

High-Rate Entanglement Sources for Space-Based Quantum Networking

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Abstract: We survey the system trades involved in selecting and building entanglement sources and other quantum technologies relevant for a satellite downlink demonstration of heralded entanglement distribution. © 2020 The Author(s)

1. Introduction

Entanglement-based quantum networks enable new and more powerful applications with performance above that which could be obtained classically. Entanglement is required for the teleportation of arbitrary quantum states and it also provides stronger-than-classical correlations between remote elements, such as distributed networks of quantum processors, clocks, or sensors. To achieve these performance gains, entanglement must be distributed between multiple network nodes. For large separations, free-space optical (FSO) links can connect remote nodes with higher channel transmissivity than the corresponding length of optical fiber. This has motivated worldwide interest in satellite-based quantum networking. Generally, FSO downlinks are preferable to uplinks because atmospheric turbulence is more easily compensated for on downlinks. However, a quantum downlink necessitates putting quantum systems, including entanglement sources, in space. Spontaneous parametric downconversion (SPDC) is the most mature technology for high-rate entangled photon pair generation, and SPDC sources have already been flown on low-earth-orbit (LEO) satellites [1, 2]. However, these source designs are not well-suited for a scalable entanglement distribution network.

We have proposed and analyzed architectures for FSO satellite downlink entanglement distribution demonstrations with extensions toward a future entanglement-based quantum network [3]. Here, we survey the design trades of space-based SPDC entanglement sources and the system impacts of those trades.

2. Downlink heralded entanglement distribution architecture

The quantum components of the proposed downlink heralded entanglement distribution architecture are shown in Fig. 1. Entanglement Source 1 is located on the satellite, and Source 2 is located at the ground station. Source 1 emits an entangled signal-idler pair; the signal is downlinked to the ground station, and the idler is detected/retained in-orbit. At the ground station, Source 2 also emits an entangled signal-idler pair. The two signal photons are sent to a Bell state measurement (BSM) device; upon a successful BSM, entanglement is swapped to the two idler photons. The BSM success heralds the presence of entanglement between the remote idler photons [4]. In a near-term demonstration, the idler photons are detected using quantum state analyzers (QSAs) to verify their entanglement, but in the future, the states of the idler photons will be stored in quantum memories until the entanglement is used in an application.

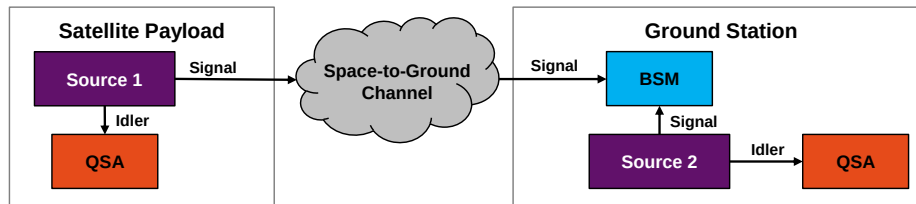


Fig. 1. Downlink heralded entanglement distribution architecture.

A successful entanglement swap requires detecting four-photon coincidence events. Without quantum memories, this requires both sources to emit photon pairs at the right times so the signal photons can interfere at the BSM. With continuous-wave (CW) pumping, this does not scale to high rates because SPDC produces pairs probabilistically. To

increase the four-photon coincidence rate, the SPDC sources must operate with pulsed pumping according to a shared clock.

3. Design trades for space-based entanglement sources

For quantum networking, there are three basic requirements for an entanglement source: high pair generation rates, high entangled state quality, and high spectral purity. The first two requirements should be self-evident: the quantum network should distribute high-quality entanglement at useful rates. The third is derived from the fact that many quantum operations, including the BSM, rely on high-visibility two-photon interference, which in turn requires the input photons to be in spectrally pure states. A space-based entanglement source needs to deliver these basic requirements while also surviving the environmental conditions of launch and orbit.

The SPDC entanglement source design choices can be divided between the three main components: the nonlinear crystal, the pump, and the entanglement generation scheme. The requirement for spectral purity strongly drives both the crystal and pump choices. Spectral purity can be obtained by spectral filtering, which has the detrimental effect of lowering the pair rate. To avoid these filtering-induced losses, we can instead engineer the properties of both crystal and pump to obtain intrinsically spectrally pure states. We choose periodically poled potassium titanyl phosphate (PPKTP) for the combination of its relatively high nonlinearity and the availability of the group-velocity matching (GVM) condition near the telecom C- and L-bands for type-II phase-matching; spectral purity is then obtained by matching the pump and crystal (phase-matching) bandwidths. Narrower phase-matching bandwidths, i.e., longer PPKTP crystals, are desirable because they are correlated with more efficient SPDC and they ease the system requirements for synchronization at the BSM [5]; the maximum achievable crystal length is currently few tens of mm, corresponding to pumping with ps pulses from a mode-locked laser (MLL). Pulsed pumping is therefore necessary to obtain both scalable four-photon coincidence rates and spectrally pure states.

The remaining design choice is the entanglement generation scheme, which includes both the entanglement degree of freedom and the optomechanical setup. This choice has the widest tradespace. Polarization is the most commonly used degree of freedom for long-distance FSO quantum communication. There are multiple methods for generating polarization entanglement using SPDC, such as crossed crystals, Sagnac interferometers, or the beam-displacer method. These methods have different merits in terms of the entangled state quality and the optical alignment stability. However, all of these methods are generally based on bulk crystals, which make it more difficult to achieve high pair generation rates. Compared to bulk, SPDC in waveguides can be orders of magnitude more efficient, but generating polarization entanglement using waveguides is currently much less mature.

Waveguided SPDC motivates the consideration of time-bin entanglement, which is well-suited for an efficient, robust, and compact space-based source setup: SPDC can be efficiently generated in a fiber-coupled waveguide device, and the early-late time-bin superposition can be produced using a commercial telecom delay-line interferometer (DLI). However, choosing time-bins increases the overall system complexity. The remote QSAs need a shared phase reference for their DLIs, which is complicated by the satellite-motion-induced Doppler shift that changes the early-late separation during the satellite's pass. This can be achieved using a downlink phase reference signal and a ground-based control system [6]. Additionally, compared to polarization, time-bins require better single-photon detectors: lower timing jitter (to resolve the time bins) and shorter reset times (to detect the $|\Psi^+\rangle = |\text{early}\rangle|\text{late}\rangle + |\text{late}\rangle|\text{early}\rangle$ Bell state). Thus, the additional system complexity can likely be concentrated almost entirely at the ground station.

In summary, space-based entanglement sources for quantum networking have performance requirements unique from ground-based sources or sources designed for a single application such as quantum key distribution. In evaluating SPDC source designs for space, we must consider the impact of the design choices, such as the entanglement degree of freedom, on the entirety of the space-ground system.

References

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