Analysis of Architectures for Entanglement Distribution from Space

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Abstract: A quantum state analysis is applied to a potential architecture for entanglement distribution from space to asses several design choices and maximize the distribution rate while maintaining entanglement quality.

1. Introduction

Quantum entanglement can be utilized to connect quantum systems distributed over long distances, enabling quantum computer networking, distributed sensing, and secure communications. Because of the exponential loss inherent in optical fiber transmission, free-space entanglement distribution could provide higher entanglement distribution rates over distances > 100 km by using a single intermediate node in space.

Our goal is to inform experiment design choices for entanglement distribution from a satellite (or space station) by analyzing a potential near term entanglement distribution architecture in terms of the maximum distribution rate and the quality of the resulting entanglement [1]. The results are compared to an ideal quantum-memory-based architecture (i.e., with quantum repeaters), which has an entanglement distribution rate proportional to the greatest single-link loss in the system [2]. This type of space node would have two entanglement sources, each of which sends its signal field down to a different ground station, while its entangled idler is routed to an Bell State Measurement (BSM) device (with memories). The BSM jointly measures two idlers — whose entangled signal photons made it to ground and were stored in quantum memories — causing their two signal photons to become entangled in a so-called entanglement swap.

Implementing such an ideal system has many challenges, including the development of quantum memories with sufficient coherence times, qubit depth, and optical interface bandwidth. In the near term we can adapt existing, needed technologies — primarily entanglement sources and single photon detectors (SPDs) — to work in space, and develop the optical synchronization methods needed to track and collect the quantum downlink and interact it with a quantum system on the ground. This is especially challenging as we move towards high-rate distribution, where wavepacket durations can be on the order of picoseconds.

The demonstration we consider implements one of the downlinks from the space node to a ground node [1]. An entanglement source in the space node sends its signal field to ground, while the entangled idler field is retained. Because there is no memory to interact with on the space node, the idler will be measured by a quantum state analyzer (QSA). On the ground, the signal can be fed directly to another QSA, or routed to a free-running (no memory) BSM. The other input to the BSM is the signal field from an entanglement source on the ground that has been synchronized to the quantum downlink. Each valid BSM measurement entangles the ground and space idlers (modulo a state correction given by the BSM result). By measuring these fields with QSAs, we can determine the rate and quality of the entanglement distribution after the entanglement swap. This type of demonstration would test the synchronization architecture, entanglement sources, and high-rate single photon detectors in space.

2. Entanglement Distribution Rate and Quality Analysis

For our analysis we propagated the joint quantum state from the entanglement sources to the set of photon detectors $\mathbf{D}$ at the BSMs and QSAs. Then, for each set of detector counts $\mathbf{d}$ (where $d_i \in 0,1,2,\ldots$) we then computed the likelihood $p_{\mathbf{D}}(\mathbf{d}) = \operatorname{tr}\left(\hat{O}_{\mathbf{D}}^{(\mathbf{d})} |\psi\rangle_{\mathbf{D}} \langle\psi|\right)$, where $\hat{O}_{\mathbf{D}}^{(\mathbf{d})} = \bigotimes_{i=1}^{N} \hat{O}_{D_i}^{(d_i)}$ for each number state projector $\hat{O}_{D_i}^{(d_i)}$ and $|\psi\rangle_{\mathbf{D}}$ is the joint state at the detectors. The state propagation used continuous-time field operators to allow for temporal misalignment of the fields entering the BSM, which was used to test the required precision of synchronization. All photon detectors were modeled as SPDs with negligible dead time and dark counts, and a quantum efficiency of 0.9, which can be achieved with arrays of super conducting single photon detectors. We assumed 1 dB coupling losses to the QSA and BSM. Finally, the analysis was formulated for polarization entanglement with a Sagnac source using spontaneous parametric downconversion (SPDC), but the mathematics are generic and our results should extend to most entanglement types that use SPDC.

