Demonstration of Controlled Quantum Teleportation for Discrete Variables on Linear Optical Devices

Artur Barasiński,[1,2,*] Antonín Černoch,[3,†] and Karel Lemr[1,‡]

[1]*RCPTM, Joint Laboratory of Optics of Palacký University and Institute of Physics of CAS, Faculty of Science, Palacký University, 17. listopadu 12, 771 46 Olomouc, Czech Republic*

[2]*Institute of Physics, University of Zielona Góra, Z. Szafrana 4a, 65-516 Zielona Góra, Poland*

[3]*Institute of Physics of the Czech Academy of Sciences, Joint Laboratory of Optics of Palacký University and Institute of Physics of CAS, 17. listopadu 50A, 772 07 Olomouc, Czech Republic*

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We report an experimental implementation of tripartite controlled quantum teleportation on quantum optical devices. The protocol is performed through bi- and tripartite entangled channels of discrete variables and qubits encoded in the polarization of individual photons. The experimental results demonstrate successful controlled quantum teleportation with a fidelity around 83%, well above the classical limit. By realizing the controlled quantum teleportation through a biseparable state, we show that tripartite entanglement is not a necessary resource for controlled quantum teleportation, and the controller's capability to allow or prohibit the teleportation cannot be considered to be a manifestation of tripartite entanglement. These results open new possibilities for further application of controlled quantum teleportation by lowering the teleportation channel's requirements.

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Introduction.—Quantum teleportation is considered one of the major protocols in quantum information science. By exploiting the physical resource of entanglement, quantum teleportation has played a prominent role in the development of quantum information theory [1–5] and represents a fundamental ingredient to the progress of many quantum technologies such as quantum gate teleportation [6], quantum repeaters [7,8], measurement-based quantum computing [9], port-based teleportation [10], and quantum network teleportation (QNT) [11–13]. Teleportation has also been used as a quantum simulator for "extreme" phenomena, such as closed timelike curves and the grandfather paradox [14].

Quantum teleportation, first proposed by Bennett *et al.* [1], is a scheme of quantum information processing which allows the transfer of a quantum state between remote physical systems without physical transfer of the information carrier. Specifically, an unknown quantum state of a physical system is measured and subsequently reconstructed at a remote location through the use of classical communication and quantum entanglement [15,16]. Without entanglement, such quantum state transfer would not be possible within the laws of quantum mechanics. For that reason, quantum teleportation is thought of as the quantum information protocol which clearly demonstrates the character of quantum entanglement as a resource.

To date, quantum teleportation has been achieved and studied in many different systems, including photonic systems, nuclear magnetic resonance, optical modes, trapped atoms, and solid-state systems (see Ref. [17] and references therein). Naturally, most attention has been focused on teleporting the state at long distance [18,19] with the recent satellite-based implementations [20]. However, even though quantum teleportation is a typically bipartite process, it can be extended to multipartite quantum protocols which have not been thoroughly studied yet. Such multipartite protocols are expected to form fundamental components for larger-scale quantum communication and computation [2].

An important extension of quantum teleportation to a multipartite case is known as controlled quantum teleportation (CQT) [21], which allows for remote quantum nondemolition (QND) measurements and forms a backbone of QNTs [17,22,23]. In the simplest case of tripartite systems, the essential concept of the CQT scheme is that the transfer of the quantum state from sender (Alice) to receiver (Bob) needs the controller's (Charlie's) classical information, and thus Charlie can determine the success or failure of teleportation by restricting the access to his information, what is commonly thought of as a clear manifestation of tripartite entanglement [23]. When Alice, Bob, and Charlie can choose any one of them to be the sender, receiver, and controller, then the CQT protocol is equivalent to a QNT, a prelude for a genuine quantum internet [24]. Here, it is also believed that parties must share a multipartite entangled state to allow teleportation between any two parties [17,23]. Furthermore, the CQT protocol as discussed in this Letter may be applied in the processing of quantum secret sharing, a prominent quantum information protocol [25].

