Deterministic quantum teleportation of photonic quantum bits by a hybrid technique

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Quantum teleportation allows for the transfer of arbitrary unknown quantum states from a sender to a spatially distant receiver, provided that the two parties share an entangled state and can communicate classically. It is the essence of many sophisticated protocols for quantum communication and computation. Photons are an optimal choice for carrying information in the form of ‘flying qubits’, but the teleportation of photonic quantum bits (qubits) has been limited by experimental inefficiencies and restrictions. Main disadvantages include the fundamentally probabilistic nature of linear-optics Bell measurements, as well as the need either to destroy the teleported qubit or attenuate the input qubit when the detectors do not resolve photon numbers. Here we experimentally realize fully deterministic quantum teleportation of photonic qubits without post-selection. The key step is to make use of a hybrid technique involving continuous-variable teleportation of a discrete-variable, photonic qubit. When the receiver’s feedforward gain is optimally tuned, the continuous-variable teleporter acts as a pure loss channel and the input dual-rail-encoded qubit, based on a single photon, represents a quantum error detection code against photon loss and hence remains completely intact for most teleportation events. This allows for a faithful qubit transfer even with imperfect continuous-variable entangled states: for four qubits the overall transfer fidelities range from 0.79 to 0.82 and all of them exceed the classical limit of teleportation. Furthermore, even for a relatively low level of the entanglement, qubits are teleported much more efficiently than in previous experiments, albeit post-selectively (taking into account only the reported values).

Since originally being proposed, the concept of quantum teleportation has attracted a lot of attention and has become one of the central elements of advanced and practical realizations of quantum information protocols. It is essential for long-distance quantum communication by means of quantum repeaters, and it has been shown to be a useful tool for realizing universal quantum logic gates in a measurement-based fashion. Many proposals and models for quantum computation rely on quantum teleportation, such as the efficient linear-optics quantum computing scheme of ref. 4 and the ‘one-way’ quantum computer using cluster states.

Although much progress has been made in demonstrating quantum teleportation of photonic qubits, most of these schemes share one fundamental restriction: an unambiguous two-qubit Bell-state measurement (BSM), as is needed to teleport a qubit using two-qubit entanglement, is always probabilistic when linear optics is used, even if photon-number-resolving detectors are available. There are two experiments avoiding this constraint, but in these either a qubit can no longer be teleported when it is delivered independently from an external resource or an extra nonlinear element leads to extremely low measurement efficiencies, of the order of $10^{-10}$ (ref. 8). A further experimental limitation, rendering these schemes fairly inefficient, is the probabilistic nature of the entangled resource states. Efficient, near-deterministic quantum teleportation, however, is of great benefit in quantum communication, where it can be used to reduce the storage times of quantum memories in a quantum repeater, and it is a necessity in teleportation-based quantum computation. An additional drawback of the previous experiments, owing to the lack of photon-number-resolving detectors, was the need either to destroy the teleported qubit or to attenuate the input qubit, thus further decreasing the success rate of teleportation.

We overcome all the above limitations by taking a different approach: continuous-variable quantum teleportation of a photonic qubit. The strength of continuous-variable teleportation lies in the on-demand availability of the quadrature-entangled states and the completeness of a Bell measurement in the quadrature bases using linear optics and homodyne detections.

So far, these tools have been used to unconditionally teleport continuous-variable quantum states such as coherent states, which works only on narrow sidebands. We overcome this incompatibility by using very recent, advanced technology: a broadband continuous-variable teleporter and a narrowband time-bin qubit compatible with that teleporter. Importantly, this qubit uses two temporal modes to represent a dual-rail-encoded qubit

$$|\psi\rangle = \alpha|0, 1\rangle + \beta|1, 0\rangle$$

where $|0, 1\rangle$ and $|1, 0\rangle$ refer to the temporal modes of the photon (expressed in the two-mode photon-number basis, with $|\alpha|^2 + |\beta|^2 = 1$). Therefore, teleportation of both modes of the qubit is accomplished by means of a single continuous-variable teleporter acting subsequently on the temporal modes of the time-bin qubits.

