



Deterministic quantum teleportation of a path-encoded state using entangled photons

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Abstract

Quantum teleportation enables a way to transmit an arbitrary qubit state from one location to another. The standard scheme for teleportation in optical setups involves three photons: an entangled photon pair and a photon carrying the quantum state to be teleported. The interaction between photons in such schemes makes quantum teleportation probabilistic. Here, we demonstrate a novel scheme for deterministic quantum teleportation of an arbitrary qubit state using only a polarization-entangled photon pair in a linear optical setup. By introducing the path degree of freedom (DOF) to one of the entangled photons and encoding the arbitrary qubit state into it, we achieve complete Bell state discrimination within our measurement strategy. This enables deterministic teleportation of a qubit state in an optical scheme with high fidelity. We report an average teleportation fidelity of 0.88 ± 0.04 . The dependence of fidelity on the visibility of single-photon interference used in our scheme highlights the possibility of further improving the teleportation fidelity.

Keywords: Deterministic teleportation; Photonic qubits

1 Introduction

Quantum teleportation enables the reconstruction of an arbitrary quantum state between two spatially separated particles without physically transmitting the state or transferring the particle itself [1–3]. By utilizing a shared entangled state between two parties and a classical communication channel, quantum teleportation has been theoretically proposed [4–6] and experimentally demonstrated across various physical systems [7–15]. Among these implementations, the ability to distribute entangled photons over long distances has emerged as a key resource for quantum communication, distributed quantum networks, and quantum computation [16–18]. This progress has further led to the teleportation of qubits encoded in different degrees of freedom (DOFs) [19], as well as in higher-dimensional states of photons [20–23].

Despite these advances, teleportation in a photonic system relying solely on linear optical settings faces a fundamental challenge due to the probabilistic nature of the photon-photon interaction. In particular, the inherently probabilistic nature of photon-photon interactions limits the success probability of the Bell-State measurement (BSM), which generates the classical information necessary for reconstructing the teleported state. Consequently, the maximum achievable efficiency for performing BSM using linear optical

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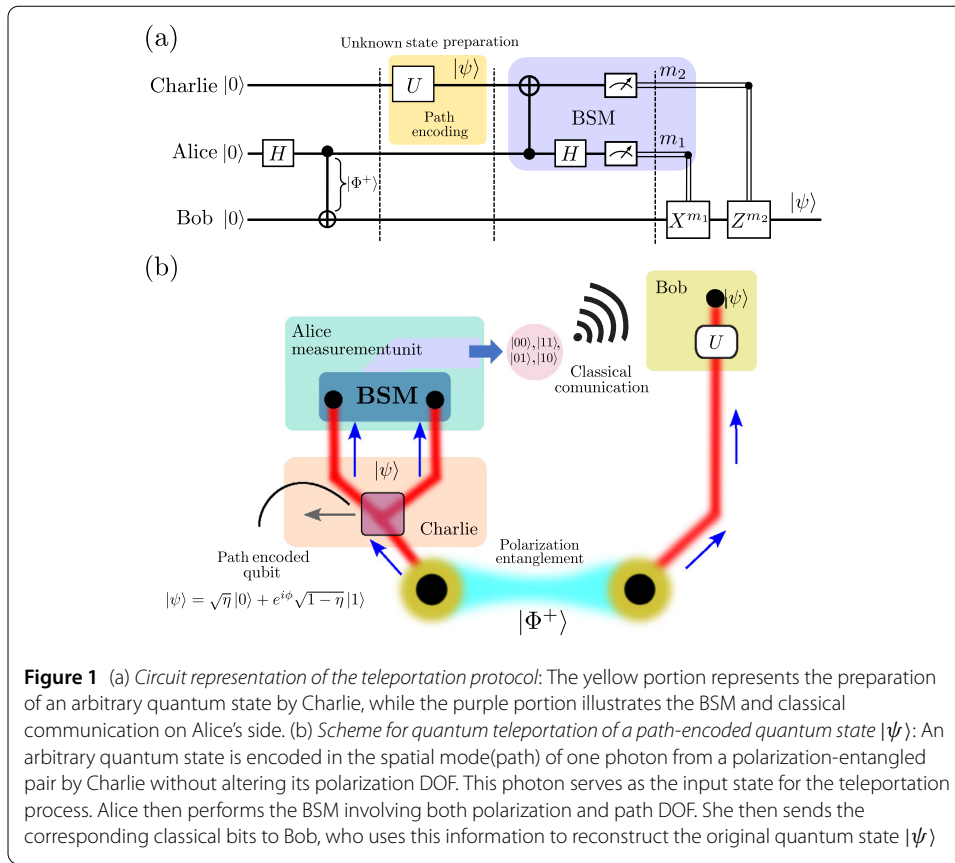


