Demonstration of Turbulence Resiliency in a Mode-, Polarization-, and Wavelength-Multiplexed Free-Space Optical Link Using Pilot-Assisted Optoelectronic Beam Mixing

Huibin Zhou, Runzhou Zhang, Hao Song, Nanzhe Hu, Haoqian Song, Kaiheng Zou, Xinzhou Su, Zhe Zhao, Kai Pang, Ahmed Almaiman, Cong Liu, Amir Minoofar, Brittany Lynn, Daeyoung Park, Robert W. Boyd*, Fellow, IEEE, Fellow, OSA*, Moshe Tur*, Fellow, IEEE, Fellow, OSA*, and Alan E. Willner*, Fellow, IEEE, Fellow, OSA*

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***Abstract*—We experimentally demonstrate turbulence-resilient free-space optical (FSO) coherent communications with multiple multiplexed data channels in different orthogonal domains, including mode, polarization, and wavelength. The turbulence resiliency is enabled by utilizing pilot-assisted optoelectronic mixing of the received beams, wherein one pilot is being mixed with its corresponding beam. By transmitting additional continuous-wave (CW) pilot tones, whose frequencies are offset from the data-carrying beams, and mixing all pilot tones and beams in a single free-space-coupled photodetector (PD) at the receiver, the turbulence-induced modal coupling could be efficiently suppressed. The paper first discusses an experimental demonstration of a turbulence-resilient mode-division-multiplexed (MDM) FSO communication link using two orbital angular momentum (OAM) beams. Each OAM beam carries an independent 2-Gbit/s quadrature-phase-shift-keying (QPSK) data channel. Experimental results indicate that (i) the channel crosstalk under both the weaker and stronger turbulence distortions are measured to be lower than ~ -25.7 dB, (ii) the turbulence-induced OAM modal coupling could be effectively suppressed for the emulated 15 random turbulence realizations, and (iii) the error-vector magnitudes (EVM) of the multiplexed QPSK data channels are measured to be lower than by 17.4% and 19.8% under the relatively weaker and stronger turbulence effects, respectively. The paper subsequently describes an experimental demonstration of a turbulence-resilient FSO link with eight 0.5-Gbit/s QPSK data channels multiplexing two OAM beams ($l = +1$ & $l = -2$), two polarizations, and two wavelengths. The measured bit-error rates (BERs) of all data channels under turbulence effects are below the 7% forward-error-correction (FEC) limit, with power penalties less than $\sim$3.7 dB.**

***Index Terms*—Free-space optical communications, optical vortices, turbulence.**

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Huibin Zhou, Runzhou Zhang, Hao Song, Nanzhe Hu, Haoqian Song, Kaiheng Zou, Xinzhou Su, Zhe Zhao, Kai Pang, Ahmed Almaiman, Cong Liu, and Amir Minoofar are with the Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, CA 90089 USA (e-mail: huibinzh@usc.edu; runzhou@usc.edu; songhao@usc.edu; nanzhehu@usc.edu; haoqians@usc.edu; kaihengz@usc.edu; xinzhous@usc.edu; zhezhao@usc.edu; kaipang@usc.edu; almaiman@usc.edu; liucong@usc.edu; minoofar@usc.edu).

Brittany Lynn is with the Naval Information Warfare Center Pacific, San Diego, CA 92152 USA (e-mail: blynn@spawar.navy.mil).

Daeyoung Park is with the Department of Information and Communication Engineering, Inha University, Incheon 22212, South Korea (e-mail: dpark@inha.ac.kr).

Robert W. Boyd is with the Institute of Optics, University of Rochester, Rochester, NY 14627 USA (e-mail: boyd@optics.rochester.edu).

Moshe Tur and Alan E. Willner are with the School of Electrical Engineering, Tel Aviv University, Ramat Aviv 69978, Israel (e-mail: tur@post.tau.ac.iltur@tauex.tau.ac.il; willner@usc.edu).

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I. Introduction

THERE is growing interest in utilizing free-space optical (FSO) communication links to increase data capacity and reduce the probability of data intercept [1]–[3]. In FSO links, there might be a desire to detect the phase of the received optical signal in order to facilitate the encoding of data in the phase domain. Such encoding enables spectrally-efficient higher-order modulation formats (e.g., quadrature-phase-shift-keying (QPSK) and various orders of quadrature-amplitude-modulation (QAM)) [4]. One typical way to recover phase information of a data channel is utilizing a conventional coherent detector that mixes the data-carrying beam with a local oscillator (LO).

However, atmospheric turbulence in various types of FSO links can induce power coupling from the transmitted beam's spatial mode to other modes [5]–[6]. Such modal coupling could degrade the performance of a single data beam coherent FSO link because the data power coupled to other modes might not efficiently mix with the LO in the receiver [7]–[8]. In addition to low-efficiency LO mixing in the receiver, turbulence in a mode-division multiplexed (MDM) FSO link utilizing multiple orthogonal data-carrying beams can cause modal coupling and inter-channel crosstalk [9]–[10]. Several approaches have been demonstrated to mitigate turbulence-induced modal coupling in FSO links, including (i) feedback-based adaptive optics [11]–[13]; and (ii) coherent detection of many modes using multiple LOs and digital signal processing (DSP) [14]–[16].

Recently, there have been reports of using pilot-assisted optoelectronic (O/E) beam mixing to automatically mitigate the turbulence-induced modal coupling without feedback or additional DSP [17],[18]. In this approach, a data channel and a frequency-offset pilot tone are transmitted and subsequently mixed together in a single square-law photodetector (PD) at the receiver. The resultant pilot-data channel mixing product is resilient to turbulence-induced modal coupling because a conjugate of the turbulence experienced by the pilot tone is automatically generated and compensates the turbulence distortion experienced by the data-carrying beam. This technique was reported: 1) experimentally for a single Gaussian data beam and Gaussian pilot tone using a single PD [17], and 2) numerically for multiple data-carrying beams of specific spatial modes (e.g., orbital-angular-momentum (OAM)) on one polarization, a single Gaussian pilot tone on the orthogonal polarization, and multiple one PD for each beam [18]. It might be desirable to experimentally demonstrate the pilot-assisted O/E beam mixing approach in a multiple-data channel FSO link using a single detector to automatically mitigate turbulence-induced modal coupling and channel crosstalk [19]–[20].