Remarkably, the main weak point of continuous-variable teleportation, namely the intrinsic imperfection of the finitely squeezed, entangled states, can be circumvented to a great extent in the present ‘hybrid’ setting when the input to the continuous-variable teleporter is a dual-rail qubit. The entangled state of the teleporter is a two-mode squeezed, quadrature-entangled state, $\sqrt{1-g_{\text{opt}}^2} \sum_{n=0}^{\infty} g_{\text{opt}}^n |n, n\rangle$, here written in the number basis with $g_{\text{opt}} = \tanh(r)$, where $r$ is the squeezing parameter. Because infinite squeezing ($r \to \infty$) requires infinite energy, maximally entangled states are physically unattainable; thus, the teleportation fidelity is generally limited by $r$. Following the standard continuous-variable quantum teleportation protocol with unit gain for the receiver’s feedforward displacement yields a largely distorted output qubit with additional thermal photons.

In contrast, non-unit gain conditions are useful in some cases. In particular, a single-mode continuous-variable teleporter with gain $g_{\text{opt}}$ creates no additional photons, because it is equivalent to a pure attenuation channel from which an intensity fraction of $1 - g_{\text{opt}}^2$ is lost to the environment. Moreover, the dual-rail-encoded qubit represents a quantum error detection code against such amplitude damping, where either a photon-loss error occurs, erasing the qubit, or a symmetric damping leaves the input qubit state completely intact. These two facts together mean that the dual-rail continuous-variable teleporter at...
elements, however, decay a little more rapidly than do the diagonal qubits is preserved during the teleportation process. These off-diagonal components are teleported and constitute the final, mixed output state. We teleport transfers input states of arbitrary dimension, all of these components act on any qubit state in the same way (Supplementary Discussion).

A time-bin qubit is heralded by detecting one half of an entangled photon pair produced by an optical parametric oscillator (OPO). The continuous-variable teleporter (g, feedforward gain) always transfers this qubit, albeit with non-unit fidelity. The teleported qubit is finally characterized by single or dual homodyne measurement to verify the success of teleportation. See Methods Summary for details. APD, avalanche photodiode; EOM, electro-optic modulator; HD, homodyne detector; LO-x and LO-p, local oscillators to measure x and p quadratures, respectively.

\[
|\psi\rangle \langle \psi| \rightarrow g_{\text{opt}}^2 |\psi\rangle \langle \psi| + \left(1 - g_{\text{opt}}^2\right) |0, 0\rangle \langle 0, 0| \tag{1}
\]

Most importantly, no additional photons are created and the quantum information encoded in \(|\psi\rangle\) remains undisturbed regardless of the squeezing level. The only effect of the teleporter is the two extra-mode vacuum term, whose fraction becomes arbitrarily small for sufficiently large squeezing, \(g_{\text{opt}} \rightarrow 1\). This technique allows us to teleport arbitrary qubit states more faithfully by suppressing additional photons, thereby realizing unconditional teleportation with a moderate level of squeezing. Equation (1) also shows that a fidelity of unity is obtainable for any non-zero squeezing level, \(g_{\text{opt}} > 0\), that the non-occurrence of a photon-loss error is detected with a probability approaching zero for \(g_{\text{opt}} \rightarrow 0\). We note that the remaining vacuum contribution could be made arbitrarily small without post-selection of the final states, by instead immediately discarding all quadrature results of the Fock-space that are too far from the phase-space origin22,27.

To demonstrate successful qubit quantum teleportation, we prepare four distinct qubit states: \(|0, 1\rangle, |1, 0\rangle, \langle 0, 1| \rightarrow i |1, 0\rangle / \sqrt{2} \) and \(|\psi_2\rangle \equiv (2|0, 1\rangle - |1, 0\rangle) / \sqrt{5}\). This set, including even and uneven superpositions of \(|0, 1\rangle\) and \(|1, 0\rangle\) with both real and imaginary phases, represents a fair sample of qubit states on the Bloch sphere. In theory, our teleporter acts on any qubit state in the same way (Supplementary Discussion).

