Phase stabilization of deployed telecom fiber links for entanglement distribution

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We report on the phase noise characterization and stabilization a pair of 43 km, dark fiber optic links between MIT Lincoln Laboratory and MIT's main campus, for use with multi-span entanglement distribution links.

We characterized the phase noise of this link (see Ref. [1]) using a 1550 nm laser at Lincoln Laboratory, we retained a portion as a reference and sent the remainder along one of the fibers to MIT. At the MIT end of the fiber a short fiber jumper sent this beam to the second optical fiber which returned the beam to Lincoln Laboratory. We combined the reference and the returned beam in a coherent optical receiver, which consisted of an integrated-optics-based 90° hybrid receiver that measured the in-phase component I and quadrature phase component Q of the returned beam's electric field, relative to the reference beam. These signals were sampled at 100 kHz and recorded. The phase of the returned beam is determined by $\phi = \arctan(I/Q)$.

The phase fluctuation as a function of delay T is given by $\Delta\phi(T) = \sqrt{\langle|\phi(t-T) - \phi(t)|^2\rangle}$. For our deployed-fiber system, $\Delta\phi(T) \propto T^{0.91}$. Brownian phase noise would result in $\Delta\phi(T) \propto T^{0.5}$, indicating that the phase noise in our fiber system is not governed by an exclusively Brownian process.

Integration of the phase power spectra indicates that a feedback control system with a bandwidth of 100 kHz will allow for phase-stable control of the fiber system. Time-of-flight (TOF) measurements of the fiber loop indicate that such a control system must track changes of up to several meters of path length change. We have implemented a closed-loop feedback system using TOF measurements that tracks long-throw changes, achieving stability to within 0.5 ns. This feedback system consists of a 25 km spool of SMF-28 optical fiber submerged in a tank of temperature controlled water. We are working now to incorporate additional control elements in order to achieve more precise tracking stability. This future fiber system with phase-stabilized operation will allow for quantum communication and quantum network demonstrations using both DLCZ and Hong-Ou-Mandel type entanglement swap operations.

We further characterized the capabilities of the fiber channel by performing a field test of a large-alphabet prepare-and-measure type QKD protocol [2]. In this protocol, the conjugate bases are photon arrival time and photon energy, and are implemented by selectively applying normal and anomalous group velocity dispersion (GVD). Information is encoded in the prepared pulse time—using pulse position modulation (PPM)—and can be shared when when Alice and Bob both apply GVD, or when neither Alice nor Bob apply GVD. If only one party applies GVD, the correlation between prepared and measured pulse time is degraded.

In our field test Alice used PPM to encode a data pattern as the raw key on a broadband 1560 nm light beam (25 GHz of bandwidth). She maintained less than one photon per pulse on average and varied the intensity of the pulses to guard against photon-number-splitting attacks. The pulses were detected with low-jitter superconducting nanowire single photon detectors. All components, apart from the detectors, were commercially available telecom components.

We tested the QKD system in three distinct setups: in the laboratory with negligible channel loss, where we achieved a secret-key rate of 20 Mbps ; in the laboratory with a 41-km fiber spool as the channel (loss 0.19 dB/km), where we measured secret-key rates of 5 Mbps; and in a field test over the 43-km deployed fiber (loss 0.37 dB/km), where we measured secret-key rates of 1.5 Mbps. Additional GVD from the deployed fiber channel was compensated by using appropriate lengths of dispersion-shifted fiber.

We are now implementing the entanglement-based version of this QKD protocol over the deployed fiber link, using the fiber stabilization system to aid in node synchronization. Our efforts will enable future demonstrations including multi-span entanglement-swapping-based quantum communication.

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