Figure 1 (a) Circuit representation of the teleportation protocol: The yellow portion represents the preparation of an arbitrary quantum state by Charlie, while the purple portion illustrates the BSM and classical communication on Alice's side. (b) Scheme for quantum teleportation of a path-encoded quantum state $|\psi\rangle$: An arbitrary quantum state is encoded in the spatial mode (path) of one photon from a polarization-entangled pair by Charlie without altering its polarization DOF. This photon serves as the input state for the teleportation process. Alice then performs the BSM involving both polarization and path DOF. She then sends the corresponding classical bits to Bob, who uses this information to reconstruct the original quantum state $|\psi\rangle$

elements, and thus achieving teleportation, remains at 50% [24]. To overcome this limitation, various approaches that exploit the multiple degrees of freedom of a single photon have been proposed. Notably, the first protocol for teleportation of photonic qubit states encoded in both polarization and spatial modes using complete hyperentangled Bell-state analysis (HBSA) based on cross-Kerr nonlinearity was proposed [25]. This was later extended to the logic-qubit regime, offering robustness against decoherence by encoding logical qubits across multiple physical qubits [26]. More recently, hyperentanglement in polarization and spatial modes has also been applied to one-step quantum secure direct communication (QSDC), enabling two-way secure communication via Bell-state measurements [27]. A few deterministic teleportation protocols have been pr-

oposed and realized in other physical platforms, particularly those employing hybrid entanglement in continuous-variable and atomic systems [28–30]. Beyond discrete variable (qubit) systems, quantum teleportation has also been demonstrated in the continuous-variable approach [31–36], as well as in hybrid configurations combining both regimes [37]. Furthermore, multipartite quantum teleportation protocols have been explored theoretically and experimentally in recent years [38–40]. Recent progress in long-distance quantum communication—such as the hyperentanglement over 50 km of noisy optical fiber and the use of independent heralded single-photon sources—represents significant progress toward developing robust and scalable quantum channels [41, 42]. These developments highlight the need for deterministic and resource-efficient photonic teleportation schemes that can be readily integrated into quantum network architectures.

Here, we demonstrate the deterministic teleportation of qubit states encoded in spatial DOF (path mode) using a photon pair entangled in polarization DOF, as compared to three photons in the standard protocol. Encoding an arbitrary qubit state in path mode on the entangled photon by Charlie does not invoke any photon-photon interaction on the Alice side. This enables deterministic and controlled operations on qubits with Alice, resulting in deterministic teleportation of an arbitrary qubit state from Alice to Bob. This demonstration differs from earlier demonstrations that encoded a qubit to be teleported in the polarization DOF of a photon and used the path DOF as an additional qubit [43]. Earlier reported works employing path encoded qubit states also involve higher dimensional state teleportation with the best fidelity of 0.75 using probabilistic BSM [20, 21], unlike the scheme reported here, which demonstrates a deterministic teleportation. Previously, a known quantum state transfer has been demonstrated in polarization and orbital angular momentum DOF via teleportation [44], but in our scheme, an arbitrary unknown quantum state teleportation is being demonstrated. That is, Alice can teleport a path-encoded qubit state without knowing the state being teleported.

We report an average teleportation fidelity of 0.88 ± 0.04 with highest being 0.99 for state $|0\rangle$ and lowest being 0.803 for state $|R\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$. The fidelity of teleportation is dependent on the interference visibility of the single-photon interference employed for BSM in this scheme. With the increase in single photon interference visibility near cent percent teleportation can be achieved. In quantum communication protocols for teleporting quantum states or qubit states in photonic quantum computation involving path degree of freedom [45, 46], the deterministic scheme presented here will be more easily employable compared to other known approaches and can be extended to long-distance quantum teleportation.

