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Design Analysis of A Compensation Technique In FSO Communication System to Mitigate Atmospheric Turbulence Effect

Abstract- Free-space laser communication systems usually experience strong channel fading caused by atmospheric turbulence. To mitigate the impact of atmospheric turbulence on free-space optical links using compensation techniques including adaptive optical (AO) system as advanced technique. Its three main components have remained constant: a wave front sensor to measure distortion, a wave front corrector to compensate for the distortion and a control system to calculate the required correction and necessary shape to apply to the corrector. Optical communication schemes utilizing adaptive optical at the transmitter are proposed. Numerical simulations show that the proposed schemes can significantly reduce the channel fading.   The main goal of any adaptive optical system is to show a phase correction in the arriving wave front that converts the distorted wave front into a plane wave. A free space optical AO system to mitigate turbulence-induced phase fluctuations has been implemented by using a wavefront sensorless architecture The AO system was designed to correct the first 20 Zernike modes by using two separated active mirrors: a tip/tilt corrector and a DM with 32 actuators. Also, standard deviation of the atmospheric tilt was computed, DM stroke, the residual phase variance, the turbulence strength for different telescope apertures.

Keywords- FSO, Adaptive Optical(AO),Compensation, Atmospheric Turbulence .

1. Introduction

Free space optical systems display sharp earthly fading relate with the turbulence-induced optical amplitude fluctuations, which increases the foul at the receiver and decreases the system capacity. The long-range FSO problems. Establishing a link between ground, air, or sea-based mobile platforms in a wide variety of weather conditions leads to severe dynamic fading and pointing errors in addition to the usual propagation losses [1].To improve link availability on long-range (>10 km) links by focusing on optical solutions, Adaptive Optics (AO) can be used to substitute static or dynamic aberrations of a light beam after generation through a corrupting medium. Generally an adaptive optical system is formative by a wave front actuator, a sensor to quantify the wave-front error and a feedback control algorithm to link these two ingredients in real time. These systems have been historically huge and high cost for wide-ranging applications [2]. Atmospheric turbulence may severe impact performance of FSO communication systems resulting in communication link determination shown as an increase of the bit error rate (BER) as the major characteristic of communication system performance, which depends on both electronic circuit related noise, and the turbulence random breaks in communication data traffic known as atmospheric signal fading [3].

2. Adaptive Optics (AO) Techniques

The atmospheric turbulence distorts a transmitted light beam in several ways. The beam wander distortion shifts the centroid of the transmitted beam due to the influence of turbulent cells larger than the beam. The beam spreading effect reduces the averaged intensity at the receiver by broadening the beam radius. Constructive and destructive interferences effects within a beam redistribute the intensity inside a beam. These effects can be grouped as scintillation effects. A profound study of the effects of phase and amplitude fluctuations was performed to 72 evaluate FSO coherent systems [4]. Figure 1 shows the principle of wave front correction. The incoming distorted wave front is converted into a plane wave by introducing adaptive optics [5].

In order to decrease the level of fading and thus increase the system performance, adaptive optics (AO) may be applied to free-space communication system. The wave front distortions at the receiver aperture can be compensated by AO wave front corrector located at the receiver, so that the received laser power can be better focused on the photo detector. The ground station of a deep space optical communication system is such an example. Adaptive optics systems enhance image specific by response and rectification the phase distortion

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given by atmosphere [6]. The main goal of any adaptive optical system is to show a phase correction in the arriving wave front that converts the distorted wave front into a plane wave. This project is interested on free space optical coherent communications, which performance is severely degraded by these distortions. The atmospheric turbulent channel results into a link deterioration and an increase of the BER. Deformable mirrors a key component of AO systems are the deformable mirrors (DMs) that create the wanted wavefront rectification [7].
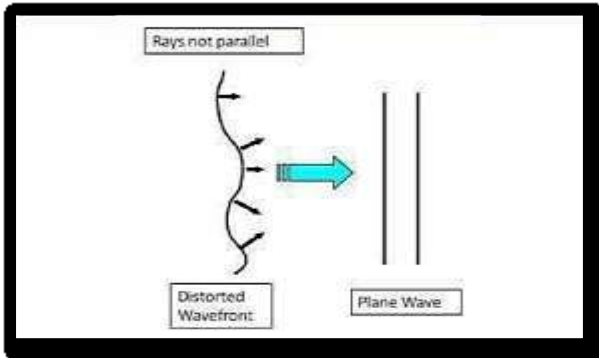

Figure 1: Principle of wave front correction by introducing adaptive optics.

