Tensor-network simulations of the surface code under realistic noise

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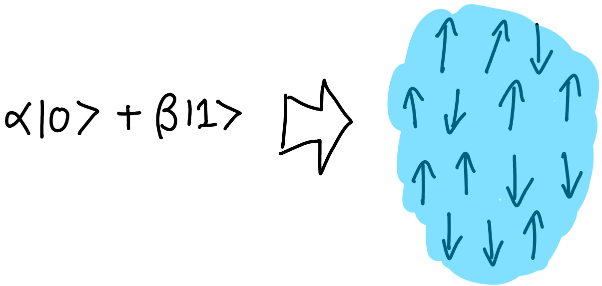
Quantum error correction

- Quantum states are fragile.
- Threshold theorem: Arbitrarily long quantum computation can be executed with arbitrarily high reliability, provided that the error rates are below a certain critical value (a threshold).
- This is possible due to quantum error correcting codes, in which a single logical qubit is encoded into the collective state of many quantum particles.
- Understanding the performance of error correcting codes is crucial.

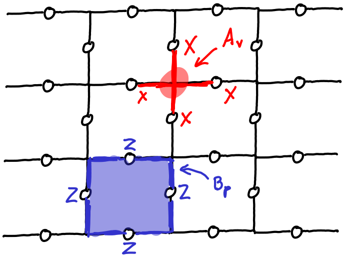


Topological codes

- The surface code has a practical realisation on a 2D lattice with nearest neighbour interactions.
- The performance of the surface code under different types of noise is usually determined with numerical simulations, however only simple noise models can currently be simulated
- Here we present an improved way to simulate the surface code under realistic local noise using tensor networks.

Error correction with the surface code

- The surface code is composed of an $L \times L$ square lattice of qubits.



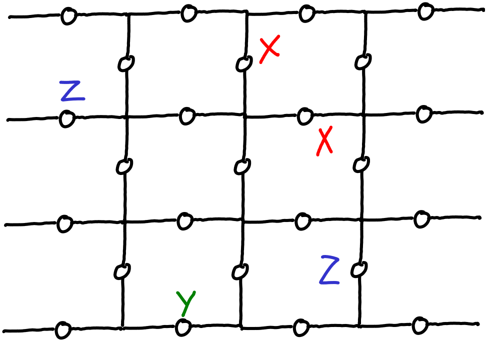
- During the error correction process, checks are measured, then a unitary correction is applied.

The performance of surface code

- Below a threshold noise value, we can make the noise on the logical qubit arbitrarily small by increasing the lattice size.
- The maximum amount of noise the code can tolerate, the *threshold*, as well as the efficiency of noise supression below threshold, depend heavily on the type of noise.
- These quantities are determined using numerical simulations.

Simulating error correction

- Local Pauli noise: $\mathcal{E}(\rho) = p_I \rho + p_x X \rho X + p_y Y \rho Y + p_z Z \rho Z$
- Errors and corrections all Pauli operators: to simulate evolution keep track of what Pauli is applied to each qubit.
- The effect on encoded information is also Pauli, and can be computed easily.



Simulations beyond Pauli noise

- Realistic noise is not Pauli.
- E.g. a large component of noise in superconducting architectures is amplitude damping

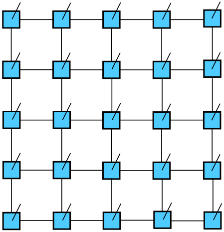
$$|1\rangle \to |0\rangle\,, \tag{1}$$
$$|0\rangle \to |0\rangle \tag{2}$$

  which is characterised by the T_1 time.
- Systematic errors (small local rotations) are also unavoidable.
- General noise is much harder to simulate.

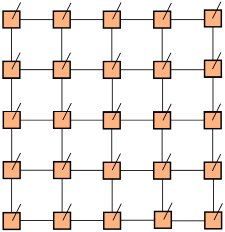
Simulations beyond Pauli noise

- Brute-force simulations have been used on distance-3 codes of up to 25 qubits.
- However, there is additional structure in the surface code to take advantage of.
- In this work we exploit the tensor network structure of the surface code to obtain a more efficient simulation algorithm.

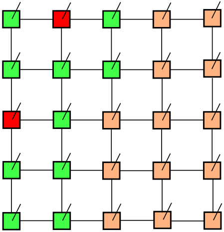
Simulation algorithm



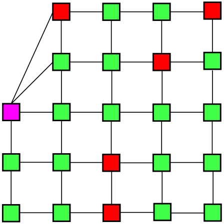
(a) Noiseless state



(b) Apply noise



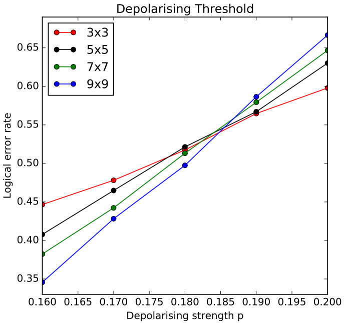
(c) Measurements

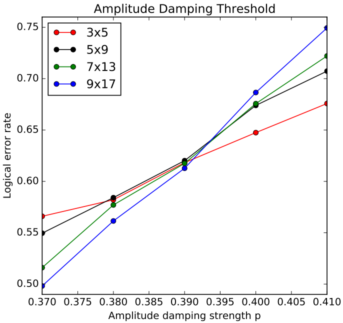


(d) Contract network

Results: Thresholds

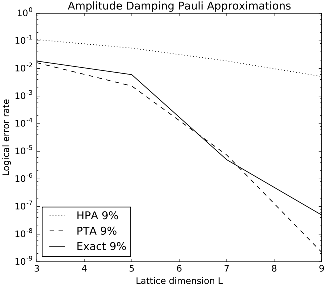
- We have used this algorithm to estimate thresholds for various noise models.

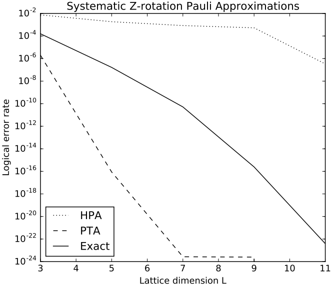




Results: Pauli comparisons

- Our simulations are exact and make no simplifications to the noise model. Does the code perform similarly with Pauli approximations to noise channels?





Future work

- Noisy measurements (3D tensor networks).
- It is likely that we can exploit additional entanglement structure in the code to develop more efficient simulation algorithms.

Conclusion

- Topological quantum codes represent a practical way to achieve fault tolerance in quantum computing.
- However, the performace of these codes in realistic conditions is not well understood.
- We have developed a tensor network method for simulating the surface code under arbitrary local noise. It is exact and allows us to probe low error rates. It is also fast enough to allow asymptotic quantities (thresholds) to be estimated.