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Vijay Nafria, Xiao Han, Ivan B. Djordjevic, "Improving free-space optical communication with adaptive optics for higher order modulation," Proc. SPIE 11509, Optics and Photonics for Information Processing XIV, 115090K (21 August 2020); doi: 10.1117/12.2568713

Event: SPIE Optical Engineering + Applications, 2020, Online Only

Improving Free-Space Optical Communication with Adaptive Optics for Higher Order Modulation

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ABSTRACT

One of the biggest challenges of free-space optical (FSO) communication is the wave-front aberration due to atmospheric turbulence. In FSO links the wave-front distortion manifests as a significant drop in received power, beam wander, information loss, and scintillation effects. The performance of FSO communication system is degraded significantly by the atmospheric turbulence effects. Fortunately, the adaptive optics system offers potential to mitigate the performance degradation, which is relevant for quantum communication applications as well. In our FSO experiment, we perform the transmission of 6.25 GBd QPSK signal over an FSO link without and with adaptive optics, operating at 1550nm. We emulate the atmospheric aberration in our indoor experimental setup by applying random Kolmogorov phase screens on spatial light modulators (SLMs). We demonstrate significant improvements in the power-collected, signal-to-noise-ratio (SNR), and bit-error-rate (BER) performance due to the application of adaptive optics.

Keywords: Free-space optical, adaptive optics, spatial light modulator, bit-error rate, SNR and QPSK

1. INTRODUCTION

Free Space Optical Communication (FSOC) offers immense potential for communication at high data rate greater than 1.0 Gbits/s for various application such as space communication, secure communication, terrestrial communication for both commercial and defense purposes [1]-[3]. Additionally, in recent times the FSOC is also used in underwater communication [4] that is geared towards understanding deep ocean, among others. In this paper, we provide results and findings of our experiment with the use of adaptive optics (AO) to counter the effects of atmospheric turbulence in a 6.25 GBd QPSK based classical communication over an FSOC links, where the atmospheric turbulence is modeled with the help of spatial light modulator. In present days the state-of-the-art adaptive optics technology [5] on earth-based telescopes is helping astronomer and scientists to counter image distortion problems due to atmospheric turbulence. AO allows them to get far clearer images of distant galaxies, stars and exo-planets at a fraction of the cost compared to putting up a telescope on a satellite.

In FSOC an optical wave propagates though air (or water) that have temperature variations along its path which thus result in changes in optical properties, such as refractive index, of the medium. These variations exhibit as scintillation or twinkling of irradiance at the receiver end. These fluctuations result in poor power reception at receiver side, low signal-to-noise ratio loss of information. Mathematically the scintillation is characterized through scintillation index (σ_I^2) that is equal to the normalized variance of fluctuation of irradiance. Scintillation index is given by [6],

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

where I denote the irradiance at receiver end. For a plane wave the scintillation index is directly proportional to Rytov variance given by expression,

$$\sigma_I^2 = 1.23\, C_n^2\, k^{7/6}\, L^{11/6}$$

where $k = 2\pi/\lambda$, L is propagation path length and C_n^2 denotes refraction structure function.

Optics and Photonics for Information Processing XIV, edited by A. A. S. Awwal, K. M. Iftekharuddin,
V. H. Diaz-Ramirez, A. Márquez, Proc. of SPIE Vol. 11509, 115090K · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2568713

In a terrestrial FSO application height of operation is constant or do not vary too much for horizontal link, unlike in astronomy telescopes. This makes the refractive structure function effectively constant for a given height. Therefore, scintillation index is only dependent on wavelength and propagation distance.

In our experimental setup we set the operating wavelength at 1550nm, which is commonly used in optical communication and it exhibits lower turbulence compared to the visible region. So, only free space optical path length is the main parameter for σ_I^2. However, in our experiment we used spatial light modulator to emulate the atmospheric turbulence effect.

The following sections of this paper we will describe the following: In Section II we give a brief description of our experimental setup, Section III we will present the results of our experimental studies and in Section IV will summarize our findings and future possibilities in this field.

