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Demonstration of Turbulence-Resilient Self-Homodyne 12-Gbit/s 16-QAM Free-Space Optical Communications using a Transmitted Pilot Tone

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Abstract *We experimentally demonstrate a turbulence-resilient 12-Gbit/s 16-QAM FSO link using pilot-assisted self-homodyne (rather than heterodyne) detection. Results show link resilience under 400 random turbulence realizations and up to ~20-dB improvement of optical-to-electrical mixing efficiency compared to conventional LO-based coherent detection. ©2022 The Author(s)*

Introduction

Free-space optical (FSO) communications have gained much interest due to the potential for higher capacity and lower probability of intercept as compared to RF technologies [1, 2]. However, a key challenge for FSO links is that atmospheric turbulence tends to distort the transmitted fundamental Gaussian beam [3]. This distortion results in spatial modal power coupling from the fundamental mode into higher-order modes, such as Laguerre-Gaussian ($LG_{l,p}$) modes of various l (azimuthal) and p (radial) spatial values [3, 4].

As opposed to amplitude-only modulation, there is value to encoding data on both the phase and amplitude of the transmitted lightwave (e.g., quadrature-amplitude-modulation, QAM) in order to increase the bits/symbol and decrease the OSNR requirement [5]. Typically, one could use coherent detection with a Gaussian mode local oscillator (LO) to recover the phase and amplitude of the data. However, turbulence can cause significant data-beam modal coupling, which can significantly decrease the optical-to-electrical (O/E) mixing efficiency with the LO [6].

Recently, it was demonstrated that a pilot beam can be simultaneously transmitted along with the data beam, such that both beams experience the same turbulence-induced modal coupling and thus can automatically and efficiently mix all modal orders in the detector [7]. This report used self-coherent "heterodyne" detection, in which the pilot and data beams were offset in center frequency to avoid signal-signal beating interference. Thus, the bandwidth utilization of the detector is reduced (e.g., increasing the required bandwidth from around 2 times that of the data by the frequency offset) [7]. A laudable goal would be to apply the concept of a pilot beam to a self-homodyne detection system, with the theoretical potential to have a better detector bandwidth utilization and other homodyne-based advantages (e.g., simpler digital signal processing (DSP)) [8, 9].

In this paper, we experimentally demonstrate turbulence-resilient self-homodyne 12-Gbit/s 16-QAM FSO communications using a transmitted pilot tone. The pilot tone is located at the same center frequency as the data channel but on a different polarization. We use a self-homodyne detection with four free-space coupled photodiodes (FS-PDs) to achieve the O/E mixing of the data and pilot. The utilized bandwidth of each PD is around half of the data bandwidth. Since the data and pilot experience similar turbulence effects [7, 10], they can be efficiently mixed to recover the 16-QAM data. Results show that the pilot-assisted self-homodyne could improve mixing efficiency by up to ~ 20 dB compared to LO-based coherent detection. The link resilience to turbulence is demonstrated under 400 random turbulence realizations.

Concept and Experimental Setup

The performance of FSO coherent detection systems can be significantly degraded by turbulence-induced modal coupling, as shown in Fig. 1(a). At the transmitter (Tx), a data channel is carried by a fundamental Gaussian beam (i.e., single $LG_{0,0}$ mode) and transmitted through turbulence. Due to the turbulence-induced modal coupling, the received data beam will contain many LG modes. In a LO-based coherent detection (e.g., homodyne or intradyne), only the $LG_{0,0}$ mode can be efficiently mixed with the LO and recovered, resulting in significant power loss and degradation of the recovered data quality. Figure 1(b) shows the concept of using pilot-assisted self-homodyne detection to increase the turbulence resilience of FSO links. At the Tx, the output from a continuous wave (CW) laser is split into to two paths, with one path modulated with a 16-QAM data channel on X polarization (pol.) and another path used as a pilot tone on Y pol.. The data and pilot beams are simultaneously transmitted through turbulence. At the receiver (Rx), the pilot tone mixes with the data beam in