In this paper, we experimentally demonstrate turbulence resilient FSO coherent communication links with multiple data channels multiplexed in different domains using the pilot-assisted O/E beam mixing and a single PD. We first discuss an experimental demonstration of a turbulence-resilient mode-division-multiplexed (MDM) FSO communication link using two OAM beams. Each OAM beam carries an independent 2-Gbit/s quadrature-phase-shift-keying (QPSK) data channel. Experimental results indicate that (i) the channel crosstalk under both the weaker and stronger turbulence distortions are measured to be lower than ~ -25.7 dB, (ii) the turbulence-induced OAM modal coupling could be effectively suppressed for the emulated 15 random turbulence realizations, and (iii) the error-vector magnitudes (EVM) of the multiplexed QPSK data channels are measured to be lower than by 17.4% and 19.8% under the relatively weaker and stronger turbulence effects, respectively. We subsequently describe an experimental demonstration of a turbulence-resilient FSO link with eight 0.5-Gbit/s QPSK data channels multiplexing two OAM beams ($l = +1$ & $l = -2$), two polarizations, and two wavelengths. The measured bit-error rates (BERs) of all data channels under turbulence effects are below the 7% forward-error-correction (FEC) limit, with power penalties less than ~3.7 dB.

II. Turbulence Resilient OAM Multiplexed FSO Link Using Pilot-Assisted O/E Beam Mixing

In this section, we demonstrate the pilot-assisted O/E beam mixing in an MDM FSO link with emulated turbulence effects. We utilize OAM modes as the orthogonal modal basis set for MDM. OAM modes are a subset of Laguerre-Gaussian (LG) basis [21]: (i) an OAM beam is characterized by its wavefront that "twists" as it propagates and the OAM order $\boldsymbol{l}$ indicates the number of 2π phase shifts in the azimuthal direction, and (ii) an OAM beam has a ring-shaped intensity profile which has little power in the beam center [22]–[23]. We compare the performance of the pilot-assisted O/E mixing and conventional LO-based detection in terms of the turbulence-induced modal coupling and channel crosstalk. Subsequently, we demonstrate a turbulence-resilient MDM FSO communication link using the pilot-assisted O/E mixing.

A. Concept

Fig. 1 illustrates the concept of utilizing pilot-assisted O/E beam mixing to achieve the modal coupling resiliency to atmospheric turbulence in an FSO link. Fig. 1(a) shows that, for an MDM FSO link, turbulence-induced modal coupling causes channel crosstalk between transmitted data channels carried by two OAM modes after the mode demultiplexing and conventional LO-based heterodyne detection. Fig. 1(b) describes a single-channel FSO link where the pilot-assisted O/E mixing is utilized to mitigate turbulence-induced modal coupling. At the transmitter, a modulated data signal $S(t)$ and a CW pilot of amplitude C are carried together by the same OAM mode, with an optical frequency difference of Δf. This pair of waves propagates co-axially through the turbulent atmosphere. Sharing the same spatial mode and of close optical frequencies, they can be assumed to experience the same turbulence-induced modal coupling, which is represented for a unit amplitude wave as shown in Eq. (1).

$$U_{r_0} = \sum_{l} \sum_{p} a_{r_0,l,p} \cdot \ LG_{l,p}\left(x,y\right) \tag{1}$$

where U_{r_0} is the modal coupling induced by the turbulence with the Fried parameter r_0 and $a_{r_0,l,p}$ are turbulence-dependent complex coefficients [17], [24]. $LG_{l,p}(x,y)$ represent the electrical field of the LG modes with an azimuthal index of l and a radial index of p With a smaller r_0 (stronger turbulence distortion), the modal coupling tends to cause more power coupled from the transmitted mode to other LG modal components [17]. If the receiver aperture can collect almost the entire beam, ideally, the complex coefficients $a_{r_0,l,p}$ for all modal components tend to satisfy $\sum\limits_{l}\sum\limits_{p}|a_{r_0,l,p}|^2 \cong 1$ [25]. After propagation, the entire spatial profiles of the two OAM waves are focused on a free-space-coupled PD. Here, the PD mixes the $C \cdot U$ and $S \cdot U$ waves to form a photocurrent as in [17]:

$$\begin{aligned} I \propto \int\int (C+S)\cdot U_{r_0}\cdot {U_{r_0}}^{*}\cdot (C+S)^{*} \\ dxdy = (C+S)\ \cdot (C+S)^{*} \iint U_{r_0}\cdot {U_{r_0}}^{*}\, dxdy \\ = \left\{|C|^2+|S|^2+2\mathrm{Re}\left[S\cdot C^{*}\right]\right\}\ \cdot \iint |U_{r_0}|^2 dxdy, \end{aligned} \tag{2}$$

