Quantum Teleportation of Shared Quantum Secret

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Quantum teleportation is a fundamental building block of quantum communications and quantum computations, transferring quantum states between distant physical entities. In the context of quantum secret sharing, the teleportation of quantum information shared by multiple parties without concentrating the information at any place is essential, and this cannot be realized by any previous scheme. We propose and experimentally demonstrate a novel teleportation protocol that enables one to perform this task. It is jointly performed by distributed participants, while none of them can fully access the information. Our scheme can be extended to arbitrary numbers of senders and receivers and to fault-tolerant quantum networks by incorporating error-correction codes.

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Quantum teleportation allows us to transfer unknown quantum states between distant parties [1–3]. It is not only a primitive of quantum communications but also an essential task in the realization of quantum networks for promising applications such as quantum cryptography [4,5] and distributed quantum computation [6]. While the original teleportation protocol transfers quantum information from one place to another [1], incorporation of multiple participants further merits consideration towards the realization of versatile quantum networks. Protocols to split quantum information from one sender to multiple receivers have been proposed [7–9] and demonstrated [10]. With this protocol, no single receiver can fully access the information unless collaborated by all the other receivers, constituting the basis of further extended quantum secret sharings [11–17] or controlled teleportations [18–23]. Teleportations of multiparty states have also been studied [24–26], however, a quantum teleportation between multiple senders and receivers has been missing so far. None of the previous protocols, to our knowledge, allow us to transfer a shared or split quantum information among multiple parties directly to others without concentrating the information in the location of single or subparties. The absence of such a protocol has thus led to the requirement of fully trusted central or intermediate nodes in the design of quantum communication networks [27,28].

Here we propose and experimentally demonstrate a secure quantum teleportation between multiple senders and receivers. Our novel teleportation protocol allows quantum information shared by an arbitrary number of senders to be transferred to another arbitrary number of receivers. Unlike all the previous methods, neither any single- nor subparties of senders and receivers can fully access the secret quantum information. We report its proof-of-principle experiment between two senders and two receivers using a four-photon entanglement network and Bell-state analyzers. The results clearly show the lack of full information owned by individual parties and, moreover, an elevated success probability of teleportation compared to the previous schemes thanks to our entanglement encoding [29].

Our protocol allows us to relay quantum information over a network in an efficient and distributed manner without requiring fully trusted central or intermediate nodes. It can be further extended to include error corrections against photon losses, bit or phase-flip errors, and dishonest parties. This work thus opens a route to the realization of secure distributed quantum communications and computations in quantum networks.

Protocol.—Suppose that a quantum secret in $|\mathcal{S}\rangle = \alpha|0_L\rangle + \beta|1_L\rangle$ with logical basis, $|0_L\rangle$ and $|1_L\rangle$, is shared by separated n parties in quantum network, through a splitting protocol [7–9]. We employ the GHZ-entanglement of photons to encode both the network and logical qubits (its extension to more general states are discussed later). The shared secret can then be written as $|\mathcal{S}\rangle_s = \alpha|H\rangle_{s_1}\cdots|H\rangle_{s_n} + \beta|V\rangle_{s_1}\cdots|V\rangle_{s_n}$, with horizontal $|H\rangle$ and vertical $|V\rangle$ polarizations of photons. The *senders*, i.e., a group of n parties, attempts to transfer the secret to the *receivers*, i.e., another group of m parties, connected in the network. None of the participants is fully trusted here so that no single or subparties of senders or receivers is allowed to access the secret during the whole process.

We introduce a distributed Bell-state measurement that can be jointly performed by separated parties. In general, Bell states of logical qubits with n photons can be decomposed into combinations of n two-photon Bell states [30], and discriminated by performing n times of standard

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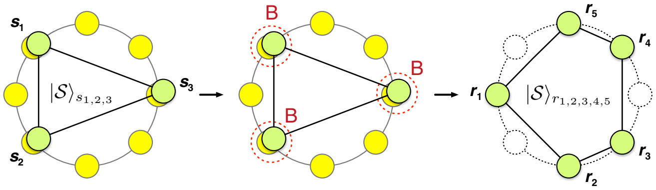

FIG. 1. Teleportation of a quantum secret $|\mathcal{S}\rangle$ between multiple senders ($n = 3$) and receivers ($m = 5$) in a quantum network by distributed Bell-state measurements. After performing the Bell-state measurement **B**, each sender s_i announces the result. Receivers can reconstruct and share the secret by the appropriate joint work of local operations. No participants can access the secret during the procedures.

