MIMO Equalization to Mitigate Turbulence in a 2-Channel 40-Gbit/s QPSK Free-Space Optical 100-m Round-trip Orbital-Angular-Momentum-Multiplexed Link between a Ground Station and a Retro-Reflecting UAV

Long Li[(1)], Runzhou Zhang[(1)], Peicheng Liao[(1)], Yinwen Cao[(1)], Haoqian Song[(1)], Yifan Zhao[(1),(2)], Jing Du[(1)], Zhe Zhao[(1)], Cong Liu[(1)], Kai Pang[(1)], Hao Song[(1)], Dmitry Starodubov[(1)], Brittany Lynn[(3)], Robert Bock[(4)], Moshe Tur[(5)], Andreas F. Molisch[(1)], Alan E. Willner[(1)]

[(1)] Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA, longl@usc.edu
[(2)] Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, CHINA
[(3)] Space & Naval Warfare Systems Center, Pacific, San Diego, CA 92152, USA
[(4)] R-DEX System, Marietta, Georgia 30068, USA
[(5)] School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, ISRAEL

Abstract *We experimentally demonstrate turbulence mitigation using 2×2 MIMO equalization in a 100-m round-trip, 40-Gbit/s OAM-multiplexed FSO link between a ground transmitter and receiver via a retro-reflecting hovering UAV. Two OAM modes are transmitted, each achieving a BER of <3.8×10^{-3}.*

Introduction

Free-space optical (FSO) communications has the potential for higher capacity and lower probability of detection as compared to RF links[1]. The communicating platforms can include ground stations and flying unmanned-aerial-vehicles (UAVs)[2]. Moreover, there has been interest in further increasing the capacity in FSO links by using space-division-multiplexing (SDM), such that multiple independent data-carrying beams are propagating over the same spatial medium. One subset of SDM is mode-division-multiplexing (MDM), in which each beam uses an orthogonal mode within a modal basis set[3].

One example of MDM is orbital angular momentum (OAM) beams, which is a subset of Laguerre-Gaussian beams[3,4]. OAM is characterized by a phase-front that “twists” in a helical fashion, and the number of 2π phase shifts in the azimuthal direction, which is represented by an integer ℓ, determines the amount of OAM that a beam carries[3,4]. In general, a key challenge for FSO links is to overcome the performance degradation due to atmospheric turbulence[5]. This issue is of greater concern for OAM-multiplexed links, since turbulence can cause phase distortions and increased crosstalk in the multi-channel environment[5]. A recent report demonstrated the use of OAM multiplexing in a 100-m round-trip link between a ground station and a flying UAV, but that experiment did not attempt to address the issue of turbulence[6].

There have been reports of OAM-multiplexed FSO links between ground transmitter and receiver where turbulence effects were mitigated using: (i) adaptive optics with deformable mirrors or spatial-light-modulators[7,8], and (ii) signal processing algorithms to increase performance for a single mode at any given time[9,10]. Moreover, there have been reports of using multiple-input-multiple-output (MIMO) equalization to mitigate turbulence effects in an OAM-multiplexed link in a lab environment either in free-space[11] or underwater[12] over roughly a 1-m distance.

In this paper, we experimentally demonstrate MIMO equalization to mitigate turbulence in a 40-Gbit/s retro-reflected 2-OAM-multiplexed FSO link between a ground transmitter and a ground receiver, connected via a flying retro-reflecting UAV over 100-m round-trip distance. The receiver is co-located with the transmitter on the ground station. A rotatable phase plate with a pseudo-random phase distribution, obeying Kolmogorov spectrum statistics is used at the transmitter to emulate weak-to-moderate atmospheric turbulence over a 1-km distance[8]. Results indicate that MIMO equalization could help mitigate the crosstalk caused by turbulence, and improve both error vector magnitude (EVM) and bit-error-rate (BER) of the signal in an OAM-multiplexed link for flying platforms. In our experiment, MIMO equalization helps achieve BER values mostly below 3.8×10^{-3} under the emulated turbulence conditions.

Concept and experimental setup

The concept of the OAM-multiplexed FSO link between a ground station and a retro-reflecting UAV is illustrated in Fig. 1(a). Multiple data-carrying OAM beams are multiplexed and transmitted from the ground station to the UAV, and reflected back to the same ground station.

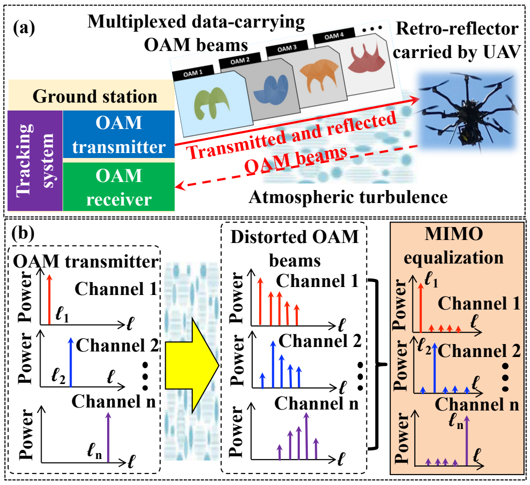

Fig. 1: Concept of an OAM-multiplexed free-space optical link between a ground transmitter and a ground receiver via an unmanned-aerial-vehicle (UAV) (a) through atmospheric turbulence and (b) using MIMO equalization to mitigate turbulence.