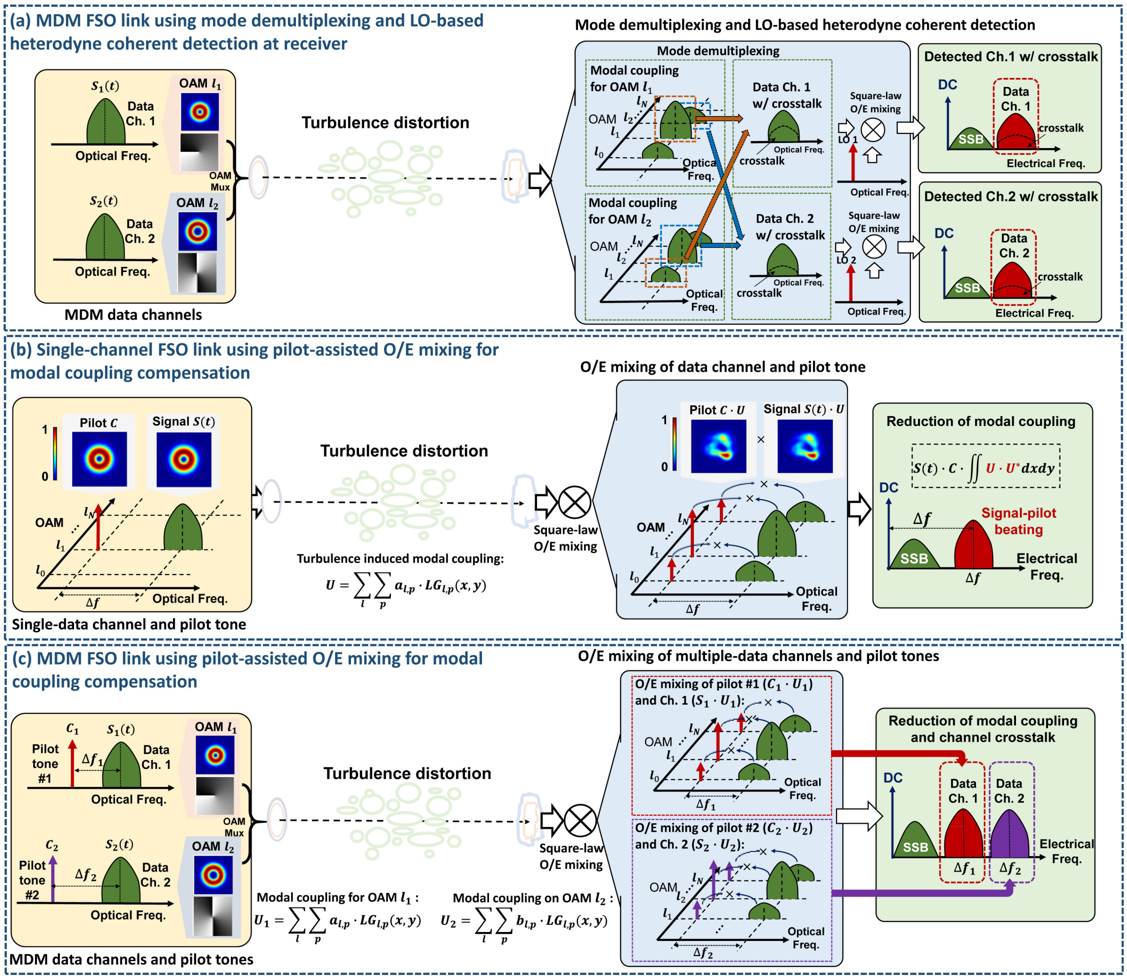

Fig. 1. (a) Turbulence-induced modal coupling could cause channel crosstalk between transmitted data channels carried by two OAM modes after mode demultiplexing and LO-based coherent detection. (b) Concept of a single-channel FSO link using pilot-assisted O/E beam mixing. Mode components of the data beam could be efficiently mixed with the corresponding component of the pilot beam. (c) Concept of the turbulence-resilient OAM-multiplexed data transmission link using two OAM beams l_1 and l_2. Two additional CW pilot tones located at the frequency difference Δf_1 and Δf_2 away from data channel's frequency are used to automatically compensate the turbulence-induced modal coupling through O/E mixing. DC: direct current; SSB: signal-signal beating.

where $*$ and $\mathrm{Re}[\cdot]$ denote the conjugate operation and real part of the complex electrical field, respectively. Note that the integral over $|U_{r_0}|^2$ is a real scalar, whose value for orthonormal modes is [17]:

$$\begin{aligned}\int\int U_{r_0} \cdot {U_{r_0}}^* dxdy &= \int\int \sum_l \sum_p a_{r_0,l,p} \cdot LG_{l,p}(x,y) \\ &\quad \cdot \sum_{l'} \sum_{p'} {a_{r_0,l',p'}}^* \cdot LG^*_{l',p'}(x,y)\, dxdy \\ &= \sum_l \sum_p \sum_{l'} \sum_{p'} \int\int a_{r_0,l,p} \\ &\quad \cdot LG_{l,p}(x,y) \cdot {a_{r_0,l',p'}}^* \\ &\quad \cdot LG^*_{l',p'}(x,y)\, dxdy \\ &= \sum_l \sum_p |a_{r_0,l,p}|^2 \cong 1 \end{aligned} \tag{3}$$

Thus, each mode component of the data beam is efficiently mixed with the corresponding component of the pilot beam and in the absence of losses the integral over $|U_{r_0}|^2$ approaches unity. However, in practice, the beam might be truncated by a limited-size receiver aperture under stronger turbulence (a smaller r_0) [26], which could result in $\sum_l \sum_p |a_{r_0,l,p}|^2 < 1$. Therefore, one may need to increase the receiver's aperture size to collect most of the distorted beam. The first two terms $|C|^2$ and $|S|^2$ in the curly brackets of Eq. (1) correspond to the direct current (DC) component and the signal-signal beating (SSB) photocurrent, respectively, while the $2\mathrm{Re}[S \cdot C^*]$ term represents the desired signal-pilot-beating photocurrent at the intermediate (electrical domain) frequency (IF) Δf.

Such a pilot-assisted O/E mixing approach could be extended in an OAM-multiplexed communication system that transmits multiple OAM beams carrying independent data streams. As shown in Fig. 1(c), two data channels at the same optical frequency are carried by two OAM beams with different OAM orders. Two additional CW pilot tones located at the frequency difference Δf_1 and Δf_2 away from data channel's frequency are also carried by the corresponding OAM beams l_1 and l_2. All OAM beams are spatially combined and co-axially propagate

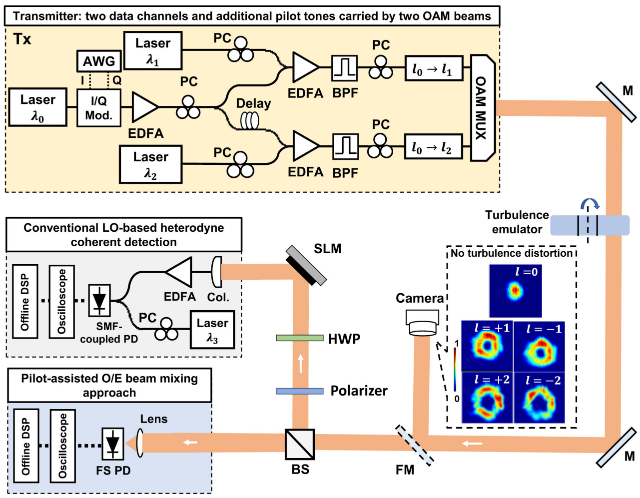

Fig. 2. Experimental setup for the two-OAM-beam multiplexed data transmission through emulated turbulence. The inset of Fig. 2 indicates the generated OAM beam profiles without any emulated turbulence effects. AWG: Arbitrary Waveform Generator; EDFA: Erbium-doped Fiber Amplifier; PC: Polarization Controller; BPF: Band Pass Filter; M: Mirror; FM: Flip Mirror; BS: Beam Splitter; HWP: Half-Wave Plate; SLM: Spatial Light Modulator; DSP: Digital Signal Processing.

