SCIENCE CHINA
Information Sciences

• LETTER •

March 2024, Vol. 67, Iss. 3, 139402:1–139402:2
https://doi.org/10.1007/s11432-023-3873-6

Experimental realization of deterministic joint remote preparation of an arbitrary two-qubit pure state via GHZ states

Nachuan LI[1], Lu XU[2] & Jin-Ming LIU[1*]

[1] *State Key Laboratory of Precision Spectroscopy, School of Physics and Electronic Science, East China Normal University, Shanghai* 200241, *China;*
[2] *Hefei Origin Quantum Computing Technology Co., Ltd., Hefei* 230088, *China*

Received 4 April 2023/Revised 14 July 2023/Accepted 28 September 2023/Published online 19 February 2024

Quantum teleportation (QT) [1] enables secure transfer of an unknown quantum state between remote locations without physically transmitting the initial state. Unlike QT, with the sender possessing complete knowledge of the initial state, remote state preparation (RSP) [2] exhibits a tradeoff between the amount of the entanglement resource used and the classical communication cost. Due to the remarkable advantages, the RSP has been extensively studied [3] in recent years. Detailed background is provided in Appendix A. This work demonstrates the experimental realization of deterministic joint RSP (JRSP) for an arbitrary two-qubit pure state [4] on the Origin 6-qubit chip. We examine the impact of four environmental noises on the JRSP process by analytically deriving and numerically calculating the average fidelity. Furthermore, we conduct experiments on the origin noise quantum virtual machine (NQVM) platform to investigate JRSP for two different initial states under the influence of these noises. The experimental fidelities are closely consistent with the theoretical predictions. Additionally, we propose a method to improve fidelity by substituting the two Hadamard gates in the Greenberger-Horne-Zeilinger (GHZ) state preparation circuit with parameterized unitary operations, specifically for preparing specific states affected by phase-flip and amplitude-damping noises. Our work offers a pathway for further developing complex quantum communication protocols.

Protocol review. Suppose that there are three valid parties in the JRSP protocol: Alice and Bob as the senders and Charlie as the receiver. Alice and Bob wish to jointly prepare an arbitrary two-qubit pure state [5] in Charlie's location:

$$|\Psi\rangle = \alpha_0|00\rangle + \alpha_1 \mathrm{e}^{\mathrm{i}\lambda_1}|01\rangle + \alpha_2 \mathrm{e}^{\mathrm{i}\lambda_2}|10\rangle + \alpha_3 \mathrm{e}^{\mathrm{i}\lambda_3}|11\rangle, \quad (1)$$

where the real parameters $\lambda_k \in [0, 2\pi]$ $(k = 1, 2, 3)$, and $\alpha_j \geqslant 0$ $(j = 0, 1, 2, 3)$ meet $\sum_{j=0}^{3} \alpha_j^2 = 1$. We assume that Alice and Bob know α_j and λ_k, respectively. Initially, the three parties share two GHZ states $|\Phi\rangle_{024(135)} = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)_{024(135)}$ as their quantum channel, of which particles 0 and 1 belong to Alice, particles 2 and 3 belong to Bob, and others belong to Charlie. To help Charlie prepare the state $|\Psi\rangle$, Alice first measures her particles and transmits her measurement result to Bob and Charlie. According to Alice's measurement result, Bob performs the corresponding local operation (LO) on his particles. Subsequently, he measures his particles and informs Charlie of his measurement outcome. Based on the classical messages from Alice and Bob, Charlie performs the corresponding LO on particles 4 and 5 and restores the desired state $|\Psi\rangle$ with unit probability. Details of the JRSP protocol are described in Appendix B.

Experimental realization. Next, we demonstrate the above deterministic JRSP protocol on the Origin Wuyuan 6-qubit chip. Six different initial states are selected to be remotely prepared: $|\Psi_1\rangle = |00\rangle$, $|\Psi_2\rangle = |11\rangle$, $|\Psi_3\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$, $|\Psi_4\rangle = \frac{1}{2}(|0\rangle + \mathrm{i}|1\rangle)(|0\rangle + \mathrm{i}|1\rangle)$, $|\Psi_5\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, $|\Psi_6\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$. We reconstruct the density matrix of $|\Psi_1\rangle - |\Psi_6\rangle$ by state tomography. The detailed process of experimental realization is described in Appendix C, and the density matrices and fidelities of the initial states are provided in Appendix G. As shown in Figure 1(a), despite the experimental noise, the measured average fidelities for all six states exceed 0.4 — the classical limit.

