Free-space single-mode receiver with adaptive optics for quantum communication

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Abstract

Satellite-based quantum communication is a promising approach for realizing global-scale quantum networks. However, due to atmospheric turbulence, achieving a highly efficient and stable spatial single-mode receiver, which is very important for daylight free-space quantum key distribution and more complex quantum information tasks involving quantum interference, is difficult. Here, we develop a spatial single-mode receiver with an adaptive optics (AO) system based on a modal version of the stochastic parallel gradient descent algorithm (M-SPGD) and conduct a field test of its performance over an 8 km urban terrestrial free-space channel. Our experimental results demonstrate the AO technology based on M-SPGD has a great boosting for single-mode receiver and is useful for large-scale quantum communication.

Principle of the M-SPGD algorithm

The performance metric J, i.e., the coupled power of SMF in our system, is taken as the objective function of the control voltage vector u of a deformable mirror, where the dimension of the voltage vector is equal to the number of actuators. The iterative update rule is given by

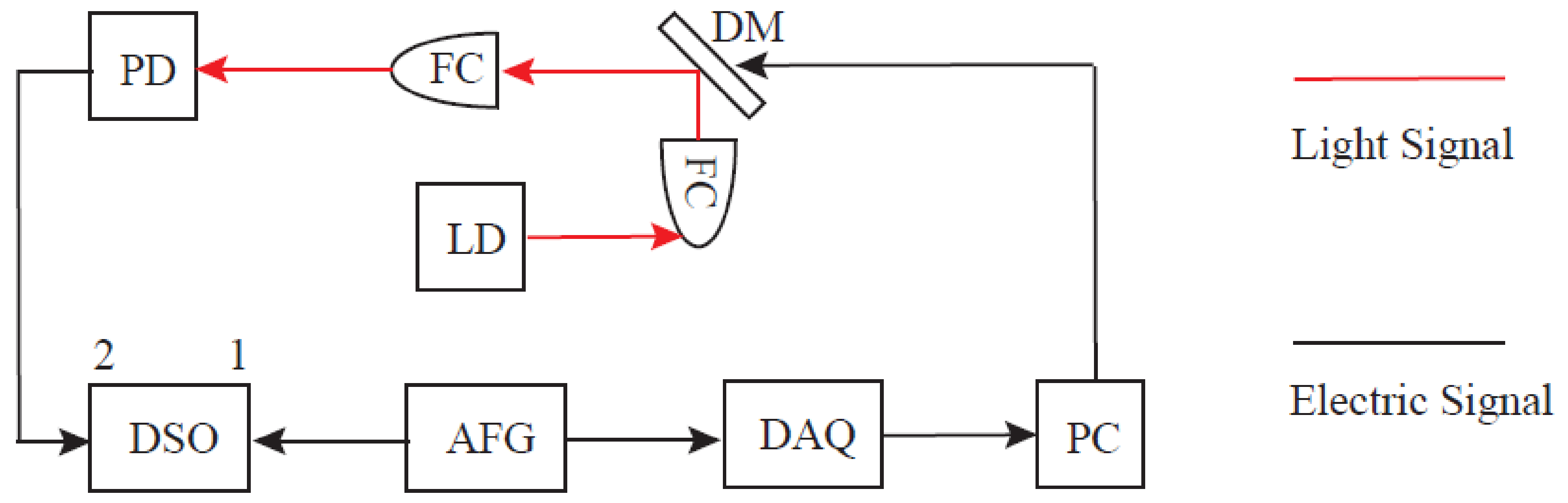
$$\boldsymbol{u}^{m+1} = \boldsymbol{u}^{m} + G \cdot \delta J^{m} \cdot \delta \boldsymbol{u}$$

where m is the iteration step, G is the gain coefficient, and δJ is the performance metric perturbation after applying a positive perturbation voltage δu to the deformable mirror. The perturbation voltage δu follows a Bernoulli probability distribution with zero mean.

The SPGD algorithm is essentially a rapid searching algorithm, thus, a smaller search space ensures a higher convergence rate. In practice, the shape of the deformable mirror for wavefront aberration compensation can be decomposed by a certain mode, for example, the Zernike mode, where the shape of the deformable mirror is described by the Zernike coefficients. The performance metric can be taken as the objective function of the Zernike coefficient vector. Although additional calculations are needed to map the Zernike coefficients to the control voltages in the iteration, the calculation speed is usually very high. Therefore, in the M-SPGD algorithm, we choose the number of Zernike modes applied to describe the shape of the deformable mirror to achieve a higher speed of wavefront distortion correction.