Although several implementation schemes of CQT have been proposed over time using, for instance, a Greenberger–Horne–Zeilinger (GHZ) state in an ion-trapped system [26], or a Brown state via cavity QED [27], quantum dots [28,29], GHZ-like states [30], so far to the best of our knowledge, the successful experimental realization of the CQT protocol has been reported only for a GHZ state of continuous variables [23]. For such systems, the GHZ teleportation channel can be contracted—for instance, using three vacuum states in the limit of infinite squeezing [31]. Naturally, in a real experiment, a maximally entangled GHZ state of continuous variables is not available because of finite squeezing and inherent losses. Therefore, the realistic state generated by three highly squeezed vacuum states is the nonmaximally entangled GHZ-like state. Consequently, CQT of a coherent state was performed with fidelity up to $F_{\mathrm{CQT}} = 64\% \pm 2\%$ [23].

To overcome the limitation caused by finite squeezing, in this Letter we present the first experimental verification of CQT on GHZ states of discrete variables. Using the four-photon source based on the process of spontaneous parametric down-conversion (SPDC), we generate a GHZ state and perform the CQT with a fidelity of $F = 83.0\% \pm 7.3\%$. Our experiment is also successfully repeated for other teleportation channels based on the GHZ states—in particular, a statistical mixture of such states, demonstrating the controller's capability of steering the teleportation process based on the classical correlations without the presence of multipartite entanglement. Such a result represents a universal feature of CQT and QNT which is deeply rooted in the operational definition of bipartite entanglement [32].

The concept of controlled quantum teleportation.—We start by reviewing the basic tripartite CQT protocol in finite-dimensional settings [21].

The protocol considers three remote parties—Alice, Bob, and Charlie—who share a pure three-qubit entangled state in advance. In the perfect scheme, the shared entangled state is taken to be a maximally entangled GHZ state, $|\mathcal{G}^{(1)}\rangle = (1/\sqrt{2})\{|H_1H_2H_3\rangle + |V_1V_2V_3\rangle\}$, where we use the polarization degree of freedom of the photons generated in the optical setup, with $|H\rangle$ and $|V\rangle$ denoting the horizontal and vertical polarization states, respectively. Initially, Alice is in possession of a qubit in mode 1 of the GHZ state and a single qubit in mode 4 in the input quantum state $|\psi_4\rangle$ which she wants to teleport. In our experiment, the input state is the polarization of an arbitrary single photon: $|\psi_4\rangle = \alpha|H_4\rangle + \beta|V_4\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. Suppose now that Alice applies a specific joint quantum measurement which projects photons in modes 1 and 4 into the maximally entangled Bell state $|\psi_{14}^-\rangle = (1/\sqrt{2})\times \{|H_1\rangle|V_4\rangle - |V_1\rangle|H_4\rangle\}$. As a result, the state of the remaining two qubits is simultaneously projected into $|\psi_{23}\rangle = \alpha|H_2\rangle|V_3\rangle - \beta|V_2\rangle|H_3\rangle$, which can be further decomposed in the new basis $\mathcal{B}_\pm = \{|+\rangle, |-\rangle\}$ as $|\psi_{23}\rangle = (1/\sqrt{2})\{\alpha|H_2\rangle - \beta|V_2\rangle\}|+_3\rangle - (1/\sqrt{2})\{\alpha|H_2\rangle + \beta|V_2\rangle\}|-_3\rangle$, where $|\pm_3\rangle = (1/\sqrt{2})\{|H_3\rangle \pm |V_3\rangle\}$. In the next step, Charlie (the controller) applies von Neumann measurements on the qubit in mode 3 in the basis $\mathcal{B}_\pm$. Consequently, the final state of the qubit in mode 2, kept by Bob, is equal to $|\psi_2\rangle = \alpha|H_2\rangle + \beta|V_2\rangle$ up to a unitary operation that depends on the outcomes of Charlie's measurements. By contrast, if Charlie decides to apply von Neumann measurements on mode 3 in the basis $\mathcal{B}_{HV} = \{|H\rangle, |V\rangle\}$, then the resulting quantum state of Bob's qubit is either $|\psi_2\rangle = |H_2\rangle$ or $|\psi_2\rangle = |V_2\rangle$. These two scenarios clearly show Charlie's power to determine the success and failure of CQT.

