

Quantum teleportation across the Danube

A real-world experiment marks a step towards worldwide quantum communication.

Efficient long-distance quantum teleportation¹ is crucial for quantum communication and quantum networking schemes². Here we describe the high-fidelity teleportation of photons over a distance of 600 metres across the River Danube in Vienna, with the optimal efficiency that can be achieved using linear optics. Our result is a step towards the implementation of a quantum repeater³, which will enable pure entanglement to be shared between distant parties in a public environment and eventually on a worldwide scale.

Quantum teleportation is based on a quantum channel, here established through a pair of polarization-entangled photons shared between Alice and Bob (Fig. 1). We have implemented this by using an 800-metre-long optical fibre installed in a public sewer system located in a tunnel underneath the River Danube, where it is exposed to temperature fluctuations and other environmental factors.

For Alice to be able to transfer the unknown polarization state of an input photon $|\chi\rangle_b$, she has to perform a joint Bell-state measurement on the input photon b and her member, c , of the shared entangled photon pair (c and d). Our scheme allows her to identify two of the four Bell states, the optimum achievable with only linear optics^{4,5}.

As a result of this Bell-state measurement, Bob's 'receiver' photon d will be projected into a well defined state that already contains full information on the original input photon b , except for a rotation that depends on the specific Bell state that Alice observed. Our teleportation scheme therefore also includes active feed-forward of Alice's measurement results, which is achieved by means of a classical microwave channel together with a fast electro-optical modulator (EOM). It enables Bob to perform the unitary transformation on photon d to obtain an exact replica of Alice's input photon b .

Specifically, if Alice observes the $|\psi^-\rangle_{bc}$ Bell state, which is the same as the initial entangled state of photons c and d , then Bob already possesses the original input state. But if Alice observes the $|\psi^+\rangle_{bc}$ state, he introduces a π -phase shift between the horizontal and vertical polarization components of photon d by applying a voltage pulse of 3.7 kV on the EOM. For successful operation, Bob has to set the EOM correctly before photon d arrives. Because of the reduced velocity of light within the fibre-based quantum channel (two-thirds of that *in vacuo*), the classical signal arrives

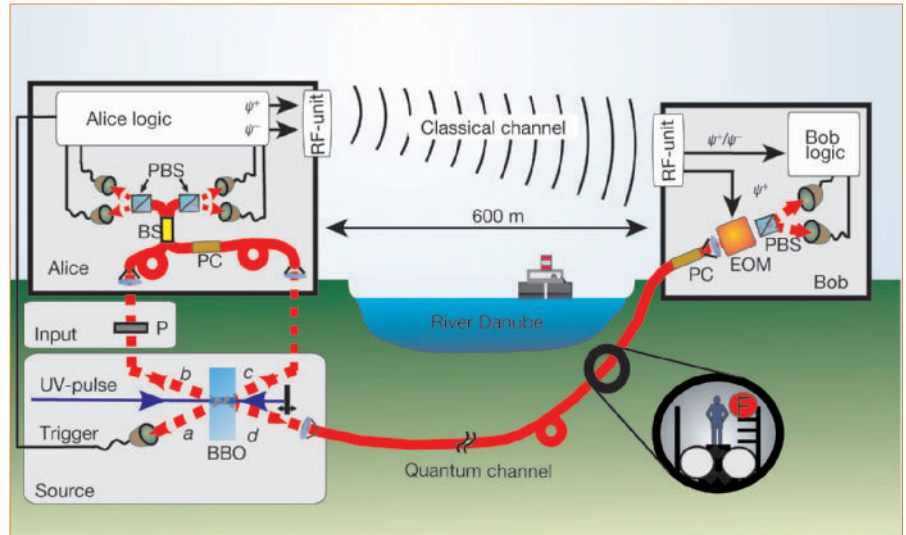


Figure 1 Long-distance quantum teleportation across the River Danube. The quantum channel (fibre F) rests in a sewage-pipe tunnel below the river in Vienna, while the classical microwave channel passes above it. A pulsed laser (wavelength, 394 nm; rate, 76 MHz) is used to pump a β -barium borate (BBO) crystal that generates the entangled photon pair c and d and photons a and b (wavelength, 788 nm) by spontaneous parametric down-conversion. The state of photon b after passage through polarizer P is the teleportation input; a serves as the trigger. Photons b and c are guided into a single-mode optical-fibre beam splitter (BS) connected to polarizing beam splitters (PBS) for Bell-state measurement. Polarization rotation in the fibres is corrected by polarization controllers (PC) before each run of measurements. The logic electronics identify the Bell state as either $|\psi^-\rangle_{bc}$ or $|\psi^+\rangle_{bc}$ and convey the result through the microwave channel (RF unit) to Bob's electro-optical modulator (EOM) to transform photon d into the input state of photon b .

about 1.5 microseconds before the photon.

We demonstrated the teleportation of three distinct polarization states: linear at 45°, left-handed circular or horizontal. The teleportation fidelity achieved was 0.84, 0.86 or 0.90 for the 45°, for each of these input states, respectively. These fidelities comfortably surpass the classical limit of 0.66 (ref. 6) and prove that our teleportation system is operating correctly. Without operation of the EOM, however, Bob observes a completely mixed polarization for the 45° and circular polarization input states, causing the observed fidelity for these states to drop to 0.54 and 0.59, respectively, in the absence of active unitary transformation. The deviation from the random fidelity of 0.5 is due to statistical fluctuations in the observed counts.

Each measurement run lasted for 28 h and the rate of successful teleportation events was 0.04 per second. Polarization stability proved to be better than 10° on the fibre between Alice's and Bob's labs, corresponding to an ideal teleportation fidelity of 0.97 over a full measurement run. Hence, despite the exposure of our system to the environment, high-fidelity teleportation was still achievable without permanent readjustments.

We have demonstrated quantum teleportation over a long distance and with high fidelity under real-world conditions

outside a laboratory. Our system combines for the first time, to our knowledge, an improved Bell-state analyser with active unitary transformation, enabling a doubling of the efficiency of teleportation compared with earlier experiments based on independent photons^{7,8}. Our experiment demonstrates feed-forward of measurement results, which will be essential for linear-optics quantum computing^{9–11}, and constitutes a step towards the full-scale implementation of a quantum repeater.

Rupert Ursin*, **Thomas Jennewein*†**, **Markus Aspelmeyer***, **Rainer Kaltenbaek***, **Michael Lindenthal***, **Philip Walther***, **Anton Zeilinger*†**

*Institute for Experimental Physics, University of Vienna, 1090 Vienna, Austria
e-mail: rupert.ursin@univie.ac.at

†Austrian Academy of Science, 1090 Vienna, Austria

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