2 Experimental setup

Suppose Alice wants to teleport an arbitrary, unknown qubit state,

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

prepared by Charlie to Bob where $|0\rangle$ and $|1\rangle$ denote the computational basis states, and the complex coefficients α, β satisfy $|\alpha|^2 + |\beta|^2 = 1$. To achieve this, she shares an entangled quantum channel and a classical communication channel with Bob. The arbitrary quantum state $|\Psi\rangle$ is encoded in the spatial mode of one photon from an entangled pair with Alice, without altering the polarization by Charlie. Alice receives this unknown qubit as well as the associated polarization qubit and performs a joint BSM using a single-photon interferometer on the path qubit state. The measurement results are then transmitted to Bob via the classical channel, who applies the corresponding unitary operation to reconstruct the quantum state on his side. The entire process of local operations and classical communication (LOCC) is carried out based on the coincidence measurement between the photons of Alice and Bob. This approach uses only a photon pair entangled in polarization DOF to represent a three-qubit state by invoking the spatial mode of one of the entangled photons. The unknown quantum state encoded in this spatial mode is teleported. Hence, there is no photon-photon interaction, which makes this scheme deterministic in comparison to other discrete variable photonic teleportation schemes.

Figure 1(b), schematically illustrates the proposed quantum teleportation scheme, where the quantum state to be teleported is encoded in the path DOF using only an entangled photon pair in polarization degree of freedom shared between Alice and Bob. The quantum state to be teleported is encoded on the entangled photon by introducing a path degree of freedom by Charlie. This is done by passing it through a variable beam splitter (for practical reasons, we have considered a beam splitter with a suitable phase shifter) with a splitting ratio corresponding to the desired qubit state Alice wants to teleport to Bob. The action of the beam splitter is independent of the polarization state of the entangled photon Alice shares with Bob. By performing the BSM on the polarization and path qubit state with Alice involving single photon interference on the path qubit state, the measurement output from the two-qubit state is obtained. The classical outcome of the measurement is communicated to Bob, and he will perform the corresponding unitary operation mapped to the classical information, thereby reconstructing the qubit state on the polarization qubit with him. Figure 1(a) presents the equivalent quantum circuit representation of the optical scheme. The second and third qubits correspond to the polarization-entangled photon pair. The qubit state to be teleported is encoded on Alice's photon via a unitary operator (U) in the form of a variable beam splitter. The C-NOT operation and Hadamard operation, followed by the joint measurement on the first two qubits, represent the BSM on the path and polarization state of the photon with Alice. To perform the C-NOT operation on the path qubit state, one has to involve a single photon interferometer [46]. In Fig. 2, the complete experimental setup for quantum teleportation is shown. In *Methods*, entangled photon source generation and its characterization are presented.

One of the entangled photon pairs, denoted as A, is sent to Charlie, who encodes an unknown qubit state to be teleported. The other photon, B, is sent to Bob for state reconstruction. To encode the arbitrary qubit state, photon A is passed through a variable beam-splitter (BS) unit held by Charlie, whose output forms the path-encoded qubit state. A general beam splitter matrix $B(\theta, \phi)$ is expressed as:

$$U_{BS}(\theta, \phi) = e^{i\phi/2} \begin{bmatrix} \cos \theta & i \sin \theta \\ i \sin \theta & \cos \theta \end{bmatrix}.$$

This matrix governs the transformation of creation and annihilation operators through the beam splitter. For an input mode $|0\rangle$, the output is