3. Modeling of (AO-FSO) Communication System

Adaptive optical communication system scheme is proposed and discussed. Figure 2 shows the structure of this scheme shows first mirror acts, in conjugation with the fast steering mirror as a Z-Mirror that allows us to calibrate the system when no distortion is introduced [8].
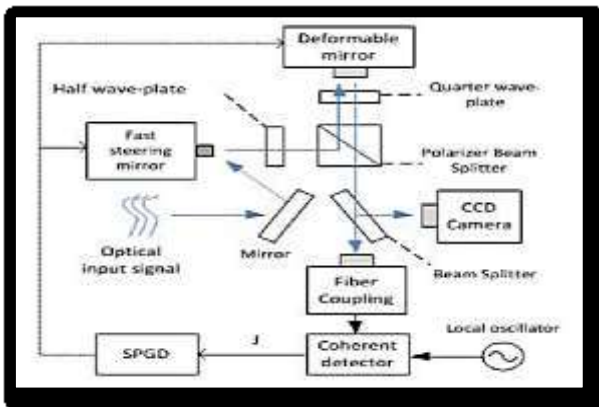

Figure 2: Adaptive AO scheme with collimated laser beam at a wavelength of 1550nm arrives to the communication link

The light is sent through a half wave plate to modify the polarization. The output polarization must be that one that maximizes the reflection on the PBS. Then, the whole linearly polarized signal is sent to the quarter wave-plate, which altersit to circular polarization. The light hits the DM where the handedness of polarized light is

reversed and then interpretedinto horizontal polarization. A beam splitter send a sample to a CCD camera and the 92% of the power is sent to the coherent detector through a fiber coupling stage to generate the control signal to the fast and deformable mirrors [9].

One of the prime parameter to characterize the wave front phase deviation son the aperture plane of the receiver is the phase difference. When AO is applied a correcting phase map is subtracted from the incoming phase wave front. The resulting residual difference of the corrected wave front is then expressed as [10]:

$$\sigma_{res}^2 = \frac{1}{\pi} \int (\varphi(\rho) - \varphi_c(\rho))^2 \, d\rho \qquad (1)$$

Two main methods are used to describe the wavefront error over a two-dimensional aperture: zonal and modal. The modal approach is based on the principle that the actuator is ableto completely compensate j Zernike modes. Where the phase difference was expressed in terms of the normalized turbulence strength and the number of corrected modes j. the correction phase map can be defined as:

$$\varphi_{c,J}(\rho, \theta) = \sum_{j=1}^{J} \alpha_{c,j} \, Z_j \qquad (2)$$

Where , the Zernike coefficient of the correcting is phase map and is the j Zernike mode. The resulting residual phase error is then:

$$\sigma_j^2 = \sigma_\varphi^2 - \sum_{j=1}^{J} |\alpha_{c,j}|^2 \qquad (3)$$

Where σ_φ^2 is the phase difference of the incoming signal. The residual errors, widely known as Zernike-Kolgomorov residual errors. The wave front correction is usually performed by two separated set of mirrors: first a steering mirror which performs the correction for the tip/tilt components and a deformable mirror which try to compensate higher order modes. The cause for the phase difference it is not equally distributed over all Zernike modes. Actually, by removing the first two Zernike modes, the resulting phase difference is reduced by a factor of. Assuming that modal restitution can be applied to the tip/tilt components by using a fast steering mirror, the other of the restitution is generally implemented by using zonal correction. In the zonal approach the aperture is composed by an array of independent sub apertures or areas. In each of these areas the wave front phase applied is estimated to minimize the resulting phase difference by performing a spatial average on each independent actuator. The phase difference after zonal correction is expressed by:

$$\sigma_Z^2 = \frac{1}{\pi} \int (\varphi(\rho) - \varphi_Z(\rho))^2 \, d\rho \qquad (4)$$

Where σ_Z^2 is the phase map applied by the zonal corrector. In the section we characterize the

analytical expressions to evaluate the performance of these techniques [11].