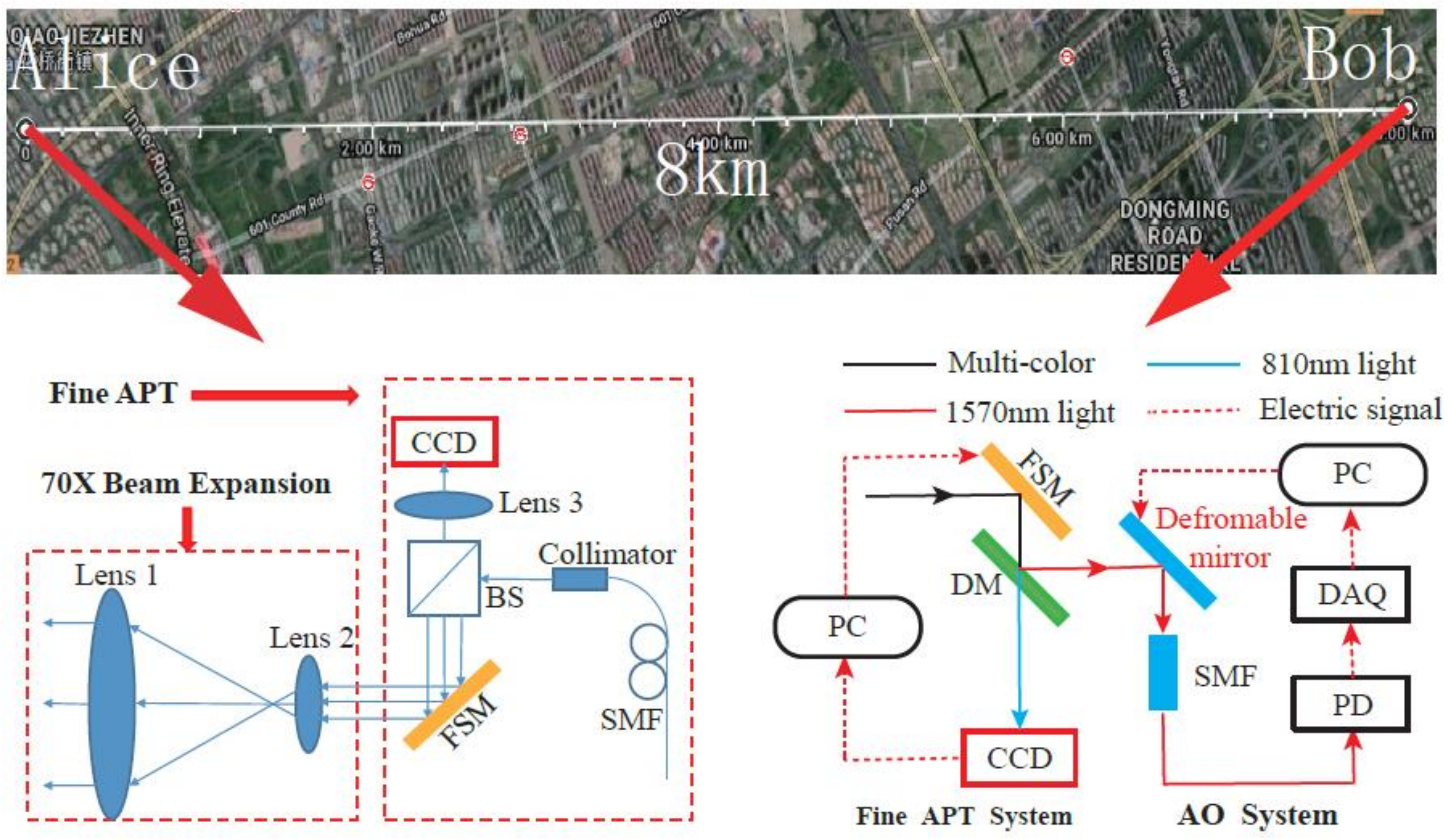
Realization of an M-SPGD AO system

We utilized a silver-coated piezoelectric deformable mirror with 40 actuators and a full stroke bandwidth of approximately 2 kHz. An infrared photodetector (PD) with a high gain and high bandwidth was used to detect the optical signal, and a multi-function data acquisition (DAQ) card was applied in our AO system. This DAQ card is used not only to read the performance metric but also for precise time-delay control in the AO closed-loop. To ensure that the readout of the performance metric occurs right after the random perturbation action of the deformable mirror, we designed the following system to measure the delay of the closed-loop control.



