Distribution of Quantum Entanglement through Fiber with Co-Propagating Classical Data

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Abstract: A complete system for distributing quantum entangled signals over fiber based on commercially available equipment will be demonstrated. Measurements are collected and controlled from a single location using an embedded optical data link.

Fiber optic cable is the most practical way of distributing quantum signals over a wide range of distances from 10's of meters to a few hundred km due to the very low loss associated with fiber propagation. This creates opportunities for quantum networking using distant quantum nodes interconnected by fiber. Quantum entanglement is perhaps the most sought-after quantum resource, but measuring quantum entanglement is inherently a distributed measurement that relies on coordinating and synchronizing data from multiple detectors that are typically in different locations. Additionally, quantum signals are generally at the sub-photon level, which makes them particularly sensitive to minute levels of noise. This can become a particularly significant issue when a fiber link is shared by both quantum and classical signals since the huge difference in photon flux creates new issues like Raman scattering and places stringent demands on cross-talk and noise leakage [1]. Though not addressed in this work, we also note that advanced future quantum networks will likely require quantum memories to facilitate applications like long distance teleportation [2]. While currently not advanced enough for practical use, it is expected that even future quantum memories will have very limited storage times. This is drastically different from classical memory, which is inexpensive, plentiful, and has a storage time that in practice is limited only by the latency demands of the application. The differences between quantum and classical networking are stark, creating a host of new issues for the quantum networking engineer [2, 3].

While advancing the state of quantum networks into powerful multi-user systems capable of sharing useful amounts of entanglement between quantum processors (sometimes termed the "quantum internet" [4]) will likely require many technological advances and may not materialize for decades, there are some quantum communication functions that are attainable with today's technology. Quantum key distribution (QKD) is the first such function and has been demonstrated in various network environments [5, 6]. Entanglement distribution is the next rung of the ladder, as it is more universal since entanglement can be used for a wide variety of applications including QKD as well as teleportation of qubits. Entanglement distribution has been demonstrated over installed fibers in a variety of bespoke experimental configurations [7, 8, 9]. In this demonstration we aim to address some of the basic issues required for distribution of entangled photons over fiber optics using commercially available equipment, helping to reduce the barrier of entry for establishing quantum communication test networks.

Figure 1 shows a conceptual diagram of the demonstration, which leverages commercially available quantum instrumentation from NuCrypt, LLC including a multi-channel entangled photon source (EPS), polarization analyzers (PAs), and remote correlation systems (RCSs). Two physically separated locations on the demo floor labeled the primary and secondary booth are interconnected though fiber. The RCS collects data from single photon detectors (SPDs), which in the primary booth location are superconducting SPDs (SSPDs) from Quantum Opus, and in the secondary booth are Single Photon Avalanche Diode (SPAD) based devices from IQ Quantique. Since correlations between SPDs that reside in different locations and are separated by various lengths of fiber must be collected, the net delay over any given fiber is accounted for by the RCS prior to correlation counting.

The EPS generates photon pairs at multiple ITU-grid channels, with each channel exiting a different fiber port. Multiple wavelength channels are fed into a N x N all-optical switch to allow them to be routed to either booth location, with or without first sending a given wavelength through a fiber loop to emulate a long-distance link. This switch-based architecture allows flexible assignment of entangled pairs to multiple users in a quantum network while incurring minimal insertion loss [3]. The fiber loop can be either a local spooled fiber, or fiber looping to and from a distant off-site remote hub connected by approximately 26 km of installed fiber. The fiber to the remote hub has an estimated 7 dB of loss in each direction (14 dB total loss) at the quantum 1550-nm band wavelengths. Since polarization stabilization is not included in this demonstration, the polarization transformation of the installed fiber should be stable over the measurement time to obtain quality results.

Quantum networking systems can benefit from both quantum and classical channels sharing the same fiber resources. The classical channel may for instance carry information that helps the quantum systems run efficiently, such as timing recovery, low-latency quantum measurement feedback, or control plane information for the quantum data plane. Such information can help to quickly establish or maintain quantum connections in a dynamic environment, as well as enable the next-wave of quantum communications technology such as teleportation. In some cases, co-propagating signals may also be desirable to allow a given quantum fiber link to carry unrelated data in order to more efficiently use limited fiber optic cable resources.

In this demonstration, a fiber data link is embedded in the RCS to facilitate system control from a single location. All measurements are controlled from the primary booth location. Commands can be sent from the primary to the secondary system, for instance to control parameters such as the detection threshold used by the RCS at the secondary location to digitize the signal coming from a co-located SPD. Raw detection data in compressed format is sent from the secondary booth back to the primary booth. This data exchange occurs using a wavelength division multiplexed data channel based on a small form factor pluggable (SFP) transceiver. The quantum channel resides in the low-loss 1550-nm band and the data link is in the ~1300-nm O-band using coarse wavelength division multiplex (CWDM) transceiver technology. This wavelength map facilitates low-loss wavelength combination/separation of the quantum/classical channels and reduces Raman scattering [10]. However, the two booth locations on the demo floor are quite close (<1 km), thereby experiencing only modest Raman scattering in the interconnecting fiber. Clock recovery is also embedded in the fiber to robustly handle path-length variations that may occur, for instance, due to temperature variations.

An optional test data channel can also be co-propagated with the quantum signal on another O-band CWDM wavelength channel to stress test the ability of the quantum channel to coexist with classical data through the long fiber loops. Again, the data channel wavelength is chosen in the O-band to control Raman scattering. Although O-band is not widely used for long distance communications it is a widely-used low-cost option for sub-80 km links. The data channel launch power is controlled by a variable optical attenuator (VOA) and can be adjusted to balance the data error rate with generated Raman noise.