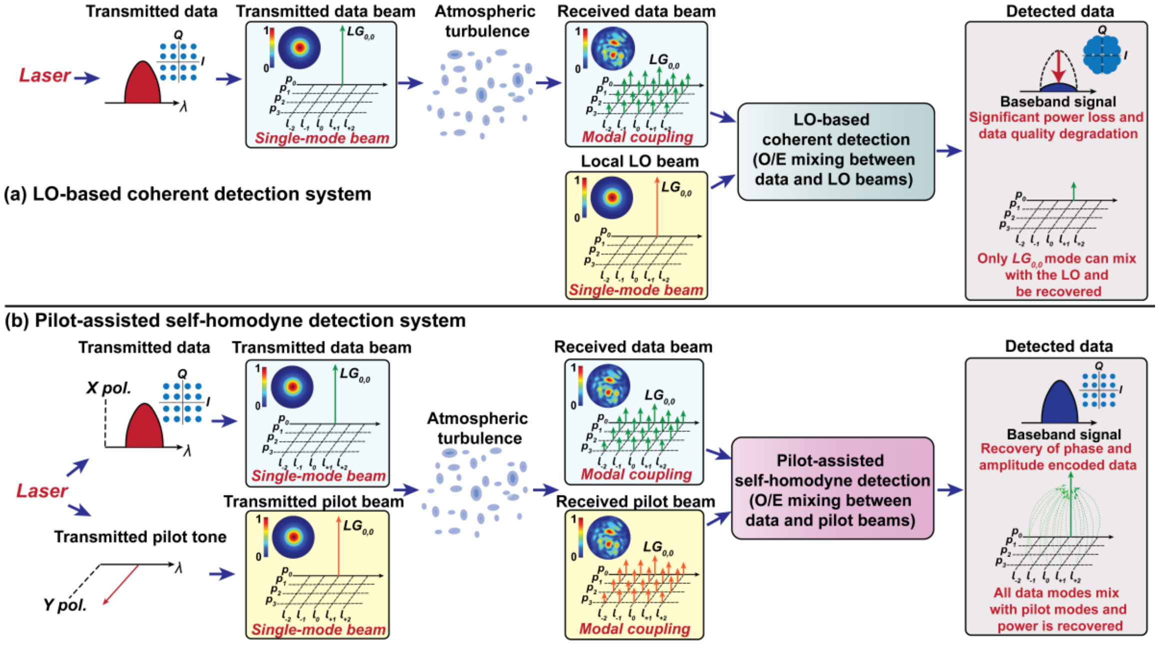

Fig. 1: (a) Atmospheric turbulence-induced modal power coupling can significantly decrease the mixing efficiency between the data and LO and cause data quality degradation. (b) By co-transmitting an orthogonally polarized pilot tone together with the data, the pilot-assisted self-homodyne detection can automatically mitigate the turbulence-induced modal coupling effects.

self-homodyne detection. Since data and pilot beams on two polarizations experience similar turbulence-induced modal coupling [10], almost all the LG modes of the data beam can automatically mix with the pilot beam, and data can be efficiently recovered.

Figure 2 shows the experimental setup. At the Tx, Laser 1 is separated into two pol. using a polarization beam splitter (PBS). A 3-Gbaud 16-QAM data channel is modulated on X pol. and subsequently combined with the pilot tone on Y pol. using a polarization beam combiner (PBC). The pair of data and pilot is coupled to free space by an optical collimator (Gaussian beam size of diameter $2w_0 \approx 3$ mm) and propagate in free space for ~1 m. We experimentally emulate the turbulence effects using glass plates, whose refractive index distributions are fabricated to emulate Kolmogorov turbulence power spectrum statistics [7]. Two rotatable glass plates with different Fried parameters (r_0) of 1.0 mm (weaker turbulence) and 0.4 mm (stronger turbulence) are used [7]. Different turbulence realizations are emulated by rotating the glass plate to different orientations. Off-axis holography is used to measure the amplitude and phase profiles of the distorted beam and its corresponding LG modal spectrum [11]. At the Rx, for the pilot-assisted self-homodyne detection, the polarization of the light is first rotated by 45° using a half-wave plate (HWP) and subsequently spilt into two copies using a beam splitter (BS) for recovering in-phase (I) and quadrature (Q) data information, respectively. For each copy, a PBS is used to separate the X and Y pol. components, each containing a pair of data and pilot. The data and pilot on each pol. mix in an FS-PD. The I information is recovered by differentially detecting the data-pilot O/E mixing on two polarizations. For recovering Q information, a quarter-wave plate (QWP) is used to induce 90° phase delay on the pilot. As show in the electrical spectra detected by FS-PDs. For each PD, ~1.5-GHz bandwidth is utilized to receive a 3-GHz data channel. For the LO-based coherent detection (homodyne or intradyne), the distorted beam is