through the same atmospheric turbulence effects. The two modes may experience different turbulence-induced modal coupling represented by Eq. (4) and (5), respectively.

$$U_{r_0,l_1} = \sum_{l}\sum_{p} a_{r_0,l,p} \cdot LG_{l,p}(x,y) \tag{4}$$

$$U_{r_0,l_2} = \sum_{l}\sum_{p} b_{r_0,l,p} \cdot LG_{l,p}(x,y) \tag{5}$$

With a smaller r_0 (stronger turbulence distortion), turbulence could induce stronger modal coupling effects on both OAM beams l_1 and l_2, which might cause larger crosstalk between two data channels carried by these two OAM beams [11]. However, the square-law detection process, outputting the photocurrents of the two modes at distinct IF frequencies, Δf_1 and Δf_2, gives rise to completely independent turbulence compensation of each mode. DSP-based off-line digital filtering and in-phase-quadrature (I-Q) demodulation are then used to independently retrieve the two data streams.

In this approach, after the O/E mixing, the detected data channels are located at different IF frequencies in the electrical domain. Thus, the total electrical bandwidth of the single detector is divided into different parts for different data channels. We note that this approach may be favorable in scenarios wherein i) the bandwidth of each data signal is limited by the transmitter, and the detector has sufficient bandwidth for multiple data channels, or ii) a sufficient number of PDs is not readily available, and a simplified receiver architecture is preferred.

B. Experimental Setup

Fig. 2 illustrates the experimental setup for the two-OAM-beam multiplexed data transmission link through emulated turbulence. At the transmitter, a laser with a wavelength of λ_0 is modulated with a 1-Gbaud Nyquist-shaped (roll-off factor of 0.1) QPSK signal by an I-Q optical modulator. The modulated light is subsequently amplified and equally split into two copies, one of which is delayed by a ~15-m single-mode fiber (SMF) to decorrelate the data sequences. These two copies are then individually combined with two CW pilot tones at different wavelengths λ_1 and λ_2, with frequency differences Δf_1 and Δf_2 away from the wavelength λ_0, respectively, commensurate with the data bandwidth. After amplification by erbium-doped fiber amplifiers (EDFA), these two sets of signal and pilot tones at wavelengths λ_1 and λ_2 are fed to an OAM multiplexer to generate co-axial OAM beams l_1 and l_2, respectively. The optical OAM beams are generated and simultaneously multiplexed using a commercially available multiple-plane light converter (MPLC) at the wavelength of ~1.55 μm (CAILabs [27]). The inset of Fig. 2 indicates the generated OAM beam profiles with OAM orders $l = -2, -1, 0, +1, +2$ without any emulated turbulence effects. In this demonstration, the OAM orders of the two multiplexed OAM beams, l_1 and l_2, are assigned from these four OAM beams together with the fundamental Gaussian beam (i.e., $l = 0$). We experimentally emulate the turbulence-induced distortion by utilizing thin glass plates whose refractive index distributions are fabricated according to Kolmogorov spectrum statistics [9]. Two rotatable glass phase plates are employed in the experiment, with Fried parameters r_0 of 1.0 mm (weaker turbulence effects) and 0.4 mm (stronger turbulence effects). After being distorted by the turbulence emulator, the OAM beams propagate a free-space distance of ~1 m and reach the receiver. At the receiver, the distorted OAM beams are equally split into two copies, one of which is sent to the pilot-assisted O/E beam mixing receiver. For the O/E mixing receiver, the beams are focused on a free-space InGaAs PD (Thorlabs DET08C) using an aspheric lens ($f =$ 16 mm, NA = 0.79). The 3-dB bandwidth of the FS-PD is ~3 GHz. As for the other copy, a spatial light modulator (SLM) is set to a demultiplexing phase pattern to convert one OAM mode of interest into the fundamental Gaussian beam, which is then coupled into a fiber collimator for signal detection. Another laser at a wavelength λ_3 is combined with this signal and subsequently sent to an SMF-coupled PD for heterodyne detection. To ensure a fair comparison, the detected electrical signals from the O/E beam mixing and the LO-based heterodyne detection are processed by the same DSP algorithm and procedures.

C. Experimental Results

Fig. 3(a) shows measured intensity profiles of the transmission of OAM $l = -2, -1, 0, +1, +2$ beams through the emulated weaker and stronger turbulence. The measured normalized inter-channel crosstalk matrices for one turbulence realization for the LO-based heterodyne detection and pilot-assisted O/E beam mixing are shown in Fig. 3(b) and Fig. 3(c), respectively. It is worth noting that the power values are measured in the optical and electrical domain for Fig. 3(b) and Fig. 3(c), respectively. The inter-channel crosstalk for the pilot-assisted O/E beam mixing approach is not significantly affected by the turbulence distortions and is measured to be lower than ~−25.7 dB under both the weaker and stronger turbulence distortions. However, we

