# Quantum teleportation over deployed fibres and applications to quantum networks


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**If a photon interacts with a member of an entangled photon pair via a so-called Bell-state measurement (BSM), its state is teleported over arbitrary distances (in principle) onto the second member of the pair [1]. Starting in 1997 [2–4], this puzzling prediction of quantum mechanics has been demonstrated many times [5]; however, with one very recent exception [6], only the photon that received the teleported state, if any, travelled far, while the photons partaking in the BSM were always measured close to where they were created. Here, using the Calgary fibre network, we report quantum teleportation from a telecommunication-wavelength photon, interacting with another telecommunication photon after both have travelled over several kilometres in bee-line, onto a photon at 795 nm wavelength. This improves the distance over which teleportation takes place from 818 m to 6.2 km. Our demonstration establishes an important requirement for quantum repeater-based communications [7] and constitutes a milestone on the path to a global quantum Internet [8].**


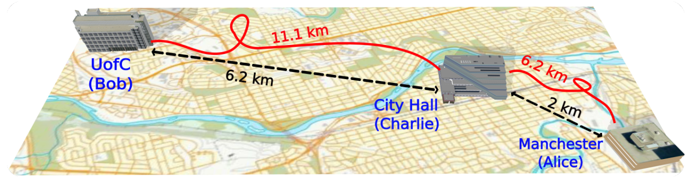


FIG. 1: **Aerial view of Calgary.** Alice is located in Manchester, Bob at the University of Calgary (UofC), and Charlie in a building next to City Hall in Calgary downtown. The teleportation distance — in our case the distance between Charlie and Bob — is 6.2 km. All fibres belong to the Calgary telecommunication network but, during the experiment, they only carry signals created by Alice, Bob or Charlie and were otherwise "dark".

While the possibility to teleport quantum states, including the teleportation of entangled states, has been verified many times using different physical systems, the maximum distance over which teleportation is possible — which we define to be the spatial separation between the BSM and the photon, at the time of this measurement, that receives the teleported state — has so far received virtually no experimental attention. To date, only two experiments have been conducted in a setting that resulted in a teleportation distance that exceeds the laboratory scale [6, 9], even if in a few demonstrations the bee-line distance travelled by the photon that receives the teleported state has been much longer [10, 11].

The reason to stress the importance of distances is linked to the ability of exploiting teleportation in various quantum information applications. One important example is the task of extending quantum communication distances using quantum repeaters [7], most of which rely on the creation of light-matter entanglement, e.g. by creating an entangled two-photon state out of which one photon is absorbed by a quantum memory for light [12], and entanglement swapping [13]. The latter shares the Bell state measurement (BSM) with standard teleportation; however, the photon carrying the state to be teleported is itself a member of an entangled pair. Entanglement swapping is therefore sometimes referred-to as teleportation of entanglement. To be useful in such a repeater, two entangled photon pairs must be created far apart, and the BSM, which heralds the existence of the two partaking photons and hence of the remaining members of the two pairs, should, for optimal performance, take place approximately halfway in-between these two locations.

Yet, due to the difficulty to guarantee indistinguishability of the two interacting photons after their transmission through long and noisy quantum channels [14], entanglement swapping or standard teleportation in the important midpoint configuration has only been reported very recently outside the laboratory [6]. This work exploited the heralding nature of the BSM for the first loophole-free violation of a Bell inequality — a landmark result that exemplifies the importance of this configuration. However, the two photons featured a wavelength of about 637 nm, which, due to high loss during transmission through optical fibre, makes it impossible to extend the transmission distance to tens, let alone hundreds, of kilometers. In all other demonstrations, either the travel distances of the two photons were small, or they were artificially increased using fibre on spool [9, 15, 16], effectively increasing travel time and transmission loss — and hence decreasing communication rates — rather than real separation. Here we report the first demonstration of quantum teleportation over several kilometers in the mid-point configuration and with photons at telecommunication wavelength.