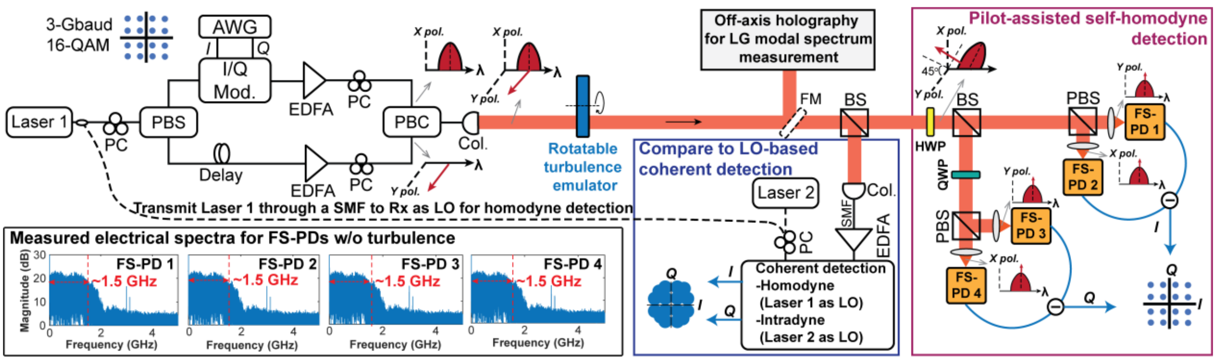

Fig. 2: Experimental setup for a 12-Gbit/s 16-QAM turbulence resilient FSO link using pilot-assisted self-homodyne detection. We compare the performance with LO-based homodyne or intradyne detection. PC: polarization controller; FM: flip mirror.

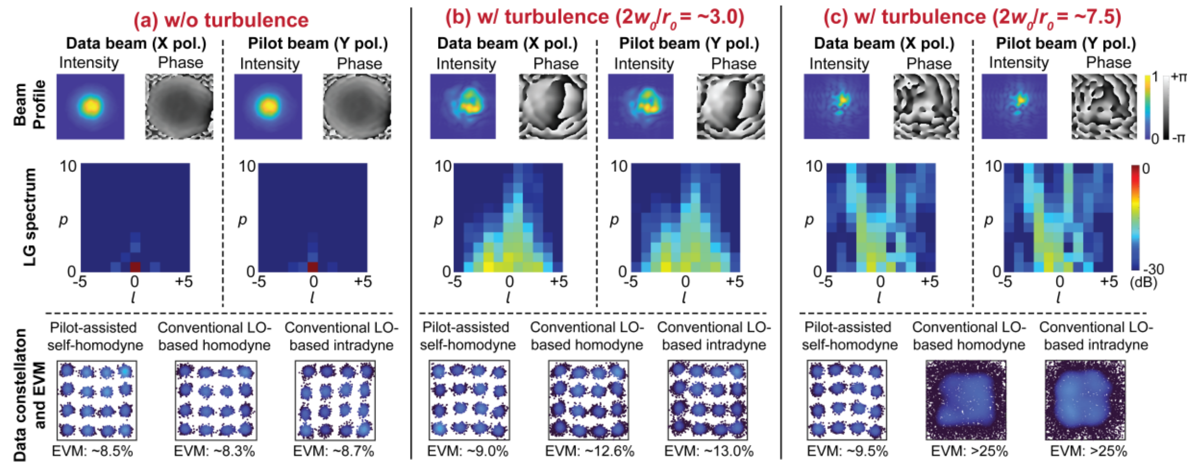

Fig. 3: Experimental results of turbulence-induced modal coupling and recovered data constellations using the pilot-assisted self-homodyne and LO-based homodyne/intradyne detection. (a) w/o turbulence, and w/ (b) weaker and (c) stronger turbulence.