When propagating in free-space, OAM beams may be distorted by turbulence, such that signal power on each particular OAM mode may leak to its neighbouring modes, and the received signal at a particular mode may contain crosstalk from its neighbours, as shown in Fig. 1(b). MIMO equalization could help reduce crosstalk among channels by applying the inverse of channel matrix to the received signals, thus mitigating system performance degradation[11,12].

Fig.2 shows the experimental setup. During the measurement, the UAV is either on the ground, hovering, or moving at a maximum speed of ~0.1 m/s, ~50-m away from the ground station. A 20-Gbit/s quadrature phase-shift keying (QPSK) signal at 1550 nm is generated and split into two branches. One branch is relatively delayed using a ~10-m single-mode fibre to decorrelate the data sequences. The two branches are fed to two input ports of a custom-designed OAM generator/multiplexer, generating multiplexed OAM beams[13]. Another 1530-nm beacon for beam tracking is sent to the $\ell = 0$ input port of the OAM multiplexer. These co-axially propagating beams then pass through a thin phase plate mounted on a rotation stage. This phase plate is designed to generate a pseudo-random phase distribution obeying the Kolmogorov spectrum statistics with an effective r_0 of 1 mm, which represents weak-to-moderate turbulence over a 1-km distance[8]. Then the beams are expanded and propagate to the gimbal-mounted retro-reflector carried by the UAV. The beam diameters after expansion are ~ 6.0 cm and ~ 4.2 cm for OAM -3 and +1, respectively. The retro-reflector reverses the beam's OAM order from $+\ell$ to $-\ell$. At the receiver, the beams after beam reduction are coupled into the OAM demultiplexer for heterodyne detection and MIMO equalization based on a constant modulus algorithm that utilizes a linear equalizer for each channel[11]. After equalization, frequency offset estimation and carrier phase recovery are applied to recover the signals, and the BERs are evaluated for all channels[11]. A two-stage beam

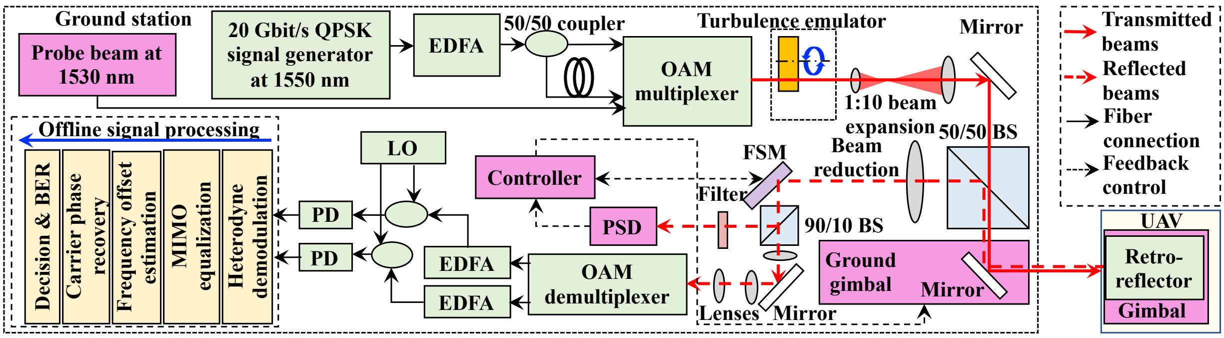

Fig. 2: Experimental setup. BS: beamsplitter; EDFA: erbium-doped fiber amplifier; FSM: fast steering mirror; LO: local oscillator; PD: photo-detector; PSD: position sensitive detector; QPSK: quadrature phase-shift keying.

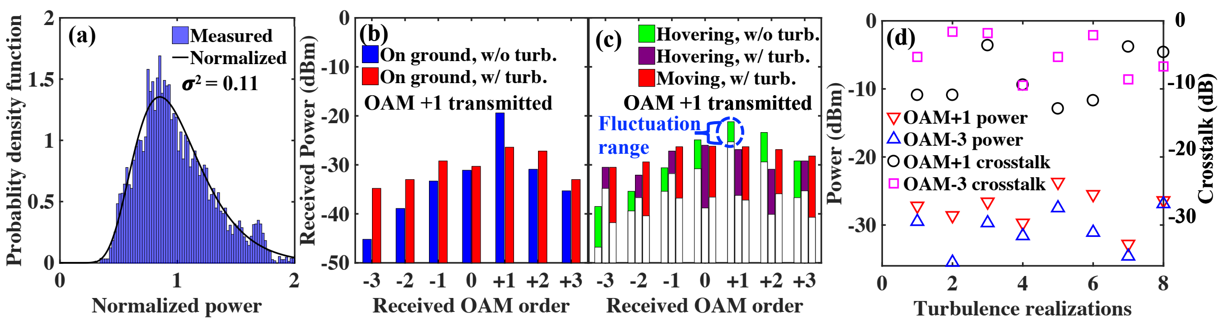

Fig. 3: Experimental results of (a) normalized histogram of power distribution when Gaussian beam is transmitted, and the Rytov various σ^2 is 0.11; (b) and (c) OAM spectrum when OAM+1 is transmitted and the UAV is on the ground/hovering/ moving ~ 50-m away, with and without turbulence plate; in (c), the extension of the colored portion of each bar represents the power fluctuation range; (d) power and crosstalk for OAM+1 and -3 when both beams are transmitted under various turbulence realizations.

