Demonstration of "Automatic" Turbulence Mitigation of 4 QPSK Channels in a Self-Coherent Free-Space Mode-Division-Multiplexed Link Using a Pilot Beam and Photodetector Array

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Abstract: We experimentally demonstrate "automatic" turbulence mitigation of a self-coherent FSO MDM link with four 1-Gbaud QPSK channels using a transmitted pilot beam and PD array without power-splitting losses or detector-bandwidth sharing. Results show <3-dB turbulence-induced penalty, as compared to a >16-dB penalty for a conventional LO-based MDM system.

1. Introduction

Free-space optical (FSO) communication links have the potential for higher capacity and lower probability of intercept when compared with radio links [1]. As with other types of communications, the ability to multiplex many data channels and transmit them simultaneously can increase the aggregate data rate [2]. One example is mode-division-multiplexing (MDM), in which each beam is tailored to have a different orthogonal spatial mode from a modal basis set [3,4]. Within MDM, one type of modal set is orbital-angular-momentum (OAM), which can be characterized by: (a) the phasefront of a wave "twists" in a helical fashion as it propagates; (b) the number of 2π phase shifts in the azimuthal direction defines the OAM order ℓ; and (c) the intensity has a ring shape with a central null for $\ell \neq 0$ [3,4].

In many systems, it is desirable to encode data on both the temporal amplitude and phase of the wave (e.g., quadrature-phase-shift-keying (QPSK)) [5,6]. Such formats can have a lower OSNR requirement than amplitude-only modulation due to the Euclidean distance between constellation points [5,6]. In fiber systems, temporal amplitude and phase can be recovered by mixing a Gaussian data beam with a Gaussian local oscillator (LO) [5,6]. However, turbulence presents a key challenge for FSO systems, since it can distort the data beam and couple power from the transmitted mode into other modes, such that the beam does not efficiently mix with the LO [7,8]. Importantly, this challenge grows in complexity for an MDM system, since the turbulence also causes inter-channel crosstalk [9].

There have been various approaches to solving the above turbulence-induced problems. Examples include using adaptive optics [10] and multiple-input-multiple-output (MIMO) digital signal processing (DSP) algorithms [11]. However, methods exist that utilize pilot beams co-transmitted with the data beams such that turbulence can be mitigated in a "automatic fashion", i.e., the receiver does not need to adapt to the turbulence conditions [7, 12, 13]. In this case, the pilot suffers a similar turbulence effect, and then the distortion conjugate is generated in a photodetector (PD) for mitigation. Specifically, this technique was reported: (1) numerically for multiple OAM-multiplexed data beams on one polarization and a single Gaussian pilot beam on the orthogonal polarization; however, beam splitters are utilized to split the power for beam mixing at multiple separate PDs [12], (2) experimentally for multiple OAM-multiplexed data beams and their corresponding frequency-offset pilot beams; however, a single PD is used such that data channels need to share the bandwidth of the detector [13]. A laudable goal might be to enable automatic turbulence mitigation without power-splitting losses or detector-bandwidth sharing.

In this paper, we experimentally demonstrate "automatic" turbulence mitigation of 4 QPSK channels in a self-coherent FSO MDM link using a pilot beam and PD array to avoid power-splitting losses or detector-bandwidth sharing. We note that compared to our previous publications using a pilot beam to "automatic" mitigate turbulence for a single Gaussian data beam [7], this paper demonstrates the "automatic" pilot-assisted approach for OAM-multiplexed MDM systems using a PD array. A Gaussian pilot beam (OAM ℓ=0) is transmitted together with 4 mode-multiplexed 1-Gbaud QPSK data channels (OAM ℓ=-1, 0, +1, +2) through turbulence. The pilot beam experiences similar spatial wavefront distortion as the data beams. At the receiver, the turbulence distortion is "automatically" mitigated by its conjugate from the mixing of the pilot and data beams in a PD array with 4 sub-PDs. Subsequently, the 4 channels are extracted by a demultiplexing matrix in signal processing, based on the mode-dependent phase delays between the pilot and OAM data beams in the azimuthal direction. Experimental results show that our approach has <3-dB turbulence-induced penalty at 7% forward error correction (FEC) limit, while a conventional LO-based MDM system suffers much larger penalties (>16-dB) and does not reach blow the FEC limit.

