

R-QIP

Reliable Quantum Information Processing

The R-QIP project aims to develop efficient and practical countermeasures against quantum errors in quantum computer systems. The focus is on solutions for medium-sized quantum computers that will be available in the near future.

- Applications
- Middleware



Motivation

Current quantum hardware is prone to errors due to, among others, decoherence, i.e., uncontrolled and undesired interactions of the data qubits with the environment. Although the quality of quantum hardware is improving, there is a consensus in the quantum computing community that quantum error correction will be necessary to carry out useful quantum computations.

A major challenge when implementing quantum error correction is the decoding of the measured syndrome, i.e., determining which error occurred so it can be corrected. This requires a good understanding of the error sources in the quantum circuit and a fast decoding which can keep up with the quantum circuit.

One of the objectives of the R-QIP project is to develop a high-speed decoder for the quantum LDPC code introduced by DLR-KN [1]. Due to the stringent timing constraints, we implement a belief-propagation algorithm on dedicated hardware, a field-programmable gate array (FPGA).

Quantum Error Correction

At a high level of abstraction, quantum error correction (QEC) consists of implementing a small number of reliable logical qubits by mapping them into a larger number of unreliable physical qubits. Although QEC introduces overhead, it can exponentially suppress quantum errors.

QEC requires injecting ancillary qubits that interact with the data qubits. Data and ancillary qubits, as well as their interactions, are subject to errors, which furthermore propagate through the associated quantum circuit. Therefore, QEC requires accounting for all possible error sources and their propagation within the quantum circuit.

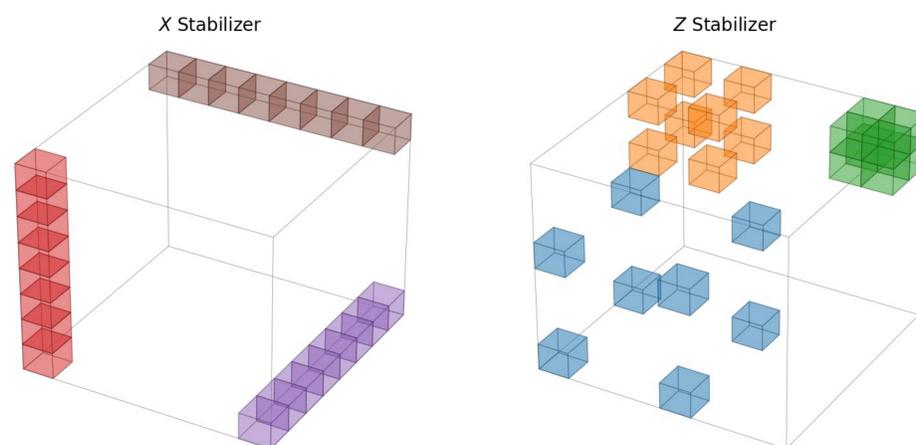


Fig. 2: 3D representation of selected stabilizers of the 3D SPC product code. The 512 qubits are arranged in a cube of size 8x8x8.

The 3D SPC Product Code

This project focusses on the 3D SPC product code $[[512, 174, 8]]$, introduced by DLR-KN [1]. It has a competitively low qubit overhead of less than three (comparing 174 logical qubits to 512 physical qubits), for the given code distance of eight. It is expected that the required number of qubits with sufficient fidelity will be reached in the short to midterm.

The code provides not only protection against up to three data qubit errors, but a meta-distance of three allows the correction of one syndrome measurement error. This facilitates the implementation of single shot decoding.

The construction of the code involves the tensor product of 9 constituent codes, leading to a 9-dimensional structure, which can be projected to 3D for visualization. Then the 512 qubits form an 8x8x8 cube. The stabilizers, which have weight 8, resemble lines parallel to the edges of the cube (X), or the corners of certain smaller cubes (Z), as visualized in Fig. 2.

Readout Circuits and Scheduling

The readout quantum circuit, which is used for syndrome extraction, has a strong influence on which errors can occur and how they affect the measurements.

It is desirable to optimize for a low circuit depth because this reduces the number of errors on idling qubits.

Additionally, it is essential to consider problematic multi-qubit errors. Specifically, the application of a stabilizer can cause a *hook error* affecting multiple qubits up to half of the stabilizer weight, as demonstrated in Fig. 1. Without optimization, the effective code distance would be drastically reduced from eight to two. It is however possible to optimize the circuit to reduce the impact of hook errors.

