Understanding and Approaching Fundamental Limits to Free-Space Optical Communication through the Turbulent Atmosphere

Joseph M. Kahn[1], Aniceto Belmonte[2] and Karthik Choutagunta[1]

1. E. L. Ginzton Laboratory, Department of Electrical Engineering, Stanford University
2. Department of Signal Theory and Communications, Technical University of Catalonia

Our work aims to understand fundamental limits to free-space optical (FSO) system capacity imposed by atmospheric turbulence and to identify transmission schemes that can approach these limits in practice.

Stochastic eigenmodes of atmospheric turbulence channels

We have determined the optimal beams for free-space transmission through atmospheric turbulence. These are stochastic eigenmodes derived analytically from a canonical turbulence model, assuming the turbulence statistics are known. Using these modes as transmit and receive bases minimizes signal degradation by turbulence, and minimizes the complexity of any signal processing for compensating the impact of turbulence. The channel-aware stochastic eigenmodes significantly outperform conventional fixed mode sets under weak or strong turbulence conditions.

Modal free-space transmission systems

The stochastic eigenmodes, or any orthogonal mode set, can be mapped to/from single-mode waveguides by fundamentally lossless modal multiplexers and demultiplexers, making implementation of modal transmission systems remarkably convenient. Modal free-space transmission systems can leverage technologies from fiber systems, including optical amplification, wavelength-division multiplexing (WDM), space-division multiplexing (SDM) and coherent detection, to vastly increase transmission capacity. Adaptive optics can be replaced by adaptive multi-input multi-output (MIMO) signal processing, improving performance by compensating both phase and amplitude fluctuations, and by better tracking fast fluctuations.

Modal multiplexers and demultiplexers

Modal multiplexers and demultiplexers – which provide a fundamentally lossless one-to-one mapping between orthogonal spatial modes and single-mode inputs and outputs – are key to enabling modal free-space transmission systems, just as they are essential for SDM fiber systems. Multi-plane light converters are among the most promising devices, as they are programmable and scalable to many modes. Their design, however, involves a non-convex optimization that has been solved only through simulated annealing over a period of hours or days. We have developed a convex design method that converges to the global optimum in just a few seconds.

Optical multi-input multi-output signal processing

In a modal free-space transmission system, adaptive MIMO signal processing can be performed digitally or optically. Optical MIMO processing can minimize power consumption and process multiple WDM channels simultaneously. Several types of fundamentally lossless optical devices – including arrays of Mach Zehnder interferometers or multi-mode interference couplers – can implement optical MIMO processing, but adapting the devices rapidly to an unknown MIMO channel is challenging. We are working on efficient methods for adapting these optical MIMO arrays. We have recently pioneered convex optimization-based phase retrieval, an efficient method for rapid identification of unknown MIMO channels that is compatible with low-complexity direct detection.