The Performance and Compensation Framework of Optical Communication in Complex Space Based on Adaptive Optics

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Abstract

In recent years, optical communication system has been widely applied in numerous countries in the world. Due to its low costs, no need for frequency spectrum license, frequency bandwidth, rapid deployment and other advantages, this system also attracts the attention and appreciation of China. However, when the light beams emitted during the operation of the optical communication system pass through the atmosphere, the atmospheric turbulence effect can exert a serious impact on their transmission, resulting in random fluctuations before transmitting light beam waves. Furthermore, problems, such as light intensity fluctuation and light spot drift, are caused, which can greatly affect the beam quality, significantly raise the bit error rate of the optical communication system in complex space, and drastically reduce the channel capacity. Besides, strong atmospheric turbulence can also cause communication interruption of the optical communication system in complex space and severely influence the reliability and stability of the communication link of the system. For this purpose, in order to address the above problems, this paper analyzes the atmospheric attenuation effect and the atmospheric turbulence effect, proposes a compensation scheme for the optical communication system in complex space based on adaptive optics, and conducts an in-depth study on the performance and compensation framework of the optical communication system in complex space.

Keywords: Adaptive Optics, Complex Space, Atmospheric Turbulence, Optical Communication System, Compensation.

1. RESEARCH BACKGROUND

1.1 Research overview

Optical communication technology in complex space is a new type of emerging technology in recent years with broad application prospects, but its limitations have caused some obstacles to its promotion and application. When optical signals are transmitted in the atmospheric channel, they are inevitably influenced by the atmospheric turbulence effect, leading to the distortion of light beams. Furthermore, the stability and reliability of the optical communication system in complex space (OCSCS) during operation are seriously compromised, so that the quality of optical communication drops significantly. The improvement of the optical power of the optical communication system can effectively weaken the adverse effects of atmospheric turbulences on beam transmission. However, if the range of optical power increase is overly large, human eyes and other parts would be harmed. For this reason, only elevating optical power is not feasible to weaken the effect of atmospheric turbulences (Han and Wang, 2013). The swift progress of science and technology has constantly perfected and developed the optical communication technology in complex space. Abundant turbulence suppression technologies have been researched and developed, such as the modulation and coding control technology and the multi-aperture transmitting and receiving technology, which are now widely used in the OCSCS. However, these new technologies have their own advantages and disadvantages, making it even more difficult to fundamentally solve the problem of beam drift (Jia et al., 2017). According to the diffraction theory, the shorter the wavelength of the light beam is, the larger the optical aperture is, the higher the resolution is, which can only be achieved in the case of ideal plane waves. However, the atmosphere is randomly changing and deviation frequently occurs. Besides, temperature changes also cause beam distortion. Hence, in order to address the above problems, we must take dynamic adjustments to overcome the dynamic interference, thus ensuring the optical communication system can always maintain a high stability and accuracy. Adaptive optics is able to solve the dynamic disturbance of atmospheric turbulences by real-time measurement and compensation of light beams, which has attracted the attention of numerous scholars (Yang et al., 2017). With the continuous advancement of adaptive optical technology, its technical concept has received increasing recognition and support from scholars, which has also
expanded the scope of application of adaptive optical technology and has become the new technology to overcome the distortion of light beams caused by atmospheric turbulence or other factors. In this way, the environment adaptability of the optical communication system is greatly improved and the problem of stochastic dynamic interference is effectively solved. At this stage, a number of scholars and technicians are trying to solve the problem of communication quality interference in the operation of the OCSCS through the application of adaptive optics. A great quantity of practical results indicate that adaptive optical technology can make real-time corrections on beam distortion in the OCSCS with significant and effective compensation effects.

1.2 Research objectives

This paper aims to further study the performance and compensation framework of optical communication in complex space based on adaptive optics, to explore the application of adaptive optical technology in complex space optical communications, and to verify the performance impact and compensation effect of the adaptive optical technology in the OCSCS. To this end, this paper first analyzes the atmospheric attenuation effect and the atmospheric turbulence effect, clarifies the cause of the atmospheric turbulence effect, and discusses the influence of these two effects on beam transmission. On this basis, this paper puts forward the compensation strategy for the OCSCS based on adaptive optics, clarifies the common analysis methods of adaptive optical technology, constructs and analyzes the model for the OCSCS based on adaptive optics, studies the bit error rate (BER) after adaptive optics compensates the OCSCS, and verifies the performance impact and the compensated effect of adaptive optical technology on the OCSCS by means of numerical simulation.

