

Entanglement Distribution over a Polarization-Stabilized Aerial Fiber

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Abstract: We experimentally demonstrate the distribution of polarization-entangled photons between two laboratories connected by a 62-km, partially-aerial fiber. Using time-multiplexed polarization stabilization, we maintain a pair rate of 1500 s^{-1} over 24 hours and achieve an average CHSH value of $S = 2.39 \pm 0.22$.

1. Introduction

In metropolitan-scale quantum networks, a key technical challenge is the reliable transmission of polarization-encoded or polarization-entangled photons through deployed fibers. Routing geometry and fiber birefringence impose random unitary transformations on the photons' State of Polarization (SOP) [1,2], rendering polarization-based quantum protocols inoperable. Such transformation changes over time due to perturbations from the environment, and can fluctuate on short time scales of seconds for aerial fibers [3].

In this work, we distribute polarization-entangled photons over a 62-km aerial fiber link connecting the National Institute of Standards and Technology (NIST) and the University of Maryland (UMD), College Park. Owing to its poor polarization stability, the aerial fiber link is dynamically stabilized using two automated polarization compensation modules deployed across the link. During a continuous 24-hour experiment, we observed a violation of the Clauser-Horne-Shimony-Holt (CHSH) inequality for more than 20 hours, with an average value of $S = 2.39 \pm 0.22$. Throughout the experiment, polarization stabilization required only 7.2% of total operation time, leaving a link up-time of 92.8% for entanglement distribution. This experiment demonstrates the feasibility of quantum networking over challenging real-world fibers.

2. Entanglement Distribution over Stabilized Fiber

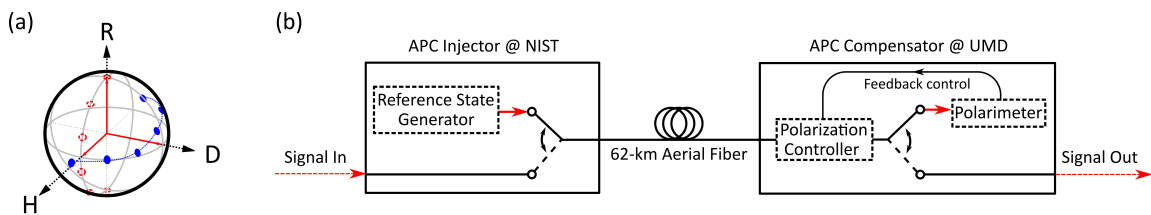


Fig. 1. (a) Sequence of six polarization reference states generated by the APC injector (red) and the corresponding states measured by the APC compensator after fiber transmission (blue). (b) Simplified schematic illustrating the working principle of the APC injector/compensator pair.

In this experiment, a polarization-entangled photon source located at NIST generates pairs of signal and idler photons that are initially prepared in a Bell state $|\Phi^+\rangle = (|HH\rangle + |VV\rangle)/\sqrt{2}$. The idler photons are locally detected at NIST, while the signal photons are transmitted to UMD through the 62-km aerial fiber link. Polarization analyzers at both laboratories select measurement bases for the incoming photon pairs, which enables us to extract the CHSH inequality parameter from the measurement results. With about 18 dB of fiber link loss, we detect approximately 1500 photon pairs per second between the two laboratories.

The aerial fiber's polarization transformation drifts rapidly and can degrade the transmitted polarization fidelity within tens of seconds. To maintain a stable polarization transformation for entanglement distribution, we implement an active fiber stabilization scheme using a pair of Automated Polarization Compensation (APC) modules, consisting of an injector and a compensator deployed across the fiber [4]. The APC injector/compensator cyclically emits/receives a set of reference polarization states (Fig. 1a) at the same wavelength as the signal photons. When active stabilization is enabled, an inline polarization controller in the APC compensator is actuated in a feedback control loop that maximizes the fidelity of the received reference states.

Because the polarization reference signals are generated at the same wavelength as the signal photons, polarization stabilization and entanglement distribution must be time-multiplexed. As shown in Fig. 1b, optical switches in the injector and compensator alternate the fiber path between polarization stabilization and entanglement distribution. Throughout the experiment, measurement of the received polarization-entangled states are triggered by the completion of a successful stabilization session, or by the timeout of a failed stabilization attempt.

3. Results

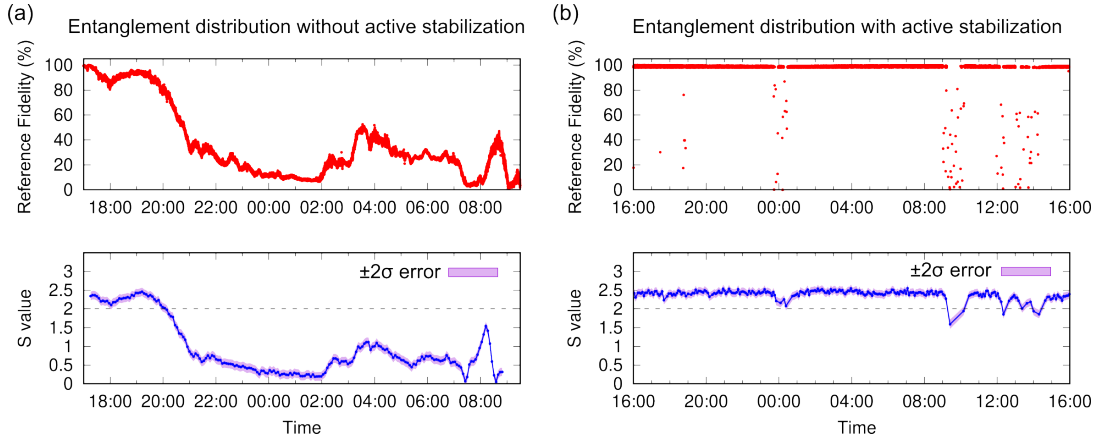


Fig. 2. (a) APC reference state fidelity and S -parameter measured over 16 hours without polarization stabilization. (b) APC reference state fidelity and S -parameter recorded over 24 hours with polarization stabilization.

During the experiment, we continuously monitor both the reference-state fidelity and the CHSH inequality parameter (S value) of the distributed entangled photons. Fig. 2a shows the measurement results obtained without polarization stabilization. In this measurement, the S value dropped below the classical bound of 2 after approximately three hours and no further CHSH violation was observed for the remainder of the 16-hour measurement.

In contrast, with polarization stabilization enabled, the APC maintained a reference-state fidelity above 98% for most of the 24-hour measurement period as shown in Fig. 2b. The average S value was 2.39 ± 0.22 , which is above the classical bound. Occasional drops in reference-state fidelity and S -value were observed mostly during measurement at day, which is likely caused by environmental disturbances that temporarily exceeded the capability of the APC compensator. Despite these disturbances, the APC only spent about 7.2% of the total operation time to perform polarization stabilization, yielding an effective 92% up-time for entanglement distribution through the stabilized aerial fiber link.

Although aerial-based optical fibers are often considered unsuitable for polarization-based quantum networking protocols, we show that stable distribution of polarization-entanglement is achievable if the fiber link is actively stabilized. Our results demonstrate the feasibility of performing entanglement distribution over challenging fiber conditions and represent an important step towards the practical implementation of metropolitan-scaled quantum networks.

References

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4. Certain commercial equipment is identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.