Now, it is important to note that the above-mentioned $|\psi_{14}^-\rangle$ state is only one of four possible Bell states which can be obtained by Alice. In general, the composed state of qubits in modes 1 and 4 can be projected into four different states $(\mathcal{P}_k \otimes I)|\psi_{14}^-\rangle$, where $\mathcal{P}_k$ is an appropriate Pauli operator [2] and $k = 0$, 1, 2, 3. When this happens, the state of particles in modes 2 and 3 becomes $\rho_{23} = \mathcal{P}_k^\dagger|\psi_{23}\rangle\langle\psi_{23}|\mathcal{P}_k$. Bob can then recover the input state by applying an accordingly chosen transformation that requires a classical communication with both Alice and Charlie. Although in the above-mentioned scheme only one of four Bell states is distinguished, teleportation is still successfully achieved, albeit only in a quarter of the cases. Moreover, it should be noted that the complete Bell state measurement which is based on nonlinear processes requires hyperentanglement or feed-forward techniques [33], and hence, it remains an experimentally challenging problem which usually causes the reduction of the signal intensity [3,34]. Therefore, the antisymmetric structure of the state $|\psi_{14}^-\rangle$ makes this state the most useful in the experimental implementation of teleportation protocols as discussed in Refs. [3,35]. In this Letter, we also take the advantage of this property and limit our Bell state measurement only to $|\psi_{14}^-\rangle$.

Finally, we note that the faithfulness of the CQT protocol shall not change if one applies a local bit flip operation on the GHZ state shared by Alice, Bob, and Charlie, say $|\mathcal{G}^{(2)}\rangle = (1/\sqrt{2})\{|H_1H_2V_3\rangle + |V_1V_2H_3\rangle\}$. A particularly interesting scenario, however, occurs if one takes a statistical mixture of two such GHZ states,

$$\rho(p) = (1-p)|\mathcal{G}^{(1)}\rangle\langle\mathcal{G}^{(1)}| + p|\mathcal{G}^{(2)}\rangle\langle\mathcal{G}^{(2)}|, \qquad (1)$$

where $0 \le p \le 1$. Then, for the equivalently balanced probabilities, the state $\rho(p = 1/2)$ belongs to the biseparable class and can be decomposed as $\rho(p = 1/2) = \frac{1}{2}\{|\chi^+\rangle\langle\chi^+| + |\chi^-\rangle\langle\chi^-|\}$, where $|\chi^\pm\rangle = \frac{1}{2}\{|H_1H_2\rangle \pm |V_1V_2\rangle\} \otimes \{\pm|H_3\rangle + |V_3\rangle\}$. This means that there are no other correlations between Charlie and the rest of the system besides the classical ones. Despite this, Charlie's capability of controlling the teleportation protocol remains unchanged [32].

To emphasize the significant role of tripartite (fully entangled and biseparable) states in the CQT protocol, let us discuss the difference between CQT and the classical control of ordinary teleportation. Suppose that Alice and Bob share either of two Bell states, $|\phi_{12}^{+}\rangle = (1/\sqrt{2})\{|H_1H_2\rangle + |V_1V_2\rangle\}$ or $|\phi_{12}^{-}\rangle = (1/\sqrt{2})\{|H_1H_2\rangle - |V_1V_2\rangle\}$, with equal probability, and the information of which Bell state is truly shared belongs only to Charlie. Then, the teleportation between Alice and Bob is successfully performed when Charlie broadcasts the information he has and is forbidden otherwise. Analogously, for the quantum protocol, the GHZ state can be written in the form $|\mathcal{G}^{(1)}\rangle = (1/\sqrt{2})(|\phi_{12}^{+}\rangle|+_3\rangle + |\phi_{12}^{-}\rangle|-_3\rangle)$, where the information "which Bell state" is encoded in the Charlie's qubit via a QND-type interaction, i.e., in the basis of $|+_3\rangle$ and $|-_3\rangle$. However, in this case the information is quantum mechanically possessed by Charlie, and hence any measurement in the logical basis implies that the teleportation is forbidden principially and not just by Bob's ignorance of Charlie's outcome (e.g., it cannot be restored by any eavesdropping). This is the main difference with the classical counterpart, valid even for the biseparable mixture $\rho(p = 1/2)$. Note that measurement in any other basis than $|0/1\rangle$ allows us to restore the teleportation at least probabilistically by implementing an appropriate filtering.