2. ATMOSPHERIC ATTENUATION EFFECT AND ATMOSPHERIC TURBULENCE EFFECT

2.1 Atmospheric attenuation effect

When a light beam is transmitted through the atmosphere, air molecules in the atmosphere are polarized by the electric field of light waves and produce forced vibration. At this time, part of the energy in the light beam provides energy for the forced vibration of air molecules that have a collision when they are forced to vibrate. Accordingly, the heat energy of the molecules ascends, and this part of the energy in the light beam transforms from the original light energy into heat energy, which is called atmospheric absorption (Yang, 2017). When the beam frequency equals to the vibration frequency of atmospheric molecules, resonance absorption would occur to the self-frequency of the beam, so that atmospheric molecules maximize the absorption of light energy. Different molecular structures demonstrate largely distinctive absorption characteristics of the spectrum, and the energy level structure of gas molecules also directly affect the absorption of the beam transmission process. It can be said that the atmospheric absorption of light beams is not only determined by the species of molecules, but also closely related to the light frequency, namely the optical length (Li and Chen, 2016). A substantial amount of studies have indicated that the atmospheric absorption of ultraviolet light beams is through N₂, O₂ and O₃, and the long-range infrared beams are absorbed by CO₂, O₂ and H₂O in the air aqueous vapour. When a beam is transmitted in the atmospheric channel, the atmospheric channel is featured with strong frequency filtering. In other words, the atmosphere absorbs certain wavelengths in the light beam to different degrees, thereby forming an atmospheric window. The influence of laser oscillating electromagnetic waves can polarize aerosol, atmospheric molecules and other different types of particles contained in the atmospheric channel, and oscillation ensues, thereby generating electromagnetic multipoles that scatter the electromagnetic waves in different directions, which is the scattering phenomenon of light in the air (Ni and Ma, 2015). Simple scattering will not cause laser energy loss, but will change the energy of the original transmission direction, leading to changes in the spatial distribution structure of laser energy as well as weakened light energy in the original transmission direction, which is the atmospheric attenuation effect. Atmospheric light scattering is divided into suspended particle scattering and atmospheric molecular scattering based on types. The scattering mode can be distinguished as Mie scattering and Rayleigh scattering according to the type of beams and the radius of the light beam particle.

2.2 Atmospheric turbulence effect

In the field of physics, temperature and velocity fields of the earth are undergoing real-time changes under the influence of surface heat radiation, wind shear caused by the earth’s drag on the airflow, human activities and other factors. In the atmospheric environment, real-time temperature changes also result in changes in wind speed, and accordingly, atmospheric density and atmospheric pressure experience real-time changes. As a consequence, the atmospheric refraction of the beam is not fixed and make real-time changes. This randomness and inhomogeneity in the refractive index of light is called a turbulent vortex. Impacted by numerous factors, atmospheric changes are random. Consequently, the atmospheric environment has a number of turbulent vortices.
with completely different pressures, temperatures, densities and velocities. The effect of wind speed will make these turbulent vortices continuously emerge and disappear, and the overlaying and cross-linking of massive turbulent vortices also make turbulent motion random. The whole process is the atmospheric turbulence effect, which can cause significant inhomogeneities in the refractive index of the atmosphere and exert a significant impact on beam transmission (Chen et al., 2015).

3. COMPENSATION FRAMEWORK OF THE OCSCS BASED ON ADAPTIVE OPTICS

3.1 Common analytical methods of adaptive optics

There are mainly three kinds of common analytical methods of adaptive optical technology: regional analysis, pattern analysis and real-time analysis. Specifically, the method of regional analysis divides the aperture into independent regions or sub-apertures. In each region, the wavefront of light beams is described by parameters such as local gradient, the length of optical axis and local curvature. The regional analysis method requires information about the aperture and applies formulas to calculate the number of drivers of the wavefront corrector or calculate the actuator by calibrating the accuracy. Besides, the fitting error of the actuator can be determined by formulas, and the error of the deformable mirror can be calculated by the atmospheric Fred parameter and the actuator spacing parameter (Niu et al., 2015). The method of pattern analysis applies the orthogonal function to analyze the wavefront of light beams in the atmospheric environment and to perform the linear combination of Zernike polynomials on the distorted waves. The orthogonal basis of Zernike polynomials can be represented by rectangular coordinates or polar coordinates, and the aberration is represented by Zernike polynomials. The process of designing the adaptive optics system should give priority to system bandwidth which is directly related to the system’s running speed. Real-time errors contain all the wavefront distortion information but also the correction delay information and the measurement delay information, and their values are greatly affected by the response time of the adaptive optics system and the dynamic characteristics of atmospheric turbulences, whose main influencing factors involve turbulences’ changes, wind speed and satellite movement. The method of real-time analysis can make real-time analysis and adjustments on the delay of the adaptive optical system (Li et al., 2015).

3.2 The model for the OCSCS based on adaptive optics

The adaptive optics system can make real-time corrections on the distorted phase of optical signals through the above analysis method. The phase conjugation technique is the correction principle of the adaptive optics system. Figure 1 illustrates the framework diagram of the OCSCS based on adaptive optical compensation. The adaptive optics system mainly consists of three parts: wavefront sensor, wavefront corrector and wavefront controller, whose cooperation forms a closed-loop feedback control loop (Han and You, 2015).

