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Discussion

# Atmospheric compensation in free space optical communication with simulated annealing algorithm

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ABSTRACT

As we know that the conventional adaptive optics (AO) systems can compensate atmospheric turbulence in free space optical (FSO) communication system. Since in strong scintillation conditions, wave-front measurements based on phase-conjugation principle are undesired. A novel global optimization simulated annealing (SA) algorithm is proposed in this paper to compensate wave-front aberration. With global optimization characteristics, SA algorithm is better than stochastic parallel gradient descent (SPGD) and other algorithms that already exist. Related simulations are conducted and the results show that the SA algorithm can significantly improve performance in FSO communication system and is better than SPGD algorithm with the increase of coupling efficiency.

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## 1. Introduction

Free space optical (FSO) communication system is widely concerned among telecommunication community for both space and ground wireless communication link. It has been mainly considered for last-mile applications [1] due to its large bandwidth potentiality, unregulated spectrum, relative low power requirement, low BER through coding techniques and easy redeployment. However, atmospheric turbulence in this system often brings phase disturbances along propagation paths that are manifested as intensity fluctuation (scintillation), beam wandering and beam broadening at receiver, which leads to significantly decrease of coupling efficiency at receiving terminal [2] and affects stability and reliability of the FSO communication system [3].

Adaptive optics (AO) system is one of the effective methods to improve beam quality by correction of wave-front distortions and has made great achievements in many applications [4–9]. In the conventional AO systems, a deformable mirror (DM) is used to compensate Hphase distortion. Generally, Shack artmann wave-front sensor (S-H sensor) [10] is used to measure optical phase deviations of incoming wave-front. Based on the wave-front aberration measured by S-H sensor, DM generates a wave-front phase to compensate the phase aberration by phase conjugation theory [11,12]. In the FSO communication system, when atmospheric turbulence is heavy or distance is long, strong scintillation will make a very different measurement for the wave-front aberration. Then the conventional AO systems, based on wave-front measurement, cannot work normally [13].

To avoid undesired wave-front measurements in strong scintillation conditions, control of the wave-front correctors (deformable mirrors) in AO system can be introduced by using recently developed control algorithm based on optimization of a system performance metric, such as SPGD algorithm. Although the concept of wave-front control without wave-front measurement has been considered in the early stages of AO technology development [14–16], it has been disregarded because of rather low control bandwidth that could be achieved even with a multi-dithering control technique [17,18]. But the situation is different today due to recent development of several novel technologies: new efficient control algorithms, their implementation with the parallel processing hard ware based on VISL microelectronics, and the emergence of high-bandwidth, wave-front correctors based on micro electro mechanical systems (MEMSs) [19]. In the study of sensorless adaptive optics used in FSO communication, one of the key problems is to find the fastest possible optimization algorithm to compensate wave-front in each frame [4,13]. In most cases, the optimization speed is limited to about 7–8 kHz by MEMS DM. The system temporal response characteristics are experimentally studied by using the method of self-induced aberrations to get coarse

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estimation of the closed-loop bandwidth independent from atmospheric turbulence conditions [13]. With the continuous development of hardware and digital processor, the performance of the system becomes better, and the high speed compensation is realizable (about thousands of Hertz), so that the instantaneous atmospheric turbulence can be considered as static.

SA algorithm, a kind of general stochastic search algorithm, is an extension of the local search algorithm. It is different from the local search algorithm since SA algorithm can access a new smaller state in the neibourhood of current state by probability. And it is a global optimization algorithm theory. In 1953, Metropolis proposed the original SA algorithm [20] but has not made positive response until Kirkpatrick proposed a modified SA algorithm [21] in 1983 and successfully used it to solve some large-scale combinatorial optimization problem. Since modern SA algorithm can effectively solve NP complicated problem, avoid least part point and overcome dependence on initial point, it is widely used in many fields, such as VLS, production scheduling [22], control, machine learning, neural network, and image processing. In this paper, a novel SA algorithm is proposed in FSO communication system to compensate the wave-front aberration without wave-front sensors. Simulation results show that the performance of FSO communication when using our new SA algorithm is significantly improved.

This paper is organized as follows: Section 2 provides models of FSO communication system, sensorless AO system, and DM. Section 3 provides the analysis of the SA algorithm, mainly the global optimization property (compared with SPGD algorithm), and the performance of the SA algorithm in FSO communication system. In Section 4, simulations are carried out to show the improved related results of SA algorithm in FSO communication system. Finally, conclusions for this paper are given in Section 5.

