Impact of Delay and Measurement Error on Remote Gate Fidelity in Quantum Data Centers

Seyed Navid Elyasi,[1] Paolo Monti,[1] and Rui Lin[1,*]

[1] *Department of Electrical Engineering, Chalmers University of Technology, Gothenburg, Sweden*

[*] *ruilin@chalmers.se*

Abstract: We experimentally study how execution delay and measurement error affect remote two-qubit gate performance in quantum data centers, benchmarking readout asymmetry and protocol dependence across shot counts, and comparing results against hardware-reported measurement error baselines.

1. Introduction

Quantum data centers (QDCs) provide scalable access to multiple quantum processing units (QPUs) interconnected through quantum communication channels. As this paradigm matures, understanding the impact of classical communication latency and hardware imperfections on distributed quantum operations becomes increasingly important. Even with optimized compilation and mapping, distributed algorithms rely on remote gate (RG) execution, most notably remote CNOT operations implemented via Cat-Comm and TP1 protocols shown in Fig.1(a) and (b) respectively, which require entanglement generation and feed-forward control [1].

While theoretical analyses often assume ideal timing and noiseless measurements, practical implementations must contend with finite readout fidelity and delay-induced decoherence. Asymmetric measurement errors can bias observed outcomes and obscure RG performance. Although prior work has studied decoherence and noise in optically interconnected QPUs, the combined effects of measurement error and entanglement generation delay remain insufficiently explored [1, 3].

Here, we experimentally investigate the joint impact of delay and measurement error on RG performance using IBM cloud-accessible quantum hardware. By varying the number of measurement shots and employing calibration circuits that prepare qubits in $|1\rangle$ and $|0\rangle$ shown in Fig.1(c.1) and (c.2) respetively, we extract readout error probabilities and benchmark them against hardware-reported values. We further introduce controlled delays from 0 to 70 μs on entangled communication qubits to evaluate the performance of Cat-Comm and TP1 protocols.

Our results show that measurement errors, which exceed values reported in hardware calibration data, together with finite sampling effects, can significantly impact the reliability of RG operations in QDCs. We further observe a systematic degradation in the fidelity of both Cat-Comm and TP1 protocols with increasing entanglement delay, underscoring the importance of delay-aware scheduling and compilation strategies.

2. Methods

All experiments were performed using IBM quantum hardware, specifically the `ibm-torino` backend, a 133-qubit Heron r1 processor. Quantum circuits were executed remotely using Qiskit through the IBM Quantum cloud interface. To investigate the effect of measurement imperfections, we implemented two calibration circuits, shown in Fig.1(c.1) and Fig.1(c.2), in which a single qubit is prepared in the computational basis states $|0\rangle$ and $|1\rangle$, respectively, followed by measurement. By comparing the measured outcomes with the prepared states, we quantify

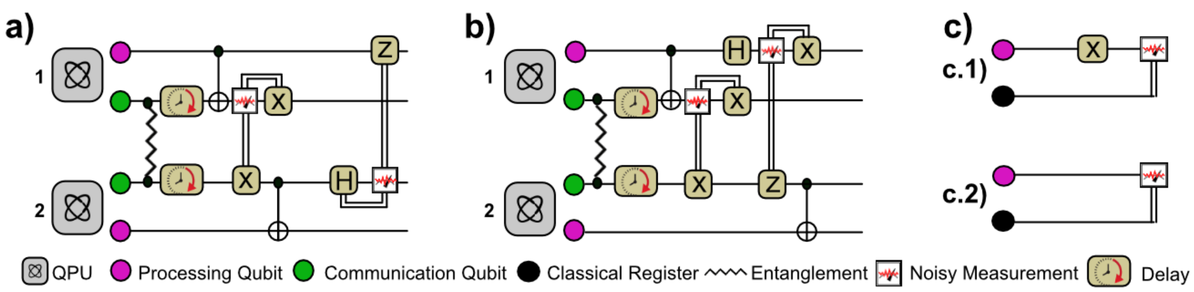

Fig. 1. (a),(b) Cat-Comm and TP1 protocols showing a remote CNOT gate between processing qubits of two QPUs with delay implemented before entanglement generation. (c) Calibration circuits to characterize measurement readout errors by preparing qubits in the $|1\rangle$ (c.1) and $|0\rangle$ states (c.2).

