HyperSpace: Hyperentangled Quantum Communication in Space

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Abstract: Photonic entanglement is a fundamental resource in quantum information processing and its distribution between distant parties is a key challenge in quantum communications. Here we provide an overview of ongoing efforts and design considerations for entanglement distribution from satellites. We discuss engineering challenges in the development of efficient, space-qualified quantum hardware and opportunities for further improvements, in particular the use of hyperentanglement, i.e., entanglement in multiple photonic degrees of freedom, for quantum communication with increased capacity.

Entanglement is the fundamental resource of the information age. With the distribution of quantum entanglement in networks, we enable a host of potential applications, such as sensors with enhanced performance, blind computing, and information-theoretically secure key distribution. The main challenge in realizing such quantum improvements on a global scale is the reliable distribution of quantum information over long distances. Currently, detector noise and unavoidable losses in fibre transmission limit the range of terrestrial quantum networks to a few hundred kilometers. To overcome this limitation, two approaches are currently being pursued in parallel: Quantum repeaters and satellite optical links. Despite remarkable progress, significant technological and scientific challenges remain on the road to a working quantum repeater architecture. In all likelihood, the future will see large hybrid network architectures consisting of space-to-ground and inter-satellite links, as well as quantum repeater nodes on ground and in space - a hybrid global quantum network that will enable global Quantum Key Distribution (QKD) as well as entirely new applications at the intersection between information processing and distributed sensing. In this vision, the local and mid-range quantum state transmission could be based on optical fibre transmission, whereas quantum communication at the international and global level would employ satellite links. This prospect has inspired a *quantum space race*, which resulted in a level of technological maturity that is now markedly reflected in the success of several experiments [1]. However, these experiments are difficult to scale up due to high hardware and operational costs. Thus, moving from proof-of-concept demonstrations to commercial applications will require scientific advances and technological innovation.

This presentation will review the progress of an ongoing polarization entanglement-based mission with small satellites, including related photonic technology developments of highly efficient space-qualified entangled photons sources [2], adaptive optics for ground stations, and engineering challenges towards integration of space-ready quantum optical hardware [3]. We discuss the prospect of future improvement, such as transferring classical wavelength multiplexing techniques to the quantum domain. In this context, a particularly promising approach could be to encode high-dimensional states (so-called d-dimensional qudits) in the time and frequency domain. This allows to process more information than with commonly used polarization qubits and has been shown to be more resistant to noise and eavesdropping [4]. Moreover, photons can exhibit entanglement in multiple photonic degrees of freedom simultaneously – so-called hyperentanglement – that can be used as a basis for faster and more resource-efficient quantum communication. Within the EU-Canadian project HyperSpace, a strategic collaboration is built towards harnessing the benefits of hyperentangled states for satellite links in a transatlantic quantum network [5].

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