Automatic Turbulence Resilience in Self-Coherent Free-Space Optical Communications

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Abstract: We review the recently reported self-coherent approaches that can enable resilient free-space optical communications using automatic optoelectronic multi-mode mixing.
OCIS codes: (060.2605) Free-space optical communications; (010.1330) Atmospheric turbulence.

1. Introduction

Compared with radio, free-space optical (FSO) communications have the potential advantages of higher data capacity and lower probability of interception [1-2]. In FSO links, an amplitude-only-modulated Gaussian data beam (*e.g.*, pulse-amplitude modulation (PAM)) can be transmitted and recovered [3]. Alternatively, FSO systems can benefit from simultaneously recovering amplitude and phase of the data beam to enable complex modulation formats [4], such as quadrature amplitude modulation (QAM) [5]. In comparison with PAM of the same modulation order and average power per bit, QAM is generally less demanding in terms of the optical signal-to-noise ratio (OSNR) of the transmitted data due to its larger Euclidean distance in the two-dimensional I/Q constellation [3]. This advantage tends to be more pronounced as the modulation order increases [3].

FSO links typically receive amplitude-encoded data by directly detecting the beam's intensity levels [2,4,6]. Alternatively, FSO systems can recover both amplitude and phase by using coherent detection, which mixes the data beam with a receiver Gaussian local oscillator (LO) beam [7]. However, atmospheric turbulence generally limits coherent detection because it induces power coupling of the data beam from the fundamental Gaussian mode to the higher-order Laguerre-Gaussian (LG) spatial modes [8]. Such turbulence-induced modal coupling can significantly degrade the data-LO mixing efficiency (*e.g.*, >20 dB [8,9]) because data power coupled to orthogonal higher-order modes does not efficiently mix with the Gaussian LO [9].

Various mitigation approaches have been demonstrated to enable amplitude and phase recovery in turbulent links [10-13]. One technique uses adaptive optics to couple the data power back to the Gaussian mode by measuring the distortion and applying a digital-signal-processing (DSP)-calculated conjugate phase to the beam [10]. Another technique uses multi-mode digital coherent combining [11-13], wherein much of the data power in higher-order modes is captured by either a multi-mode fiber [11-12] or an array of single-mode fiber (SMF) apertures [13]. Subsequently, the power from each of the multiple modes is recovered by a separate coherent detector and combined using DSP [11-13]. Since turbulence may induce coupling to a large number of modes, a laudable goal would be to automatically compensate for such power coupling without additional DSP and to do so in a single element that efficiently scales to recover all the captured modes.

In this talk, we review the recent demonstration of self-coherent FSO communication schemes that exhibit resilience to turbulence-induced LG modal power coupling. In our approach, the amplitude and phase of the transmitted 16-QAM data are retrieved using a pilot-assisted self-coherent (PASC) detector [14]. Specifically, we transmit both a Gaussian data beam and a frequency-offset Gaussian pilot tone beam such that both beams experience similar turbulence and modal coupling. Subsequently, a photodetector mixes all corresponding pairs of the beams' modes. During mixing, a conjugate of the turbulence-induced modal coupling is generated and compensates for the modal coupling experienced by the data, and thus the corresponding modes of the pilot and data mix efficiently. **Moreover, in this talk, we review the recently demonstrated extended applications of our self-coherent approach in FSO links**, including the following: (*i*) enhanced misalignment tolerance using PASC [15]; (*ii*) bandwidth enhancement by using PASC with a photodetector (PD) array [16]; (*iii*) improved utilization rate of PD bandwidth by applying self-homodyne to PASC [17]; and (*iv*) enhanced power sensitivity by optoelectronic multi-mode mixing in differential-phase-shift keying (DPSK) [18].