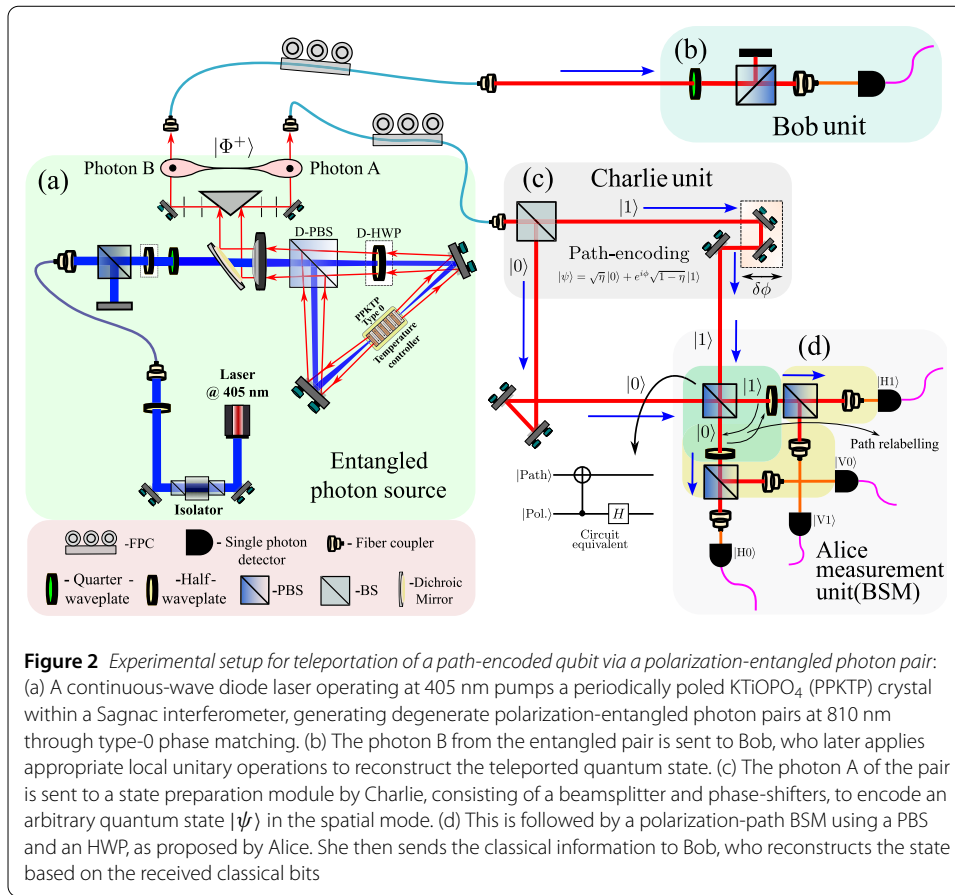
$$|\psi\rangle_{\text{out}} = \cos(\theta) |0\rangle + i \sin(\theta) |1\rangle,$$

up to a global phase. Introducing a relative phase ϕ between spatial modes yields the general path-encoded quantum state

$$|\psi\rangle_{\text{out}} = \cos(\theta) |0\rangle + ie^{i\phi} \sin(\theta) |1\rangle.$$

This corresponds to the qubit state to be teleported to Bob. For convenience, we write it as

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle = \sqrt{\eta} |0\rangle + e^{i\phi} \sqrt{1-\eta} |1\rangle, \quad (2)$$



such that $|\alpha|^2 + |\beta|^2 = 1$, where η and $(1 - \eta)$ denote the reflection and transmission probabilities, respectively. This transformation leaves other degrees of freedom, such as polarization, unaffected. Non-polarizing beam-splitters with different splitting ratios are used to generate such states; however, the operation is constrained by the limited availability of precise splitting ratios and the residual difference in S and P polarization splitting due to fabrication tolerances. Nevertheless, arbitrary path-encoded quantum states can be prepared using suitable linear optical components, allowing mapping to any point on the Bloch sphere through the tunability of the variable beam splitter setup [47]. This actually showcases the versatility of our scheme for arbitrary qubit encoding. The path lengths are matched within the coherence length of the photons, and the phase stability is maintained using a piezoelectric actuator. In addition to the path, other degrees of freedom can also be exploited to realize arbitrary single-qubit states [48].

Prior to introducing the arbitrary path state, the path encoding of photon A is incorporated into the initial polarization entangled state,

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|H\rangle_A |0\rangle_{AP} |H\rangle_B + |V\rangle_A |0\rangle_{AP} |V\rangle_B \right), \quad (3)$$

where $|0\rangle_{AP}$ represents the spatial mode of photon A before path encoding. Charlie encodes the arbitrary qubit state using the variable beam-splitter, resulting in the three-qubit

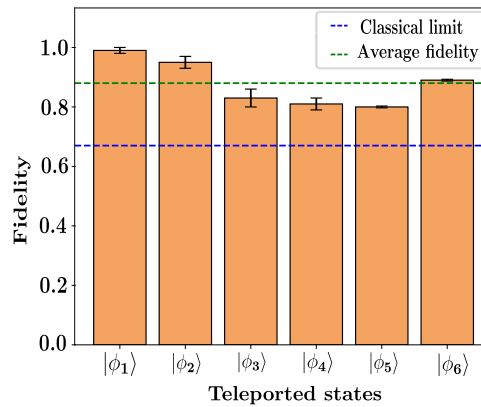


Figure 3 Experimental results for quantum teleportation: Coincidence counts between the detectors on Alice's side and Bob's side were used to obtain the Stokes parameters and reconstruct the polarization state of Bob's photon. Six states: $|\phi_1\rangle = |0\rangle$, $|\phi_2\rangle = |1\rangle$, $|\phi_3\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$, $|\phi_4\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$, $|\phi_5\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$, $|\phi_6\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$, were encoded and teleported over a distance of 2 meters with an average fidelity of $F = 0.88 \pm 0.04$

state,

$$|\Psi\rangle_1 = \frac{1}{\sqrt{2}} \left(|H\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |H\rangle_B + |V\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |V\rangle_B \right). \quad (4)$$

This state is suitable for teleporting one qubit using only two entangled photons (in polarization degree) and an additional path degree of freedom.

