Demonstration of Turbulence Resilient Self-Coherent Free-Space Optical Communications Using a Pilot Tone and an Array of Smaller Photodiodes for Bandwidth Enhancement

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Abstract: We demonstrate a 4-Gbit/s 16-QAM turbulence-resilient self-coherent free-space optical link using a pilot tone. An array of smaller photodiodes is used to potentially increase the overall bandwidth under turbulence (D/r_0 = ~8.4).

OCIS codes: (060.2605) Free-space optical communications;(010.1330) Atmospheric turbulence.

1. Introduction

Atmospheric turbulence is a key limitation in free-space optical (FSO) communication systems [1]. For amplitude-only data encoded systems, turbulence can cause scintillation and power loss [2]. The challenge is perhaps far greater for phase-and-amplitude encoded high-modulation-format systems. This is because: (i) the data beam going through turbulence will have power coupled from the fundamental Gaussian mode into many higher-order spatial modes [3], and (ii) these higher-order spatial modes do not efficiently mix with a fundamental-Gaussian-mode local oscillator (LO) that is conventionally used for detecting phase-encoded data [3,4].

Recently, a turbulence-resilient pilot-assisted self-coherent FSO communication link was demonstrated by using automatic optoelectronic mixing of many modes [5]. From the transmitter, an additional Gaussian pilot beam with a frequency offset is sent coaxially with the Gaussian data beam, such that both beams experience similar turbulence-induced modal coupling. At the receiver, both beams are captured by a free-space detector and a conjugate modal coupling of the pilot beam is automatically generated to compensate for the modal coupling in the data beam. Therefore, the beams are efficiently mixed and the amplitude and phase of the data (*e.g.*, 16-QAM) can be recovered.

The above approach used a free-space detector to efficiently mix the corresponding pairs of higher-order modes between the data and pilot beams.[5] Typically, receivers that detect phase and amplitude encoding with a local oscillator use a photodetector (PD) coupled with single-mode fiber [6]. As mentioned in [5], higher-order modes do not couple efficiently into a single-mode fiber, but it is important to note that fiber-coupled detectors can typically be smaller and higher bandwidth than free-space detectors [7]. Therefore, a laudable goal would be to try and increase the bandwidth of the free-space detector and still preserve the automatic turbulence resilience due to mode mixing. Towards this end, we substitute a single PD with multiple smaller PDs to increase the overall bandwidth [7].

In this paper, we experimentally demonstrate a pilot-assisted turbulence resilient self-coherent FSO communication link using an array of smaller PDs for bandwidth enhancement. The experimental results show that (i) under 100 turbulence realizations (D/r_0 = ~8.4), the pilot-assisted self-coherent PD-array receiver recovers 1-Gbaud 16-QAM data with the bit error rate (BER) below 7% forward error correction (FEC) limit and (ii) either without and with turbulence effects, the 1-Gbaud 16-QAM data constellation recovered by the array of smaller PDs has lower error vector magnitude (EVM) than that of single larger PD.

2. Concept and experimental setup

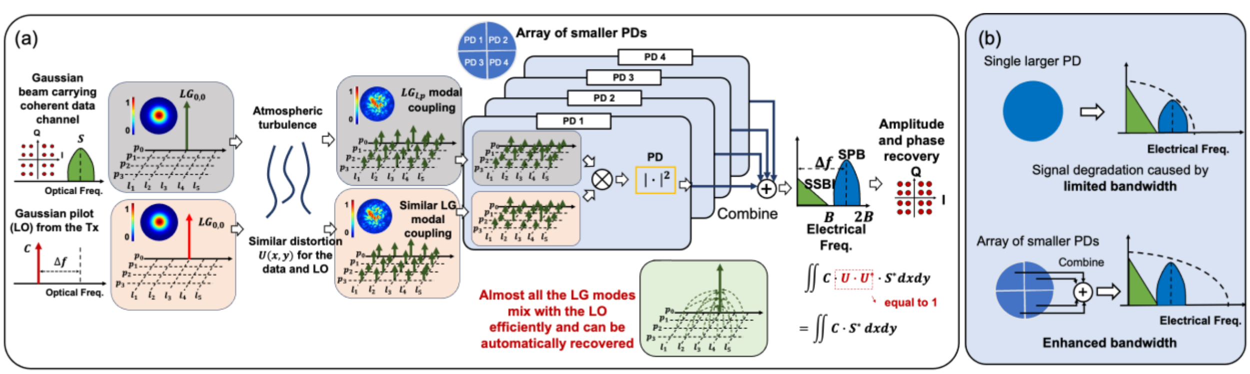

Fig. 1. (a) Concept of turbulence resilient self-coherent FSO communications using a pilot tone and an array of smaller photodiodes. (b) Concept of utilizing the array of smaller photodiodes for bandwidth enhancement. SSBI: signal–signal beating interference; SPB: signal–pilot beating.