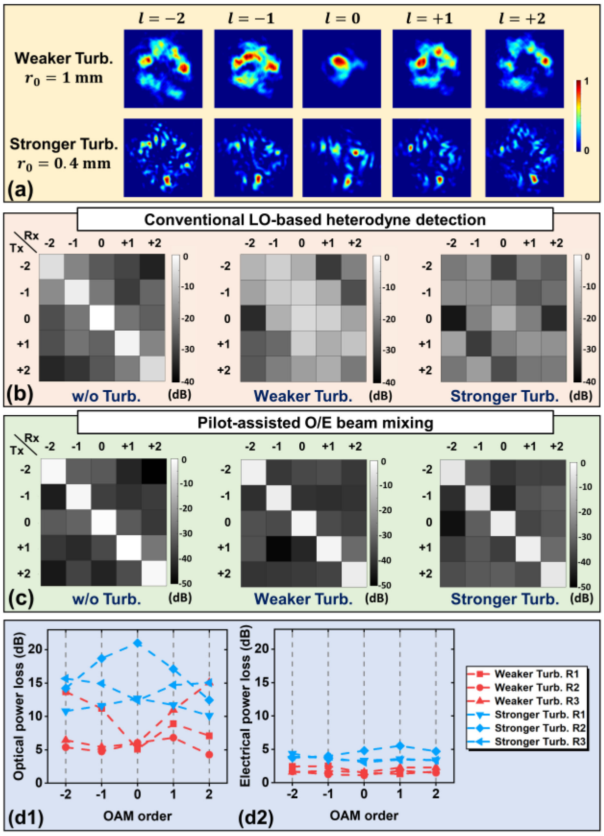

Fig. 3. Experimental results of measured inter-channel crosstalk under weaker and stronger turbulence distortions. (a) Measured beam profiles for OAM beams $l = -2, -1, 0, +1, +2$. (b) Measured inter-channel crosstalk using conventional LO-based heterodyne coherent detection. (c) Measured inter-channel crosstalk using pilot-assisted O/E beam mixing. (d) Measured signal power loss for OAM beams $l = -2, -1, 0, +1, +2$ by using the conventional LO-based heterodyne detection in (d1) and the pilot-assisted O/E beam mixing in (d2).

observe severe turbulence-induced crosstalk between the OAM beams for the LO-based heterodyne detection under the same turbulence effects. We further measure the mode-dependent loss (MDL) of transmitted OAM beams by using the pilot-assisted O/E beam mixing or LO-based heterodyne detection. As shown in Fig. 3(d1), the MDL for the LO-based heterodyne detection can be >4.2 dB and >10.1 dB for the weaker and stronger turbulence effects, respectively. However, as shown in Fig. 3(d2), the MDL for the O/E beam mixing under weaker and stronger turbulence distortions are measured to be <2.5 dB and <5.5 dB, respectively. The smaller power loss might be due to the O/E beam mixing recovering the modal coupling of different data channels in the electrical domain.

We subsequently demonstrate a 4-Gbit/s OAM-multiplexed FSO communication link under different emulated turbulence strengths, with each OAM beam carrying a 1-Gbaud Nyquist-shaped QPSK data stream. Fig. 4(a1) shows the optical spectra at the transmitter carried by the multiplexed OAM beams, including 1-Gbaud Nyquist-shaped data channels and extra CW pilot tones. The carrier (pilot)-to-signal power ratios (CSPRs) are $\sim$0.8 and $\sim$0.9 for the data channel carried by OAM beams l_1 and l_2, respectively. The resultant electrical spectrum using the O/E OAM beam mixing at the receiver appears in Fig. 4(a2). We observe the DC component, SSB term, and the transmitted two data channels at two different intermediate frequencies (IF) Δf_1 and Δf_2 in the electrical domain. Fig. 4(b) shows the measured distorted spatial profiles of different sets of the two multiplexed OAM beams l_1 and l_2 under different turbulence realizations and the corresponding calculated error-vector magnitudes (EVM) [4] using the pilot-assisted beam mixing approach. The EVMs of the data channels using a conventional LO-based heterodyne detection are also shown in Fig. 4(b) for comparison. As shown in Fig. 4(b1), both approaches can achieve near-error-free data transmission without turbulence effects (*i.e.*, $D/r_0 \sim 0$), and the EVMs are measured to be $\sim$13.4% and $\sim$14.9% using the pilot-assisted beam mixing method and $\sim$15.8% and $\sim$13.8% using the conventional heterodyne detection for OAM l_1 and l_2 beams, respectively. The transmitted free-space optical powers are $\sim$1.6 dBm and $\sim$3.7 dBm for OAM l_1 and l_2 beams, respectively. Under the spatial distortion by the emulated turbulence effects, the OAM beams could barely preserve the standard ring-shaped intensity profiles and a large number of bit errors occur using the conventional LO-based heterodyne detection. Figs. 4(b2-b5) show four examples of turbulence-induced spatial distortion and inter-channel crosstalk for different OAM beams with the OAM order selected from different combinations $\{l_1, l_2\} = \{+1, -1\}$, $\{+2, -2\}$, $\{+1, -2\}$. When the OAM beams are distorted by the weaker turbulence, having a Fried parameter of 1 mm (*i.e.*, $D/r_0 \sim 3.8$ and 4.6), as shown in Fig. 4(b2-b3), both the two multiplexed data channels suffer from the turbulence-induced crosstalk and the EVMs of data channels increase from <16% to >36% using the conventional LO-based heterodyne detection. Under the stronger turbulence of $D/r_0 \sim 9.5$ and 11.5, as shown in Fig. 4(b4-b5), the DSP algorithms could not readily recover the I-Q information of the data channels due to the higher inter-channel crosstalk (e.g., -4.2 dB in Fig. 4(b4) compared to -7.4 dB in Fig. 4(b2) for OAM $l_1 = +1$) induced by the stronger turbulence distortion. However, when the distorted OAM beams are O/E mixed by the FS-PD, the two multiplexed data channels are not significantly influenced by the turbulence effects, and the measured EVMs exhibit similar performance to the case of no turbulence effects, albeit with only $\sim$2% increased EVM.

Fig. 4(c) summarizes the EVM comparison for different multiplexed OAM sets under 15 different realizations including the weaker ($r_0 =$ 1 mm in Fig. 4(c1)) and the stronger ($r_0 =$ 0.4 mm in Fig. 4(c2)) turbulence conditions. We observe that the pilot-assisted O/E beam mixing approach can reduce the EVMs of the two multiplexed channels by up-to 41.5% and by 6.9%–42.1% for the weaker and the stronger turbulence distortions, respectively. Furthermore, the O/E beam mixing exhibits certain resilience of OAM inter-channel crosstalk to these 15 random turbulence distortions, measured as the data channels' EVMs variation from 12.9% to 17.4% and from 12.4% to 19.8% for the weaker and stronger turbulence effects, respectively. We note that the variation of the achieved EVMs is likely due to the difference in coupling efficiencies for distorted OAM beams upon propagation into the PD.

