Entanglement protection of high-dimensional states by adaptive optics

Giacomo Sorelli[1], Nina Leonhard[2], Vyaceslav N. Shatokhin[1], Claudia Reinlein[2], Andreas Buchleitner[1]
[1]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104 Freiburg, Federal Republic of Germany
[2]Fraunhofer Institut for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745, Jena, Federal Republic of Germany

giacomo.sorelli@physik.uni-freiburg.de

Abstract: We theoretically study the potential of adaptive optics (AO) to protect entanglement of high-dimensional photonic orbital-angular-momentum (OAM) states against turbulence-induced distortions. We show that AO is able to reduce the crosstalk among the OAM modes and, consequently, the entanglement decay as well as photon losses. Finally, we test the AO-corrected output states against high-dimensional Bell inequalities and prove that the transmitted entanglement allows for secure communication even in the strong scintillation regime.

High-dimensional, discrete quantum systems (qudits) present several advantages over simple two-level systems (qubits). For example, in entanglement based quantum key distribution (QKD) an eavesdropper can be detected using Bell inequalities, which are the more violated the larger the dimensionality of the employed states. Photonic orbital angular momentum (OAM) states are a promising candidate for the realisation of such high-dimensional quantum systems. However, the helical phase front of OAM-carrying light beams is fragile with respect to turbulence induced refractive index fluctuations. Adaptive optics (AO) can compensate for these effects: AO uses wavefront measurements to steer in real time corrective elements, such as deformable mirrors, in order to correct turbulence induced phase distortions.

In the present contribution, we discuss the ability of AO to protect maximally-entangled states of two OAM qudits of dimension $d = \{2,3,4\}$ transmitted through a turbulent channel for a vast range of turbulence conditions. To that end, we numerically simulate the propagation of the entangled photons through turbulence and consider two AO models [1]. The first model performs a full reconstruction of the phase profile, with resolution limited only by our numerical grid. This corresponds to the ideal AO, unachievable in real experiments. On the contrary, the second model only stabilises the direction of the incoming beam with a tip-tilt mirror.

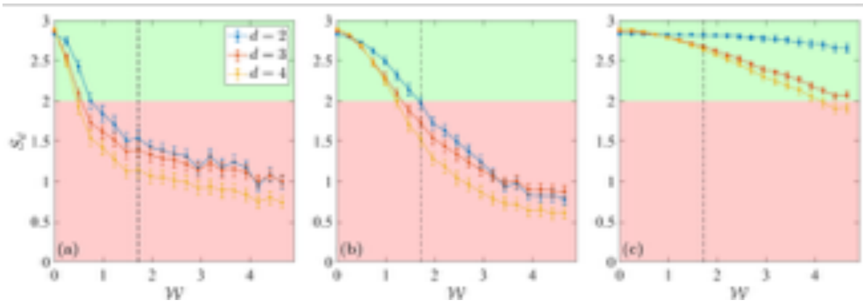

Fig.1: Bell parameters vs. turbulence strength for different degrees of AO corrections: (a) no, (b) tip-tilt and (c) ideal correction. The (red) green area indicates the region where a Bell inequality is (not) violated. The vertical line indicates the transition from weak to strong scintillation. Errors are inferred via error propagation from standard deviations around the mean of the density matrix of the output state, calculated from 500 realisations of turbulence. Figure adapted from [2].

After identifying which states can be efficiently protected, we characterise entanglement evolution in different dimensions using generalised Bell inequalities. On the one hand, our results (see Fig.1) show that the stronger violation of Bell inequalities by high dimensional states cannot compensate for their faster degradation [2]. On the other hand, we show that AO can significantly increase the turbulence threshold at which the photon's non-classical correlations are lost [2]. We thus conclude that AO can enable entanglement distribution with OAM qudits in free space.

[1] N. Leonhard et al. "Protecting the entanglement of twisted photons by adaptive optics", *Phys. Rev. A* **97,** 012321 (2018).
[2] G. Sorelli et al. "Entanglement protection of high-dimensional states by adaptive optics", *New J. Phys.* in press (2019).