![Figure 1. Schematic Diagram of a Framework for a Complex Space Optical Communication System Based on Adaptive Optical Compensation](image)

When the OCSCS emits a light beam, the beam passes through the turbulent atmosphere, thereby distorting the wavefront of the light beam. The distorted light beam is transmitted to the beam splitter through the wavefront...
corrector, and the splitter lens isolate the distorted light beams. Part of the beam is transmitted to the receiving end of the system and the target signal is received. The other part of the separated beam traverses the wavefront sensor that measures the distortion wavefront information of the beam and sends these measured distortion information to the wavefront controller that reconstructs the wavefront. In this way, the distorted wavefront of the beam is obtained. Afterwards, based on the distortion wavefront control algorithm, the control signal is sent into the wavefront corrector that deforms according to the control signal of the wavefront controller. Thus, the distorted beam can be conjugate with the distorted wavefront and the distortion wavefront is further corrected, thus forming an adaptive optical closed loop control system. Eventually, the wavefront distortion of the beam is properly adjusted, and the system can obtain accurate target signals (Zhang et al., 2015).

3.3 Compensation BER of the OCSCS based on adaptive optics

The BER of the OCSCS is an important index to measure the system performance. Noise is assumed to be the Gaussian white noise with a mean value of zero, and the system performs intensity modulation through OOK. The BER of this system is calculated through the formula: \( BER = \frac{1}{2} \int_{0}^{\infty} s(M) \text{erf}(\frac{\sqrt{\text{SNR}} - M}{\sqrt{2} \sqrt{\text{SNR}}}) dM. \) In the formula above, \( M \) is light intensity; \( \text{SNR} \) is signal-to-noise ratio; \( BER \) is bit error rate; \( s(M) \) represents the probability density of light intensity fluctuation; the gamma-gamma distribution that best fits the dynamic features of atmospheric turbulences is applied. Accordingly, the formula for the probability density of the light intensity fluctuation can be derived as 

\[ s(M) = \frac{M^{M-1}}{\Gamma(M)^2} \text{erf}(\frac{\sqrt{\text{SNR}} - M}{\sqrt{2} \sqrt{\text{SNR}}}) K_\alpha \beta \left( \frac{aBM}{\sqrt{\text{SNR}}} \right). \]

In this formula, \( \alpha = \frac{1}{\sigma_{\ln x}^{-1}} \) and \( \beta = \frac{1}{\sigma_{\ln y}^{-1}} \) (Liu et al., 2014). Figure 2 illustrates the working scheme of the BER of the OCSCS based on adaptive optics.

![Schematic Diagram of BER of a Complex Spatial Optical Communication System Based on Adaptive Optics](image)

**Figure 2.** Schematic Diagram of BER of a Complex Spatial Optical Communication System Based on Adaptive Optics

3.4 Numerical simulation and analysis of the OCSCS based on adaptive optics

In order to verify the performance impact and compensation effect of the OCSCS based on adaptive optical technology, this paper adopts MATLAB simulation software in the simulated experiment. The simulation results verify the relationship between the system correction modulus and the BER of the downlink. When the correction modulus enlarges, the BER of optical communication in complex space drastically drops. Meanwhile, the increase of the compensation modulus greatly enhances the performance of the system, which further proves the satisfactory effectiveness of adaptive optical technology in terms of the uplink of the OCSCS (Huang et al., 2014). Furthermore, the simulation results also truly reflect the relationship between the system correction modulus and the uplink. When the correction modulus is enlarged, correspondingly, when the optical beam is transmitted in optical communication in complex space, the generated BER is substantially reduced. Meanwhile, the augment of the compensation modulus greatly enhances the performance of the system, which further proves that the adaptive optical technology holds satisfactory effectiveness in the downlink of optical communication in complex space (Xiong et al., 2013). In addition, in view of the curve chart, the compensation effect of the OCSCS based on adaptive optical technology is observed visually. The results indicate that, when the compensated modulus is within 5 orders, the curve in the graph is steep, which testifies that the adaptive optical technology can achieve a remarkably significant compensation effect with only few compensation moduli. This states that, when using adaptive techniques to compensate the OCSCS, in most cases, a satisfactory calibration effect can be realized simply with the selection of the low-order tilt for correction (Jia et al., 2013).
4. CONCLUSION

This paper analyzes the effects of atmospheric attenuation and atmospheric turbulence, explores the influence mechanism of atmospheric turbulences on the optical communication in complex space, proposes the performance and compensation methods of optical communication in complex space based on adaptive optics, clarifies the main analytic methods of adaptive optical technology, and makes an in-depth study on the model framework of the OCSCS based on adaptive optics. Based on this, the method of calculating the BER of the OCSCS based on adaptive optics is discussed. By virtue of MATLAB simulation software, simulated tests are conducted on the compensation effect and performance of the adaptive optical technology in the OCSCS. As indicated by the analysis on numerical simulation, the improvement of the correction modulus of the adaptive optics system can play a significant role in compensating the atmospheric turbulences, and the BER of the system is sharply reduced, which further verifies the effectiveness of adaptive optics in solving the atmospheric turbulence problem in optical communication.

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