Figure 1(a) shows the concept of turbulence resilient pilot-assisted self-coherent FSO communications using an array of smaller PDs. At transmitter, the Gaussian data beam is sent together with a coaxial Gaussian pilot beam with a frequency offset. Experiencing similar turbulence-induced distortion, the two beams have similar modal coupling to higher-order $LG_{l,p}$ modes. The indices l and p of the 2-dimensional $LG_{l,p}$ spatial modal set represent the beam's spatial distributions along the azimuthal and radial directions, respectively. At the receiver, the similarly distorted data and pilot beams are coupled together into the PD array. In each PD, the truncated multi-mode pilot beam is mixed efficiently with the similarly truncated multi-mode data beam. By combining the output of the PDs, almost all the LG modes of data beam mix with the pilot beam as LO, and thus the turbulence-induced modal coupling is automatically compensated. Subsequently, the amplitude and phase information of the data can be recovered. In addition, with a similar total receiving area, the larger PD and the array of smaller PD could capture a similar amount of spatial modes while the array of smaller PD tends to generally support a larger bandwidth as shown in Fig. 1(b).

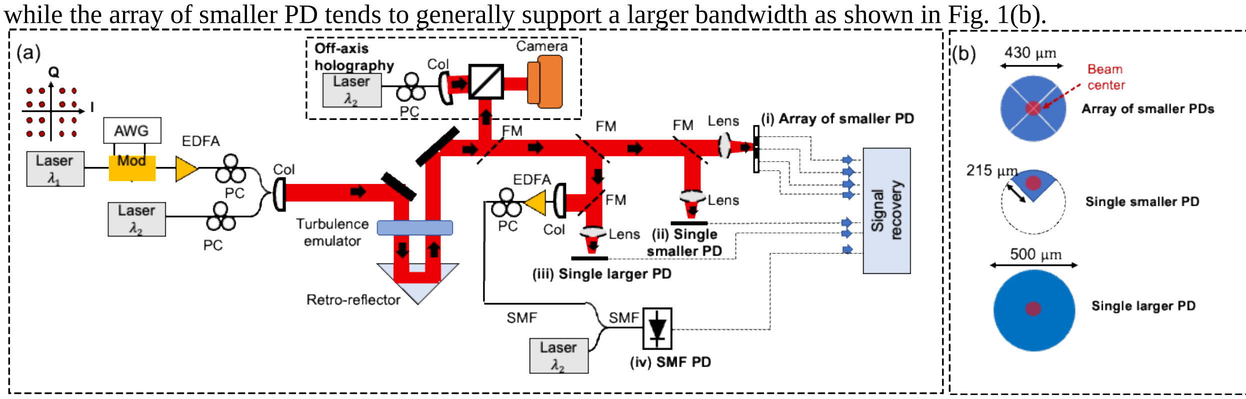

Fig. 2. (a) Experimental setup of an FSO link through emulated turbulence. AWG: Arbitrary Waveform Generator; EDFA: Erbium-doped Fiber Amplifier; PC: Polarization Controller; ; FM: flip mirror; SMF: single-mode fiber; DSP: Digital Signal Processing. (b) Size of the free-space PD used in our experiment. For the array of smaller PDs and single smaller PD, a PX00M3 quadrant InGaAs PD from Albis is used. For the single larger PD, a Thorlabs FDGA05 InGaAs PD is used.

Figure 2(a) shows the experimental setup of an FSO link through emulated turbulence. We experimentally emulate the turbulence-induced distortion by utilizing rotatable thin glass plates whose refractive index distributions are according to Kolmogorov spectrum statistics. By using a retroreflector, the beam propagates through two independent areas of the turbulence plate and thus experiences a relatively stronger turbulence distortion ($r_0 \sim 0.26\ mm$). We transmit a pair of data-carrying and pilot beams with a beam size of 2.2 mm. A 16-QAM data channel at a wavelength of $\lambda_1 \approx 1550\ nm$ is generated. The pilot tone at a wavelength of λ_2 with a frequency offset with a range from ~0.8 GHz to ~2.6 GHz compared to λ_1. At the receiver side, we used a flip mirror to control the path of the optical beam towards different detectors (i-iv). The size of the PDs we used in our experiment is shown in Fig. 2(b). The amplitude and phase profiles of the beam are measured by off-axis holography [8].