2. EXPERIMENTAL SETUP

The experimental setup is divided into two parts one is the AO system which is in our quantum communications (QC) Lab and other one is QPSK system which is located in our classical communications (CC) Lab. Both the labs are connected directly via an optical fiber link. We have developed an indoor AO-based FSOC hardware-software solution. Figure 1 summarize our AO setup.

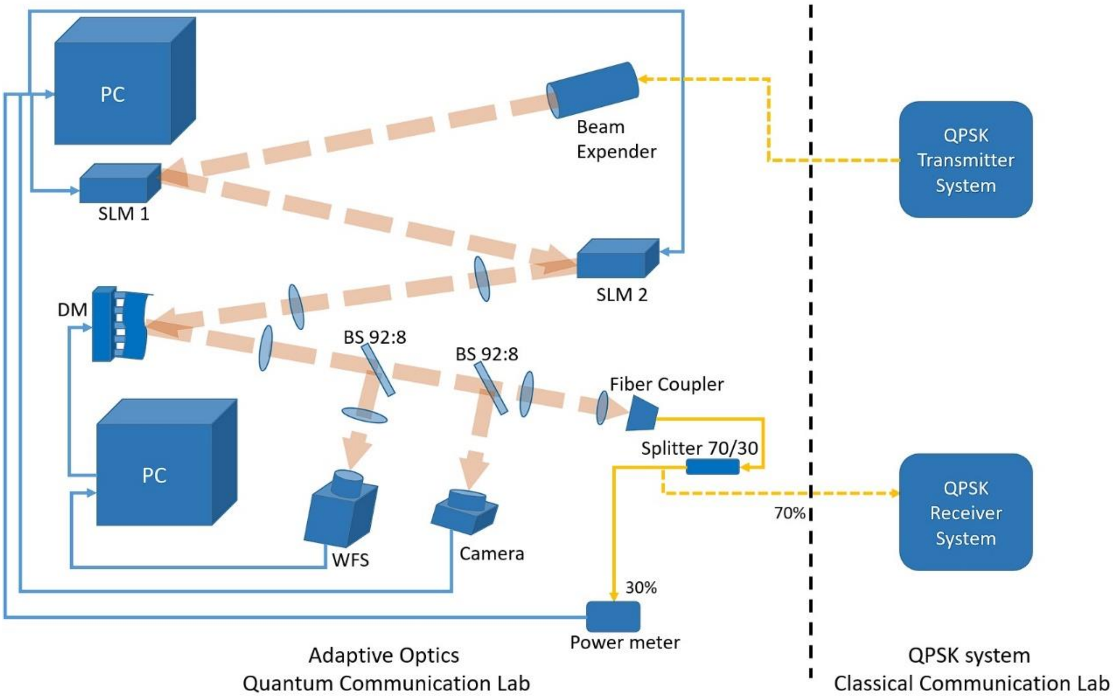

Figure 1. Free space optical communication with adaptive optics.

As in any typical AO setup we make use of a wavefront sensor (WFS) and a deformable mirror (DM). Our software solution is a GUI that we have developed using the APIs and SDK provided by respective manufactures of the WFS, DM and a frame grabber that captures images from WFS. In our indoor experiment we emulate atmospheric aberration using spatial light modulators (SLMs) by displaying random Kolmogorov phase screens on these SLMs. Bearing the complexity of this experiment we are only applying Kolmogorov phase on second SLM and this is the SLM that is in conjugate plane to our DM. First SLM is for future extension of our project and future research, as for this experiment it is just a flat reflective mirror. Figure 2 is an actual photograph of the AO optical bench.