2. Concept

As shown in Fig 1 (a), a conventional LO-based MDM coherent FSO link can be significantly degraded by turbulence effects. This is due to the turbulence induced distortion of the spatial wavefront of the received beams, giving rise to

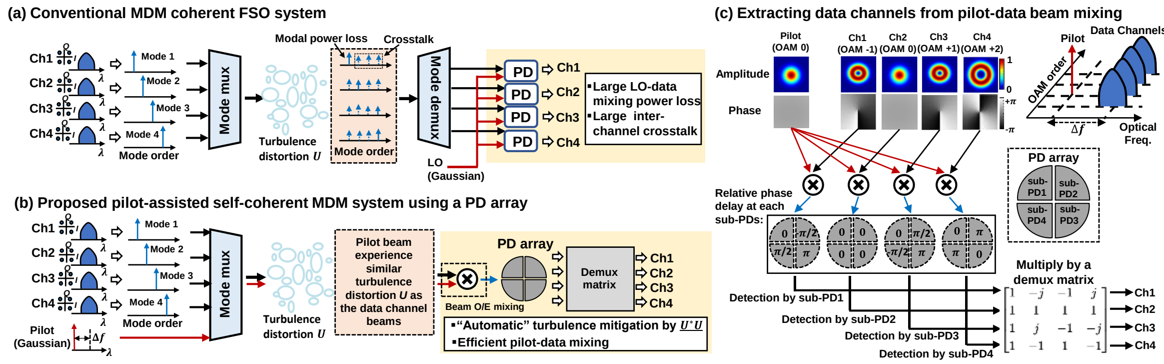

Fig. 1. (a) Conventional LO-based coherent MDM FSO system can be significantly degraded by turbulence-induced modal power loss and inter-channel crosstalk. (b) Our proposed pilot-assisted self-coherent MDM FSO system using a PD array. Turbulence-induced wavefront distortion is "automatically" mitigated by its conjugate during the pilot-data beam mixing at the PD array. (c) Extracting the 4 data channels by applying a demultiplexing matrix on the signals detected by 4 sub-PDs based on the phase belays between the pilot and data beams in the azimuthal direction.

modal power coupling from the transmitted mode to other spatial modes [7,9]. Here, we propose a pilot-assisted self-coherent MDM FSO system using a PD array that can "automatically" mitigate turbulence, as shown in Fig. 1 (b). At the transmitter (Tx), a frequency-offset Gaussian pilot beam is transmitted together with 4 mode-multiplexed channels through turbulence. The Gaussian pilot beam serves as a probe to sense the turbulence and experiences similar turbulence-induced spatial wavefront distortion (U) as the data beams [12,13]. At the receiver (Rx), the distorted pilot and data beams mix in a PD array with 4 sub-PDs. During the pilot-data beam mixing, the turbulence-induced spatial wavefront distortion and its conjugate are both "automatically" produced and multiplied together (U^*U), thereby mitigating the distortion experienced by the data beams. To extract the 4 MDM channels, we use the independent outputs from the sub-PDS and apply a demultiplexing matrix in DSP according to the relative phase-front phase delays between the pilot and OAM data beams in the azimuthal direction [14,15]. Figure 1 (c) shows an example for 4 channels carried by OAM ℓ=-1, 0, +1, +2. For each pilot-data mixing term, different sub-PDs can detect different mode-dependent phase delays. We apply a demultiplexing matrix to signals detected by 4 sub-PDs, such that they are phase matched and can be constructively combined to obtain each desired channel [14]. We note that, for demultiplexing given mode orders, the matrix is fixed and does not need to adapt to turbulence. Although we show a system with four 1-Gbaud QPSK channels, the technique can support more modes and a higher data rate by using a larger-bandwidth PD array with more sub-PDs.

