An Architecture for Synchronizing Photonic Bell State Measurements Across Lossy, Time-Varying Channels

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Abstract: We propose a means for synchronizing picosecond-class photon generation at a Bell State Measurement device attempting to perform entanglement swapping with received photons that have been transmitted through the atmosphere from a moving platform.

Interconnections between quantum resources have the potential to multiply the benefits of those resources and even lead to unique capabilities. Distributed quantum computing ([1]), blind quantum computing ([2]), and enhanced sensor arrays (e.g., [3]) are a few applications that are already being pursued, and there is no doubt that further uses will be discovered or invented. Although simpler QKD-type applications are already being sold and fielded, these new, more complex applications will require the distribution of high-fidelity entanglement between users. Such a core need is the basis of teleportation of quantum information, as well as other remote quantum functions.

It is well known that photons (at a system's selected wavelength) are the prime means of transmitting quantum information. It would seem like one of an entangled pair of photons could simply be sent to a distant user; but until highly capable and efficient, photonically-addressable quantum memories are developed, channel loss and other probabilistic effects make it almost required at present to have the receiver perform a heralded, photonic entanglement swap with a local resource. Even with future memories, it is likely that such a swap will be required.

The most direct way to perform such a swap is to make a photonic Bell State Measurement (BSM) between the (possibly received) photon and a local photon. ([4]; see Figure 1.) Such a "measurement" requires that the two photons overlap in time and spectrum at a beamsplitter, in a fashion similar to that in the Hong-Ou-Mandel interferometer ([5]. See also [6] for a complete analysis.) For photon pairs created in a Spontaneous Parametric Down Conversion (SPDC) process (presently the highest rate method of pair generation, ([7])) present day pump pulse durations and nonlinear crystal lengths lead to photons with durations between hundreds of femtoseconds and perhaps a few tens of picoseconds. Thus, in order to perform a BSM with an incoming photon, a receiver needs to create photons of very similar durations and spectra that are synchronized to the incoming photons to perhaps 5-10% of the photon duration. One could envision doing this in the lab by painstakingly hand-tuning delay equalization between fixed sources. However, we are interested in very long free-space distances, where link delays can change via fast moving sources and/or receivers as well as via atmospheric variations and turbulence.

We can observe that classical digital communications systems (via wire, fiber, or free-space) either include a receiver that can synchronize itself to the incoming signal, or has an architecture where a "clock" signal is sent in parallel. Because our stream of prepared photons contains so little energy, it seems that the parallel transmitted clock approach makes more sense for quantum communications where a swap is required. Unfortunately, for photons arriving at gigahertz or even multi-gigahertz rates, a simple multi-gigahertz modulation on an optical carrier would almost certainly be inadequate as a clock for creating picosecond-class photons that exactly overlap with incoming photons. These incoming photons will have seen Doppler shifts and random timing jitter

Our proposal, then, is to transmit the very wide-bandwidth pump signal used by the transmitting user to create the stream of SPDC photon pairs. (See Figure 2 for the proposed architecture.) Thanks to the extremely wide spectral band of the free-space transmission channel (including a carefully engineered pair of transmit and receive optics) as well as its linearity and ability to transmit high peak power pulses, such a signal can be transmitted in parallel with the single photons. A typical transmitter architecture starts with a mode-locked laser (either passively or actively locked) at a short wavelength, which is then fed to a non-linear crystal or other device or subsystem that generates entangled pairs at longer wavelengths. (See Fig 2. Also, see [7].) The optical transmission system could be designed to send both these wavelengths, but our proposed design has the entangled pairs (or at least the transmitted one) fall in the fiber telecom band, which is also the workhorse optical band for free-space lasercom. By creating the pump signal in this same band, we then have the option of amplifying it (using near-standard fiber telecom components) at either the transmitter end or receiver end or both (also giving us the ability to split the pump for multiple destinations), and then frequency-doubling it to be used as the SPDC pump. A careful selection of wavelengths then allows wavelength-division multiplexing (and de-multiplexing) techniques to be used at both ends of the link. These facets are all summarized in Fig 2.

This architecture then has both the picosecond-class photons and the terahertz-class pump signal being transmitted in parallel, thus seeing the (very nearly) same channel which is varying both by motions of the terminals and micro-dynamics of the atmosphere (if, indeed, the link is atmospheric.)

Depending on the exact wavelength plan, there is the possibility that there could be a deleterious wavelength-dependent dispersion difference between the single photons and the pump signals. We have examined this possibility and deduced that any major effect, which could be dependent upon the length of the atmospheric part of the channel and thus the elevation angle between, say, a satellite and the ground, would be slowly changing. Thus, a means of continuously (but slowly) adjusting the time delay between received photons and locally-created photons could be included in the system architecture. Our analysis also shows that faster, jitter-like dispersion differences should be small (for reasonably small wavelength differences) and should thus be negligible in this system. (Slight imperfections existing throughout will likely need further purification anyway.)

Conclusion

We have presented a means of synchronizing very short photon transmissions in order to distribute entanglement between fast-moving platforms and atmospheric channels. The system emphasizes operations in the fiber- and free-space laser communications bands.

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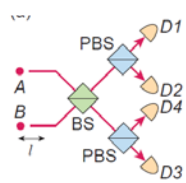

Figure 1 Photonic Bell State Measurement architecture (from [4]) Inputs A&B; BS=Beam splitter; PBS=Polarizing BS; Di=photon counters

Figure 2 Proposed architecture for high-rate entanglement distribution