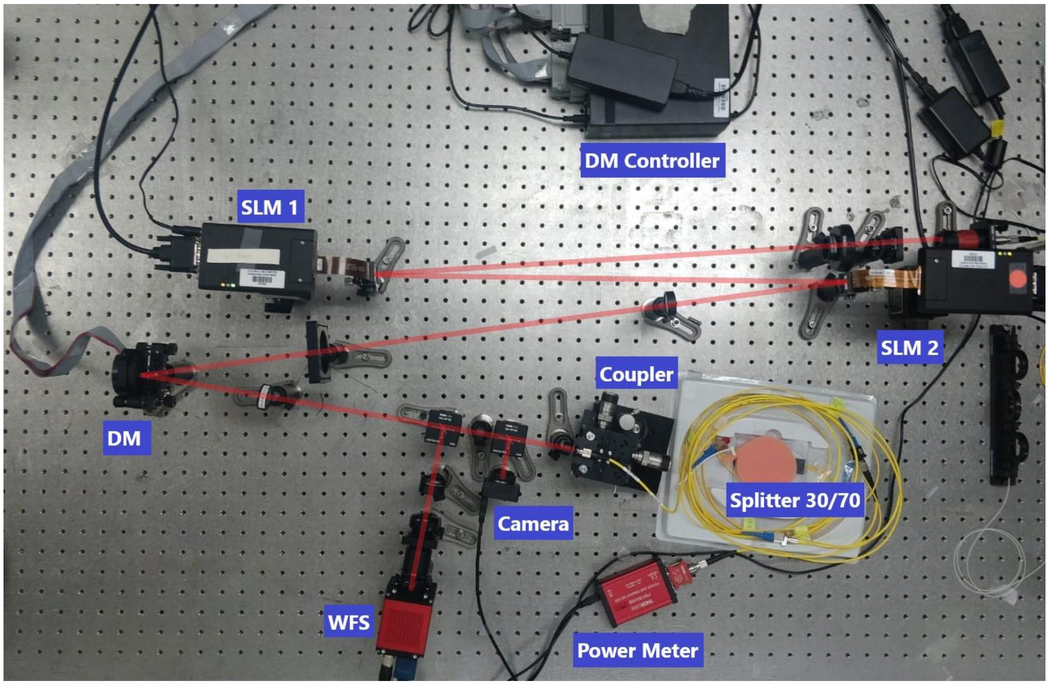

Figure 2. Adaptive optics workbench setup.

The QPSK setup in our CC Lab is shown in Figure 3. At the transmitter side, we applied a tunable laser with center frequency f=193.3THz and sent the laser beam to the Mach-Zehnder (MZ) I/Q modulator. A 6.25G Baud (GBd) QPSK radio frequency (RF) signal was generated by a 25GHz sampling rate arbitrary waveform generator (AWGen), which is employed as the digital-to-analog converter (DAC). The resulting optical signal was boosted by an erbium-doped fiber amplifier (EDFA) and coupled with amplified spontaneous emission (ASE) noise and sent to the free space optical transmission system.

At the receiver side, the optical signal was detected by an integrated coherent receiver (ICR), and the received baseband signal was collected by an analog-to-digital convertor (ADC) at sampling rate 50 GHz and stored locally for offline digital signal processing (DSP).

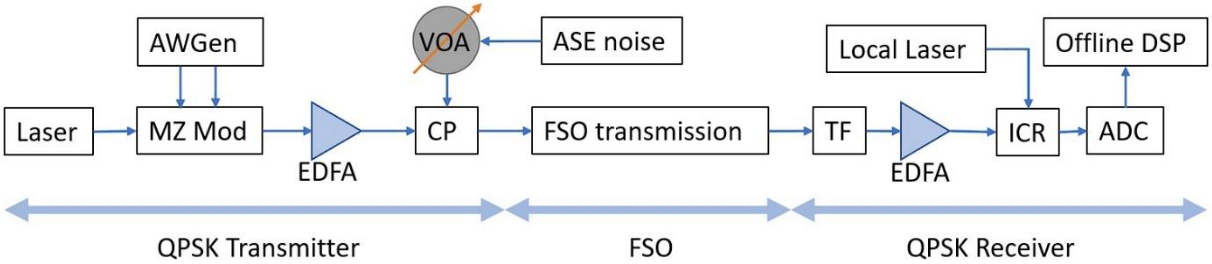

Figure 3. Experimental setup. AWGen: arbitrary waveform generator, CP: coupler, MZ Mod: Mach-Zehnder modulator, VOA: variable optical attenuator, TF: tunable filter, ICR: integrated coherent receiver, ADC: analog-to-digital convertor