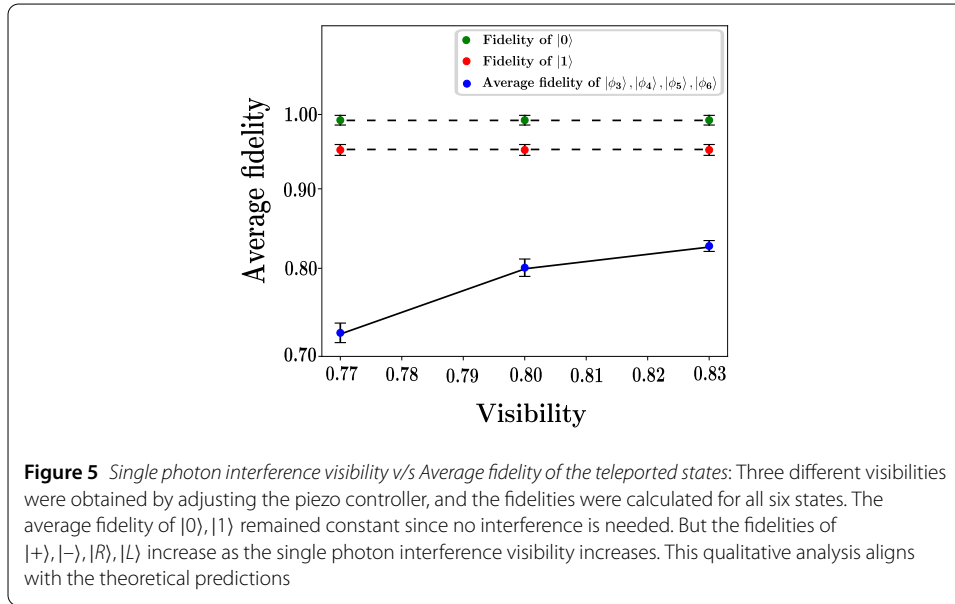
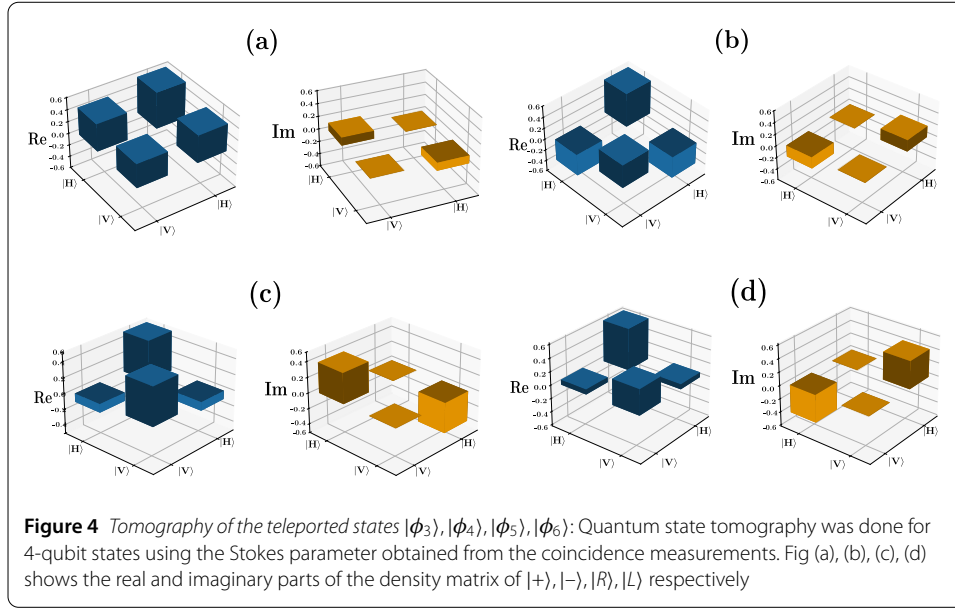
Now, teleportation proceeds via a Bell-state measurement (BSM) on Alice's qubits. The first step employs a polarizing beam splitter (PBS), acting as a C-NOT gate operation with polarization as the control and path as the target. This operation transforms the state $|\Psi\rangle$ into:

$$|\Psi\rangle_2 = \frac{1}{\sqrt{2}} \left(|H\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |H\rangle_B + |V\rangle_A (\alpha |1\rangle_{AP} + \beta |0\rangle_{AP}) |V\rangle_B \right). \quad (5)$$