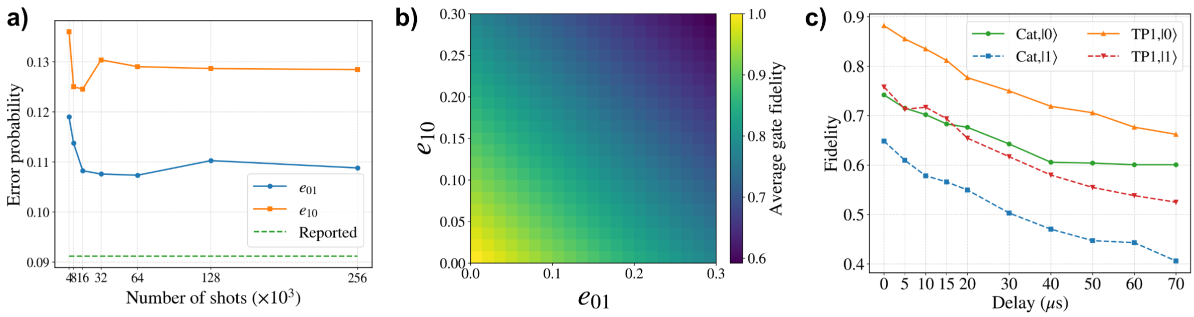

Fig. 2. (a) Readout error calibration. (b) Cat-Comm fidelity under asymmetric measurement error. (c) Effect of execution delay on Cat-Comm and TP1 protocols.

the readout error of the hardware and benchmark it against the measurement error values reported by IBM in the backend calibration data. Experiments were repeated for multiple shot counts ranging from 4,000 to 256,000 shots in order to study statistical convergence and sampling effects under realistic remote execution conditions.

Since measurement error cannot be actively modified at the hardware level, we instead analyze its impact on the fidelity of Cat-Comm protocol under asymmetric readout errors. We define the probability of preparing the qubit in $|0\rangle$ and measuring it as $|1\rangle$ as e_{01}, and the probability of preparing the qubit in $|1\rangle$ and measuring it as $|0\rangle$ as $_{10}$. Using the experimentally extracted values of e_{01} and e_{10}, we model the expected fidelity of Cat-Comm by defining noisy positive operator-valued measures (POVMs) as $\pi_0 = (1-e_{01})\,|0\rangle\langle 0| + e_{01}\,|1\rangle\langle 1|$ and $\pi_1 = (1-e_{10})\,|1\rangle\langle 1| + e_{10}\,|0\rangle\langle 0|$. These operators allow us to map the experimentally observed readout asymmetry directly onto the expected protocol fidelity.

In the second part of the study, we extend our analysis to investigate the effect of execution delay on the success of RG operations. Specifically, we examine two protocols, Cat-Comm and TP1, under controlled delays introduced prior to the initiation of the RG sequence. Delays ranging from 0 to 70 μs were applied, as shown in Fig.1(a) and Fig.1(b), allowing the entangled resource state to undergo decoherence before use.

3. Results

Fig.2.(a) shows the readout calibration results used to extract the measurement error probabilities e_{01} and e_{10}. Both values exceed the measurement error reported by IBM for the `ibm-torino` backend, with e_{10} consistently larger than e_{01}. This asymmetry is attributed to the additional X gate applied during preparation of the $|1\rangle$ state, whose imperfection combines with readout error and qubit relaxation. Using the experimentally extracted error values, Fig.2.(b) presents the theoretically computed Cat-Comm fidelity obtained from QuTiP simulations, illustrating how asymmetric readout errors lead to reduced fidelity within the experimentally relevant parameter regime.

Fig.2.(c) shows the impact of execution delay on remote gate performance for the Cat-Comm and TP1 protocols. Increasing delay prior to protocol execution results in performance degradation for both cases, consistent with decoherence of the entangled resource. However, TP1 exhibits a better fidelity than Cat-Comm, indicating greater robustness to delay-induced noise. This behavior suggests that TP1 is less sensitive to realistic scheduling and communication delays encountered in quantum data center environments. All data, job IDs, and associated codes to reproduce the results are available in the Github repository [2].

4. Conclusion

In summary, we have shown that realistic measurement imperfections and execution delays can significantly influence the performance of RGs in QDCs. Our results highlight the importance of accounting for asymmetric readout errors and delay-induced decoherence when evaluating protocol fidelity, and suggest that delay-robust approaches such as TP1 offer practical advantages for near-term remote quantum operations.

Acknowledgments:

This work is supported by VR and GENIE. We thank Chalmers Next Labs for providing us premium access to IBM devices.

References

1. K. Campbell, A. Lawey, and M. Razavi. *Quantum Science and Technology*, 10(1):015052, 2024.
2. S. N. Elyasi. GitHub repository, 2026. https://github.com/nelyasi/QDC-Quantum2.0-Measurement.
3. S. N. Elyasi, P. Monti, J. Li, and R. Lin. *arXiv preprint arXiv:2509.04029*, 2025.