Experimental implementation.—The experimental setup consists of a four-photon source, a GHZ preparation stage and three stations operated by Alice, Bob, and Charlie (see Fig. 1). Photons are generated in a BBO crystal cascade [36] by means of spontaneous parametric down-conversion pumped by femtosecond pulses at 413 nm. The first pair of photons (modes 1 and 2) is generated while the pumping pulse propagates through the crystals in the forward direction. Subsequently, it gets reflected on a mirror and generates a second pair of photons (modes 3 and 4) on its way back. Pump beam polarization is controlled by a half-wave plate (HWP) and a polarization dispersion line (BDA) to correct for polarization group velocity dispersion [37]. Proper polarization of the pumping beam allows it to generate photons in modes 1 and 2 in an entangled state $|\Phi_{12}^{+}\rangle = (1/\sqrt{2})\{|H_1H_2\rangle - i|V_1V_2\rangle\}$. Photons 3 and 4 are collected from only one of the crystals, obtaining thus a separable state $|H_3H_4\rangle$. After being subjected to procedures described below, the photons are collected to single-mode optical fibers and detected by a set of four avalanche photodetectors. Simultaneous fourfold coincidence detections are recorded.

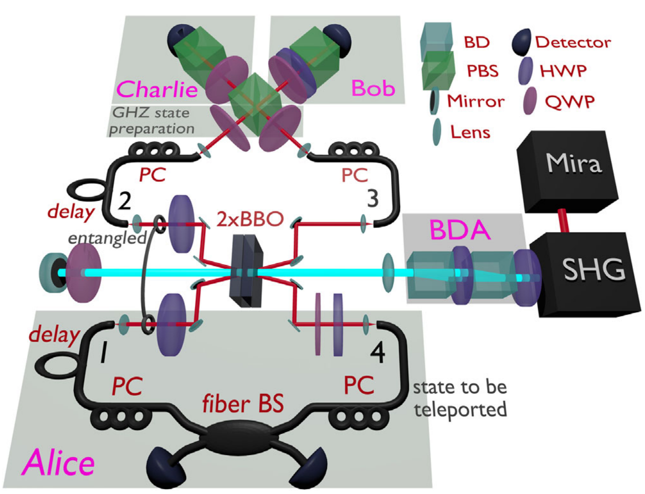

FIG. 1. Scheme of the experimental setup for the controlled quantum teleportation as described in the text. The components are labeled as follows: BS, beam splitter; PBS, polarizing beam splitter; PC, polarization controller; HWP, half-wave plate; QWP, quarter-wave plate; BDA, beam displacer assembly; BD, beam displacer. The abbreviation SHG stands for the second harmonic generation, and Mira is the femtosecond laser system manufactured by Coherent.

In the next step, we generate the GHZ state $|\mathcal{G}^{(1)}\rangle$ in Eq. (1). To achieve that, the polarization of the photon in mode 3 is changed to circular, $|R_3\rangle = (1/\sqrt{2})\{|H_3\rangle + i|V_3\rangle\}$, and then it overlaps with the photon in mode 2 on the polarizing beam splitter (PBS). With a success probability of $\frac{1}{2}$, these two photons leave the PBS by different output ports and, together with the photon in mode 1, form the GHZ state $|\mathcal{G}^{(1)}\rangle$ [38]. Although we have not repeated the GHZ state preparation testing in the same way as the authors of Ref. [39], we have performed testing of individual component blocks of our setup—namely, we have observed purities of about 90% of the generated Bell state (modes 1 and 2) together with similarly pure Bell state preparation with photons in mode 2 and 3 on the PBS. (Note: this was tested when projecting mode 1 onto the $|H\rangle$ state.) We label the photon modes leading to Bob's and Charlie's apparatus by the numbers 2 and 3, respectively.

Alice subsequently encodes the to-be-teleported qubit into the polarization state of the photon in mode 4 using a HWP and a QWP. Then she projects the state of photons in modes 1 and 4 onto a singlet Bell state $|\psi_{14}^{-}\rangle$ by post-selecting on photon antibunching behind a balanced fiber beam splitter.

At this point, Charlie decides whether to allow or deny the teleportation. In order to allow it, Charlie projects the state of the photon in mode 3 to circular polarization. Similarly, to deny the teleportation, Charlie projects his photon onto horizontal polarization. Due to the nature of coincidence-based measurement, Alice's and Charlie's actions happen simultaneously.

Bob receives the teleported qubit encoded in the state of the photon in mode 2. He then subjects this photon to a polarization projection measurement using a sequence of a HWP, a QWP, and a polarizer. To evaluate the performance of the teleportation, we measure the fidelity of the teleported state $F = \langle\psi_4|\rho_2|\psi_4\rangle$, where ρ_2 is the resulting state of the photon in mode 2 (mixed in general). Based on the coincidence counts observed for different combinations of input states encoded by Alice and Bob's projection measurement, F is calculated as [40]

$$F = \frac{f_{\parallel}}{f_{\parallel} + f_{\perp}}, \tag{2}$$

where $f_{\parallel}$ stands for the coincidence rate observed when Bob projects on the state identical to Alice's encoding choice. Likewise, $f_{\perp}$ stands for the coincidence rate observed when Bob projects on an orthogonal state.