To simulate errors in actual quantum systems, we employ the Origin NQVM, which provides a closer approximation to realistic quantum behavior by incorporating noise. Specifically, we consider the preparation process of GHZ states subjected to the Markovian noises: phase-flip (P), bit-flip (B), amplitude-damping (A), and depolarizing (D). These noises can be described using Kraus operators. We investigate the impact of these four noises on the JRSP of any two-qubit pure state, deriving the average fidelity analytically. For example, the average fidelity of JRSP of any two-qubit pure state in the presence of phase-flip noise is calculated as

$$\begin{aligned} F_{\mathrm{av}}^{P} = \frac{1}{9} p\{4p\,[2p(p\,(2p-5)+5)-5]+5\} \\ \cdot \{6p[4p\,(2p\,(p\,(2p-5)+5)-5)+5]-13\}+1, \quad (2) \end{aligned}$$

where p describes the probability of the qubit coupling with its environment. The numerical results of JRSP in other noise environments are provided in Appendixes D and H.

---

[*] Corresponding author (email: jmliu@phy.ecnu.edu.cn)

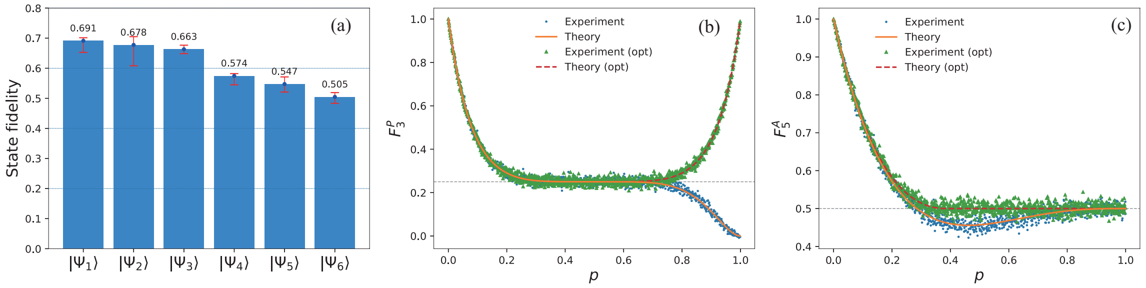

Figure 1 (Color online) (a) Experimental results of remote preparation of six initial states using the Origin Wuyuan 6-qubit chip. Error bars (marked in red) represent the deviation from average fidelities shown in the blue dots. (b) Fidelity of JRSP of $|\Psi_3\rangle$ in the phase-flip noise environment. (c) Fidelity of JRSP of $|\Psi_5\rangle$ affected by the amplitude-damping noise.

Furthermore, we verify the theoretical fidelities of JRSP for a separated state $|\Psi_3\rangle$ and a maximally entangled state $|\Psi_5\rangle$ using the Origin NQVM. The corresponding experimental results are shown in Appendix E. To improve the fidelity of the JRSP protocol, we propose substituting the two Hadamard gates in the GHZ state preparation circuit with parameterized unitary operations. For remotely preparing $|\Psi_3\rangle$ in the presence of phase-flip noise (Figure 1(b)), we find that before optimization, F_3^P decreases towards zero when p approaches 1, but after optimization, F_3^P increases with the p values exceeding 0.5. For remotely preparing $|\Psi_5\rangle$ in the presence of amplitude-damping noise (Figure 1(c)), we achieve theoretical fidelity (F_5^A) improvements above 0.5 through our optimization approach.

Summary. By employing two tripartite GHZ states as the entanglement channel, we realized the deterministic JRSP protocol of six unique initial two-qubit states on the Origin Wuyuan 6-qubit chip, with the measured average fidelities exceeding 0.4. Moreover, we employ the Origin NQVM to simulate the JRSP protocol in the presence of four noise environments. To enhance fidelity, we proposed substituting the two Hadamard gates in the GHZ state preparation circuit with parameterized unitary operations. Simulated results on NQVM indicate that this approach can be implemented in the actual JRSP experiment. Our work proves the experimental feasibility of JRSP of an arbitrary two-qubit state and could pave the way for developing and verifying more complex quantum communication tasks.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 92265209, 91950112, 11174081). We are notably grateful to the Origin Quantum Cloud.

Supporting information Appendixes A–H. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Bennett C H, Brassard G, Crépeau C, et al. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. Phys Rev Lett, 1993, 70: 1895–1899
2 Lo H K. Classical-communication cost in distributed quantum-information processing: a generalization of quantum-communication complexity. Phys Rev A, 2000, 62: 012313
3 Han D, Sun F, Wang N, et al. Remote preparation of optical cat states based on Gaussian entanglement. Laser Photon Rev, 2023, 17: 2300103
4 Xiao X Q, Liu J M, Zeng G. Joint remote state preparation of arbitrary two- and three-qubit states. J Phys B-At Mol Opt Phys, 2011, 44: 075501
5 Liu J M, Feng X L, Oh C H. Remote preparation of arbitrary two- and three-qubit states. Europhys Lett, 2009, 87: 30006