Experimental Analysis of State Injection for Error-Corrected Quantum Systems

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Reducing the large resource overheads required by current methods to achieve a universal gate set for logical qubits will bring universal quantum computation closer to reality. A logical $T = Z^{1/4}$ gate is necessary to achieve a logical universal gate set, but implementing it is resource-intensive. It is commonly implemented via *state injection*, *state distillation* and *gate teleportation* [1]. These are, respectively, encoding a specific ancilla state into its logical equivalent, increasing the logical ancilla state's fidelity with error-correction, and running a specific circuit of Clifford gates on it and the logical qubit to equivalently implement the T gate on the logical qubit. The higher the fidelity of the injected state, the less resource-intensive distillation is required. Our experiment hence compared three injection methods to compare the fidelity of their injected states. The first, standard method copies a GHZ state across data qubits using CNOT gates, but this can catastrophically propagate errors [1]. The second reduces the logical error rate with a phase of post-selection before fully encoding the state [2]. The third is the novel protocol *transversal injection*, which rotates a physical qubit before applying the code stabilisers to give an encoded non-Clifford state heralded by its stabiliser eigenvalues [3]. With post-selection this can be used to achieve desired injected states. There exists no experimental realisation of transversal injection nor experiments analysing the effectiveness of any injection protocol. We present here a theoretical and numerical analysis to address this using the surface code and the superconducting qubits of Rigetti. As full logical state tomography is not possible in the surface code due its lack of a native Y gate, we demonstrated the logical qubits using their Rabi oscillation spectra. This was used to find the fidelities of the injected states from each protocol at different code distances. Our results also show that the visibility of the Rabi curves will correspond to the effective Pauli error rate of Rigetti's hardware. Our analysis will be followed by running the experiment on Rigetti's hardware to experimentally demonstrate transversal injection and each injection method, to compare them, and to bound the hardware's Pauli error rate.

[1] A. G. Fowler, M. Mariantoni, J. M. Martinis and A. N. Cleland, Surface codes: Towards practical large-scale quantum computation. *Physical Review A* **86**(3), 032324 (2012).

[2] Y. Li, A magic state's fidelity can be superior to the operations that created it. *New Journal of Physics* **17**(2), 023037 (2015).

[3] In preparation: Gavriel, J. et al., Transversal Injection: A method for direct encoding of ancilla states for non-Clifford gates using stabiliser codes (2022).