# Path Entangled Quantum Networks

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We present recent results on heralded path entanglement for quantum networking using a new measurement paradigm, displacement-based detection. These include results for a multipartite entanglement witness and a detection loophole-free EPR steering experiment as well as first results on the heralded amplification of path entanglement over loss-equivalent distances of up to 50 km. The ensemble of this work represents a fascinating and flexible toolbox for testing concepts of device-independent protocols as well as for entanglement distribution in complex quantum networks and for quantum repeaters.

The distribution of entanglement is a key resource for quantum communication [1]. Path entanglement, also called single-photon entanglement, represents possibly the simplest form of entanglement to generate, and one that lies at the heart of some of the most efficient quantum repeater architectures [3]. Nonetheless, in the context of quantum communication, a means of measuring these states in distributed scenarios has proven difficult. The measurement, and subsequently the characterisation, of these states has been recently addressed by adopting the relatively old idea of what we call displacement-based detection [4]. This scheme combines aspects of discrete- (photon counting) and continuous- (local oscillator) variable detection, which our group and collaborators have recently used to demonstrate a genuine multipartite entanglement witness [5] and detection loophole-free EPR steering [6] experiments.

In this talk we will use these experiments to firstly introduce how we generate high-fidelity heralded entangled states and secondly, how the novel displacement-based measurement scheme works. In particular, the high coupling efficiencies and purity for the heralded single photon sources (HSPS) allows us to herald good quality entangled states at rates of the order of 10 kHz. In our initial work on multipartite entanglement we demonstrated the violation of a genuine entanglement witness for a 3-partite system, however, we will also discuss how this is easily extended to much larger schemes with minimal overhead in complexity. A particular advantage of this type of entanglement is that the heralding rate is independent of the number of modes involved. This also opens the way to performing entanglement swapping operations for multipartite systems as the required Bell state measurement simply involves combining two of the many modes on a beamsplitter followed by a single photon detection.

The third aspect of this talk will discuss the concept of heralded photon amplification (HPA), or noiseless linear amplification [7], which is a teleportation-based protocol that has been proposed as a means to overcome loss in the critical case of device-independent quantum key distribution (DI-QKD) [2]. More generally, it can also be seen as an entanglement distillation protocol, whereby the herald for the amplifier announces, or selects, a subset of states that have a higher degree of entanglement than before.