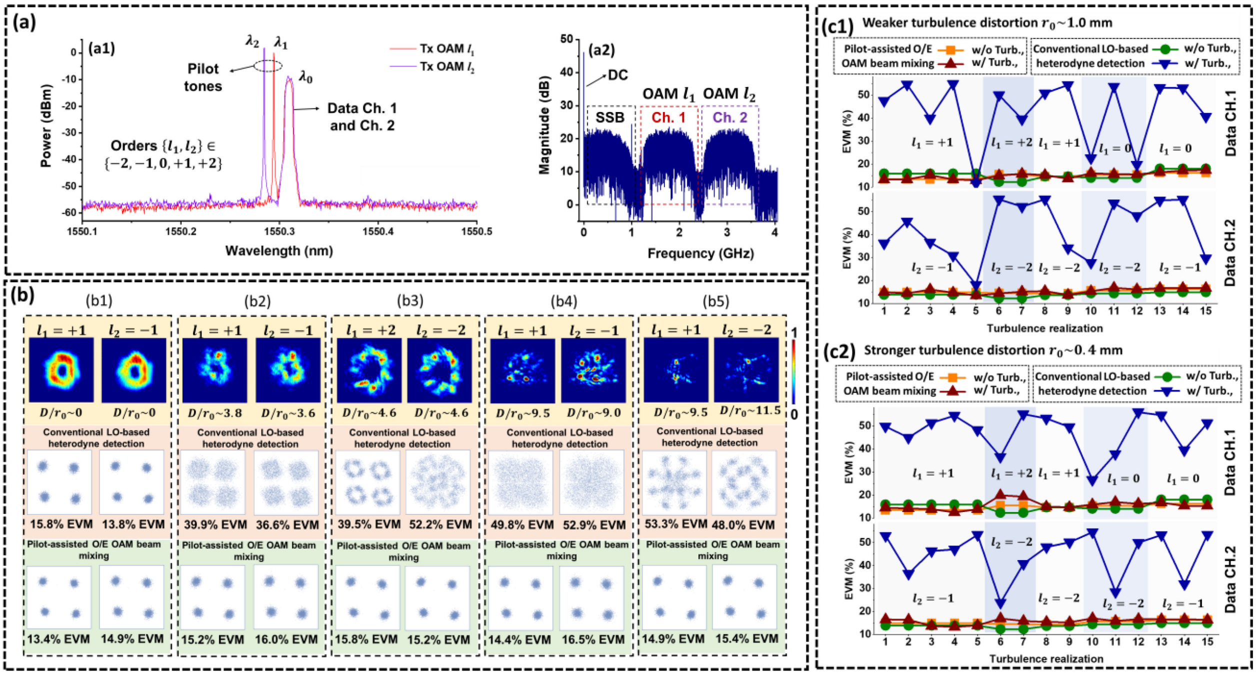

Fig. 4. Experimental results of 4-Gbit/s OAM-multiplexed data transmission under different strengths of the emulated turbulence. (a1) The optical spectra at the transmitter carried by the multiplexed OAM beams including 1-Gbaud Nyquist-shaped data channels and the extra CW pilot tones. (a2) The resultant electrical spectrum using the pilot-assisted O/E OAM beam mixing at the receiver. (b) Comparison of the received 2-Gbaud QPSK constellation diagram using the conventional LO-based heterodyne detection and O/E beam mixing. The transmitted free-space optical powers ∼1.6 dBm and ∼3.7 dBm for OAM beams l_1 and l_2, respectively. Measured EVM values under two different turbulence strength with the Fried parameters r_0 of 1.0 mm and 0.4 mm in (c1) and (c2), respectively.

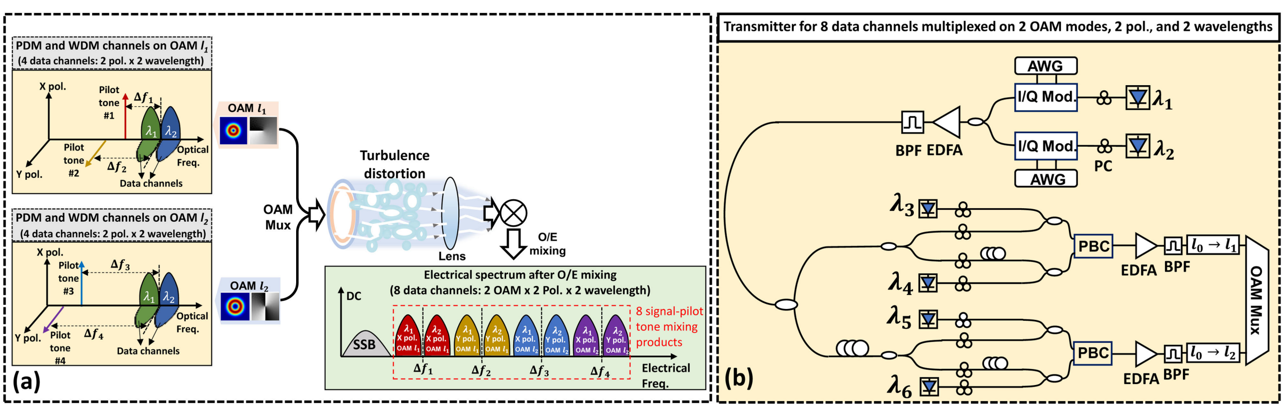

Fig. 5. (a) Concept of the turbulence resilient link combining OAM (l_1 and l_2), polarization (pol. X and Y) and wavelength (λ_1 and λ_2) multiplexing. For each OAM mode, two pilot tones are located at different polarizations with different Δf. The turbulence-induced distortions are automatically mitigated by the pilot-assisted O/E mixing. (b) The transmitter side of the experimental setup for the turbulence resilient link combining two OAM, two polarization, and two wavelength multiplexing. The receiver side of the experimental setup is the same as the setup shown in Fig. 2. AWG: Arbitrary Waveform Generator; EDFA: Erbium-doped Fiber Amplifier; PC: Polarization Controller; PBC: Polarization Beam Combiner; BPF: Band Pass Filter.

III. Turbulence Resilience in a Mode-, Polarization-, and Wavelength-Multiplexed FSO Link Using Pilot-Assisted Beam Mixing

In this section, we extend the turbulence-resilient technique to accommodate multiple multiplexing domains, including mode, polarization, and wavelength. We characterize the performance of the channel crosstalk when utilizing the pilot-assisted O/E mixing and demonstrate the turbulence resiliency in a mode-, polarization, and wavelength- multiplexed free-space optical link with eight multiplexed channels (two OAM modes, two polarizations, and two wavelengths).