Experimental results.—We test the CQT protocol on a linearly polarized, balanced ($\alpha = \beta$) input state, i.e., $|\psi_4\rangle = (1/\sqrt{2})\{|H_4\rangle + |V_4\rangle\}$. This choice of $|\psi_4\rangle$ is quite natural, i.e., by the very description of the GHZ state preparation, as both $|H\rangle$ and $|V\rangle$ polarization can be considered as preferred directions in the experiment. Therefore, the input state polarized at 45° represents one of the most challenging tasks, and other commonly analyzed states yield an approximately equal or greater teleportation fidelity [20,35,39,41].

For the purposes of preliminary testing, in the first experiment we have operated our setup in the regime of ordinary uncontrolled quantum teleportation [1]. To achieve this, the polarization of the third photon is kept horizontal to be directly transmitted on PBS onto Charlie's detector. As for Bob's projection measurement, it is performed using the combination of HWP and PBS. Again, fourfold coincidences are registered, this time with the photon in mode 3 serving only as a trigger. Based on Eq. (1), the faithfulness of uncontrolled quantum teleportation has been found to be $F = 83.1\% \pm 4.9\%$, which is in line with recent experiments on photonic qubits (e.g., Refs. [20,39]).

The probabilistic nature of our four-photon source causes undesired higher-order SPDC terms to contribute to the detected signal. The presented fidelities therefore need to be corrected for these imperfections of the source to be faithful characteristics of the protocol implementation itself. A detailed analysis of these corrections is presented in the Supplemental Material [42].

In the second experiment, we have performed the teleportation on the GHZ state. In order to do this, we set back the polarization of the photon in mode 3 to circular, $|R_3\rangle$, thus generating the $|\mathcal{G}^{(1)}\rangle$ channel. By proper operating of the QWP and the polarizer, we analyze two scenarios of teleportation. In the first one, when Charlie allows for the teleportation, the fidelity calculated from the fourfold coincidences $F_{\text{allowed}} = 77.9\% \pm 8.1\%$. This result exceeds the classical limit of 66.7% and thus certifies the quantum nature of our teleportation experiment. In the second scenario, i.e., without Charlie's permission, the fidelity of $F_{\text{denied}} = 57.2 \pm 5.0\%$ meets the second condition of CQT. These results clearly show the success of CQT through the GHZ state of discrete variables. Similar measurements have been performed for the $|\mathcal{G}^{(2)}\rangle$ channel.

TABLE I. Measured fidelities for the linearly polarized input state $|\psi_4\rangle = (1/\sqrt{2})\{|H_4\rangle + |V_4\rangle\}$ and several teleportation channels: ρ_{ref} denotes a two-photon teleportation channel $|\Phi_{12}^{+}\rangle\langle\Phi_{12}^{+}|$ with the photon in mode 3 serving only as a trigger (see text), while $\rho(p)$ is given in Eq. (1). The last two columns correspond to the process when controller allows and denies the teleportation, respectively. All uncertainties are obtained by numerical calculations assuming a Poisson distribution of the fourfold coincidences.

Channel	$F_{\text{allowed}}(\%)$	$F_{\text{denied}}(\%)$
ρ_{ref}	83.1 ± 4.9	...
$\rho(p=0)$	77.9 ± 8.1	57.2 ± 5.0
$\rho(p=1)$	83.0 ± 7.5	51.8 ± 6.7
$\rho(p=1/2)$	80.2 ± 5.7	55.1 ± 5.0

This kind of GHZ state can be prepared by slight modification of the experimental setup. Specifically, both HWPs in mode 2 and in Bob's analyzer part are rotated by $\pi/4$. The corresponding fidelities are presented in Table I and visualized in Fig. 2. What is important is that in this configuration, the CQT is realized with an even greater fidelity of around 83% with a simultaneous decrease of F_{denied}.