tracking system is used[6]. A coarse tracking system controls the ground gimbal to ensure that the OAM beams are pointing to the UAV, while a fine tracking system keeps the reflected OAM beams hit the centre of the OAM demultiplexer[6].

Results and discussions

To characterize the parameters of the emulated turbulence, we measure the Rytov variance σ^2 using a Gaussian beam and a 1-mm diameter point detector[6]. Fig. 3(a) presents the measured power distribution when the phase plate rotates at 40 rpm, and σ^2 is found to be 0.11. The D/r_0 for OAM -3 and +1 beams are ~6.0 and ~4.2, respectively, where D is the beam diameter. Fig. 3(b) and 3(c) show the measured OAM spectrum when only OAM +1 beam is transmitted under various flight conditions. The shaded portion of each bar in Fig. 3(c) represents the power fluctuation range when the the UAV is hovering or moving[6]. The turbulence phase plate is fixed at a random angle. Results show that turbulence increases the crosstalk from unwanted modes. Fig. 3(d) shows the instantaneous power and crosstalk for both channels when OAM -3 and +1 are simultaneously transmitted under various turbulence realizations. These realizations are selected when the phase plate randomly rotates to different angles. We note that the OAM -3 channel generally has lower power and suffers from higher crosstalk compared with the OAM +1 channel. This may be due to the relatively larger D/r_0 of the OAM -3 beam.

In the BER measurements, OAM -3 and +1 beams are transmitted, each carrying a 20- Gbit/s QPSK signal. Fig. 4(a) shows BERs for both channels as functions of transmitted power when

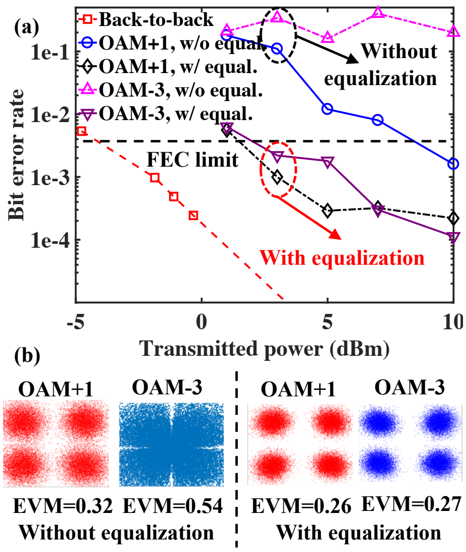

Fig. 4: (a) Bit-error-rate (BER) curves and (b) recovered QPSK constellations at transmitted power of 10 dBm for all channels with and without MIMO equalization when OAM +1 and -3 are transmitted. The UAV is hovering ~ 50-m away. FEC: forward-error-correction.

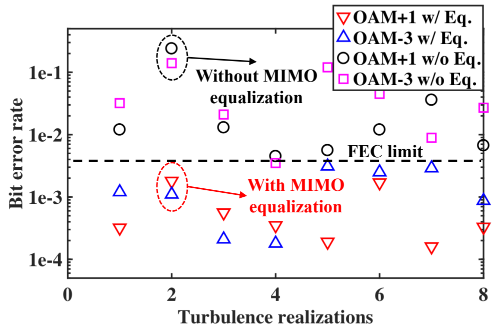

Fig. 5: BERs for both channels with and without MIMO equalization under various turbulence realizations. The UAV is hovering ~ 50-m away.

the UAV is hovering ~50-m away with phase plate fixed at a random angle. It is shown that the measured BER curve of OAM -3 without MIMO equalization exhibits a severe error floor due to the inter-channel crosstalk. We observe that the BERs dramatically decrease to below the 7% overhead forward error correction (FEC) limit of 3.8×10^{-3} for all channels after MIMO equalization. The received QPSK constellation and corresponding EVM for each channel at a transmitted power of 10 dBm are shown in Fig. 4(b). We then rotate the phase plate randomly to different angles to test the system under various turbulence realizations. Fig. 5 shows the measured BERs for both channels under 8 different turbulence realizations. We notice that the BER improvement of using MIMO equalization varies for different realizations, but the BERs could mostly be kept below 3.8×10^{-3} with MIMO equalization.

Acknowledgements

We acknowledge the generous support of Air Force Office of Scientific Research (AFOSR) FA9550-16-C-0008; National Science Foundation (NSF) ECCS-1509965 and IIP-1622777; Vannevar Bush Faculty Fellowship program from ASD (R&E) and Office of Naval Research (ONR) N0014-16-1-2813.

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