The experimental density matrix of the input state, \(|\psi_1\rangle\), is shown in Fig. 2a. This input state is not a pure qubit state, but rather a mixed state with a 25 ± 1% vacuum contribution, a 69 ± 1% qubit contribution and a 6 ± 1% multiphoton contribution. Because the continuous-variable teleporter transfers input states of arbitrary dimension, all of these components are teleported and constitute the final, mixed output state. We note that in our first analysis we do not discard any of these contributions from the input or the output states, thus ensuring that none of the quantum states that enter or leave our teleporter is pre-selected or post-selected, respectively.

First we present the output state of unit-gain teleportation with \(g = 1.01 ± 0.03\) (Fig. 2b). All the matrix elements obtained are in good agreement with theory; the qubit contribution decreases, whereas the contribution of the multiphoton terms grows owing to the finite squeezing. The off-diagonal elements of the qubit \((0, 1), (1, 0), (1, 0)|0, 1\rangle\) retain the original phase information of the input superposition between \(|0, 1\rangle\) and \(|1, 0\rangle\), demonstrating that the non-classical feature of the qubits is preserved during the teleportation process. These off-diagonal elements, however, decay a little more rapidly than do the diagonal elements \((0, 1)|0, 1\rangle, (1, 0)|1, 0\rangle\), illustrating that the quantum superposition of the qubit is the feature most susceptible to error in an experimental situation.

Next we turned down the gain, \(g\), and observed the new output state. Figure 2c shows the output state at \(g = 0.79\) (close to \(g_{\text{opt}} = 0.77\)). Compared with Fig. 2b, from Fig. 2c it can be seen that the qubit components are almost undisturbed, but that the vacuum grows and the occurrence of extra multiphoton components is suppressed. Thus, here the input–output relation is similar to the pure-attenuation model with a loss fraction of \(1 - g_{\text{opt}} = 0.41\). The bar graph in Fig. 3 shows the \(g\) dependence of the qubit and multiphoton components in the output state, clearly demonstrating that gain tuning reduces the creation of additional photons in continuous-variable teleportation.

The performance of the teleporter can be assessed by means of the fidelity. In our deterministic scheme, we must take into account the vacuum and multiphoton contributions, which was not the case in previous non-deterministic teleportation experiments using post-selection. The overall fidelity between the input state, \(\hat{\rho}_{\text{in}}\), and the output state, \(\rho_{\text{out}}\), is:

\[
F_{\text{state}} = \left[ \text{Tr} \left( \sqrt{\sqrt{\hat{\rho}_{\text{in}}} \rho_{\text{out}} \sqrt{\hat{\rho}_{\text{in}}}} \right) \right]^2
\]

When \(g = 0\) has a qubit fraction of \(\eta\), the classical bound on \(F_{\text{state}}\) is \(F_{\text{thr}} = 1 - \eta/3\), which is the best fidelity achievable without entanglement (Supplementary Discussion). Therefore, \(F_{\text{state}} > F_{\text{thr}}\) is a success condition for unconditional quantum teleportation. Alternatively, we may also assess our teleporter by calculating the fidelity after post-selecting the qubit components alone: \(F_{\text{qubit}} = (|\langle \psi | \rho_{\text{out}}^\text{qubit} | \psi \rangle|\), where \(|\psi\rangle\) is the ideal qubit state and \(\rho_{\text{out}}^\text{qubit} \) is obtained by extracting from the output density matrix the qubit subspace spanned by \(|(0, 1)|, |1, 0\rangle\) and then renormalizing it. We note that \(F_{\text{qubit}} > 2/3\) is the success criterion of post-selective teleportation with a pure input qubit and a mixed output qubit28.

As shown in Fig. 3, the \(g\) dependence of these two fidelities is in good agreement with the theoretical predictions. The maximal fidelities are obtained at \(g = 0.79\). Most importantly, here, we satisfy not only the usual qubit-subspace teleportation criterion, \(F_{\text{qubit}} = 0.875 ± 0.015 > 2/3\), but also the fully non-post-selected, Fock-space criterion, \(F_{\text{state}} = 0.817 ± 0.012 > F_{\text{thr}} = 0.769 ± 0.004\), thus demonstrating deterministic, unconditional quantum teleportation of a photonic qubit. As well as for the input qubit, \(|\psi_1\rangle\), the Fock-space criterion is also fulfilled for the other three qubit states, \(|0, 1\rangle, |1, 0\rangle\) and \(|\psi_2\rangle\), with the same experimental \(r\) and \(g\) values, for which states \(F_{\text{state}}\) values of \(0.800 ± 0.006\), \(0.789 ± 0.006\) and \(0.796 ± 0.011\) were respectively observed (theoretically, \(F_{\text{state}}\) and \(F_{\text{qubit}}\) are independent of the
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The teleportation is only post-selective (component becomes more dominant, the qubit components retain ftuations, such as extra loss and phase fluctuations of the squeezing. The fidelity curves (Supplementary Information) are also plotted, in the same colours.

