Towards high-dimensional entanglement-based quantum communication in free space

Sebastian Ecker *[1], Fabian Steinlechner*[1], Matthias Fink[1], Bo Liu[1,2], Jessica Bavaresco[1], Marcus Huber[1], Thomas Scheidl[1], and Rupert Ursin[1,3]

[1]Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences
[2]School of Computer, NUDT, 410073 Changsha, China
[3]Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics

Abstract

Quantum entanglement is a fundamental resource in quantum information processing and its generation, manipulation and distribution between distant parties are all key challenges in the pursuit of global quantum communications. In this context, high-dimensional encoding has been shown to improve robustness and channel capacities in secure quantum communications. The transmission of genuine high-dimensional entanglement under real-world atmospheric link conditions, however, is an ongoing experimental challenge.

Here, we give an overview of our efforts towards implementing high-dimensional quantum communication protocols in long-distance free-space links. We report on a proof-of-concept experiment in which we, for the first time, use energy-time and polarization hyperentanglement to transmit 4-dimensional entanglement via a 1.2-km-long intra-city free-space link. We discuss how this approach can be adapted for high-dimensional free-space QKD and report on the progress of ongoing experiments.

Distributing quantum entanglement between distant parties is a key challenge in the pursuit of a worldwide quantum network. Quantum repeaters and optical satellite links have both been proposed to overcome the distance limitations of fiber-based quantum networks. In order to test the viability of a world spanning quantum satellite network, several proof-of-concept studies have already demonstrated high-fidelity transmission of photonic entanglement via terrestrial long-distance free-space links [1, 2]. However, until recently entanglement was encoded in the polarization degree of freedom (DOF), thus limiting the accessible state space to two dimensions.

High-dimensional entanglement can yield significant benefits in the implementation of advanced quantum information processing protocols, such as resilient encoding schemes for quantum communications with increased channel capacity. Energy-time entanglement, which naturally arises in the process of spontaneous parametric down-conversion, is an established photonic DOF; it is routinely used for the distribution of entanglement in fiber-based quantum cryptography networks but has only recently been considered as a viable option for atmospheric free-space quantum communications [3, 4]. The dimensionality can be further increased by exploiting simultaneous entanglement in several DOF [5]. This so-called hyperentanglement has previously been used in various quantum protocols, for example, in efficient purification schemes or hyper-entanglement-assisted Bell-state measurements in a laboratory setting, but not yet been demonstrated outside a protected laboratory environment.

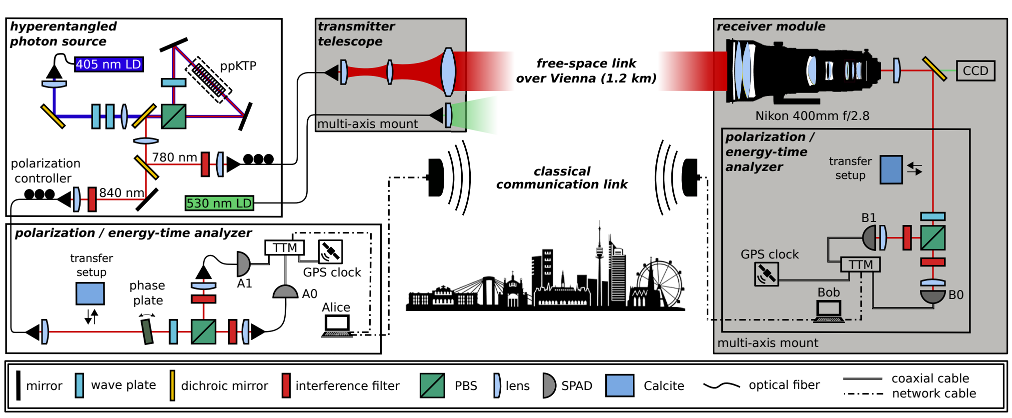

Figure 1: Sketch of the experimental setup. Energy-time/polarization hyperentangled photons were produced in a laboratory at IQOQI. The photons were distributed to Alice and Bob via a free-space link and and optical single-mode fiber, respectively. Bob's photons were collected using a telephoto objective and guided to an energy-time or polarization analyzer. Alice's and Bob's measurement modules featured an additional transfer setup that could be inserted for measurements in the energy-time DOF.

*These authors contributed equally.