Bell-state measurements (**B**). As its logical outcome is irrespective of the order of performed **B** measurements, it is possible to separate all **B**s spatially or temporally with help of classical communications to share their results among the nodes where a **B** is respectively performed [30].

The teleportation protocol between multiple parties in a quantum network is illustrated in Fig. 1: each separate sender performs **B** on two photons, one from $|\mathcal{S}\rangle_s$ and the other from the network channel, and announces the result. Conditioned on the results of all performed **B**, the reduced state of the channel at the receivers' locations is in $|\mathcal{S}\rangle_r = \alpha|H\rangle_{r_1}\cdots|H\rangle_{r_m} + \beta|V\rangle_{r_1}\cdots|V\rangle_{r_m}$ plus *logical* Pauli operations [29]. The receivers jointly carry out appropriate *local* Pauli operations according to the results announced by the senders to retrieve $|\mathcal{S}\rangle_r$.

For example, when $n = 2$, teleportation of a shared secret $|\mathcal{S}\rangle_s = \alpha|H\rangle_1|H\rangle_2 + \beta|V\rangle_1|V\rangle_2$ via network channel $(|H\rangle_{1'}|H\rangle_{2'})_s|H\rangle_r^{\otimes m} + (|V\rangle_{1'}|V\rangle_{2'})_s|V\rangle_r^{\otimes m}$ is explained by the joint state

$$
\begin{aligned}
&(|\phi^+\rangle_{s_1}|\phi^+\rangle_{s_2} + |\phi^-\rangle_{s_1}|\phi^-\rangle_{s_2})(\alpha|H\rangle^{\otimes m} + \beta|V\rangle^{\otimes m})_r \\
&\quad + (|\phi^+\rangle_{s_1}|\phi^-\rangle_{s_2} + |\phi^-\rangle_{s_1}|\phi^+\rangle_{s_2})(\alpha|H\rangle^{\otimes m} - \beta|V\rangle^{\otimes m})_r \\
&\quad + (|\psi^+\rangle_{s_1}|\psi^+\rangle_{s_2} + |\psi^-\rangle_{s_1}|\psi^-\rangle_{s_2})(\alpha|V\rangle^{\otimes m} + \beta|H\rangle^{\otimes m})_r \\
&\quad + (|\psi^+\rangle_{s_1}|\psi^-\rangle_{s_2} + |\psi^-\rangle_{s_1}|\psi^+\rangle_{s_2})(\alpha|V\rangle^{\otimes m} - \beta|H\rangle^{\otimes m})_r,
\end{aligned}
$$

where $|\phi(\psi)^\pm\rangle_{s_i}$ are the Bell state of the two photons in modes (i, i') that sender s_i holds. If the results of **B**s (which detect $|\phi^-\rangle$ and $|\psi^-\rangle$ out of the four Bell states with the other two states not being discriminated from each other) of the two senders are $|\phi^-\rangle$ and *failure*, respectively, the case corresponds to the second term, therefore the receivers can reconstruct $|\mathcal{S}\rangle_r$ by a phase flip ($\hat{\sigma}_z$: $|H\rangle \to |H\rangle$, $|V\rangle \to -|V\rangle$) at any one receiver's location. Likewise for other results, the secret can be recovered by the receivers. It is straightforward to extend the protocol for arbitrary n number of senders [30].