2. Conceptual scheme and experimental results [14]

Figure 1 shows the concept of simultaneous recovery of amplitude and phase of QAM data by utilizing PASC [14]. We transmit a Gaussian pilot beam with a frequency offset from the Gaussian data beam such that both beams experience similar turbulence-induced LG modal coupling (denoted as U). Subsequently, a single free-space-coupled PD mixes the received multi-mode data beam with the multi-mode pilot beam in self-coherent detection [14]. During mixing, a conjugate of the turbulence-induced modal coupling of the pilot beam is automatically generated and used to compensate for the modal coupling in the data beam, expressed as [14]:

$$\iint U \cdot U^* dxdy \approx 1$$

Specifically, each data-pilot LG modal pair efficiently mixes and contributes to the intermediate frequency signal. Since the data and pilot experience similar modal coupling, our approach can simultaneously mix and recover nearly all of the captured data modes using a single PD.

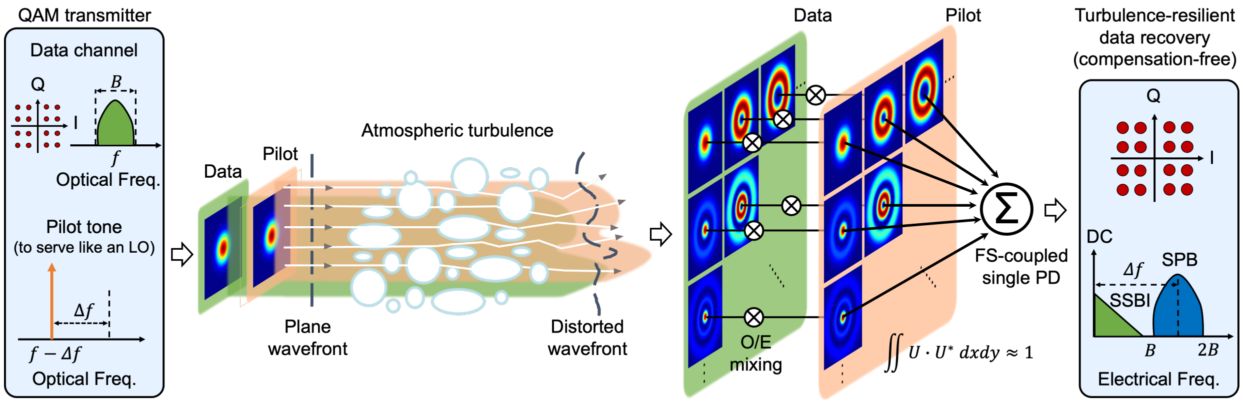

Figure 1. Concept of simultaneous amplitude and phase recovery of QAM data in turbulent FSO links [14]. DC: direct-current; SSBI, signal–signal beating interference; SPB: signal-pilot beating; O/E: optoelectronic; FS: free-space; PD: photodetector.

Figure 2 shows the turbulence-induced LG modal power coupling and the correspondingly recovered 16-QAM constellations using the pilot-assisted self-coherent detection. Varied from no turbulence ($2\omega_0/r_0{\sim}0$) to stronger turbulence effects ($2\omega_0/r_0{\sim}5.5$), the self-coherent detection can achieve near-error-free performance with error vector magnitudes (EVMs) ranging from ~8.1% to ~10.1%. However, with respect to a LO-based coherent detection, its performance is significantly degraded because much of the data power residing in higher-order LG modes is not efficiently recovered.