## 2. System model

### 2.1. FSO communication system model

The functional block diagram of FSO communication system is shown in Fig. 1 [2].

Laser point source, taken as the transmitting terminal, emits Gaussian laser beam. Since atmospheric disturbances reduce fiber coupling efficiency at receiving terminal, communication quality is seriously affected. Sensorless AO system is used here to compensate wave-front aberrations and the related detailed description is in Section 2.2. After compensation for wave-front aberration, the laser beam is coupled into a single mode fiber. Coupling efficiency is a main indicator for FSO communication system in which higher coupling efficiency means better system performance. And another important indicator is BER. Based on theoretical analysis and simulations, the coupling efficiency of the above system can be significantly improved and its BER can also be reduced. Finally the laser signal is received by optical receiver.

### 2.2. Sensorless AO system model

The functional block diagram of sensorless AO communication system is shown in Fig. 2 [13].

In the sensorless AO system, laser beam passes through the beam-steering system with tracking mirror (TM) for correction of large amplitude wave-front tilts and fast-steering mirror (FSM) for correction of atmospheric-turbulence-induced tilts and jitter. Higher order wave-front aberration is compensated with MEMS DM driven by SA algorithm controller. Active mirrors of AO subsystems are depicted as transmissive elements to simplify the schematic. Fast digital camera (FDC) in image plane $p'$ of entrance pupil is used for recording the aberrations. This AO system utilizes a 32-element piston-type DM as a wave-front corrector [19,23]. The mirror is placed on an image plane of the AO receiver system pupil plane. Generally speaking, the DMs can access KHz bandwidth and the above frequencies. Adaptive optics systems operate at high frequencies, typically several hundred to several thousand Hz.

We focus on compensation of higher order (above the 3rd order) wave-front aberration. The theoretical block diagram of wave-front aberration compensation by DM is shown in Fig. 3. In this Fig, $\varphi(r)$ is initial wave-front aberration, $u(r)$ is compensation phase $\phi(r) = \varphi(r) + u(r)$ is residual phase,$J$ is performance metric and $\mathbf{u} = \{u_1, u_2, \cdots, u_{32}\}$ is control signal of actuators with 32-element DM. AO system mainly uses DM to correct wave-front aberration $\varphi(r)$, an imaging system to record focal spot, a performance metric analyzer to calculate system performance metric $J$ from the data of focal spot, and SA algorithm to produce control signal $\mathbf{u}$ for DM according to the changes of $J$.

### 2.3. DM model

Based on clear aperture and separation distances between actuators in a unit circle, the normalized layout of 32-element DM actuators is shown in Fig. 4.

We approximate the influence function of DM by Gaussian Model

$$S_j(x, y) = \exp\left\{\ln \omega\left[\frac{1}{d}\sqrt{(x - x_j)^2 + (y - y_j)^2}\right]^{\alpha}\right\} \tag{1}$$

where $\omega$ is the coupling coefficient determined by the sizes of electrode actuators and the DM. $(x_j, y_j)$ is the center coordinate of the $j$th actuator. $d$ is the normalized interval between the adjacent actuators, and $\alpha$ is the Gaussian index. The phase compensation $u(x, y)$ generated by the deformable mirror is

$$u(x, y) = \sum_{j=1}^{32} v_j S_j(x, y) \tag{2}$$

where $v_j$ is the $j$th voltage of the actuators. We can see that the numeral relationship between the phase aberration generated by the DM and voltages applied on the actuators is linear.

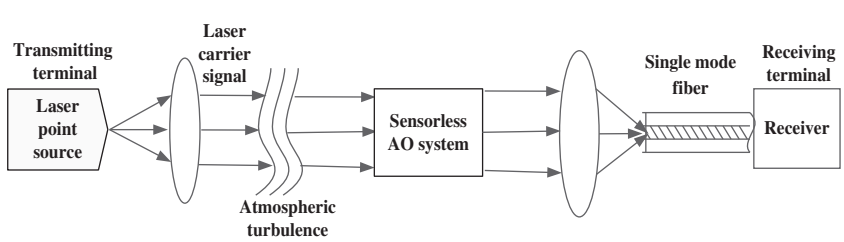


**Fig. 1.** Functional block diagram of FSO system.

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