coupled into a single-mode fiber (SMF), amplified by an Erbium-doped fiber amplifier (EDFA), and mixed with an LO. For homodyne detection, we split the power of Laser 1 and transmit it through an SMF to Rx as an LO [9]. For intradyne detection, a separated Laser 2 is used as an LO, and additional DSP is used to mitigate laser frequency offset and phase noise [9].

Experimental Results

Figure 3 shows the turbulence-induced LG modal power coupling and recovered 16-QAM constellations under example realizations of the weaker and stronger turbulence. As shown in Fig. 3 (b), under one random realization of weaker turbulence, the measured LG spectrum shows that the power is mainly coupled from $LG_{0,0}$ mode to the neighboring LG modes. Figure 3 (c) shows that the stronger turbulence effect can induce a power loss of >20 dB on $LG_{0,0}$ mode and that power can be coupled to a large number of other LG modes. The results also show that data and pilot beams on two polarizations experience similar turbulence-induced distortion and modal power coupling. For both realizations, the performance of the pilot-assisted self-homodyne detection is not severely affected by these turbulence effects and the 16-QAM data can be recovered with error vector magnitude (EVM) values from ~8% to ~10%. We also show the recovered 16-QAM data for conventional LO-based homodyne and intradyne detection. The recovered data quality degrades from EVM values of ~8% without turbulence to >25 % for stronger turbulence.

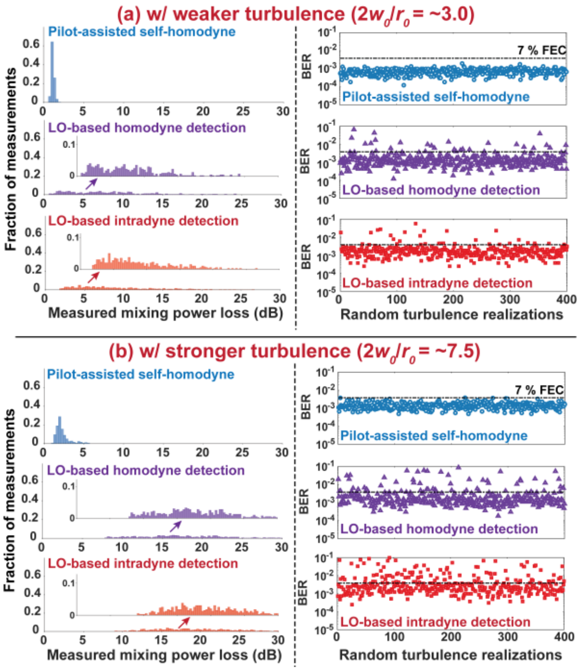

Fig. 4: Experimentally measured O/E mixing power loss and BERs for the pilot-assisted self-homodyne and LO-based homodyne and intradyne detection under 400 random (a) weaker and (b) stronger turbulence realizations.

We measure the turbulence-induced O/E mixing power loss of the pilot-assisted self-homodyne detection under 400 random realizations of the emulated turbulence, as shown in Fig. 4. The pilot-assisted self-homodyne detection has an O/E mixing loss of < 3 dB and < 5 dB for 99% weaker turbulence realizations and 90% of the stronger ones. However, for LO-based coherent detection, the mixing power is degraded and ranges from ~2 to ~26 dB and from ~8 to ~30 dB under weaker and stronger turbulence strengths, respectively. We also measure bit-error rates (BERs) of the data under different turbulence realizations. Results show that the pilot-assisted self-homodyne detection can achieve BER values below the 7% forward error correction (FEC) limit for all realizations. However, due to the strong modal-coupling-induced power loss, the performance of the conventional LO-based coherent detection can be scientifically degraded and does not achieve the 7% FEC limit for some realizations.

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