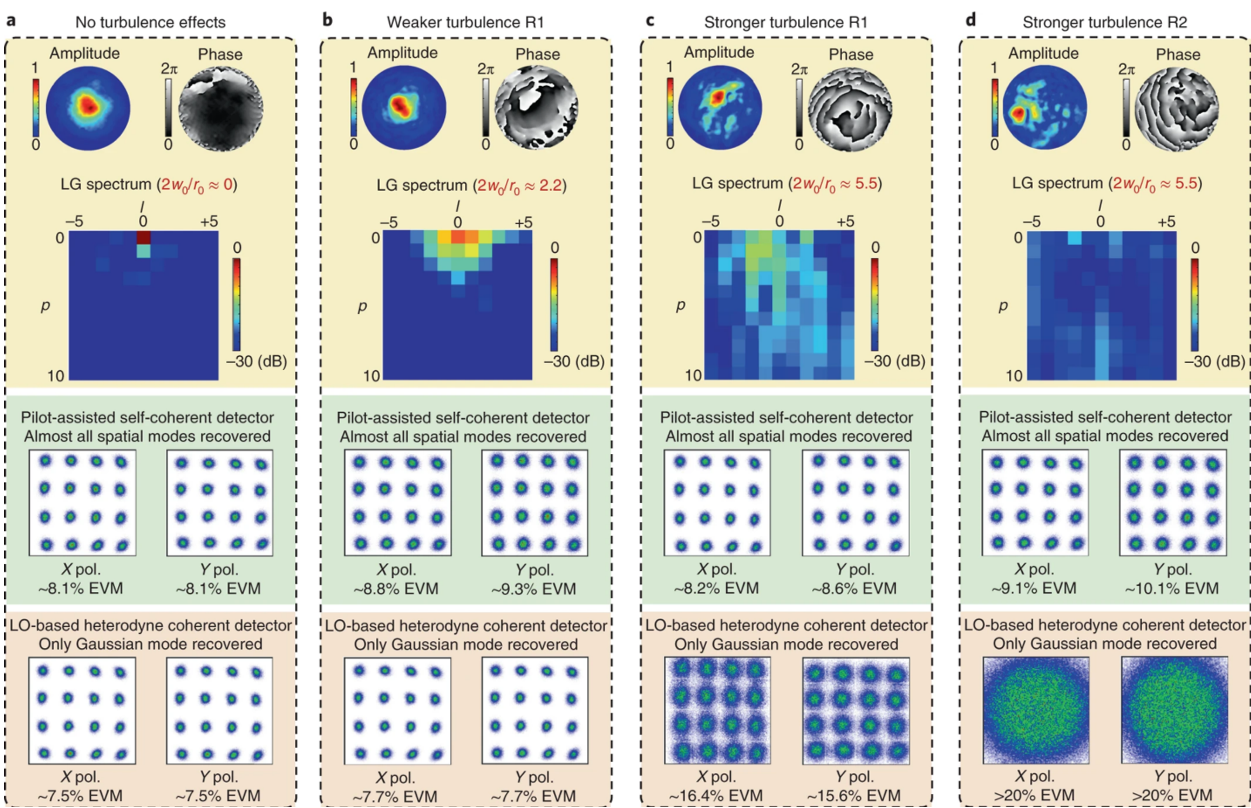

Figure 2. Experimental results of turbulence-induced LG modal power coupling and recovered 16-QAM data qualities using the pilot-assisted self-coherent detector [14]. (a) No turbulence distortion; (b) One example realization of the weaker turbulence distortion ($2\omega_0/r_0{\sim}2.2$); (c-d) Two different example realizations of the stronger turbulence distortion ($2\omega_0/r_0{\sim}5.5$). Each polarization carries a 6-Gbit/s 16-QAM data.

