Low Depth Parity Check Gate Set for Quantum Error Correction

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The application of quantum computers to useful problems demands that they operate fault-tolerantly. This invariably requires the application of quantum error correction (QEC) [1], i.e. a scheme that can detect and correct the errors in the quantum computer faster than they occur. A key requirement is that the physical qubits have error rates below a fault-tolerance threshold, which depends on the details of the QEC scheme and its implementations [2]. Designing QEC schemes with high fault-tolerance threshold reduces the demands on the physical hardware, and makes practical quantum computing more plausible [2].

The Surface code is one example of a well-performing QEC code since it has a relatively high threshold. However, this threshold is highly dependent on the noise model. The standard surface code relies upon four-body parity checks, which are implemented using a universal set of gates for quantum computation, namely four sequential CNOT gates and single-qubit measurements [3]. Physical errors on the CNOT gates accumulate along the circuit and deteriorate its performance.

In this work, we exploit the insight that a QEC code needs not use universal logic gates, but can be simplified to perform solely the task of error detection and correction. By building gates that are fundamental to QEC rather than universal computation, we can boost the threshold and ease the experimental demands on the physical hardware. We call these gates low-depth parity check (LDPC) gates, since they perform a two-body parity check measurement in a single operation, instead of requiring a sequence of 1- and 2-qubit gates. We insert the LDPC gates within a 'widget' that yields directly the measurement of the product of two Pauli operators (M_{pp2}), namely the XX and ZZ operators. We present a rigorous formalism for constructing and verifying the LDPC gate set, designed specifically for QEC circuits. We then proceed to apply this technique to the two-body parity check circuits which are necessary for the implementation of the Honeycomb code, which requires only two-body parity check circuits [4] instead of the four-body checks needed in the surface code.

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