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## Free-space optical communication with orbital angular momentum coding: prediction and correction of turbulence effects in atmospheric and underwater links

**Abstract**: In the last few years interest in free-space optical (FSO) communication has increased significantly owing to its unique features: increased bandwidth, license-free spectrum, high data rates, point-to-point security and high power efficiency. In comparison to radio-frequency systems, FSO communication can achieve 105 times higher bandwidth at 20 times smaller receiving antennae, both gains being due to orders-of-magnitude smaller wavelength at which FSO operates.

Still, none of the benefits of FSO can be realized when propagating the laser beam in turbulence, either atmospheric or underwater, when no countermeasures are employed to compensate for rapid wavefront fluctuations. Spatial and temporal changes in the index of refraction render FSO essentially useless when link distance exceeds 1 km and/or when turbulence strength increases. This remains the case irrespective of the type of the channel multiplexing method which had been employed to increase transmission rates: polarization-, wavelength-, or spatial multiplexing schemes are all susceptible to turbulence, along with absorption and scattering effects.

In the last three years, a new technology has emerged which promises several orders of magnitude increase in FSO transmission rates: orbital angular momentum (OAM) coding. Angular momentum is one of the most fundamental physical quantity in both classical and quantum mechanics. It is classified as spin angular momentum (SAM) and orbital angular momentum (OAM). SAM is associated with the spin of the photon and thus, it is related to polarization. On the other hand, OAM is associated with the helicity of the photon's wavefront. By engineering vortex beams one can then propagate, in principle, an infinite number of states (for comparison, SAM allows for only two states to be coded). This makes OAM a potential candidate for high-capacity communication systems.

It has been reported that OAM beams are highly sensitive even to weak atmospheric turbulence because of redistribution of energy among various OAM states leading to time-varying crosstalk. This makes practical implementation of an OAM-based FSO system in the presence of atmospheric turbulence challenging. One solution is to combine an FSO terminal with an adaptive optics (AO) module. Nevertheless, conventional Shack-Hartmann wavefront sensing cannot be readily used for reconstructing the helical wavefront of the OAM beam, due to its phase singularities or branch points caused by turbulence. The situation is even less understood for underwater propagation scenarios. Only when the characteristics of the intervening medium are properly analyzed and suitable wavefront-sensing strategies put forward, can OAM-based FSO be a feasible alternative to acoustic and tethered underwater communications for short distances.

In this presentation I will give a description of OAM experiments over a 400-m double-pass path in Ettlingen and also experiments with a Gaussian beam over a 7.2 km path between Karlsruhe and Ettlingen. Additionally, experiments aiming at characterization of water turbulence in our 1.5-m water tank filled with distilled water will be described. Finally, I will talk about our demonstration of AO correction of water turbulence effects on a 532-nm laser beam propagating 5 times through the tank.