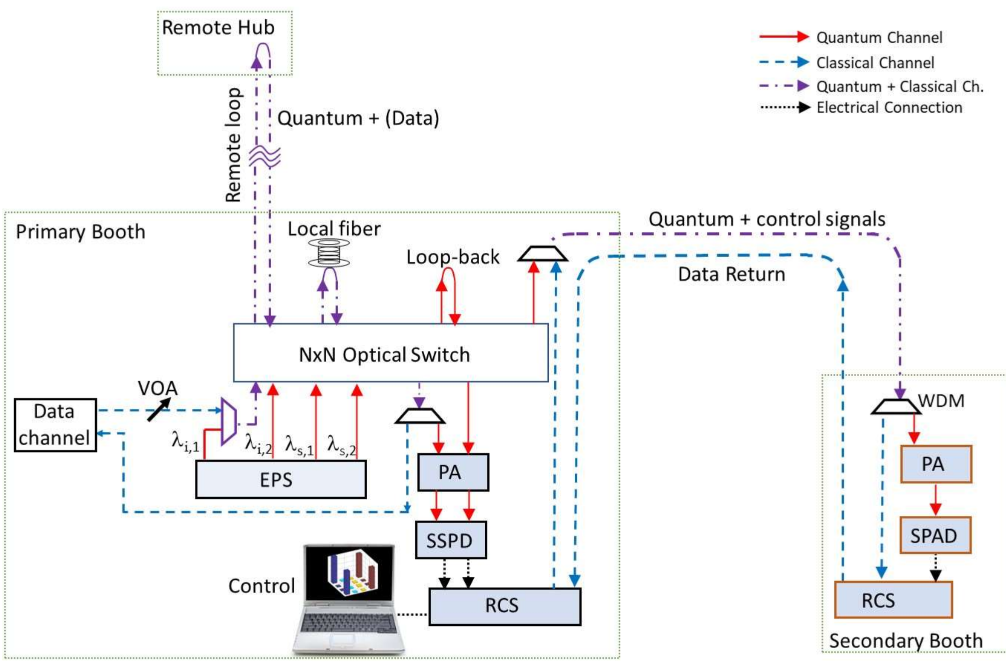

Figure 1: Simplified diagram of the three location demonstration. The Primary Booth has the EPS, a photon detection chain that includes a superconducting single photon detector (SSPD), and an NxN optical switch. The switch is configured to either send an idler wavelength ($\lambda_{i,1,2}$) to either the primary or secondary booth, either with or without first propagating the idler though a fiber loop. The fiber loop can be either a local fiber test spool or a remote loop that leads to and from a remote hub connected by ~26 km of installed fiber each way. The corresponding signal wavelength can also either be measured locally or sent to the secondary booth location. The secondary booth communicates measured data via a fiber data return connection.

The RCS samples the output of a nearby SPD, which may be an analog or digital signal depending on the detector. The threshold and sampling rate of the RCS input channel is adjustable, with the sampling instant being derived from the clock recovery system. The RCS can be interfaced to gated or un-gated detectors, with un-gated detectors being used in this demonstration. Two types of measurements can be selected by the control software at the primary booth: either two-photon interference (TPI) or quantum state tomography (QST). The QST uses six polarization bases at each location, leading to a 36-measurement tomography. The data from these 36 measurements are collected and processed by the system control software to find the state matrix and in turn determine metrics like the fidelity of the state with respect to an ideal entangled state [11]. The QST requires that the polarization transformation of the fiber is stable over the measurement time but can account for polarization changes between measurement times via a computationally calculated rotation matrix.

TPI, on the other hand, requires the bases states at each detector be properly aligned prior to measurement. This alignment can be performed using embedded classical alignment signals inside the EPS [12], or by applying the QST-measured rotation matrix. In either case the PA's are configured with some initial polarization transformation to account for the fiber and additional phase shifts are applied on top of the initial setting to measure a desired measurement basis. Correlation-count fringes with one detector held at a sequence of fixed basis states, such as horizontal (H) and diagonal (D), can then be recorded to plot TPI fringes.

When a co-propagating data channel is sent together with the quantum signal, the background photon counts are elevated due to Raman scattering. While this effect negates the value of the ultra-low dark count rate of SSPDs, the high detection efficiency (e.g. >80%) and the short dead time (50 ns) of the SSPDs still lead to higher detection rates than would be possible with alternate technologies. Since the SPD photon efficiency is not temporally gated, noise photons outside the expected pulse arrival time can still lead to detector saturation. Noise also degrades the natural quantum signal-to-noise ratio which is sometimes quantified by the coincidence-to-accidental count ratio (CAR). Narrow optical filters and appropriate post-processing of the detection events, so as to ignore photon counts that are outside the expected optical pulse location, are useful tools employed to help control the impact of Raman scattering.

In summary, we demonstrate how commercially available equipment can be interconnected to distribute entanglement over fiber. Single photon detectors of both the superconducting and avalanche style are located in two separate physical locations. Fiber connections share data and commands between the locations, and an NxN optical fiber switch allows the signal photons to also be propagated through long lengths of either installed or spooled optical fiber loops. The fiber loop can also carry a classical signal to stress-test the quantum system's ability to handle co-propagating classical data. Issues typical of fiber quantum communication links including accounting for fiber delay and path-length drift are addressed, and system control and data analysis is conveniently handled at a single-site. The demonstration shows the ability of commercial equipment to interface to create basic quantum communication functions.

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