To start the experiment the transmitter side of the QPSK system modulated a beam with QPSK data in CC Lab. The modulated beam is fed to the beam expander on AO system optical bench in QC Lab and from there it gets beamed to the two SLMs as shown in Figures 1 and 2. We apply Kolmogorov phase screen on second SLM that distorts the beam wavefront. After SLMs the beam lands on the DM and from there it gets reflected toward the fiber coupler and into an optical fiber. The beam is then finally sent to the receiver side of the QPSK system in CC Lab via an optical fiber link. We used two 92:8 beam splitters (BS), first one for the WFS and second one for a scientific camera for observations. Most of the power (~80%) is coupled into the fiber, out of which 30% is kept for observation in QC Lab and 70% is send to CC Lab. We set up our AO system in a typical fashion where DM and WFS are in feedback servo loop configuration. In this feedback loop, the WFS measures the wavefront distortions after the beam get reflected by the DM. The WFS information is fed to the controlling computer via a frame-grabber. The controlling computer, running our software solution, computes the correction information for the DM controller that translates it into voltages to individual actuator pokes of the DM. These pokes in turns changes the shape of the DM to correct for atmospheric turbulence effects. In CC Lab we perform coherent detection and measurement for received power, compute SNR and bit-error rate (BER).

3. EXPERIMENTAL RESULTS

In our experiments we focus our attention to demonstrating improvement in parameters such as measured power at the receiver end, SNR and BER of our AO assisted FSOC link. Our goal is to show that we can make use of adaptive optics to counter scintillation i.e. irradiance fluctuations. In order to achieve this, we have run experiment using individual Kolmogorov phase screens recorded on an SLM. These phase screens have been displayed on SLMs which introduce azimuthal phase distortion on a beam being reflected. We performed measurements related to power, SNR and BER before and after the application of the AO.

In our 1st experimental run, we applied 100 phase screens to SLM changing one after another as we tried to emulate a very turbulent atmosphere. Figure 4 shows the improvements made by applying AO. We measured an average of 36% improvement in receiver power.