3. Experimental Setup and Results

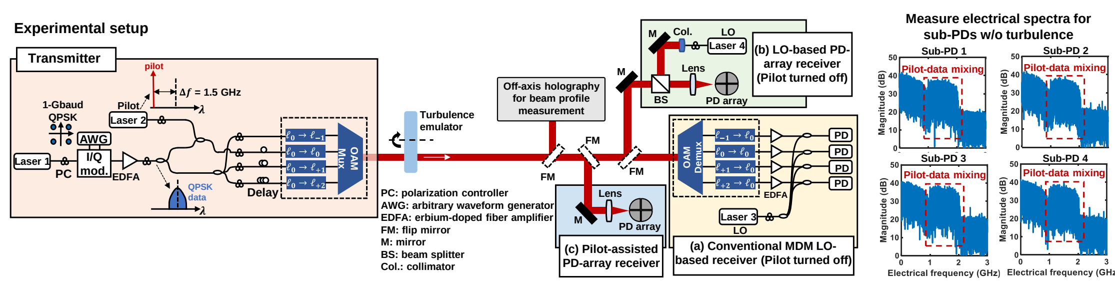

Fig. 2. Setup for an MDM FSO link with four 1-Gbuad QPSK channels (OAM mode ℓ=-1, 0, +1, +2).

At the Tx, we generate a 1-Gbaud QPSK signal by modulating Laser 1 at the wavelength of ~1.55 µm. After pre-amplification, the signal is split into four channels, and their polarizations are intendedly controlled and aligned. Fibers are used to decorrelate different data channels. A pilot tone is generated by Laser 2 and has a small 1.5-GHz frequency offset to the data channel (small-to ensure the same turbulence effects similar to signal beams). This frequency offset is needed, though, to provide a guard band for reducing the signal-to-signal beating interference. The 4 channels and the pilot tone are converted into different modes (Ch1-Ch4: OAM ℓ=-1, 0, +1, +2; pilot: OAM ℓ=0) and multiplexed together using a multiple-plane light converter (MPLC) (CAILabs [16]). A rotatable glass phase plate is used to emulate the turbulence effects with Fried parameter r_0=1 mm (stronger turbulrnce) and 3 mm (weaker) [7, 9]. Link length is ~1 m. At the Rx, we measure the turbulence-induced wavefront distortion of the beams using off-axis holography [17]. Three different receivers are compared in the experiment: (a) conventional LO-based MDM coherent receiver where an MPLC mode demultiplexer is used to demultiplex channels and a Gaussian LO (Laser 3) is mixed with each channel in a signal-mode-fiber coupled PD for data recovery, (b) LO-based PD array receiver where a Gaussian LO (Laser 4) is mixed with all data channels in a PD array, and (c) proposed pilot-assisted self-coherent PD

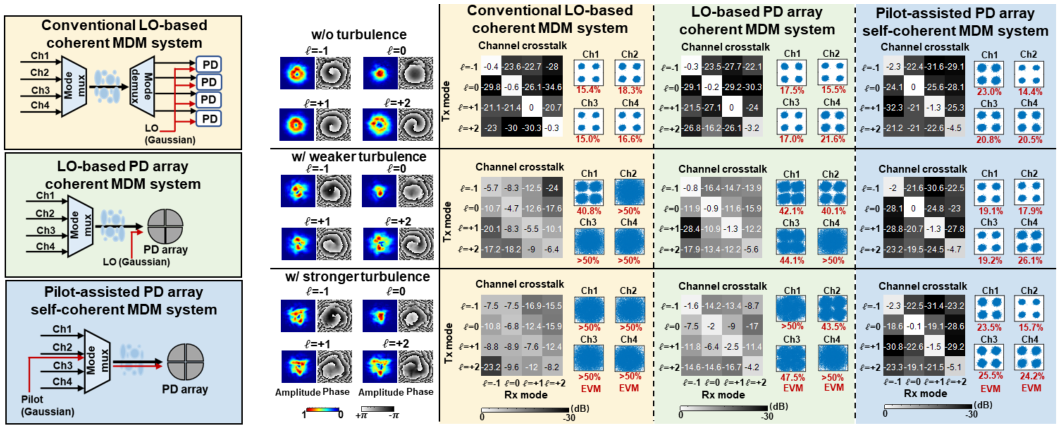

Fig. 3. Beam profiles, crosstalk, data constellations, and EVM with and without a weaker/stronger turbulence realization. Pilot-assisted PD-array system is much less degraded due to the "automatic" turbulence mitigation. The transmitted power of each data channel is ~0 dBm.