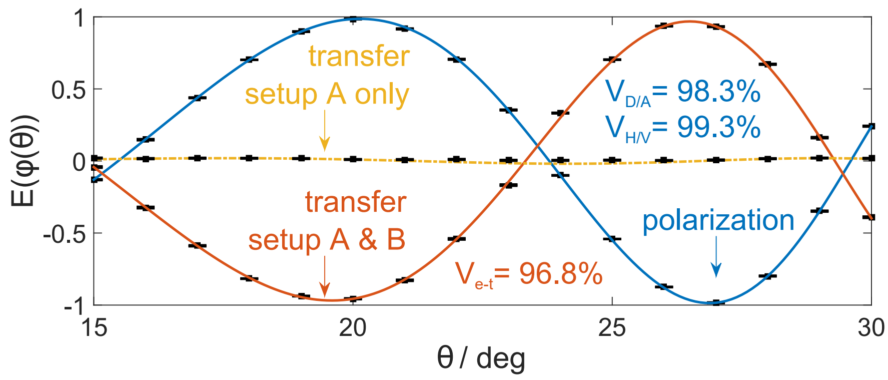

Figure 2: Experimental results. Two-photon correlation functions $E(\phi(\Theta))$ in the polarization (blue) and energy-time (red) DOF as a function of the variable phase shift $\phi(\Theta)$ introduced in Alice's measurement module. Almost no interference was observed when the energy-time to polarization transfer setup was introduced in Alice's detection module only, thus excluding single-photon energy-time coherence.

The experimental setup for our proof-of-concept field trial [6] is depicted in Fig. 1. A source of hyperentangled photons and a detection module (Alice) were located at the Institute for Quantum Optics and Quantum Information (IQOQI) and a receiver station (Bob) was located at the University of Natural Resources and Life Sciences (BOKU) in Vienna. The source produced polarization entangled signal and idler photons via type-0 down-conversion in a Sagnac loop configuration. The emission time of a photon pair is uncertain within the significantly longer coherence time of the pump laser [7], thus resulting in an energy-time and polarization hyperentangled state:

$$|\Psi\rangle_{\text{total}} = |\Phi\rangle_{\text{pol}} \otimes |\Phi\rangle_{\text{e-t}} \propto (|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B) \otimes \int \mathrm{d}t\, |t\rangle_A |t\rangle_B \,,$$

where H and V denote horizontal and vertical polarization states and t denotes photon emission time. The subscripts A and B label the respective spatial mode for Alice and Bob. Note that our proof of concept demonstration focused on a two-dimensional subspace of the high-dimensional energy-time space.

Photon A was guided to a local measurement module and photon B was guided to a transmitter telescope on the roof of the institute. After transmission over the 1.2-km-long free-space link, the photons were received by a telescope and detected in Bob's measurement module. The measurement modules for Alice and Bob each featured a polarization analyzer and an optional transfer setup that coupled the energy-time DOF to the polarization DOF for the analysis of energy-time entanglement [8].

We observe high-visibility two-photon interference in both polarization and energy-time subspaces (see Fig. 2). The measured visibilities certify entanglement in both subspaces individually. Additionally, they establish a lower bound on the Bell-state fidelity of the hyperentangled state of 0.9419, thus certifying genuine 4-dimensional entanglement [9] and 1.4671 ebits of entanglement of formation.

We have thus successfully distributed hyperentangled photon pairs via an intra-city free-space link under conditions of strong atmospheric turbulence. We experimentally certify entanglement in both polarization and energy-time subspaces individually, and, for the first time, high-dimensional quantum entanglement that has been transmitted via a real-world free-space link. While polarization-entangled photons have been studied in numerous field trials with strong atmospheric turbulence, our results clearly demonstrate the feasibility of also exploiting energy-time/polarization hyperentanglement under similar conditions.

The transmission of quantum information embedded in a genuine high-dimensional state space under real-world link conditions is a first important step towards real-world implementations of advanced quantum information processing protocols in the future. In particular, it enables the implementation of high-dimensional QKD protocols over long-distance free-space links, and, ultimately, over satellite links with only minor changes to existing mission proposals. Note, that the potential dimensionality of energy-time entanglement is orders of magnitudes larger than certified in this first proof-of-concept experiment. We hope that our results will motivate both further theoretical research into energy-time entanglement experiments conceivable at relativistic scenarios with satellite links, as well as experimental research into the exploitation of hyperentanglement in long-distance free-space quantum communications.

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