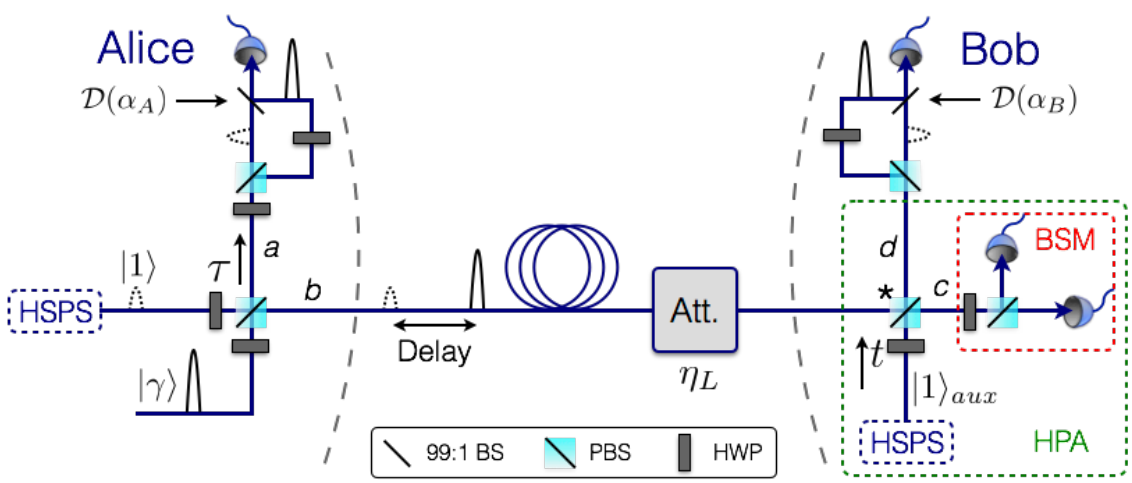


FIG. 1. Experimental schematic: Two heralded single-photon source (HSPS) are used to herald entanglement between modes $a$ and $b$, and create an auxiliary photon for the heralded photon amplifier (HPA), which are also entangled between modes $c$ and $d$. Transmission loss is simulated by attenuating (Att.) mode $b$. A detection at the Bell state measurement (BSM) heralds the final state between Alice (mode $a$) and Bob (mode $d$). A co-propagating coherent state $|\gamma\rangle$ is used to perform the weak displacement operations at the 99:1 beamsplitter (BS) before detection with single photon counters.

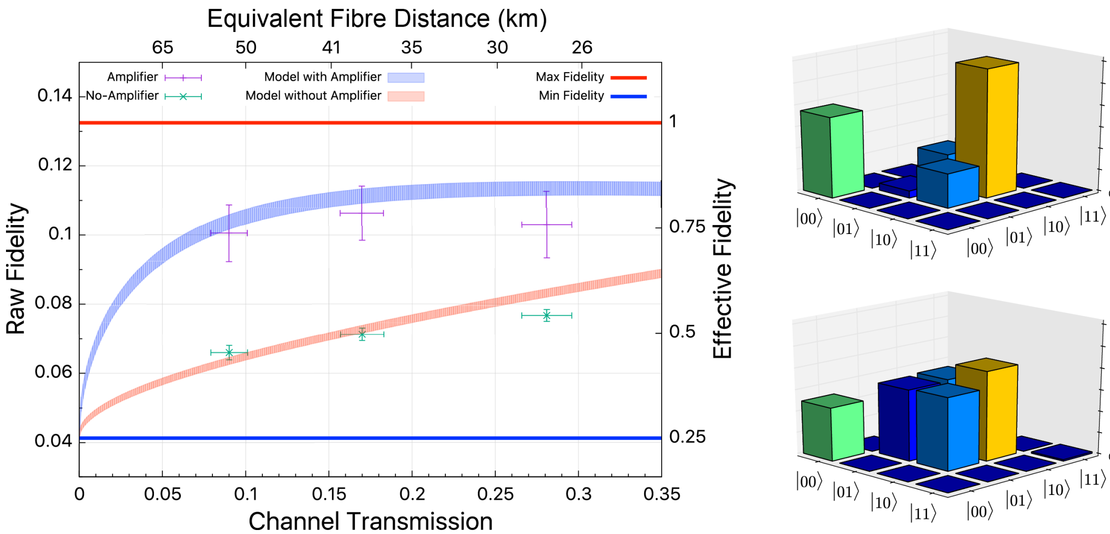


FIG. 2. Left) Measured Fidelities with and without the amplifier for different channel transmissions. The upper (blue) and lower (pink) bands are calculated values of the Fidelity, with the maximally entangled state, using the expected state before and after amplification. The top axis shows the fibre distance that has equivalent transmission of our channel. The right axis shows the expected Fidelities we would obtain in the case Alice and Bob use single photon detectors with unit efficiency. Right) Reconstructed density matrices for the states before (top) and after (bottom) the HPA for a loss-equivalent distance of 50 km.

Using the set-up shown in Fig. 1, we bring together these three concepts: heralded path entanglement generation; displacement-based detection, and heralded photon amplification, demonstrating that high Fidelity entanglement can be distributed over distances equivalent to up to 50 km. Fig. 2 shows the results for the initial and final states as measured using a displacement-based detection scheme and characterised by their Fidelity with respect to a maximally entangled state [8]. In the tomographic reconstructions on the left, we clearly see how the HPA both reduces the $|00\rangle$ component and coherently recovers the loss from the $|01\rangle$ component.

The combination of high-fidelity heralded path entanglement and displacement-based detection, along with these first results demonstrating heralded photon amplification, represent a fascinating and flexible toolbox for testing concepts of device-independent protocols, entanglement distribution in quantum networks, phase stabilisation and synchronisation in quantum repeater architectures, as well as developing certification methods for highly multipartite entangled systems.

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