The delay, which is about 900 μs, can be precisely measured. We utilize the high-speed DAQ card to accurately control the delay, and a delay of approximately 900 μs is applied to the readout of the performance metric after the disturbance command is issued. The iterative frequency of our AO system is approximately 500 Hz. To obtain optimal performance from the algorithm, an optimization of the parameters, particularly the disturbance step size and gain coefficient, is required. The algorithm we designed automatically attempts different combinations of disturbance step sizes and gain coefficients, and the average SMF coupled power is used as the evaluation criterion to select the parameters.

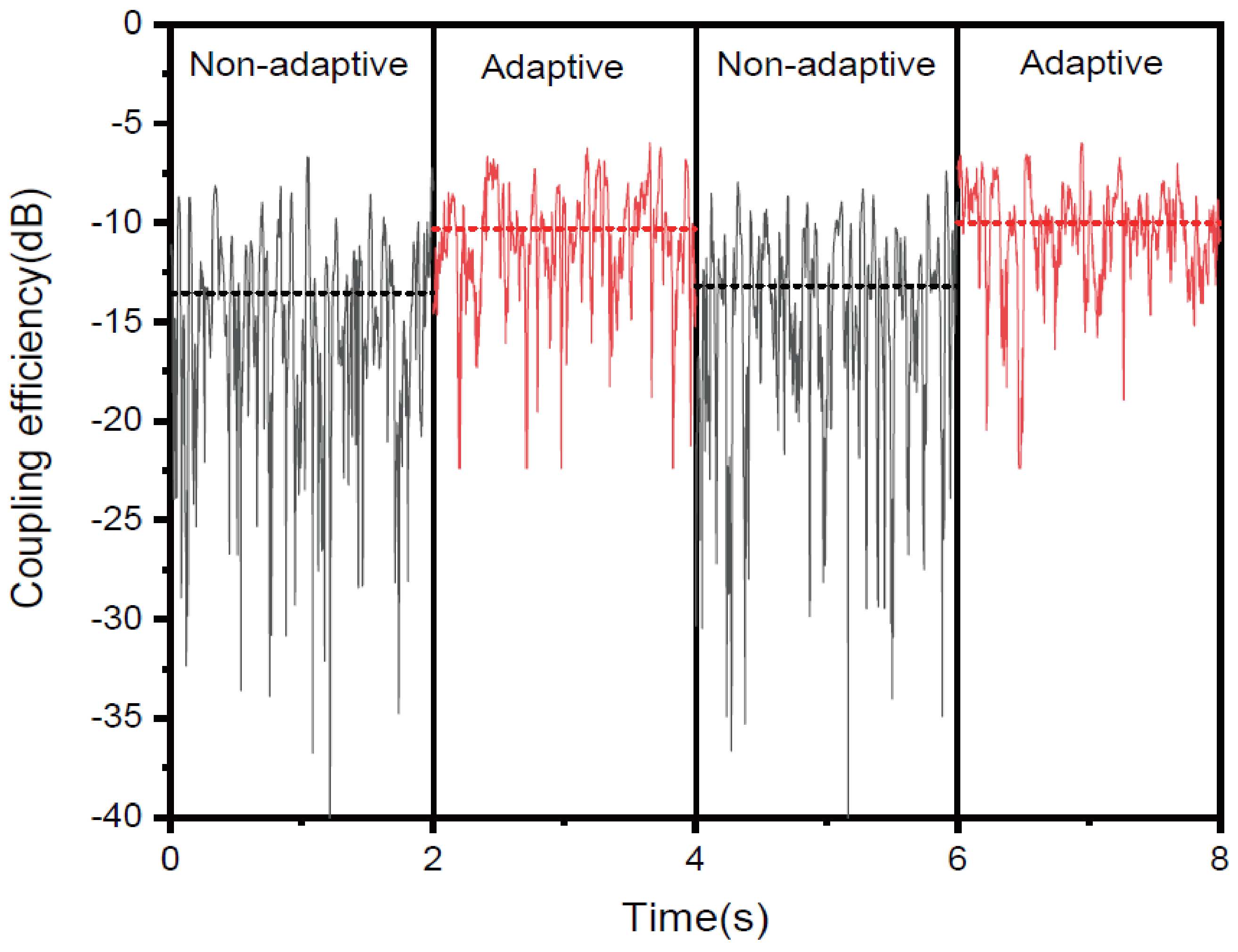