Accessible information.—Any subparties cannot fully access the quantum secret during the teleportation procedures. For example, assume that one sender s_j attempts to reconstruct the secret at his or her location based on the announced results by the other senders. After all the other senders except s_j perform a **B**, the remaining state is either $|\phi^-\rangle_{s_j}(\alpha|H\rangle + \beta|V\rangle)_r + |\phi^+\rangle_{s_j}(\alpha|H\rangle - \beta|V\rangle)_r$ or $|\psi^-\rangle_{s_j}(\alpha|V\rangle + \beta|H\rangle)_r + |\psi^+\rangle_{s_j}(\alpha|V\rangle - \beta|H\rangle)_r$ (here $m = 1$ for simplicity). By tracing out the receiver's party, the reduced state at his or her party is either $|\alpha|^2|H,H\rangle\langle H,H| + |\beta|^2|V,V\rangle\langle V,V|$ or $|\alpha|^2|H,V\rangle\langle H,V| + |\beta|^2|V,H\rangle\langle V,H|$ unless the whole channel is possessed by him or her. Therefore, only the amplitude information is accessible to s_j. The same holds for any subparties of senders and receivers (see [30] for information security comparison with [26]).

Experimental demonstration.—We demonstrate quantum teleportation between two senders ($n = 2$) and two receivers ($m = 2$) via a four-photon quantum network channel (GHZ state) using total six photons. Figure 2(a) shows the schematic of our experimental setup. Photons are generated by spontaneous parametric down-conversion (SPDC) in BBO crystals [30,35]. Two polarization-entangled photon-pairs ($|H\rangle|H\rangle + e^{i\phi_k}|V\rangle|V\rangle$, $k = 1, 2$) generated by BBO_1 and BBO_2 are projected to a four-photon GHZ state, $|\mathrm{GHZ}_4\rangle \equiv |H\rangle^{\otimes 4} + |V\rangle^{\otimes 4}$, by postselection at modes $s_{1'}$ and $s_{2'}$ [36]. The resulting phase between the $|H\rangle^{\otimes 4}$ and $|V\rangle^{\otimes 4}$ components after the postselection are set to zero by a phase shifter Φ_1 in Fig. 2(a), which is a combination of two quarter-wave plates (QWPs) whose slow axes are along 45° and one rotatable half-wave plate (HWP) in between. Input states of the form $\alpha|H\rangle|H\rangle + \beta|V\rangle|V\rangle$, where α and β are complex constants, are generated through modes s_1 and s_2 by BBO_3 (green box). The magnitudes and the relative phases of α and β are controlled by tilting the BBO crystals to change the coupling efficiency of the photons to the collecting single-mode fibers (SMFs) and by rotating the HWP in another phase shifter Φ_2 at s_1, respectively.

Figure 2(b) shows the structure of an optical-fiber-based Bell-state analyzer (BSA) that executes **B**. Optical fiber components such as fiber nonpolarizing beam splitters (FBSs) and fiber polarizing beam splitters (FPBSs) replace the bulk optics components in the original design [37] to reduce the space and facilitate alignment. We note that two single-photon detectors (SPDs) are concatenated by an additional FBS at each output port of an FPBS. Coincidence counts (CCs) of the two SPDs identify the failure events of a **B**. The conventional schemes using one SPD at each output port cannot discriminate these failure events from the errors caused by photon losses. The success probability of the failure detection is 50% with the current scheme, and can reach near-unity by using 1-by-N($\gg 1$) optical router plus N SPDs or a highly efficient photon-number resolving detector. The length of fibers of interfering paths are equalized within 1 cm to suppress the effect of dispersion, and the birefringence caused by fiber curvature