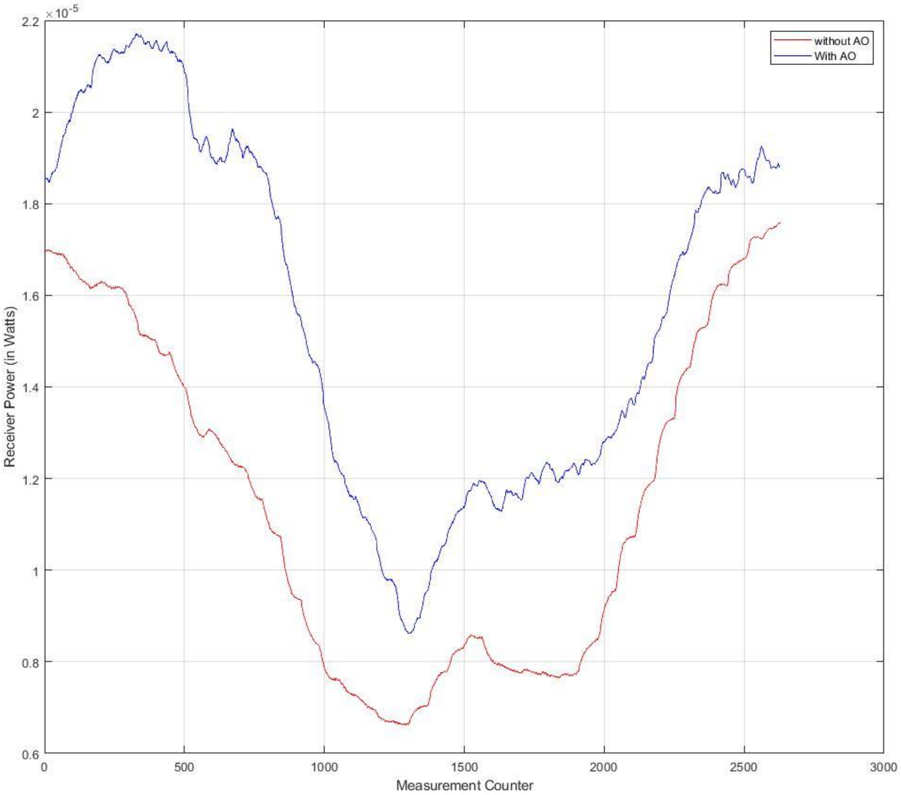

Figure 4. Receiver power comparison for with and without applying adaptive optics in a varying phase distortion.

Next up with same AO setting we ran QPSK on 11 individual phase screens one per measurement run by keeping the same screen static for whole time, from calibration to measurement with and without applying AO. In this scenario we were able to compute the SNR. Figure 5 show the results we measured. We recorded an overall 42% improvement in received power and an average SNR of 0.7dB. For certain phase screens we measured the SNR up to 2dB.

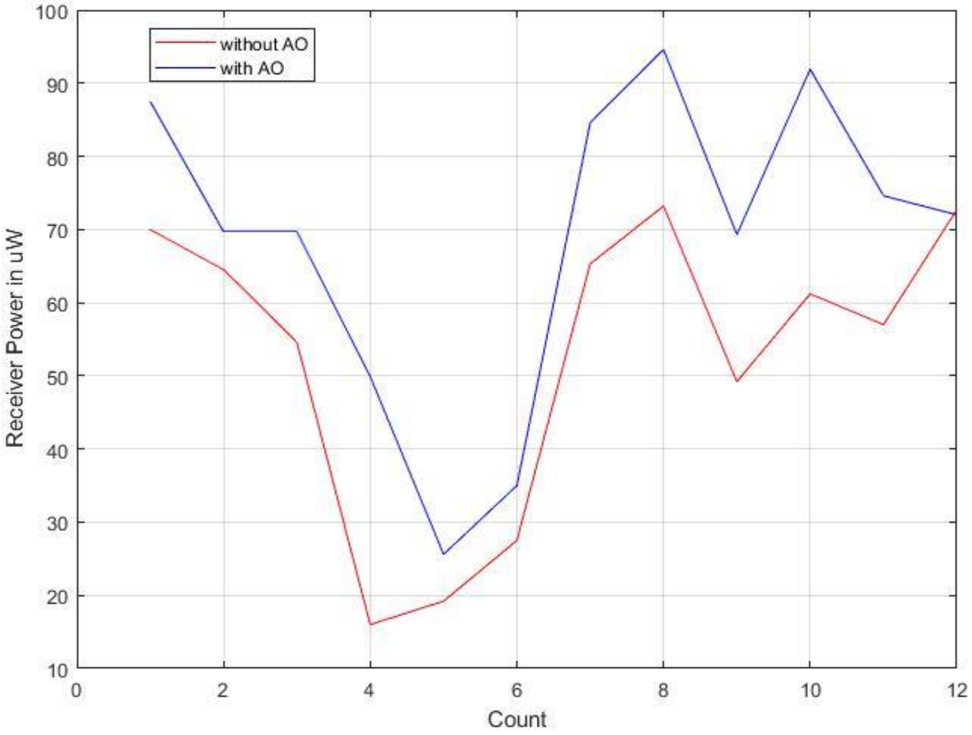

Figure 5. Adaptive optics performance in moderate turbulence regime.

In the final run we applied only one phase screen and performed AO calibration. In one case receiver has showed the improvement from 2.2x10^{-6}W to 52.3 x10^{-6}W after applying AO and SNR value was about 2.2dB. We performed similar measurement for several random phase screen and the corresponding results are tabulated below (see Table 1).

Table 1. SNR and bit-error rate with and without applying adaptive optics in a varying phase distortion.