3. Experimental results and discussion

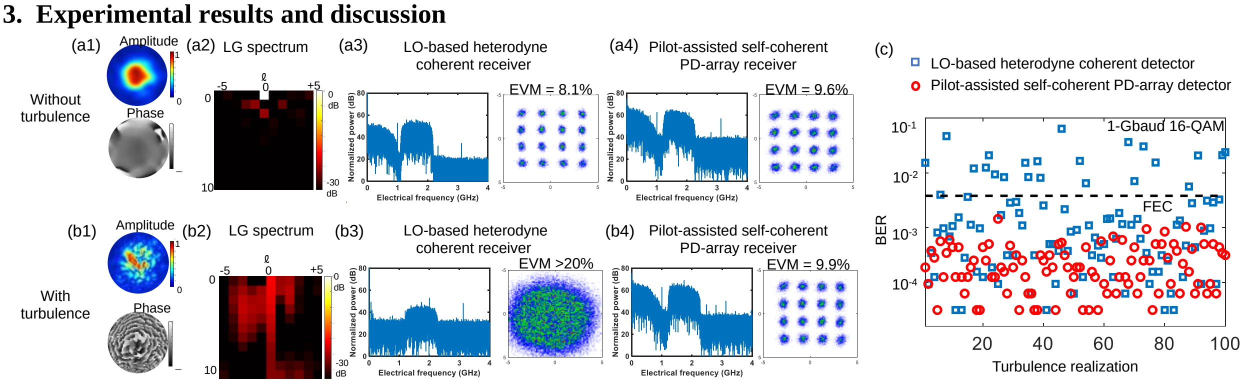

Fig. 3. Measured (a1-b1) amplitude and phase profiles, (a2-b2) LG spectrum without and with turbulence effects (one turbulence realization). Measured electrical spectra and recovered 1-Gbaud 16-QAM data constellation for (a3-b3) the LO-based heterodyne coherent detector and (a4-b4) the pilot-assisted self-coherent PD-array receiver without and with turbulence effects (one turbulence realization). (c) Measured BER performance of the recovered 1-Gbaud 16-QAM signal under 100 turbulence realizations (D/r_0 ~8.2). FEC: forward error correction.

Figure 3 (a1) shows the measured amplitude and phase profile of the transmitted Gaussian beam without turbulence effects. The measured LG spectrum shows that there is little modal power coupling to higher-order spatial modes as shown in Fig. 3(a2). Without turbulence effects, both the LO-based heterodyne coherent receiver and self-coherent

PD-array receiver can recover an EVM of 8%-9% for the 1-Gbaud 16-QAM data. With turbulence effects, the amplitude and phase profiles of the transmitted Gaussian beam are distorted, and the power is coupled to a large number of modes as shown in Fig. (b1-b2). Under such turbulence realization, the power of the data beam cannot be efficiently coupled to SMF and the transmitted 16-QAM data fails to be recovered by the LO-based heterodyne coherent receiver as shown in Fig. (b3). Figure 3(b4) shows that the performance of the pilot-assisted self-coherent PD-array receiver is not severely affected and the 16-QAM data is recovered with an EVM of 9.9%. Figure 3(c) shows the measured BERs for the pilot-assisted self-coherent PD-array detector under 100 turbulence realizations. The PD-array receiver can achieve BER values below the 7% FEC limit for all realizations.