Now, we perform the CQT through the statistical mixture $\rho(p)$ given in Eq. (1) when $p = 1/2$. To emulate this, we have simply summed up the respective coincidence counts obtained for $|\mathcal{G}^{(1)}\rangle$ and $|\mathcal{G}^{(2)}\rangle$. We find the resulting fidelity to be $F_{\text{allowed}} = 80.2\% \pm 5.7\%$ when Charlie permits the teleportation and $F_{\text{denied}} = 55.1\% \pm 5.0\%$ otherwise. This means that both conditions of CQT are satisfied also for the $\rho(p = 1/2)$ channel, despite it belonging to the biseparable

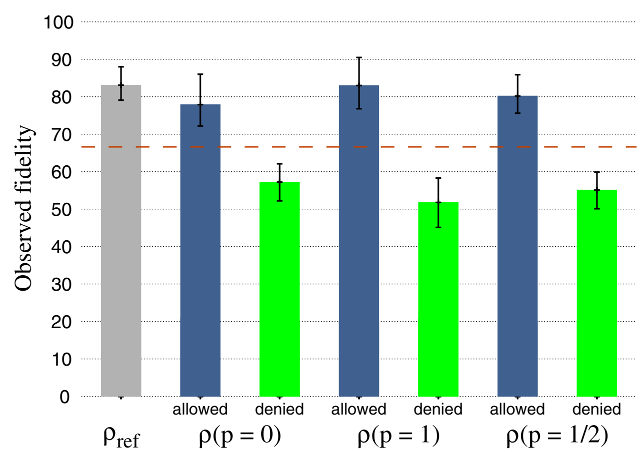

FIG. 2. Teleportation fidelities measured for several quantum channels (see Table I). The gray bar refers to a standard uncontrolled quantum teleportation performed as a preliminary test. Blue bars correspond to teleportation faithfulness F_{allowed} achieved with the controller's permission, while F_{denied} results are shown in green. The horizontal dashed line marks the classical limit of 66.7%. Black line segments represent the confidence intervals.

class and there being no entanglement between Charlie's photon and the remaining two photons. In order to verify this fact experimentally, one can use the well-known methods such as θ protocol [47] or XY protocol [48]. In fact, both protocols have been successfully applied recently for experimental detection of tripartite entanglement in the GHZ states [47]. Since we use the entangled photon source with the same efficiency as in Ref. [47], the outcome of multipartite entanglement detection protocol is similar, and it is out of the scope of this Letter. To the best of our knowledge, this is the first demonstration of CQT based on the biseparable states.

Conclusions.—In summary, we have presented a proof-of-principle experimental demonstration of CQT through various kinds of GHZ states of discrete variables with the fidelities well above the classical limit. Our experiment shows that tripartite entanglement is not a necessary recourse for CQT. In fact, the classical correlation between a controller and a joined "sender-receiver" subsystem is sufficient in order to allow or forbid the teleportation. In a broader context, our results open new possible ways of implementation of CQT, lowering the requirements for state preparation and preservation, which is of practical importance in realizing more complicated quantum computation and quantum communications among many parties. In particular, one can consider the three-qubit Werner state $(\rho_W = q|\mathcal{G}^{(1)}\rangle\langle\mathcal{G}^{(1)}| + (1-q)I/8)$, which can be thought of as an imperfect preparation of the GHZ quantum channel. The ability to perform CQT through biseparable Werner states (i.e., for $1/3 < q \leq 3/7$) implies that the CQT is less fragile against noise than the tripartite entanglement, as described in Ref. [32]. Furthermore, as the three-qubit Werner states are invariant under qubit permutation, the CQT can be successfully performed no matter how we split the qubits between Alice, Bob, and Charlie. In our experiment, despite the probabilistic nature of the GHZ state preparation and the teleportation itself, the roles of Alice, Bob, and Charlie can also be swapped (see the Supplemental Material for detailed analysis [42]). In other words, fundamentals of our experiment can be easily used in the demonstration of a QNT for biseparable states. This conclusion is in contrast with common opinion: "Only if we use a fully inseparable tripartite entangled state can we succeed in teleportation between an arbitrary pair in the network" [23]. The explanation of this phenomenon is based on the concept of localizable entanglement [49], which plays a central role in CQT and QNT [32]. Our experiment shows nontrivial application of localizable entanglement, leading to results which cannot be predicted by standard quantifiers of multipartite entanglement.

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[*]artur.barasinski@upol.cz
[†]acernoch@fzu.cz
[‡]k.lemr@upol.cz

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