Phase screen	**Signal-to-noise ratio (SNR)**		**Bit-error rate (BER) (10^{-5})**	
	Without AO	With AO	Without AO	With AO
1	10.007	12.197	192.5636	8.3723
2	10.67	12.649	79.1656	4.1334
3	11.986	13.492	14.2329	0
4	10.402	10.859	105.4914	54.4202
5	12.24	12.307	6.4954	5.3144

In Figure 6 we see the QPSK signal constellation after the phase recovery. The left plots of figure 6 shows the 2D QPSK constellation in the presence of the wavefront distortion caused by SLMs. The plots on the right shows the improvement due to application of AO. Notice the improvement in phase recovery due to the AO is clearly visible. Top plots correspond one instance of atmospheric turbulence, while bottom ones to second instance.

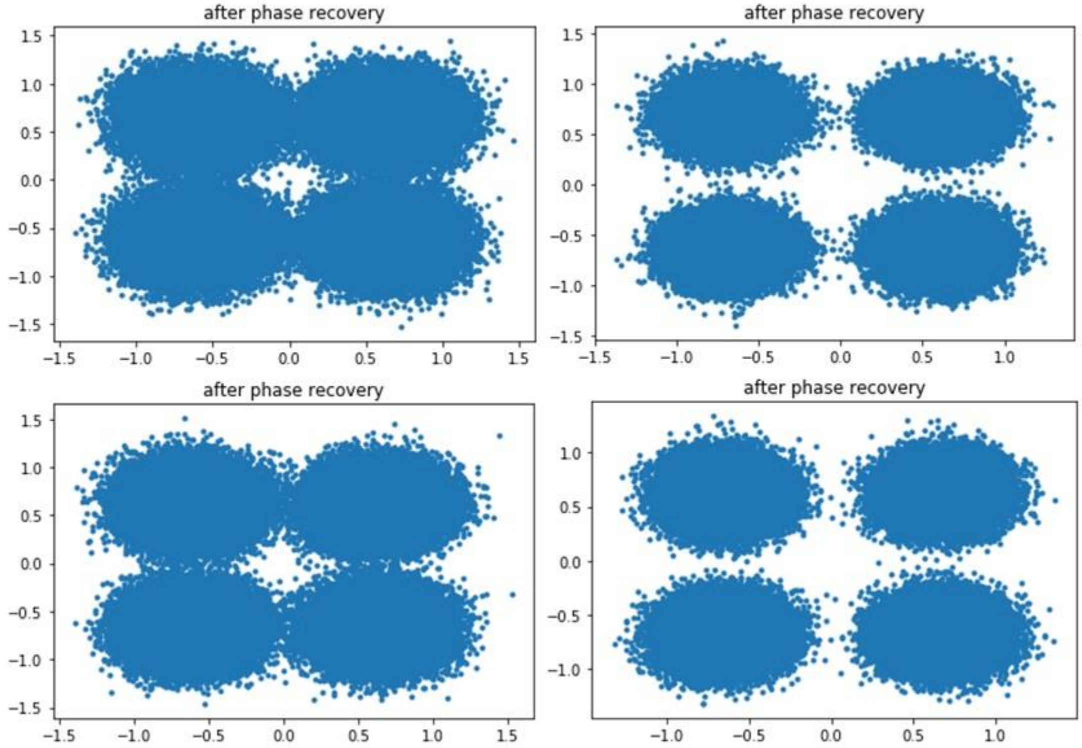

Figure 6. QPSK constellations after phase recovery, without(left) and with(right) the application of adaptive optics. (Top)) One realization of atmospheric turbulence and (bottom) another instance of turbulence.

4. CONCLUDING REMARKS

In this paper, we have studied the improvements in 6.25 GBd QPSK transmission over an FSO link with the help of adaptive optics, operating at 1550nm. We have emulated the atmospheric aberration in our indoor experimental setup by applying random Kolmogorov phase screens on spatial light modulators (SLMs). We have demonstrated the significant improvements in the power-collected, signal-to-noise-ratio, and bit-error-rate performance thanks to the application of adaptive optics.

In follow-up paper, we plan to extend our study to more realistic outdoor FSO link at University of Arizona between ECE and Optical Sciences buildings.

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