront sensor (WFS, HASO from Imagine Optic Inc.) for wavefront measurements. Note that the Gaussian beacon beam can also carry an independent data stream and the temporal phase signal imposed does not affect the spatial wavefront detection by the WFS. To enable the WFS to detect the residual wavefront distortion of the Gaussian beam, the plane of SLM-3 is imaged onto the plane of the WFS. Mathematically, the residual wavefront  $\varphi(x, y)$  can be described by a linear combination of Zernike polynomials  $Z_0(x, y), Z_1(x, y), \dots, Z_n(x, y)$  as [4]

$$\varphi(x, y) = \sum_{k=0}^{\infty} a_k Z_k(x, y)$$

in which  $a_0, a_1, \dots, a_n$  are coefficients that can be calculated through the partial derivation of the deformation wavefront using the least-squares method by the WFS [5]. In our experiment, up to the 19th order Zernike polynomial is used to estimate the wavefront distortion of the Gaussian beam.

A feedback controller is used to communicate between the wavefront corrector SLM-3 and the WFS and provide the correction pattern as a control signal to update the phase pattern on SLM-3. Once the loop converges, an ultimate correction pattern is then obtained for this turbulence realization. This phase pattern is subsequently used to correct the OAM beams emitted from TX-1 and pre-distort the OAM beams from TX-2. Note that for simplicity, only one wavefront corrector is used in the AO system and is shared when compensating the Gaussian beacon beam and the OAM beams for one turbulence realization [6]. In a practical case, two wavefront correctors that are updated with the same correction pattern by the feedback controller may be required to compensate the wavefront of the Gaussian beacon beam and the OAM beams. As a polarization sensitive SLM is employed for the wavefront corrector, a half-wave-plate (HWP) HWP-2 is used to align the polarization of the Gaussian beacon beam or OAM beams with the polarization orientation of SLM-3. HWP-3 is polarization adjusted to direct the Gaussian beam to the WFS. For example, if the ultimate correction pattern for one turbulence realization is obtained, HWP-2 is then rotated by  $90^\circ$  to ensure that the OAM beams rather than the Gaussian beam are phase corrected by SLM-3. Since the OAM beams from TX-2 are on the same polarization as those from TX-1 in our experiment, they are spatially phase modulated and distorted by SLM-3 before passing through emulated atmospheric turbulence. The beams exiting from SLM-3 inside the AO system are imaged onto the demultiplexing SLM to reduce the effect of turbulence-induced tilt/tip on OAM multiplexing.

## References

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