A. Concept and Experimental Setup

Fig. 5(a) shows the concept of the turbulence resilient link combining OAM, polarization, and wavelength multiplexing. At the transmitter, for each OAM mode (l_1 or l_2), independent data channels located at different wavelengths (λ_1 and λ_2) and different polarizations (pol. X and pol. Y) are multiplexed. Two pilot tones on the two polarizations are added with a frequency difference Δf (Δf_1 and Δf_2 for OAM l_1, and Δf_3 and Δf_4 for OAM l_2) compared with the data channels. After OAM multiplexing, the pilot and data channels of the same OAM mode (and polarization) are expected to experience similar turbulence-induced modal coupling. After propagating through the turbulent atmosphere, the beam spatial profiles of the OAM beam carrying both the pilot and multiplexed data channels are focused on an FS-PD. At the receiver, the free-space PD would mix the similarly distorted pilot-carrying and data-carrying beams with the same polarization and same OAM mode, and generate signal-pilot beating terms at different frequency Δf in the electrical domain. The turbulence-induced modal coupling on each data OAM beam could be compensated through pilot-assisted beam mixing. By choosing the proper frequency spacing Δf, data channels can be down-converted to different frequencies and separated with little turbulence-induced crosstalk.

Fig. 5(b) shows the transmitter side of the experimental setup for the turbulence resilient link combining OAM, polarization, and wavelength multiplexing. The receiver side is the same as the setup shown in Fig. 2. At the transmitter, two different carriers (λ_1 and λ_2) are modulated with two data channels independently and multiplexed. After pre-amplification, the wavelength-multiplexed data channels are split into four parts, and their polarizations are intentionally controlled. Four pilot tones are combined with the data channels. Polarization beam combiners (PBC) are used to achieve polarization multiplexing. SMFs are used to induce delays to decorrelate different data channels. Two pilot tone and data combinations are converted into OAM modes l_1 and l_2. We choose two OAM modes $l_1 = +1$ and $l_2 = -2$ as an example to demonstrate the turbulence resilience of the system. At the receiver, the proposed turbulence-resilient receiver using the pilot-assisted O/E beam mixing and conventional LO-based heterodyne detection are compared. Since we use a single FS-PD (3 dB bandwidth of ∼3 GHz) to receive eight data channels at different IF frequencies in this experiment, the baud rate for each data channel is set to be 0.25 GBaud.

B. Experimental Results

We measured normalized channel crosstalk using conventional LO-based heterodyne detection with and without turbulence for data channels located at λ_1 and λ_2, respectively, as shown in Fig. 6(a). The results indicate that, for both λ_1 and λ_2, the turbulence mainly induces crosstalk between different OAM modes. OAM $l_1 = +1$ experiences ∼−11 dB and ∼−9 dB crosstalk, whereas OAM $l_2 = -2$ experiences ∼−10 dB and ∼−2 dB crosstalk for weaker turbulence and stronger turbulence, respectively. The pilot tones and data channels from different polarizations might experience little crosstalk (<−20 dB), which maintains the turbulence resilience of the pilot-assisted O/E beam mixing approach when applying polarization multiplexing. Fig. 6(b) shows the crosstalk matrix using the pilot-assisted O/E beam mixing. The results show

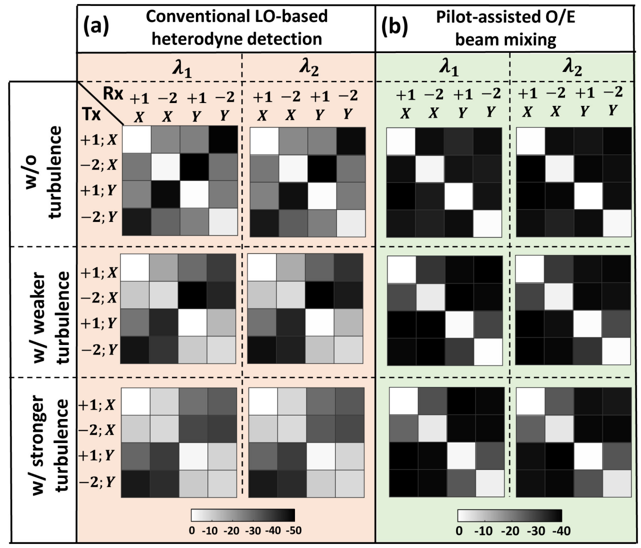

Fig. 6. Normalized crosstalk (in dB scale) between different data channels for λ_1 and λ_2 using (a) the conventional LO-based heterodyne detection and (b) the pilot-assisted O/E beam mixing without and with weaker or stronger turbulence.

that the inter-channel crosstalk of different data channels carried by different OAM modes and polarization is not significantly affected by the turbulence distortions. The crosstalk between two OAM modes is measured lower than ∼−22.6 dB and the crosstalk between two polarizations is lower than ∼−28.9 dB.

Fig. 7(a) shows the optical spectrum of the pilot tones and data channels of the OAM $l_1 = +1$and OAM $l_2 = -2$. The CSPRs are ∼1.4, ∼1.0, ∼0.9, and ∼1.6 for the pilot 1, 2, 3, and 4, respectively. The corresponding electrical spectrum with eight data channels after pilot tone-data mixing is shown in Fig. 7(b). Figs 7(c) show the constellations and EVM performance of different data channels when using the conventional LO-based heterodyne detection and pilot-assisted beam mixing with and without turbulence. The results show that the EVM performance for the conventional LO-based heterodyne detection degrades quickly as the turbulence effects become stronger (EVM >32.5% for stronger turbulence). The pilot-assisted O/E beam mixing suffers much fewer degradations for all eight data channels (EVM <22.2% for stronger turbulence).