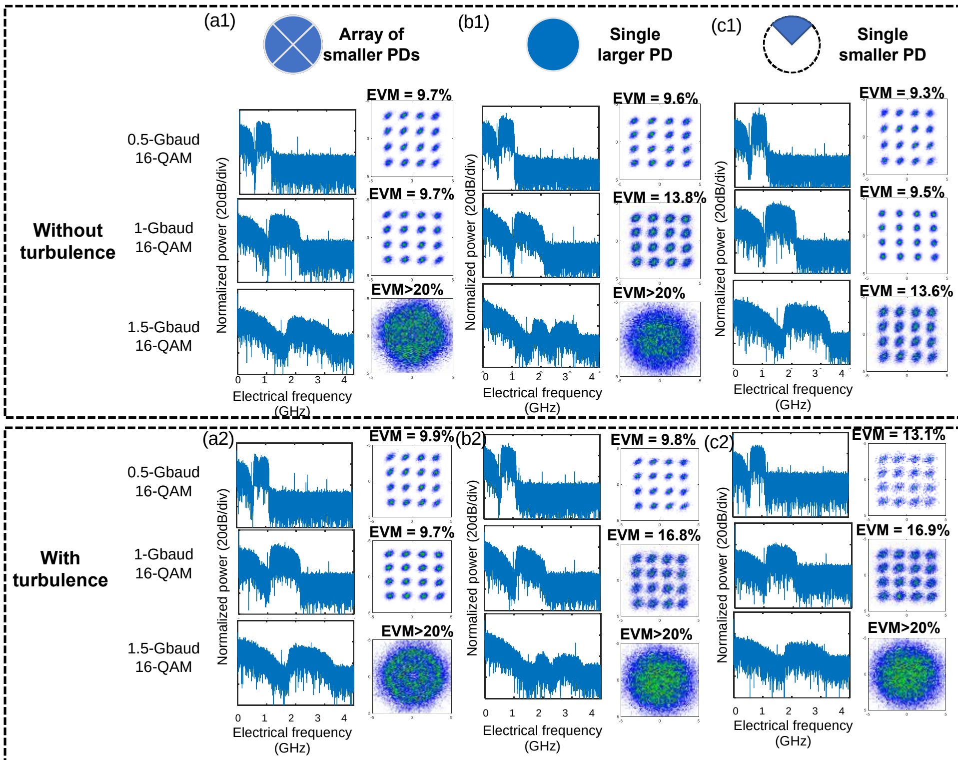

Fig. 4 Measured electrical spectra and recovered 16-QAM data constellation with different baud rates for different free-space PDs: (a1-a2) an array of smaller PDs, (b1-b2) single larger PD and (c1-c2) single smaller PD without and with turbulence effects. For (a2-c2), data in each row are measured under the same turbulence realization.

Figure 4 shows the measured electrical spectra and recovered 16-QAM data constellations with different baud rates for different free-space PDs. Without turbulence effects, the array of smaller PDs, single larger PD, and single smaller PD can recover 0.5-Gbaud 16-QAM data constellations as shown in Fig. 4(a1-c1), respectively. When the baud rate increases to 1 Gbaud, the data recovered from a single larger PD degrades due to its bandwidth. When the baud rate increases to 1.5 Gbaud, the array of smaller PDs fails to recover the data constellation. This could be potentially due to different frequency response (especially at higher frequency) of the PD-array photodiodes and combining the output of multiple PDs could lead to the decreased signal-to-noise ratio. With turbulence effects (Fig. 4(a2-c2)), single smaller PDs have degraded data constellation of 0.5-Gbaud 16-QAM data while the array of smaller PDs and single larger PD show similar EVM performance, as in the cases without turbulence effects (Fig. 4(a1-c1)). This could be because the single smaller PD tends to recover a smaller amount of spatial modes, thereby showing larger data degradation with turbulence effects. When the baud rate increases to 1 Gbaud, the data recovered by the array of smaller PDs show lower EVM than that of the lower bandwidth single larger PD.

Acknowledgment Support of VBFF through ONR N00014-16-1-2813; Airbus Institute for Engineering Research; ONR through MURI Award N00014-20-1-2558; DSCA 4441006051; DURIP (FA9550-20-1-0152); Qualcomm Innovation Fellowship.

References

[1] M.A. Khalighi et al., IEEE commun. Surv. Tutor 16, 223 (2014).
[2] H. Yuksel et al., J. Opt. Netw. 4, 364 (2005).
[3] R.J. Noll et al., J. Opt. Soc. Am. A 6, 207 (1976).
[4] Y. Dikmelik et al., Appl. Opt. 44, 4946 (2005).
[5] R. Zhang et al., Nat. Photonics 15, 743 (2021).
[6] K. Kikuchi, J. Lightwave Technol. 34, 157 (2016).
[7] T. Umezawa et al., J. Lightwave Technol. 36, 3684 (2018).
[8] Y Zhou et al., Proc. OSA Advanced Photonics Congress (2020).