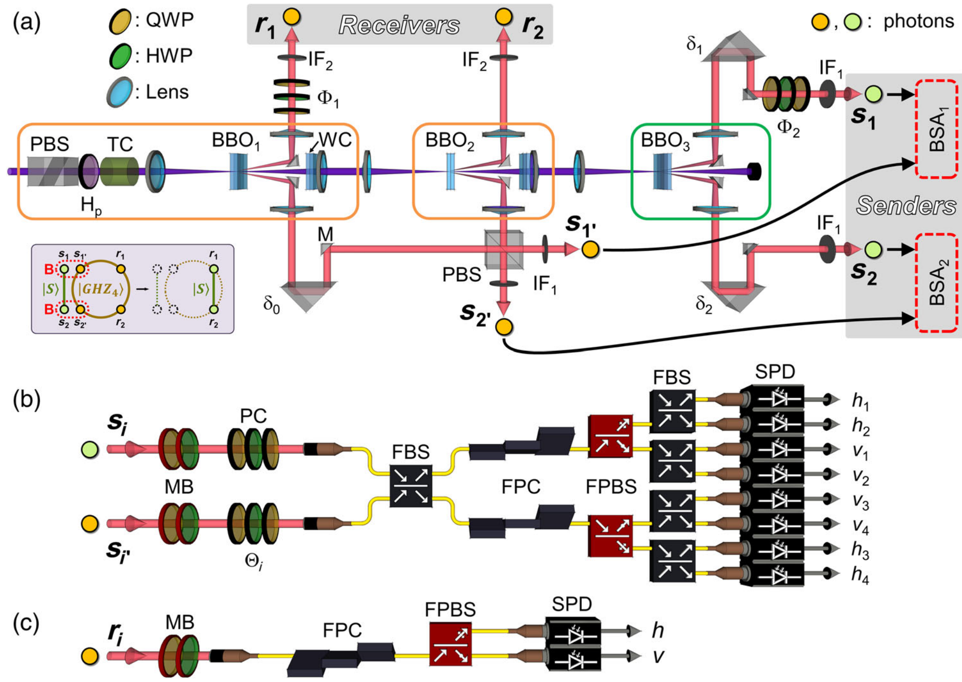

FIG. 2. Experimental setups. (a) Overall schematic for teleportation between two senders and two receivers (inset: conceptual diagram). A four-photon GHZ state and a two-photon entangled input state are generated. (b) Structure of the optical-fiber-based local Bell state analyzer. (c) Polarization analyzer for single photons. M: mirror, PBS: polarizing beam splitter, BBO: beta barium borate crystal pair (two mutually orthogonal 1-mm plates), TC: temporal walk-off compensator (16-mm-thick quartz plate), WC: spatial walk-off compensator (180°-rotated BBO), QWP: quarter-wave plate, HWP: half-wave plate, H_p: HWP for pump, IF_i: interference filter (half-maximum bandwidth of 3 nm and 20 nm for $i = 1$ and 2, respectively), MB: measurement basis controller, PC: polarization controller based on a combination of quarter-, half-, and quarter-wave plates (QHQ), FPC: fiber paddle polarization controller, Θ_i, Φ_j: relative phase shifter between the H and V polarizations using a QHQ, FBS: fiber beam splitter, FPBS: fiber polarizing beam splitter, SPD: single-photon detector. $h\,(v)$: the signal heralding the detection of horizontally (vertically) polarized photons.

is compensated by fiber paddle polarization controllers (FPCs) and combinations of quarter-, half-, and quarter-wave plates (QHQ). We describe a new (more convenient than previous works [38,39]) procedure to set the FPCs and the QHQs (denoted as PC and Θ_i) in [30]. Interference filters (IFs, half-maximum bandwidth of 3 nm at $s_{1,2}$ and $s_{1',2'}$ and 20 nm at $r_{1,2}$) at the end of each path in Fig. 2(a) maintain the indistinguishability between photons from independent pairs.

The teleported two photons proceed to the receiver modes r_1 and r_2. Their polarization states are measured by fiber-based polarization analyzers shown in Fig. 2(c). A QWP and a HWP (noted "MB") at each entrance of photons (on the left) in Figs. 2(b) and 2(c) set the polarization basis measured by the SPDs when characterizing the initial state, the four-photon GHZ state, and the final state. During the teleportation experiments, the measurement bases of BSAs are set as X to fix the detectable Bell sates as $(|\psi^-\rangle, |\phi^-\rangle)$. Two-, four-, and sixfold coincidences of total 20 SPDs in Fig. 2(a) are analyzed by an FPGA-based logic unit.