Fig. 8 compares the BER performance of eight multiplexed data channels without turbulence and with weaker or stronger turbulence for the conventional LO-based heterodyne detection and the pilot-assisted O/E beam mixing. It should be noted that the transmitted optical power for the pilot-assisted O/E beam mixing approach includes the power of the 4 CW pilots. For the conventional LO-based heterodyne detection, only modulated data channels are transmitted with CW pilots tuned off. The results show that, for all eight data channels, the weaker turbulence induces ∼10dB power penalty for the conventional heterodyne detection. Under stronger turbulence, the data channels carried by OAM $l_1 = +1$ suffer from ∼15 to ∼20 dB power penalty. The data channels carried by OAM $l_2 = -2$ could not reach the 7% forward-error-correction (FEC) limits

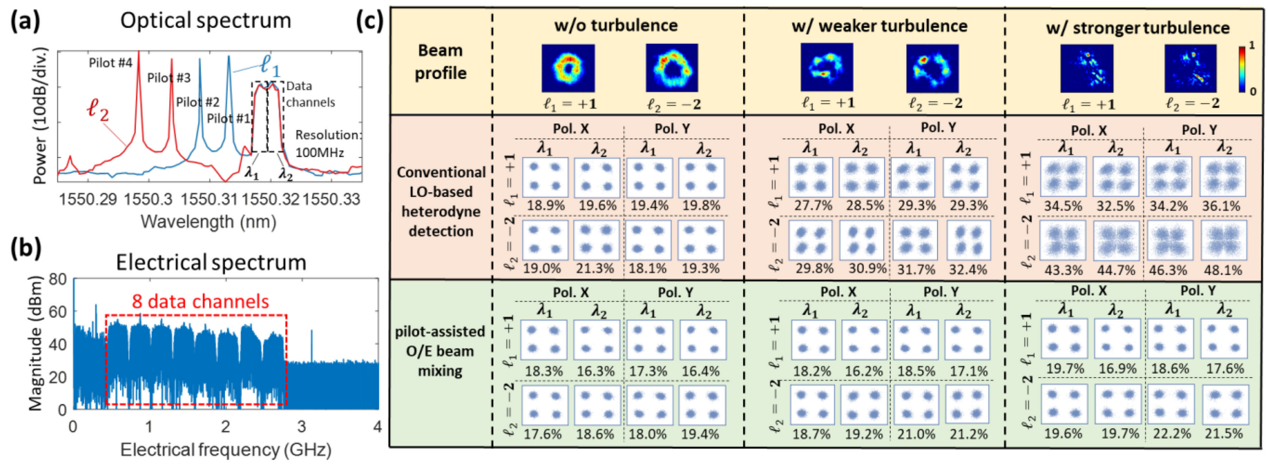

Fig. 7. (a) Optical spectra of the transmitted pilots and data channels carried by the OAM $l_1 = +1$ and OAM $l_2 = -2$. (b) Electrical spectrum with eight received data channels after the wave mixing of the pilot tone and data channels. (c) Beam profiles, data channel constellations and EVM performance (under the corresponding constellations) for the conventional LO-based heterodyne detection and the pilot-assist O/E beam mixing.

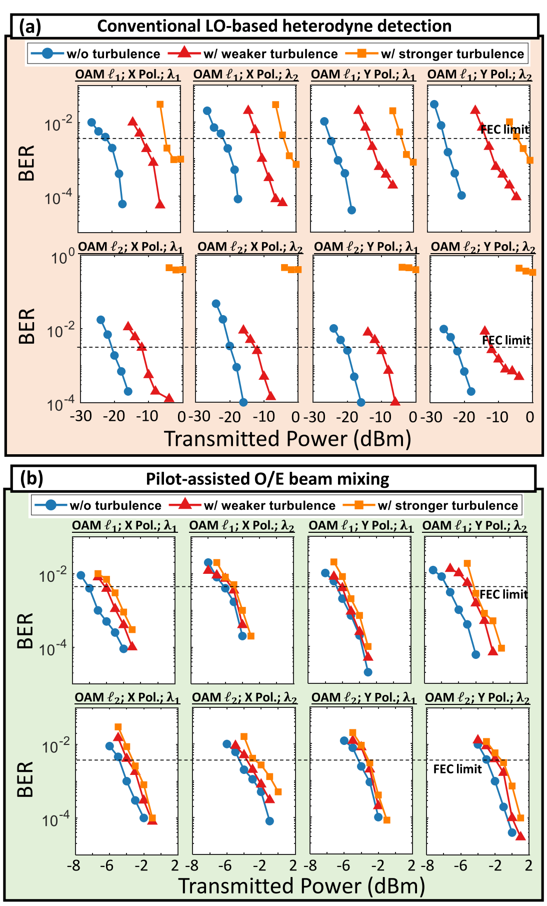

Fig. 8. BER performance of eight multiplexed data channels with different transmitted optical power at transmitter for (a) the conventional LO-based heterodyne detection and (b) the turbulence resilient link using pilot-assisted O/E beam mixing. FEC limit: 3.8e-3.

due to the stronger turbulence-induced power loss and modal crosstalk. The pilot-assisted beam mixing approach can achieve below the 7% FEC limit under the stronger turbulence realization for all eight data channels. Compared to the case of no turbulence effects, the BER performance for the pilot-assisted beam mixing approach shows power penalties of <3.7dB at the 7% FEC limit. We note that the data rate could be further extended by (i) transmitting data signals with higher-order modulation formats (e.g., 16-QAM) [17] and/or (ii) utilizing a PD with a larger bandwidth to receive data signals with higher baud rates. Although the PD's bandwidth is ~3 GHz in our demonstration, free-space-coupled PDs with a bandwidth of ~49 GHz have been reported [28], such that a >100-Gbit/s data rate could be potentially supported.

IV. Conclusion

In this paper, we experimentally demonstrate a 2-Gbit/s turbulence resilient coherent FSO link with 8 data channels multiplexed in different domains (2 polarizations, 2 wavelengths, and 2 OAM modes) using a pilot-assisted O/E beam mixing approach. Turbulence effects on the data-carrying beam could be automatically compensated by their conjugates generated from the similarly turbulence-distorted pilot beam during the O/E mixing in a single PD, without additional optical or digital signal processing. Using the proposed pilot-assisted O/E mixing approach, the channel crosstalk under both the weaker and stronger turbulence distortions is measured to be lower than ~−22.6 dB. Compared to the case of no turbulence effects, the BER performance for the pilot-assisted beam mixing approach shows power penalties of <3.7 dB at the 7% FEC limit.

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