Free-space Forwarded-pump Entanglement Source Synchronization

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Abstract: We investigate entanglement source synchronization using a forwarded-pump signal sent over a 3.2-km free-space retro-reflected link. Results show sub-picosecond alignment between the sources. The paper considers several fundamental and practical aspects of this approach. © 2022 Massachusetts Institute of Technology

As quantum communication systems mature from laboratory prototypes to fielded systems, establishing techniques to synchronize and align to quantum signals will be critical for high-fidelity operations. In general, entanglement swapping operations require indistinguishability of interacting photons, and therefore alignment must be achieved in the relevant degrees of freedom, which can include polarization, wavelength, and timing. The specific challenges depend on the signal format, the location and motion of the sources, and the loss and dynamics of the optical channel. One of the most challenging cases is high-rate free-space entanglement distribution involving satellite links, in which signal bandwidths can be large, sources can move at orbital speeds, and there can be a fluctuating atmospheric channel. There are many considerations in a viable system synchronization design, which may, for example, require complex feedback control loops. However, a simple approach using a forwarded pump signal was recently proposed [1]. This paper describes aspects of the approach, its experimental implementation, and results.

Fig. 1 shows the experimental configuration. A source produces 1550-nm-band polarization entangled photons from 775-nm pump photons generated by doubling a strong pump beam originating in a 1-GHz mode locked laser. The source uses a Sagnac configuration similar to that described in [2], but with waveguide-based periodically poled KTiOPO4 nonlinear crystals. The pump photons are filtered and dispersion managed to yield ~1 ps duration photons. The non-degenerate signal and idler photons are separated by ~7 nm from the centrally-located pump signal. This doubled-pump architecture means that both the weak entangled photon signal and the strong pump signal can be delivered across a link and then wavelength separated at the receiver, which can reamplify the pump and use it to generate entangled photons. Because the pump and entangled photons co-propagate and are close in wavelength, residual timing differences from effects such as source jitter, channel delay, and source motion should be small and therefore do not have to be actively tracked, thereby greatly simplifying the implementation.

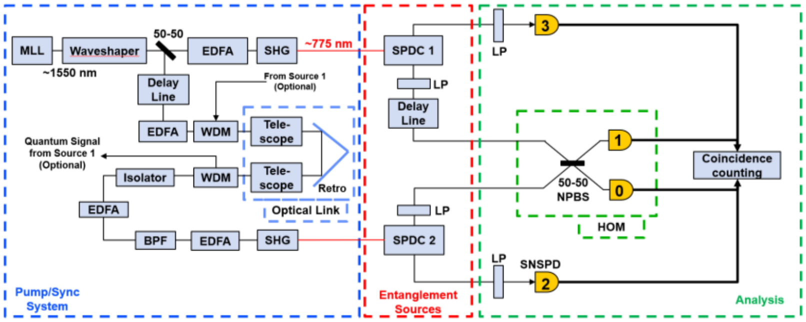

Fig. 1. Experimental configuration. 1550-nm photons from a mode locked laser (MLL) are filtered and dispersion managed (Waveshaper) before amplification with an Erbium-doped fiber amplifier (EDFA) and second harmonic generation (SHG). A spontaneous parametric downconversion source (SPDC1) produced entangled photon pairs. Pump photons also pump an identical second source (SPDC2). Pump photons can stay local to the laboratory or pass over a retro-reflected free-space optical link. Wavelength division multiplexers (WDMs) combine and separate the weak quantum signal from the pump, and an isolator protects against amplified spontaneous emission from the EDFA preamplifier, which is followed by a bandpass filter (BPF) and second EDFA. After passing through adjustable linear polarizers (LPs) and a 50/50 non-polarizing beam splitter (NPBS), photons from each source are detected with superconducting nanowire single photon detectors (SNSPD) followed by coincidence counting electronics.

The pump signal can pass directly from between sources within the laboratory, or instead be directed over a retro-reflected free-space optical link for a 3.2-km total horizontal propagation distance [3]. This enables testing over a severe fading channel with 40-50 dB total link loss. It is notable that while the large loss of such a link is routine for lasercom systems, it can severely impact the achievable quantum communication rates given the direct loss sensitivity of entangled photon states. To be able to test the pump forwarding technique, the quantum signal photons were not sent across the link, but instead separated and maintained in the laboratory. But wavelength separation optics at the transmitter and receiver were included that would allow operation on a lower loss link. The fact that the quantum signals do not travel over the link means that this is a more severe test of synchronization since what would otherwise be common-mode effects (e.g. link delay) are not removed. But practically the atmospheric effects are slowly changing and do not limit the data collection.