An expression to estimate the standard deviation of the atmospheric tilt as a function of the telescope aperture is given by:

$$\sigma_{tite} = \sqrt{0.184 \left(\frac{D}{r_o}\right)^{5/3} \left(\frac{\lambda}{r_o}\right)^2} \qquad (5)$$

Using the Noll's approach, the tip/tilt corrected phase wavefront presents a phase variance expressed as:

$$\sigma_{DM}^2 = \sigma_3^2 \sigma = 0.134 \left(\frac{D}{r_o}\right)^{5/3} \qquad (6)$$

The required actuator stroke for a deformable mirror is estimated as:

$$S_{DM} = \frac{\lambda}{2\pi}.2.5.\sigma_{DM} \qquad (7)$$

The residual phase variance after applying zonal correction by a DM is given by [12]:

$$\sigma_{res.m}^2 = k \left(\frac{r_s}{r_o}\right)^{5/3} \qquad (8)$$

4. Simulation Results & Discussions

This design study was based on an advanced computer program allow to carry out the field FSO system characterization and performance measurement under a various levels of turbulences. Figure 3 shows σtilt as a function of the coherence length ro for wavelength 1550nm and different telescope apertures when D= (20, 60, 80, 100) cm respectively. The maximum atmospheric Tilt can be expressed as:Mtilt= + σtilt, so for the given apertures and considering realistic values of >10 mm, the maximum tilt is around 1mrad. Also we need to include a 0.5 factor due to the fact that an angular movement of the mirror corresponds to twice the beam angular shift. Assuming that no amplification is used, the maximum angular depletion needed in our system is ±0.5mrad. The required DM Stroke for compensating tip/tilt corrected wave fronts as a function of the normalized turbulence strength is shown in Figure 4.

The residual phase variance as a function of the Fried parameter ro and the interactuator spacing rs is shown in Figure 5.

Standard deviation of the atmospheric tilt as a function of the turbulence strength for different telescope apertures is shown in Figure 6.

Residual phase variance asa function of the turbulence strength for different telescope apertures is shown in Figure 7.
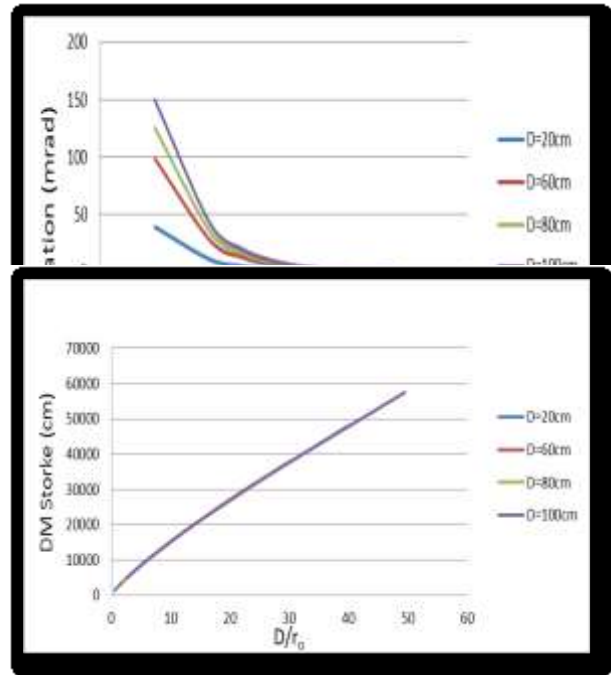