For each set of system parameters we have found the per-mode entangled-pair rates — constrained to ≤ 0.1 pairs per mode for all entanglement sources — that maximize the entanglement distribution rate while maintaining a CHSH value of $S > 2$ [4]. We have found that S has a weak dependence on the space-source pair-rate, except for large S values or a very low space-to-ground loss. In general, the optimal value was at our constraint of 0.1. Conversely, there was a strong dependence on the ground-source pair-rate, which can be seen in Fig. 1. As expected, S was found to be proportional to the temporal wavepacket overlap function.

Optimization of the single quantum downlink connected to a free-running (no memories), synchronized BSM showed the maximum entanglement distribution rate post-swap to be proportional to the square of the downlink loss (see Fig. 2), instead of the expected linear dependence (as was found when the quantum downlink was analyzed without a swap). This is because the ground-source pair-rate needed to be reduced linearly with the space-to-ground link-loss to maintain the CHSH constraint; fundamentally, this flux reduction was required to prevent ground-source double-pairs from dominating space/ground coincidences in the BSM. We are actively investigating if this scaling holds for other quality metrics, such as the post-swap state fidelity.

The use of ideal photon number-resolving (PNR) detectors would prevent this scaling degradation because double pairs could be detected and ignored, so the ground source rate would not need to decrease with the link loss. However, for a realistic 0.9 quantum efficiency and 1 dB coupling losses to the ground QSA, the doubles rate is only suppressed by about 5.5 dB, and once the link loss surpasses this margin the rate-scaling reverts to the square of the link loss. Additionally, because the QSA has one detector for each polarization, it already detects and heralds double-pairs half of time. As seen in Fig. 2, the combination of these effects means the PNR rate is only about 1.5 dB higher than the SPD rate for relevant link losses. These results predicts that, for a 1 GHz pulse rate and a 20 dB link loss, we can distribute entanglement at a rate of 640 kHz, with a post-swap rate of 2.5 kHz (SPD) or 3.6 kHz (PNR). At a 30 dB link loss these rates become 64 kHz, 25 Hz, and 36 Hz.

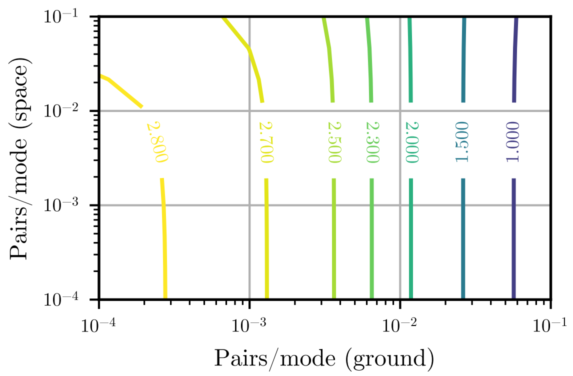

Fig. 1: Contour plot of CHSH value S for a 20 dB downlink with an entanglement swap on ground, as a function of the ground and space entanglement source strengths.

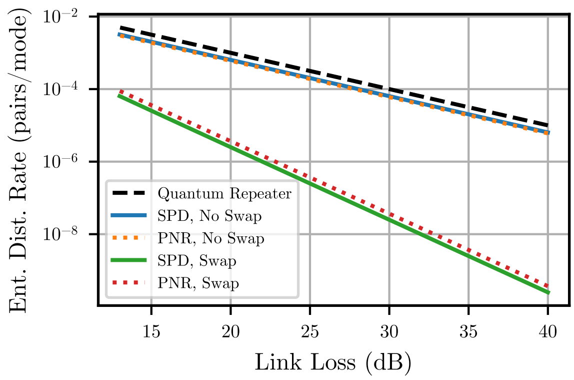

Fig. 2: Maximized entanglement distribution rate per temporal mode for $S > 2$ and an entanglement generation rate of less than 0.1 pairs per temporal mode.

Finally, we note that a future entanglement distribution architecture described in the introduction (with memories at the BSMs) will not see this scaling degradation. Each BSM operates at the lower of the two flux rates entering it; the ground-source rate can be reduced to prevent double pairs, but the single-pair rate will still be higher than the received rate (after loss) from space, and we maintain the linear scaling show in Fig. 2.

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