Fig. 2 shows the transmitted pump spectrum and the pass band of the wavelength separation optics. The result in Fig. 2b is limited by the optical spectrum analyzer, and other techniques using tunable lasers show that >90 dB isolation is achievable with a single filter, and this can be increased by cascading filters. The average optical power sent to the telescope is ~22 dBm, so for 50-dB link loss, the receiver collects about 1 µW, which is sufficient power for a well-designed preamplified receiver to reamplify with adequate signal-to-noise ratio needed for pumping the second entanglement source. Because of the potentially large pump photon peak-to-average power ratio, care must be taken to limit non-linear spectral broadening of the pump into the channel reserved for the weak quantum signal.

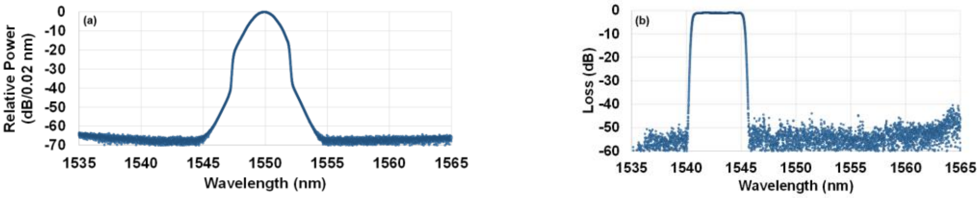

Fig. 2. (a) Optical Spectrum Analyzer (OSA) measurement of the filtered and amplified pump signal transmitted across the link. (b) Measured spectral profile of the WDM filter used to separate the weak quantum photons at ~1543 nm from the strong pump signal at 1550 nm. Background is limited by the OSA, but other measurements indicate >90 dB isolation.

Fig. 3 shows the four-fold coincidence rate between the two sources and the expected Hong-Ou-Mandel dip [4] for the in-laboratory configuration (Fig. 3a-b) and over the link (Fig. 3c-d). The width of the dip is a measure of the photon duration, and shows that the photons from the two entanglement sources are temporally aligned. In the second case, the center location of the dip moves slowly over time as the total atmospheric delay changes.

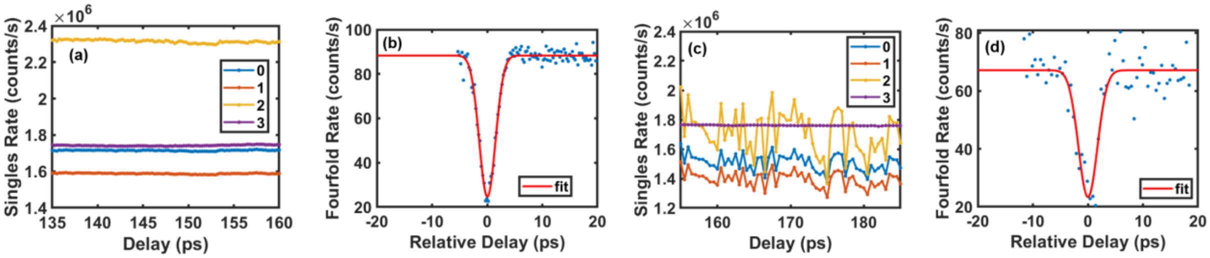

Fig. 3. (a,b) Singles and four-fold rate for in-lab signal. Channels 0-3 correspond to detector labels on Fig. 1. (c,d) Singles and four-fold rate with pump signal sent over free-space link.

This paper has outlined a method for synchronizing distant entanglement sources, and demonstrated the feasibility of the concept. The method allows synchronization without complex control loops. The impact of this approach varies from fundamental to merely practical depending on the system architecture and source technologies. These considerations include source wavelength and repetition rate tunability, source phase noise, Doppler shifts resulting from source motion, link latency, and atmospheric dynamics. A next step in the work would be to demonstrate synchronization when both pump and quantum photons co-propagate over a lower loss link.

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