Figure 2 | Experimental density matrices. By means of homodyne tomography, two-mode density matrices are reconstructed both for the input and the output states in photon-number bases24:

\[ \hat{\rho} = \sum_{l,k,m,n=0}^{\infty} \phi_{klmn} |k, l\rangle \langle m, n| \]. The bars show the real or imaginary parts of each matrix element \( \phi_{klmn} \). Blue, red and green bars correspond to the vacuum, qubit and multiphoton components, respectively. a, Input state, \( |\psi_i\rangle \). b-d, Output states for different values of \( r \) and \( g \). of the input and output qubit components) is still much higher than in previous experiments (\( \ll 1\% \)), even for this relatively low squeezing level. This shows the great advantage of our hybrid approach over the standard approaches.

In conclusion, we experimentally realized unconditional quantum teleportation of four distinct photonic qubit states, exceeding the fidelity limits of classical teleportation in a deterministic fashion. In our scheme, once the input qubit states are prepared, there is no need to preprocess or post-select them, and the teleported states freely emerge at the output of our teleporter.

METHODS SUMMARY

Our experimental set-up is shown in Fig. 1. The time-bin qubit is conditionally created at a rate of \( \sim 5,000 \text{s}^{-1} \) using a continuous-wave laser24 (wavelength, 860 nm), by extending the technique of ref. 30. Each time bin has a frequency bandwidth of 6.2 MHz around the laser frequency. Our continuous-variable teleporter23 operates continuously with a bandwidth of 12 MHz around the laser frequency, which is sufficiently wide to cover the qubit bandwidth—ultimately enabling us to teleport qubits in a deterministic fashion. In our teleporter, two single-mode squeezed states (each with an ideal, pure squeezing parameter \( r \)) from two optical parametric oscillators are suitably mixed at a 50:50 beam splitter to generate the quadrature-entangled beams. This entanglement source is permanently available with no need for any probabilistic heralding mechanism. At the sending station of the teleporter, the input qubit is first combined with one half of the entangled beams at a 50:50 beam splitter. A complete continuous-variable BSM is then performed by measuring the two output modes of the beam splitter through two homodyne detections of two orthogonal quadratures. These homodyne signals are classically communicated to the receiving station, where they are multiplied by a gain factor \( g \) and fed forwards by means of a displacement operation on the other half of the entangled beams. Time synchronization of this final displacement is achieved by introducing an optical delay to the corresponding entangled beam. Finally, the output state is characterized by single or dual homodyne measurement24. For every state, 100,000 sets of quadrature values are recorded and the corresponding two-mode density matrix is reconstructed using the maximum-likelihood technique without compensating finite measurement efficiencies.