3. Extended applications of PASC in FSO systems [15-18]

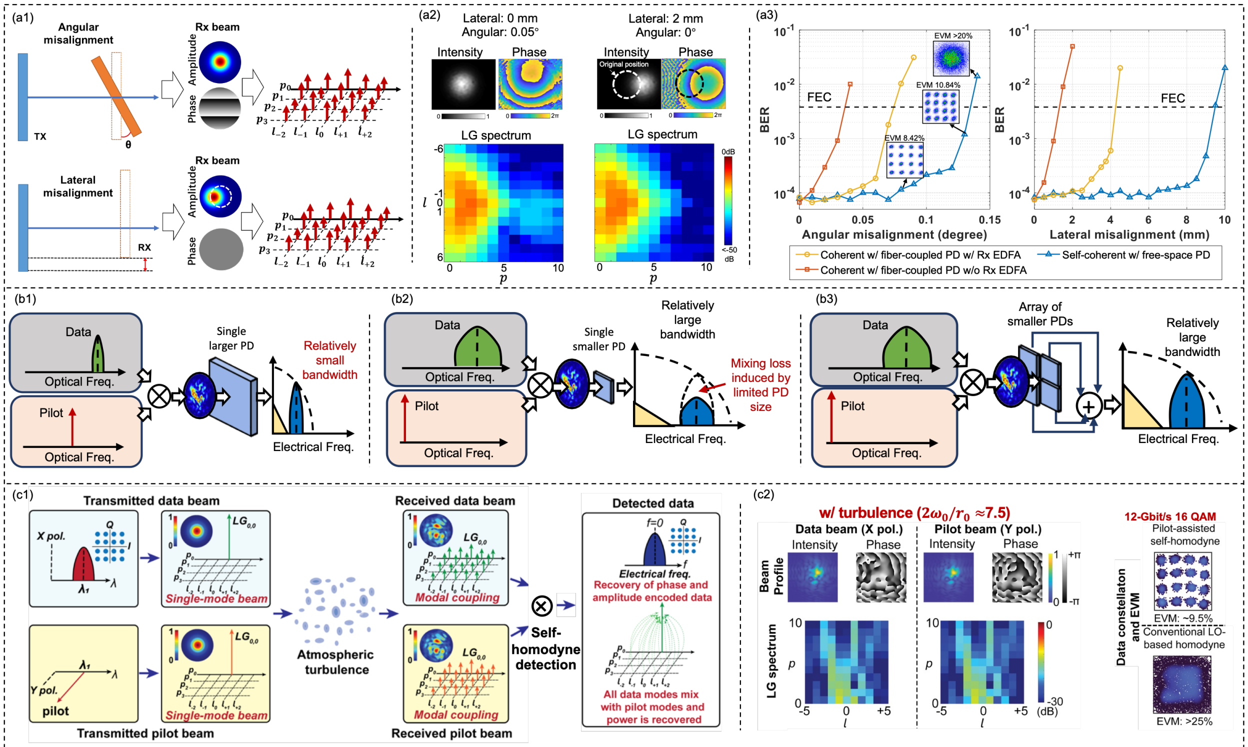

Figure 3. Extended applications of PASC in FSO systems. (a) Enhanced misalignment tolerance using PASC [15]; (b) Bandwidth enhancement using PASC with a PD array [16]; (c) Improved utilization rate of PD bandwidth by applying self-homodyne to PASC [17].

Figure 3 shows the extended applications of our PASC approach [15-18]. As shown in Figs. 3(a1-a3), the receiver can be misaligned with the transmitter due to improper setup and vibration. Both angular and lateral misalignments can induce LG modal coupling. Using the PASC approach, the bit-error-rate (BER) performance can be achieved below the 7% FEC threshold for up to 0.13° angular- or 9-mm lateral misalignments [15]. As shown in Figs. 3(b1-b3), in general, a single larger free-space PD tends to have a narrower bandwidth (Fig. 3(b1)) and decreasing the PD area is likely to induce a higher electrical mixing loss because part of the turbulence-distorted optical beam can be truncated by the limited PD size (Fig. 3(b2)). However, an array of smaller PDs, which has sufficiently larger aggregated PD area, can potentially alleviate the tradeoff between the PD area and PD bandwidth (Fig. 3(b3)) [16]. As shown in Figs. 3(c1-c2), we demonstrate the utilization of PASC in self-homodyne detection to increase the turbulence resilience of FSO links, in which the data and pilot beams are located in orthogonal polarizations [17]. Since data and pilot beams on two polarizations experience similar turbulence-induced modal coupling, almost all the LG modes of the data beam can automatically mix with the pilot beam and the 16-QAM data can be efficiently recovered. Compared to our PASC approach, there is no frequency guard band required between the pilot and data, therefore the utilized bandwidth of each PD is around half of the data bandwidth. Finally, we demonstrate the utilization of PASC in DPSK to achieve a power-efficient FSO link [18].

Acknowledgement 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); US Office of Naval Research through a MURI award (N00014-20-1-2558); Defense Security Cooperation Agency (4441006051); Airbus Institute for Engineering Research; Naval Information Warfare Center Pacific (N6600120C4704); US Office of Naval Research (N00014-17-1-2443); Qualcomm Innovation Fellowship; DURIP (FA9550-20-1-0152); AFOSR (sub-award of FA9453-20-2-0001).

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