To remain consistent with the mathematical formalism, the path after PBS is relabeled in Fig. 2, as suggested in Ref. [46]. A half-wave plate (HWP) then implements the Hadamard operation on the polarization qubit state. The Hadamard operation should produce a coherent superposition. It is achieved by allowing a single photon to interfere from two paths and ensuring that we obtain single-photon interference with high visibility. Maintaining high interference visibility is essential to preserving the purity of the teleported state. In our setup, we achieved a maximum visibility of 83%. After the complete BSM, the final state is

$$|\Psi\rangle_F = \frac{1}{\sqrt{2}} \left(|H\rangle_A |0\rangle_{AP} (\alpha |H\rangle_B + \beta |V\rangle_B) + |V\rangle_A |0\rangle_{AP} (\alpha |H\rangle_B - \beta |V\rangle_B) + |H\rangle_A |1\rangle_{AP} (\beta |H\rangle_B + \alpha |V\rangle_B) + |V\rangle_A |1\rangle_{AP} (\beta |H\rangle_B - \alpha |V\rangle_B) \right). \quad (6)$$

For measurement of the output state, a PBS directs the four output states to distinct detectors. Coincidence detections between any one of Alice's detectors (Photon A) and Bob's (Photon B) yield two classical bits, which are communicated to Bob. Based on this



information, Bob applies the corresponding unitary operation on the photon on his side to reconstruct the qubit state originally encoded by Alice in the path degree of freedom. We prepared and teleported 6 input states: $|\phi_1\rangle = |0\rangle, |\phi_2\rangle = |1\rangle, |\phi_3\rangle = (|0\rangle + |1\rangle)/\sqrt{2}, |\phi_4\rangle = (|0\rangle - |1\rangle)/\sqrt{2}, |\phi_5\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}, |\phi_6\rangle = (|0\rangle + i|1\rangle)/\sqrt{2}$.

Figure 4 presents the fidelity of all the 6 teleported states, with an average fidelity $F = 0.88 \pm 0.04$, which is greater than the classical bound of 0.67. The highest fidelity we have obtained is 0.99 for teleporting the state $|0\rangle$ and the lowest of 0.803 for state $|R\rangle = (|0\rangle - i|1\rangle)/\sqrt{2}$. Quantum state tomography of the four representative teleported states is shown in Fig. 4. In Fig. 5, the Fidelity of the teleported state for different single-photon interference visibility is shown.

This indicates that the fidelity of teleportation is dependent on the interference visibility of the single-photon interference used for BSM in the scheme. The average fidelities for $|0\rangle$ and $|1\rangle$ remain constant, as no interference is required for BSM on them. However, for the state $|1\rangle$, an additional reflection in the path caused reduced coupling, resulting in a lower fidelity compared to the state $|0\rangle$. With this, we can establish that by increasing the single-photon interference visibility, near 100% teleportation can be achieved. This ensures a robust and deterministic non-classical teleportation. A detailed analysis of the teleportation fidelity is provided in the *Methods* section.