We first generate three input states for teleportation, (a) $|H\rangle|H\rangle + |V\rangle|V\rangle$, (b) $|H\rangle|H\rangle + i|V\rangle|V\rangle$, (c) $|H\rangle|H\rangle$, and a four-photon GHZ state (see [30] for the measurement results of the generated states). Then we measure the teleported output states. Sixfold CCs are recorded while varying the measurement bases in modes r_1 and r_2 for quantum state tomography (QST) [40]. The unit counting period was 20 h for each basis and the average CC was 1.5 cph. To complete the teleportation protocol, unitary Pauli operations are applied to the received photons by rearranging the count records among the QST measurement bases $(XX, XY, \ldots, ZZ)$, depending on the results of the **B**s. For example, when the **B**s result in one $|\phi^-\rangle$ and one failure event, the measured logical Bell state is $|\Phi_L^-\rangle$, therefore, to compensate for the local phase-flip operation, the count records measured on the X and Y bases in mode r_1 (or mode r_2) are exchanged between +1 and -1 data. The reconstructed three output states are shown in Figs. 3(a)–3(c). The fidelities between the teleported states in Figs. 3(a)–3(c) and the input states are (a) 0.84(4), (b) 0.78(6), and (c) 0.75(5), and exceed the classical bound (2/3) for single logical qubit transfer [41,42] by 1.7–4.3 standard deviations. The individual states either in r_1 or in r_2 lack phase information. The infidelities can be attributed to imperfections of the initial input and GHZ states and other experimental errors [30].

Discussion.—Our protocol differs from the previous designs [27,28] in which a trusted node plays a major role to connect the participants and transfers the information.

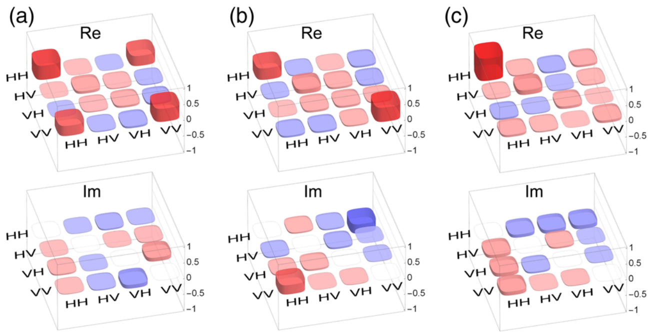

FIG. 3. Reconstructed density matrices of teleported output states of (a) $|H\rangle|H\rangle + |V\rangle|V\rangle$, (b) $|H\rangle|H\rangle + i|V\rangle|V\rangle$, and (c) $|H\rangle|H\rangle$.

It may be useful to establish a long-distance quantum communication via distributed nodes, none of which necessarily relays the full quantum information. This is also applicable to the storage and retrieval of quantum secret with spatially separate quantum memories [43]. Verification strategies of multipartite entanglement [44,45] are useful to prepare the entangled network in the presence of dishonest parties.

We note that our work is not limited to the GHZ state encoding. It can be extended further to be fault-tolerant by error correction encoding against photon losses, operation errors, and dishonest participants. For example, a parity state encoding [46] can be employed to correct the effects of photon losses, errors, and dishonest parties to some extent [30]. It allows, in principle, to transfer quantum information with arbitrarily high success probabilities even under losses and errors [47,48]. Encoding with other type of entangled states such as cluster states are worth considering further. For example, it is possible to increase the success probability of Bell-state measurement by cluster-state encoding [49]. Combination of such encoding schemes and secret sharing protocols based on cluster states [13–15] may be valuable.

While our protocol is developed based on photonic qubits, further studies with continuous variables [50–52] or optical hybrid approaches [53,54] are also anticipated. Long-distance teleportation [52] and quantum secret sharing [16,17] using continuous-variable quantum states may open the possibility of deterministic teleportation of shared information in a quantum network.

Our experiment fulfills the requirements to overcome the two-qubit teleportation experiment [26] in which subparties can obtain the full quantum information [30]. The success probability of our teleportation experiments (50%) furthermore beats the limit (25%) of the conventional protocol considering the maximum success probability 1/2 of standard Bell-state measurement [55,56], thanks to both the theoretical encoding scheme and the experimental measurement technique. This is, to our knowledge, a first experimental result showing the advantage of the Bell-state analyzer with entanglement encoding [29]. The presented experimental techniques would be also applicable to other recently advanced quantum communication protocols [47–49].

In summary, we have proposed and experimentally demonstrated a novel quantum teleportation protocol to transfer shared quantum secret between multiple parties in network. Our work brings about a conceptual extension of multipartite quantum communication to open a route to the realization of distributed quantum communications and computations in versatile quantum networks.