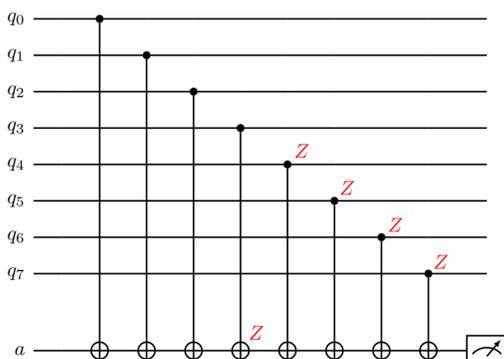


Fig. 1: Example circuit with hook error

Belief-Propagation Decoding

Belief Propagation (BP) is a message-passing algorithm that is well suited for implementation on a specialized hardware because of its efficiency and parallelizability. It operates on a („Tanner“) graph, which describes the effect of each error on the generalized measurements („detectors“), by iteratively updating belief values for those errors.

The Tanner graph for the given code and measurement schedule is relatively large and, due to the hook errors, relatively dense, which makes the application of belief-propagation challenging. To mitigate this, the decoder graph is simplified in a suitable way.

Belief propagation comes in multiple variants and with multiple parameters, which must be optimized. Systematic experiments and considerations suggest, for example, to use a min-sum update rule and a row-wise serial schedule.

Outlook

The first version of the FPGA decoder is currently being implemented. In the near future the decoder will be integrated in a setup that will generate synthetic error syndromes for demonstration purposes. The mid-term goal is employing the decoder in real quantum-memory experiments, as envisioned in Fig. 3.

Compact and Reordered CNOT Schedules

Reordering the CNOT gates within a type of stabilizer changes which measurements are affected by a hook error. This determines how well hook errors can be identified from a given syndrome and whether this error can reduce the effective code distance. At the same time, the gate ordering influences the circuit depth, thereby affecting the accumulation of idling errors.

A brute-force optimization over all possible schedules is unfeasible, but good schedules can be found relying on heuristics.

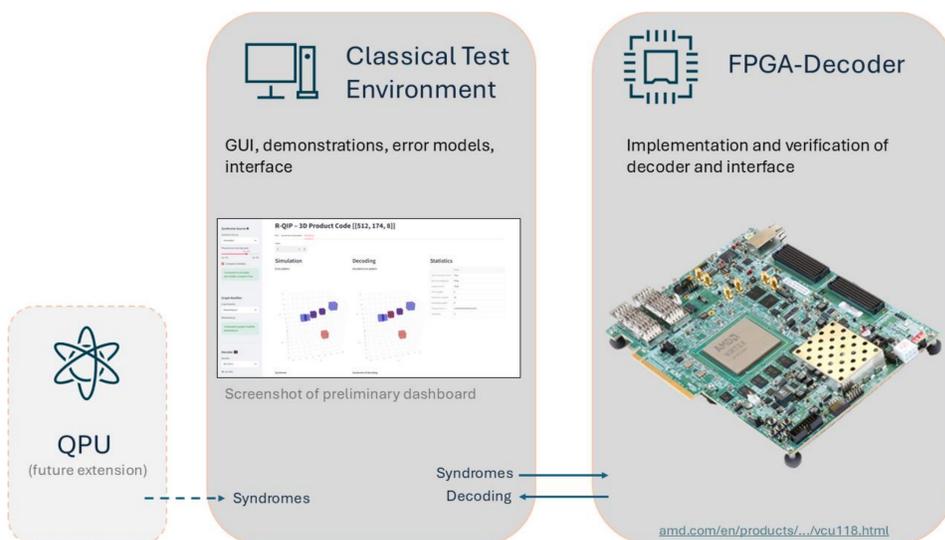


Fig. 3: Overall setup. The decoder is implemented on an FPGA. The syndromes are simulated in a classical test environment, which has an interface to the hardware decoder or a digital twin. The goal is that it is easy to integrate syndromes from real quantum memory experiments in the future.

[1] D. Ostrev, D. Orsucci, F. Lázaro, und B. Matuz, „Classical product code constructions for quantum Calderbank-Shor-Steane codes“, Quantum, Bd. 8, S. 1420, (Juli 2024)

More information about the project on our website



A project of



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