Experiment setup

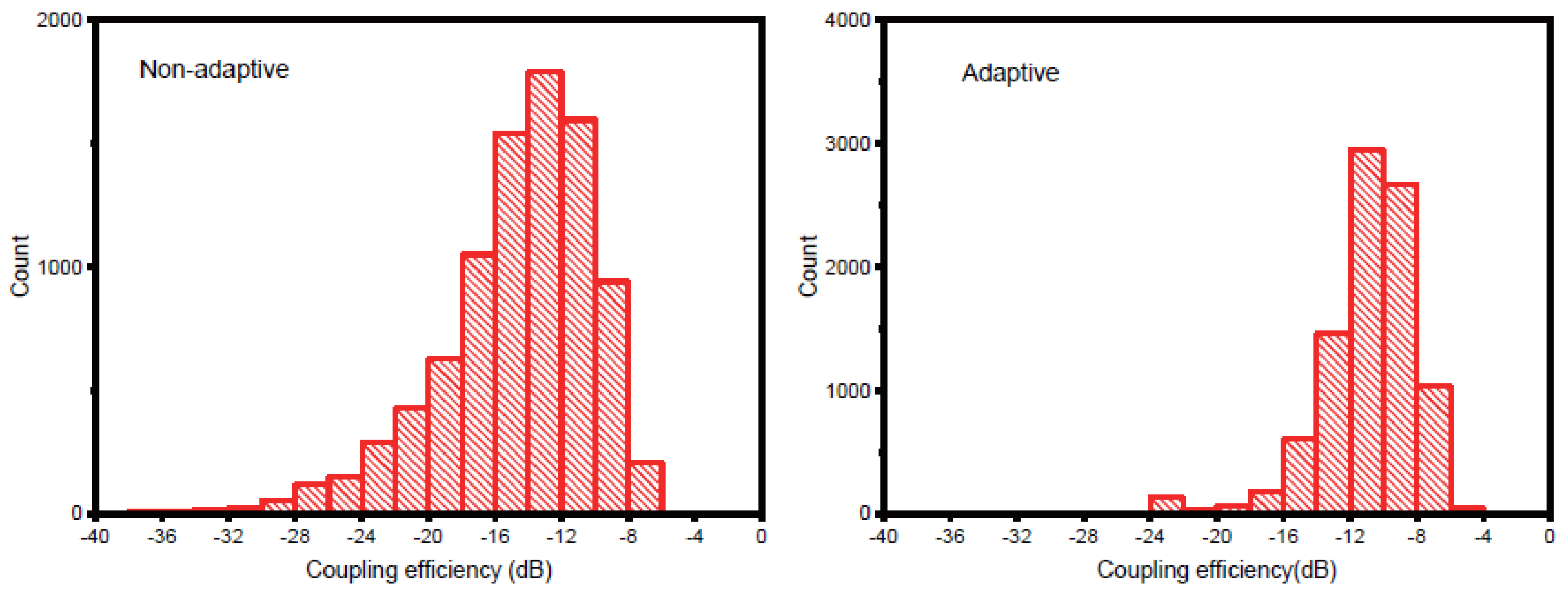


Based on numerous tests over an 8-km free-space link, the results show that our M-SPGD algorithm AO system can effectively improve the SMF coupling efficiency and suppress intensity fluctuations. Moreover, we also used angle-of-arrival fluctuation method to estimate the Fried parameter r0 in order to characterize the strength of the atmospheric turbulence.

$$r_0 = 3.18 k^{-6/5} D^{-1/5} \delta_\alpha^{-6/5}$$

Result





For a normalized atmospheric coherence length of D/r0 = 5.4 (r0 = 7.4 cm @810 nm), the M-SPGD AO system improved the single-mode coupling efficiency from 4.8% to 9.7% and the coupling efficiency fluctuation is obviously suppressed