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1. Bennett, C. H. et al. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. 70, 1895–1899 (1993).
2. Briegel, H.-J., Dür, W., Cirac, J. I. & Zoller, P. Quantum repeaters: the role of imperfect local operations in quantum communication. Phys. Rev. Lett. 81, 5932–5935 (1998).
3. Gottesman, D. & Chuang, I. L. Demonstrating the viability of universal quantum computation using teleportation and single-qubit operations. Nature 402, 390–393 (1999).
4. Knill, E., Laflamme, R. & Milburn, G. J. A scheme for efficient quantum computation with linear optics. Nature 409, 46–52 (2001).
5. Raussendorf, R. & Briegel, H. J. A one-way quantum computer. Phys. Rev. Lett. 86, 5188–5191 (2001).
6. Bouwmeester, D. et al. Experimental quantum teleportation. Nature 390, 575–579 (1997).
7. Boschi, D., Branca, S., De Martini, F., Hardy, L. & Popescu, S. Experimental realization of teleporting an unknown pure quantum state via dual classical Einstein-Podolsky-Rosen channels. Phys. Rev. Lett. 80, 1121–1125 (1998).
8. Kim, Y.-H., Kulik, S. P. & Shih, Y. Quantum teleportation of polarization state with a complete Bell state measurement. Phys. Rev. Lett. 86, 1370–1373 (2001).
9. Marcikic, I., de Riedmatten, H., Tittel, W., Zbinden, H. & Gisin, N. Long-distance teleportation of qubits at telecommunication wavelengths. Nature 421, 509–513 (2003).
10. Pan, J.-W., Gasparoni, S., Aspelmeyer, M., Jennewein, T. & Zeilinger, A. Experimental realization of freely propagating teleported qubits. Nature 421, 721–725 (2003).
11. Ma, X.-S. et al. Quantum teleportation over 143 kilometres using active feed-forward. Nature 489, 269–273 (2012).
12. Lütkenhaus, N., Calsamiglia, J. & Suominen, K.-A. Bell measurements for teleportation. Phys. Rev. A 59, 3295–3300 (1999).
13. Pan, J.-W. et al. Multiphoton entanglement and interferometry. Rev. Mod. Phys. 84, 777–838 (2012).
14. Vaidman, L. Teleportation of quantum states. Phys. Rev. A 49, 1473–1476 (1994).
15. Braunstein, S. L. & Kimble, H. J. Teleportation of continuous quantum variables. Phys. Rev. Lett. 80, 869–872 (1998).
16. Furusawa, A. et al. Unconditional quantum teleportation. Science 282, 706–709 (1998).
17. Hofmann, H. F., Ide, T., Kobayashi, T. & Furusawa, A. Information losses in continuous-variable quantum teleportation. Phys. Rev. A 64, 040301(R) (2001).
18. Polkinghorne, R. E. S. & Ralph, T. C. Continuous variable entanglement swapping. Phys. Rev. Lett. 83, 2095–2099 (1999).
19. Nielsen, M. A. & Chuang, I. L. Quantum Computation and Quantum Information 380–386 (Cambridge Univ. Press, 2000).
20. Braunstein, S. L. & Kimble, H. J. A posteriori teleportation. Nature 394, 840–841 (1998).
21. Yonezawa, H., Braunstein, S. L. & Furusawa, A. Experimental demonstration of quantum teleportation of broadband squeezing. Phys. Rev. Lett. 99, 110503 (2007).
22. Ide, T., Hofmann, H. F., Kobayashi, T. & Furusawa, A. Continuous-variable teleportation of single-photon states. Phys. Rev. A 65, 012313 (2001).
23. Lee, N. et al. Teleportation of nonclassical wave packets of light. Science 332, 330–333 (2011).
24. Takeda, S. et al. Generation and eight-port homodyne characterization of time-bin qubits for continuous-variable quantum information processing. Phys. Rev. A 87, 043803 (2013).
25. Bowen, W. P. et al. Experimental investigation of continuous-variable quantum teleportation. Phys. Rev. A 67, 032302 (2003).
26. Jia, X. et al. Experimental demonstration of unconditional entanglement swapping for continuous variables. Phys. Rev. Lett. 93, 250503 (2004).
27. Mišta, L. Jr, Filip, R. & Furusawa, A. Continuous-variable teleportation of a negative Wigner function. Phys. Rev. A 82, 012322 (2010).
28. Jouza, R. Fidelity for mixed quantum states. J. Mod. Opt. 41, 2315–2323 (1994).
29. Massar, S. & Popescu, S. Optimal extraction of information from finite quantum ensembles. Phys. Rev. Lett. 74, 1259–1263 (1995).
30. Zavatta, A., D’Angelo, M., Parigi, V. & Bellini, M. Remote preparation of arbitrary time-encoded single-photon ebits. Phys. Rev. Lett. 96, 020502 (2006).

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Author Contributions A.F. planned and supervised the project. P.v.L. and S.T. theoretically defined the scientific goals. S.T. and T.M. designed and performed the experiment, and acquired the data. S.T. and M.F. developed the electronic devices. S.T., T.M. and M.F. analysed the data. S.T. and P.v.L. wrote the manuscript with assistance from all other co-authors.

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