An aerial map of Calgary, identifying the locations of Alice, Bob and Charlie, is shown in Fig. 1. Alice, located in Manchester (a Calgary neighbourhood), prepares phase-randomized attenuated laser pulses at 1532 nm wavelength with different mean photon numbers $\mu_{\rm A} \ll 1$ in various time-bin qubit states $|\psi\rangle_A = \alpha|e\rangle + \beta e^{i\phi}|\ell\rangle$, where $|e\rangle$ and $|\ell\rangle$ denote early and late temporal modes, respectively, $\phi$ is a phase-factor, and $\alpha$ and $\beta$ are real numbers that satisfy $\alpha^2 + \beta^2 = 1$. Using 6.2 km of deployed fibre, she sends her qubits to Charlie, who is located 2.0 km away in a building next to Calgary City Hall. Bob, located at the University of Calgary (UofC) 6.2 km from Charlie, creates pairs of photons — one at 1532 nm and one at 795 nm wavelength — in the maximally time-bin entangled state $|\phi^+\rangle = 2^{-1/2}(|e,e\rangle + |\ell,\ell\rangle)$. He sends the telecommunication-wavelength photons through 11.1 km of deployed fibre to Charlie, where they are projected jointly with the photons from Alice onto the maximally entangled state $|\psi^-\rangle = 2^{-1/2}(|e,\ell\rangle - |\ell,e\rangle)$. This leads to the 795 nm wavelength photon at Bob's acquiring the state $|\psi\rangle_B = \sigma_y|\psi\rangle_A$, where $\sigma_y$ is the Pauli operator describing a bit-flip combined with a phase-flip. In other words, Charlie's measurement results in the teleportation of Alice's photon's state, modulo a unitary transformation, over 6.2 km distance onto Bob's 795 nm wavelength photon.

The main difficulty in long-distance quantum teleportation is to ensure the required indistinguishability between the two photons subjected to the BSM at Charlie's despite them being created by independent sources and having travelled over several kilometres of deployed fibre. Varying environmental conditions during the measurements significantly impact the polarization and arrival times of the photons — of particular concern being variations of path-lengths differences. Without the active feedback that our setup performs in an automized way, quantum teleportation would be impossible.

To confirm successful quantum teleportation, Bob then performs a variety of projective measurements on this photon, whose outcomes, conditioned on a successful BSM at Charlie's, are analyzed using different approaches. More precisely first, Alice creates photons in an equal superposition of $|e\rangle$ and $|\ell\rangle$ with a fixed phase, and Bob makes projection measurements onto states described by such superpositions with various phases. Conditioned on a successful BSM at Charlie's, we find sinusoidally varying triple-coincidence count rates with a visibility of $(38 \pm 4)\%$ and an average of 17.0 counts per minute. This result alone already represents a strong indication of quantum teleportation: assuming that the teleported state is a statistical mixture of a pure state and white noise, the visibility consistent with the best classical strategy and assuming Alice creates single photons is 33% [19].

We now create photons in, and project them onto, well defined states, e.g. $|e\rangle$, $|\ell\rangle$, $|\pm\rangle \equiv 2^{-1/2}(|e\rangle \pm |\ell\rangle)$, and $|\pm i\rangle \equiv 2^{-1/2}(|e\rangle \pm i\,|\ell\rangle)$. This allows us to reconstruct the density matrices $\rho_{\rm out}$ of various quantum states after teleportation, and, in turn, calculate the fidelities