Figure 4: DM Stroke required for compensating tip/tilt corrected wave fronts versus the normalized turbulence strength.
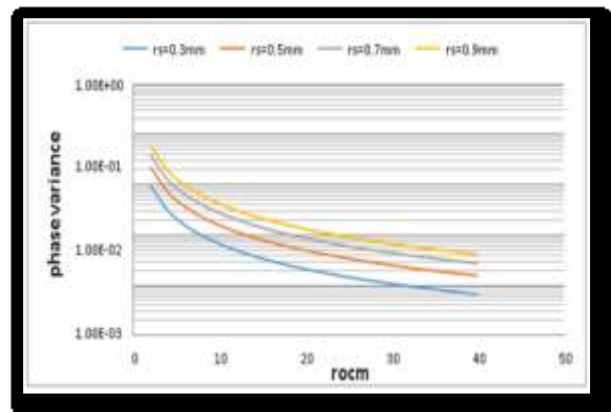

Figure 5: Residual phase variance versus of the Fried parameter ro and the inter actuator spacing rs for typical values of ro between 2 and 40 cm and rs (0.3,0.5,0.7,0.9)mm ,k=0.23)
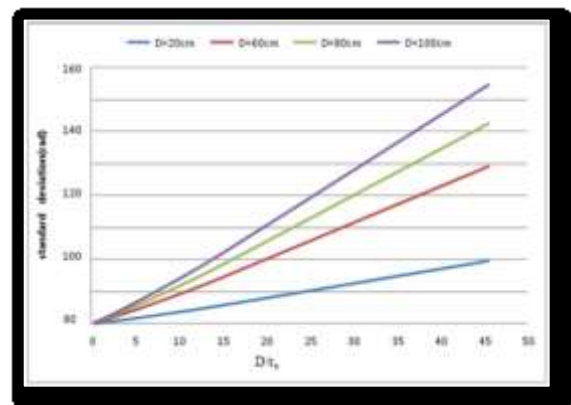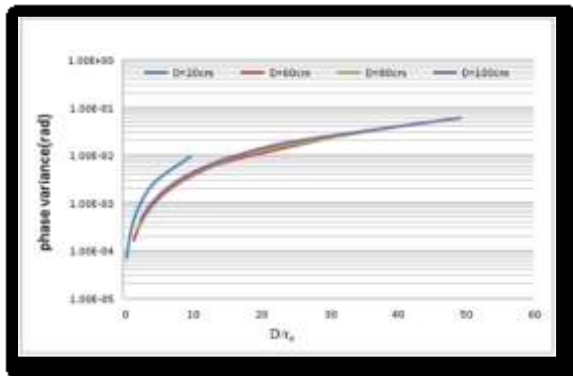

Figure 6: Standard deviation of the atmospheric tilt as versus of the turbulence strength for different telescope apertures

improve performance to acceptable levels. We have found that for most typical link designs, wavefront phase fluctuations are the dominant impairment, and compensation of a modest number of modes can reduce performance penalties by several decibels.

Figure 7: Residual phase variance versus of the turbulence strength for different telescope apertures

5. Conclusions

This paper proposes adaptive free-space laser communication schemes to compensate atmospheric turbulence induced channel fading and power loss by using the AO unit in the transmitter to control the laser beam. The impact of atmospheric turbulence-induced scintillation and phase aberrations on the performance of free-space optical links in which the receiver uses modalwavefront compensation and synchronous homodyne or heterodyne detection was studied using compensation technique, including adaptive optics. Standard deviation of the atmospheric tilt as versus of the coherence length ro and different telescope apertures, Residual phase variance versus of the Fried parameter ro and the interactuator spacing rs, DM Stroke required for compensating tip/tilt corrected wave fronts, Standard deviation of the atmospheric tilt, Residual phase variance versus the normalized turbulence strength for different telescope apertures for wave length 1550nm. Separately quantified the effects of amplitude fluctuations and wave front phase distortion on system performance, and have identified two different regimes of turbulence, depending on the receiver aperture diameter normalized to the coherence diameter of the wavefront phase. When the normalized aperture diameter is relatively small, amplitude scintillation dominates and, as phase fluctuations have little impact, performance is virtually independent of the number of modes compensated. When the normalized aperture is larger, amplitude fluctuations become negligible, and phase fluctuations become dominant, so that high-order phase compensation may be needed to

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