array receiver. The PD array used in the experiment is a four-quadrant InGaAs PD with a 3-dB bandwidth of ~1.5 GHz and a total photodetection area of ~0.14 mm^2 [18,19]. For LO-based approaches (a) & (b), we turn the pilot (Laser 2) off and control the power and wavelength of the LO to be the same as that of the pilot in approach (c). As shown in Fig. 3, due to the increased modal power loss and channel crosstalk induced by turbulence, the performance of the two LO-based receivers degrades quickly and the error vector magnitude (EVMs [20]) of 4 channels can go high up to >50%. The proposed pilot-assisted receiver suffers much less degradation (EVMs < ~26%).

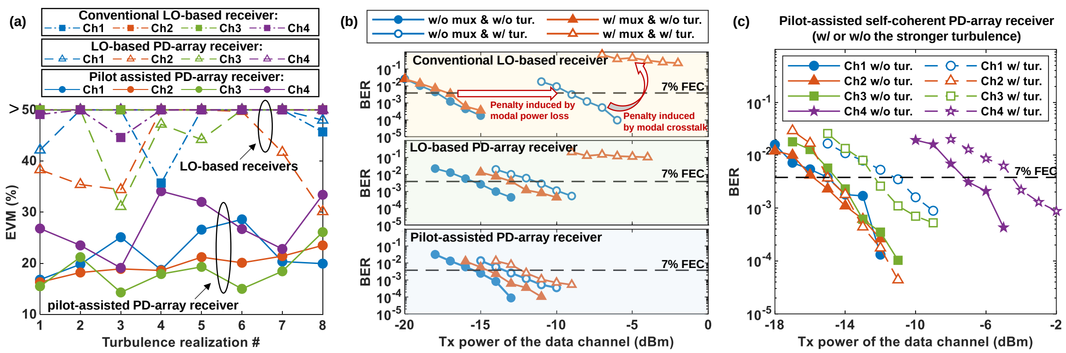

Fig. 4. (a) EVMs under 8 different random stronger turbulence realizations. (b) BERs of the data Ch3 (OAM ℓ=+1) with and without multiplexing and turbulence (the stronger turbulence case shown in Fig. 3). (c) BERs of the 4 multiplexed channels under the stronger turbulence.

We subsequently test the performance under different turbulence realizations as shown in Fig. 4 (a). Under 8 different realizations, all 4 channels can have EVMs less than ~35% when using pilot-assisted self-coherent PD-array receiver. However, for the two LO-based receivers, data channels have much larger EVMs (>50 % for multiple turbulence realizations). To investigate the penalty induced by turbulence-induced modal power loss and crosstalk, we measure the bit error rate (BER) performance of the data Ch3 (OAM ℓ=+1) with and without channel multiplexing and turbulence. For the conventional LO-based receiver, the power penalty induced by modal power loss and crosstalk is>6 dB and >10 dB, respectively. For the LO-based PD array receiver, the crosstalk-induced penalty is still large (>10 dB), while the modal power loss is relatively smaller (~3 dB), which might benefit from the spatial diversity effects of the multiple sub-PDs [21]. For these two receivers, the BER doesn't reach below the 7% FEC limit due to large channel crosstalk. For the pilot-assisted PD-array receiver, both modal power loss and crosstalk induce much smaller penalties due to the "automatic" turbulence mitigation. As shown in Fig. 4 (c), all channels can reach the 7% FEC limit and the penalty induced by turbulence is < 3 dB. The relatively worse performance of Ch4 might be due to the lower mixing efficiency between the pilot (OAM ℓ=0) and Ch4 data (OAM ℓ=+2) beam.

Acknowledgment: Office of Naval Research (N00014-20-1-2558); Vannevar Bush Faculty Fellowship sponsored by the Basic Research Office of the Assistant Secretary of Defense for Research and Engineering and funded by the Office of Naval Research (N00014-16-1-2813); Airbus Institute for Engineering Research; DSCA 4441006051; Qualcomm Innovation Fellowship; Air Force Office of Scientific Research (sub-award of FA9453-20-2-0001)

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