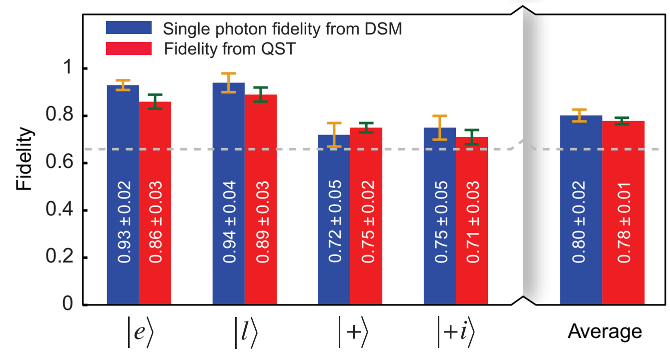


FIG. 2: Individual and average fidelities of four teleported states with expected (ideal) states, measured using quantum state tomography (QST) and the decoy-state method (DSM). For the DSM we set $\mu_{\rm SPDC} = 0.06$. Error bars (one standard deviation) are calculated assuming Poissonian detection statistics and using Monte-Carlo simulation.

$F = {}_{\rm B}\langle\psi|\,\rho_{\rm out}\,|\psi\rangle_{\rm B}$ with the expected states $|\psi\rangle_{\rm B}$. The results, depicted in Fig. 2, show that the fidelity for all four prepared states exceeds the maximum classical value of 67% [19]. In particular, the average fidelity $\langle F\rangle = [F_e + F_l + 2(F_+ + F_{+i})]/6 = (78{\pm}1)\%$ violates this threshold by 12 standard deviations.

One may conclude that this result shows the quantum nature of the disembodied state transfer between Charlie and Bob. However, strictly speaking, the 66% bound only applies to Alice's state being encoded into a single photon, while our demonstration, as others before, relied on attenuated laser pulses. To extract the appropriate experimental value, we therefore take advantage of the so-called decoy-state method, which was developed for quantum key distribution (QKD) to assess an upper bound on the error rate introduced by an eavesdropper on single photons emitted by Alice [20, 21]. Here, we rather use it to characterize how a quantum channel — in our case the concatenation of the direct transmission from Alice to Charlie and the teleportation from Charlie to Bob — impacts on the fidelity of quantum states encoded into individual photons [24]. Towards this end, we vary the mean number of photons per qubit emitted at Alice's between three optimized values, $\mu_{\rm A} \in \{0, 0.014, 0.028\}$, and calculate error rates and transmission probabilities for each value independently. The results, also depicted in Fig. 2, show again that the fidelities for all tested states exceed the maximum value of 2/3 achievable in classical teleportation. Finally, by averaging the single-photon fidelities over all input states, weighted as above, we find $\langle F^{(1)}\rangle \geq (80{\pm}2)\%$ — as before significantly violating the threshold between classical and quantum teleportation.

Our measurements establish the possibility for quantum teleportation over many kilometres in the important mid-point configuration — as is required for extending the distance of quantum communications using quantum repeaters. We emphasize that both photons travelling to

Charlie are at telecommunication wavelength, making it possible to extend the Alice-Bob distance from its current value of 8 kilometres by at least one order of magnitude. This corresponds to the distance of an elementary quantum repeater link, which involves teleportation of entanglement, at which communication links based on spectrally multiplexed quantum repeaters start to outperform direct qubit transmission [24, 26]. We also note that the 795 nm photon, both in terms of central wavelength as well as spectral width, is compatible with quantum memory for light — a key element of a quantum repeater — in cryogenically-cooled thulium-doped crystals. In particular Tm:YGG features a spectral acceptance that exceeds the bandwidth needed for most practical applications [27]. By implementing a photon-echo type protocol in this crystal, we have recently demonstrated storage times of up to 100 $\mu$sec [28]. Finally, we note that quantum teleportation involves the interesting aspect of Alice transferring her quantum state in a disembodied fashion to Bob without him ever receiving any physical particle. In other words, Bob is only sending photons (all of them members of an entangled pair) and thus better able to protect his system from any outside interference, e.g. from an adversary. This points to similar considerations of security as measurement-device-independent QKD [29], albeit in a more flexible quantum network setting that could allow, e.g., distributed quantum computing [8]. These key features make our demonstration an important step towards long-distance quantum communication, and ultimately a global quantum Internet.


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