3 Conclusion

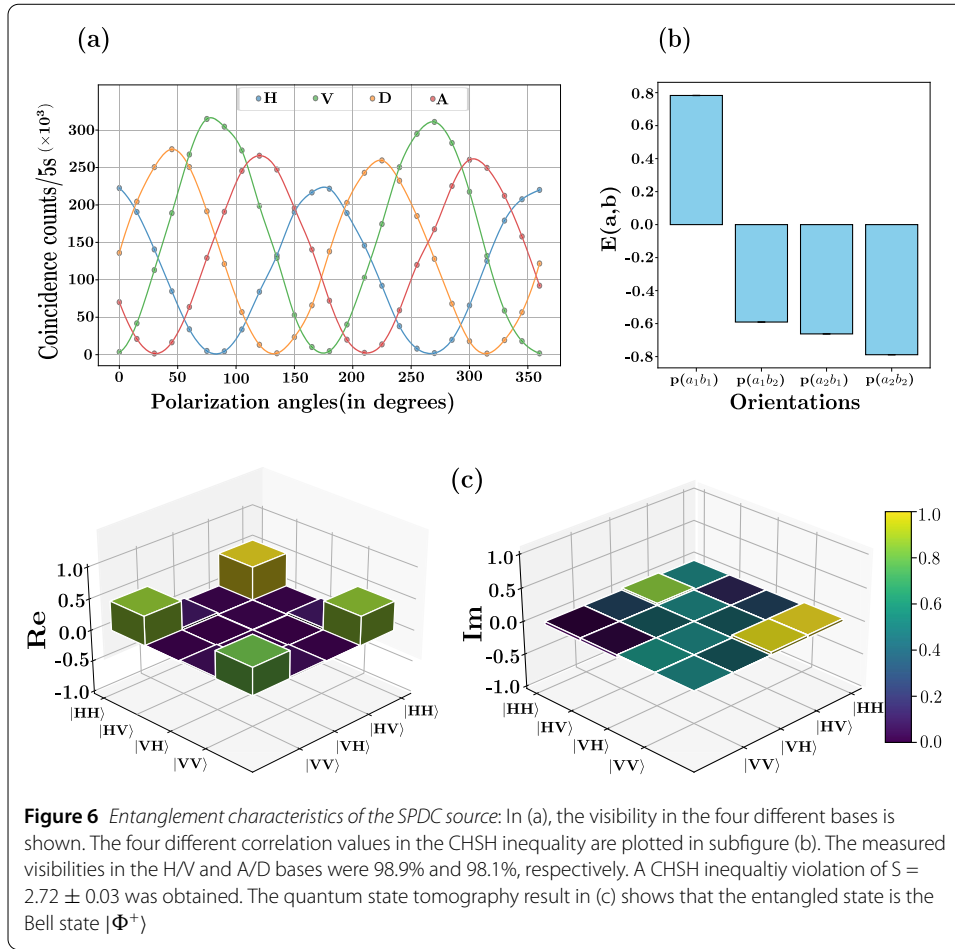
In summary, we have reported a deterministic teleportation of qubit states with fidelities higher than those of other qubit teleportation protocols reported in photonic systems. The possibility of encoding any arbitrary qubit state into the path degree of freedom of an entangled photon pair makes the scheme readily applicable to practical applications. The role of single-photon interference in the path qubit state is crucial for achieving high teleportation fidelity. Notably, except for teleporting the states $|0\rangle$ or $|1\rangle$, the interference in the path qubit state directly influences the fidelity of the teleported state. By employing a high-precision single-photon interferometer on the path qubit state for BSM, a near cent percent fidelity can be achieved. Although the experiment was performed with a separation of only two meters between Alice and Bob, the achievable distance is fundamentally constrained by the ability to share entangled photons between two parties with high fidelity. The proposed scheme can be adopted to encode qubit states into other degrees of freedom of photons, thereby realizing deterministic teleportation. This technique can also be utilized for the teleportation of higher-dimensional quantum states and to enhance the probability of teleportation. The demonstrated high fidelity, combined with the deterministic nature of our scheme, opens up new possibilities for practical quantum communication, quantum network, and quantum computation applications. In extending our teleportation scheme to longer distances, one would face challenges such as photon loss, polarization drift, timing synchronization, and phase instability. These can be mitigated by employing low-loss and high-extinction-ratio fibers with real-time polarization control, precise time synchronization systems, and phase-stabilization techniques. Incorporating such strategies could enable practical deployment of our scheme over large-scale quantum networks.

4 Methods

Entangled Photon Source: A polarization entangled photon pair AB represented by the state,

$$|\Phi^+\rangle_{AB} = \frac{|H\rangle_A |H\rangle_B + |V\rangle_A |V\rangle_B}{\sqrt{2}} \quad (7)$$

is prepared using a PPKTP crystal (Raicol-crystal) via spontaneous parametric down conversion (SPDC) process, where quasi-phase matching is achieved through periodic poling with a period of $3.425\mu\text{m}$. This corresponds to type-0 phase matching, and we have utilized a Sagnac-loop configuration to generate the polarization entanglement [49, 50]. Figure 2(a) presents the entangled photon pair generation unit; the results characterizing



the entangled photon pair used for quantum teleportation are shown in Fig. 6. The measured visibilities in the H/V and A/D bases were 98.9% and 98.1% respectively Fig. 6(a). The CHSH inequality violation, $S = 2.72 \pm 0.03$ was obtained from the correlation values $E(a,b)$ shown in Fig. 6(b). The quantum state tomography results in Fig. 6(c) show that the entangled state is the Bell state $|\Phi^+\rangle$.