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[1] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70**, 1895 (1993).
[2] D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Nature (London) **390**, 575 (1997).
[3] S. Pirandola, J. Eisert, C. Weedbrook, A. Furusawa, and S. L. Braunstein, Nat. Photonics **9**, 641 (2015).
[4] C. H. Bennett and G. Brassard, in *Proceedings of IEEE International Conference on Computers*, Systems and Signal Processing, Bangalore, India (IEEE Press, Piscataway, NJ 1984), pp. 175–179.
[5] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1991).
[6] H. J. Kimble, Nature (London) **453**, 1023 (2008).
[7] A. Karlsson and M. Bourennane, Phys. Rev. A **58**, 4394 (1998).
[8] A. Karlsson, M. Koashi, and N. Imoto, Phys. Rev. A **59**, 162 (1999).
[9] M. Hillery, V. Bužek, and A. Berthiaume, Phys. Rev. A **59**, 1829 (1999).
[10] Z. Zhao, Y.-A. Chen, A.-N. Zhang, T. Yang, H. J. Briegel, and J.-W. Pan, Nature (London) **430**, 54 (2004).
[11] Y.-A. Chen, A.-N. Zhang, Z. Zhao, X.-Q. Zhou, C.-Y. Lu, C.-Z. Peng, T. Yang, and J.-W. Pan, Phys. Rev. Lett. **95**, 200502 (2005).
[12] S. Gaertner, C. Kurtsiefer, M. Bourennane, and H. Weinfurter, Phys. Rev. Lett. **98**, 020503 (2007).
[13] R. Cleve, D. Gottesman, and H.-K. Lo, Phys. Rev. Lett. **83**, 648 (1999).
[14] D. Markham and B. C. Sanders, Phys. Rev. A **78**, 042309 (2008).

[15] B. A. Bell, D. Markham, D. A. Herrera-Martí, A. Marin, W. J. Wadsworth, J. G. Rarity, and M. S. Tame, Nat. Commun. **5**, 5480 (2014).
[16] A. M. Lance, T. Symul, W. P. Bowen, B. C. Sanders, and P. K. Lam, Phys. Rev. Lett. **92**, 177903 (2004).
[17] Y. Zhou, J. Yu, Z. Yan, X. Jia, J. Zhang, C. Xie, and K. Peng, Phys. Rev. Lett. **121**, 150502 (2018).
[18] C.-P. Yang, Shih-I. Chu, and S. Han, Phys. Rev. A **70**, 022329 (2004).
[19] F.-G. Deng, C.-Y. Li, Y.-S. Li, H.-Y. Zhou, and Y. Wang, Phys. Rev. A **72**, 022338 (2005).
[20] X.-H. Li and S. Ghose, Phys. Rev. A **91**, 012320 (2015).
[21] H. Yonezawa, T. Aoki, and A. Furusawa, Nature (London) **431**, 430 (2004).
[22] A. Barasiński, I. Arkhipov, and J. Svozilík, Sci. Rep. **8**, 15209 (2018).
[23] A. Barasiński, A. Černoch, and K. Lemr, Phys. Rev. Lett. **122**, 170501 (2019).
[24] J. Lee and M. S. Kim, Phys. Rev. Lett. **84**, 4236 (2000).
[25] S. Ghosh, G. Kar, A. Roy, D. Sarkar, and U. Sen, New J. Phys. **4**, 48 (2002).
[26] Q. Zhang, A. Goebel, C. Wagenknecht, Y.-A. Chen, B. Zhao, T. Yang, A. Mair, J. Schmiedmayer, and J.-W. Pan, Nat. Phys. **2**, 678 (2006).
[27] Q.-C. Sun, Y.-L. Mao, S.-J. Chen, W. Zhang, Y.-F. Jiang, Y.-B. Zhang, W.-J. Zhang, S. Miki, T. Yamashita, H. Terai, X. Jiang, T.-Y. Chen, L.-X. You, X.-F. Chen, Z. Wang, J.-Y. Fan, Q. Zhang, and J.-W. Pan, Nat. Photonics **10**, 671 (2016).
[28] M. Pant, H. Krovi, D. Towsley, L. Tassiulas, L. Jiang, P. Basu, D. Englund, and S. Guha, npj Quantum Inf. **5**, 25 (2019).
[29] S.-W. Lee, K. Park, T. C. Ralph, and H. Jeong, Phys. Rev. Lett. **114**, 113603 (2015).
[30] See the Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.124.060501 for further details and proofs, which include additional Refs. [31–34].
[31] R. Ursin, T. Jennewein, M. Aspelmeyer, R. Kaltenbaek, M. Lindenthal, P. Walther, and A. Zeilinger, Nature (London) **430**, 849 (2004).
[32] X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Naylor, B. Wittmann, A. Mech, J. Kofler, E. Anisimova, V. Makarov, T. Jennewein, R. Ursin, and A. Zeilinger, Nature (London) **489**, 269 (2012).
[33] H.-S. Zhong, Y. Li, W. Li, L.-C. Peng, Z.-E. Su, Y. Hu, Y.-M. He, X. Ding, W. Zhang, H. Li, L. Zhang, Z. Wang, L. You, X.-L. Wang, X. Jiang, L. Li, Y.-A. Chen, N.-L. Liu, C.-Y. Lu, and J.-W. Pan, Phys. Rev. Lett. **121**, 250505 (2018).
[34] P. W. Shor, Phys. Rev. A **52**, R2493 (1995).
[35] R. Rangarajan, M. Goggin, and P. Kwiat, Opt. Express **17**, 18920 (2009).
[36] A. Zeilinger, M. A. Horne, H. Weinfurter, and M. Żukowski, Phys. Rev. Lett. **78**, 3031 (1997).
[37] K. Mattle, H. Weinfurter, P. G. Kwiat, and A. Zeilinger, Phys. Rev. Lett. **76**, 4656 (1996).
[38] T. D. Jennewein, Quantum communication and teleportation experiments using entangled photon pairs, Ph.D. thesis, University of Vienna, 2002.
[39] S. M. Lee, M. Kim, H. Kim, H. S. Moon, and S. W. Kim, Quantum Sci. Technol. **3**, 045006 (2018).
[40] D. F. V. James, P. G. Kwiat, W. J. Munro, and A. G. White, Phys. Rev. A **64**, 052312 (2001).
[41] S. Massar and S. Popescu, Phys. Rev. Lett. **74**, 1259 (1995).
[42] A. Hayashi, T. Hashimoto, and M. Horibe, Phys. Rev. A **72**, 032325 (2005).
[43] K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, Nature (London) **452**, 67 (2008).
[44] A. Pappa, A. Chailloux, S. Wehner, E. Diamanti, and I. Kerenidis, Phys. Rev. Lett. **108**, 260502 (2012).
[45] W. McCutcheon, A. Pappa, B. A. Bell, A. McMillan, A. Chailloux, T. Lawson, M. Mafu, D. Markham, E. Diamanti, I. Kerenidis, J. G. Rarity, and M. S. Tame, Nat. Commun. **7**, 13251 (2016).
[46] T. C. Ralph, A. J. F. Hayes, and A. Gilchrist, Phys. Rev. Lett. **95**, 100501 (2005).
[47] S.-W. Lee, T. C. Ralph, and H. Jeong, Phys. Rev. A **100**, 052303 (2019).
[48] F. Ewert, M. Bergmann, and P. van Loock, Phys. Rev. Lett. **117**, 210501 (2016).
[49] K. Azuma, K. Tamaki, and H.-K. Lo, Nat. Commun. **6**, 6787 (2015).
[50] S. L. Braunstein and H. J. Kimble, Phys. Rev. Lett. **80**, 869 (1998).
[51] A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik, Science **282**, 706 (1998).
[52] M. Huo, J. Qin, J. Cheng, Z. Yan, Z. Qin, X. Su, X. Jia, C. Xie, and K. Peng, Sci. Adv. **4**, eaas9401 (2018).
[53] S. Takeda, T. Mizuta, M. Fuwa, P. van Loock, and A. Furusawa, Nature (London) **500**, 315 (2013).
[54] S.-W. Lee and H. Jeong, Phys. Rev. A **87**, 022326 (2013).
[55] J. Calsamiglia and N. Lütkenhaus, Appl. Phys. B **72**, 67 (2001).
[56] H. Weinfurter, Europhys. Lett. **25**, 559 (1994).