Teleportation fidelity analysis: Our scheme achieves superior teleportation fidelity compared to previous works through its minimal complexity design. While the fidelity falls short of unity due to experimental imperfections, we identify three primary limiting factors. The first is entanglement purity. The output state from the entanglement source can be expressed as

$$\Psi = p |\Psi\rangle_{AB} \langle\Psi|_{AB} + (1-p) \hat{\mathbb{I}} \quad (8)$$

where p denotes the purity parameter. When $p = 1$, the state is a pure Bell state.

However, in practical scenarios, $p \leq 1$, indicating the presence of noise or mixedness in the state. This reduction in purity leads to degraded entanglement quality, which in turn lowers the fidelity of the quantum teleportation protocol. Our polarization entangled photon source employs a type-0 Sagnac interferometer configuration, where the purity of the entangled state critically depends on the efficient collection of photon pairs emitted at di-

ametrically opposite points of the SPDC ring. A crucial consideration is that the diameter of the SPDC ring is temperature-dependent, as changes in crystal temperature alter the phase-matching conditions. This thermal variation shifts the ring diameter, thereby affecting the optimal collection points and ultimately influencing the quality of entanglement. Under our experimental conditions, the maximum entanglement visibility we achieve is 98.9% and 98.1% in H/V and A/D basis, respectively. Another contributing factor is the efficiency of the Bell state measurement. In our implementation, the teleportation fidelity of any superposition $\alpha |0\rangle + \beta |1\rangle$ of path-encoded qubits is ultimately constrained by the single-photon interference visibility at the Bell-state measurement (Fig. 5). In a conventional Mach–Zehnder interferometer, the interference visibility is primarily determined by (i) precise matching of the optical path lengths, (ii) optimal spatial overlap of the two arms, and (iii) maintenance of a well-defined polarization state. In our setup, since the PBS is used to recombine the two paths $|0\rangle$ and $|1\rangle$, a linear polarizer is placed immediately after the PBS to erase the which-path information and recover path indistinguishability. However, the finite extinction ratio of this polarizer imposes an additional upper limit on the achievable interference visibility and consequently restricts the maximum teleportation fidelity. Finally, non-ideal optical components and random errors also affect the fidelity. The non-ideal behavior of our optical components introduces deviations from theoretical predictions. Specifically, the non-polarizing beam splitter (BS) used by Charlie for state encoding demonstrates polarization-dependent splitting ratios. Under ideal conditions, the transformation rules would be:

$$\begin{aligned} |H\rangle_A |0\rangle_{AP} |H\rangle_B &\rightarrow |H\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |H\rangle_B \\ |V\rangle_A |0\rangle_{AP} |V\rangle_B &\rightarrow |V\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |V\rangle_B. \end{aligned}$$

However, in our experimental implementation, we observe polarization-dependent deviations:

$$\begin{aligned} |H\rangle_A |0\rangle_{AP} |H\rangle_B &\rightarrow |H\rangle_A (\alpha |0\rangle_{AP} + \beta |1\rangle_{AP}) |H\rangle_B \\ |V\rangle_A |0\rangle_{AP} |V\rangle_B &\rightarrow |V\rangle_A (\gamma |0\rangle_{AP} + \delta |1\rangle_{AP}) |V\rangle_B \end{aligned}$$

, where $|\alpha|^2 + |\beta|^2 = 1$ and $|\gamma|^2 + |\delta|^2 = 1$, but with $\alpha \neq \gamma$ and $\beta \neq \delta$ due to the BS imperfections. Additional experimental uncertainties arise from manual adjustments of waveplates and mirrors, which can introduce potential alignment errors that may further impact the system's performance. These combined factors contribute to the reduced teleportation fidelity.

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Author contributions

A.T.K. and C.M.C. conceptualized the scheme. A.T.K., K.S. and S.P.D. designed and constructed the experimental setup. A.T.K., K.S. and S.P.D. performed the experiments and collected the data. A.T.K., K.S. and C.M.C. analyzed the data and wrote the manuscript with input from S.P.D.

Data availability

No datasets were generated or analysed during the current study.

Declarations**Competing interests**

The authors declare no competing interests.

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