公開

研 究 終 了 報 告 書

「Numerical Methods for Studying Real World Quantum Devices」

研究期間： 2019 年 10 月～2023 年 3 月
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1. 研究のねらい

The goals of this project were to develop numerical methods for studying the effect of noise on quantum information processing tasks. Using these techniques and other techniques we could then propose new methods to overcome noise in current quantum computing architectures.

2. 研究成果

（1）概要

Over the period of my Sakigake project I have produced a number of results relating to the numerical study of noise in quantum computers. These include numerical techniques based on tensor network methods, as well as new methods to overcome noise using quantum error correction.

Quantum error correction is a method that is necessary for combatting noise that arises in real world quantum computers. Quantum error correction is challenging to implement, and understanding how noise affects it is crucial.

The numerical methods I developed can be classified as either simulation methods or decoding methods. These exploit the structure of quantum error correcting codes and the noise affecting it to obtain new insights about quantum error correction. We have studied challenging noise processes such as biased noise, coherent noise and leakage using these methods.

We have also studied new types of error correcting codes (random codes) which are notoriously difficult to study due to the classical processing (decoding) required. We have shown that tensor networks can solve some classes of this problem.

（2）詳細

1. Tailoring error correction to biased noise (Ref. 2)

Quantum error correction works by encoding a small number of protected qubits into the collective state of a large number of quantum particles: a quantum error correcting code. By performing certain multi-qubit measurements on the physical particles of the code, one can deduce the locations of errors, which can then be compensated for in subsequent operations.

A topic or recent interest is to design quantum error correcting codes that are tailored to particular types of noise. By designing an error correcting code specifically to deal with the types of errors most common in the architecture, its performance (in terms of the strength of noise it can tolerate) can be substantially increased.

In this work we look at a type of noise called biased noise, where one type of error occurs much more frequently than other types of error. This type of noise is observed in many architectures, including superconducting Kerr Cat qubits, for which dephasing errors occur far more frequently than other types of error.

We demonstrate that the well known surface code, an error correcting code currently being actively developed by several groups (including Google and IBM), can be modified slightly to achieve extremely high performance against biased noise.

My main contribution was showing that the decoding problem for the surface code can be dramatically simplified when the noise is strongly biased. In other words, it is much easier to determine the location of errors when we have prior knowledge that the noise is biased, and this substantially improves the performance of the error correcting code.

It was known that the optimal decoding problem for the surface code can be reformulated as a tensor network. What I showed is that the entanglement structure in this tensor network is much simpler when the noise biased, thereby making decoding much more efficient and accurate. The thresholds obtained using this method, at the time, were state of the art: substantially higher than what had been observed with the surface code previously.

2. Error correction using Kerr-cat qubits and the XZZX surface code (Refs. 1 and 3)

This project builds upon the previous result regarding noise-biased qubits and the surface code. Here we consider an error correcting code together with a particular physical qubit. The error correcting code is called the XZZX code, which is a simple modification of the surface code. The physical qubit is the Kerr-Cat qubit, which can be implemented in superconducting architectures.

In this work we demonstrated numerically that the combination of the XZZX code with Kerr-cat qubits forms an error correcting system that has a remarkably high tolerance to noise. This is due to the fact that the Kerr-cat qubit produces highly biased noise, which is dominated by phase flips. The XZZX code has a high threshold against such noise.

We performed detailed numerical simulations which involved master equation simulations of the Kerr-cat qubit dynamics, as well as exact and approximate (Pauli) simulations of the surface code using the noise model obtained from the former.

The thresholds that we calculated with our numerical simulations were much higher than has previously been seen for the surface code under more generic (depolarising) noise. There is now significant interest in this type of biased noise qubit architecture (for instance, it is actively being pursued by Amazon).

In a related work, we showed that an important procedure for fault-tolerant quantum computation, called magic state injection, can also be significantly improved by making use of the native operations available in a biased noise architecture. With the assumption of a biased noise model, we see a two-order of magnitude lower error probability compared to conventional state preparation.

3. Error correction with codes defined by low-depth random circuits (submitted to PRL, arXiv:2212.05071)

One of the major challenges of practical error correction is the daunting overhead it imposes on quantum computations. While the surface code and variants of it are appealing due to their high thresholds and 2D connectivity, their main drawback is their low encoding rate: for practical computations, thousands of physical qubits may be required for each encoded qubit.

In this work we study a new approach to error correction based on low depth random circuits, which have the potential to have a much higher rate than the surface code. In this approach, the code is defined with respect to a low-depth random Clifford encoding circuit constrained to local connectivity.

Previous studies of these codes were limited due to the fact that they assume an erasure noise model (in which error locations are known) or obtain bounds on their performance without explicitly describing a decoding algorithm. Decoding appears to be challenging part about studying these codes, i.e. until now there was no explicit algorithm which could accurately determine the error, given the outcomes of check measurements beyond erasure noise.

In this work we propose a new decoding algorithm for these codes, based on tensor networks. We focus on codes with 1D connectivity and log-depth encoding circuits. Numerically we show that, with our tensor network decoder, these codes achieve an exceptionally high rate. For depolarising noise, these codes appear to achieve the hashing bound, which is the rate achieved by fully random stabilizer codes. This is remarkable since it implies that we can obtain the same performance as fully random codes (which have $O(n)$ weight checks and high-weight encoding circuits) using only log-depth encoding circuits and $O(\log n)$ weight checks even when constrained to 1D connectivity.

4. Methods for determining critical noise parameters for error correction (in preparation)

There has been considerable research effort dedicated to the development of noise characterisation methods. For error correction, one of the advantages of having an accurate description of the noise is that the decoding can be performed much more accurately. In other words, simply by using more classical information about noise in the classical decoding algorithm, an error correcting code can much more accurately and efficiently correct physical errors.

However, practical noise characterisation methods are limited, and can usually only extract some limited set of noise parameters accurately and efficiently. This imposes some limits on the performance of error correction, since decoders can only use limited noise information.

In this work we develop a tensor network method that can be used to determine which noise parameters are most important for surface code performance. We have applied the method to a variety of noise types including biased noise, coherent noise and inhomogeneous noise. We find that, while physical noise requires a large number of parameters to fully describe, it is only necessary to characterise a small number of them accurately in order to obtain near-optimal surface code performance.

This work potentially motivates the development of new noise characterisation techniques that can efficiently extract the parameters that most strongly affect performance.

5. Simulating realistic noise using tensor network methods (in preparation)

An indispensable tool in understanding the effect of noise of quantum information processing is classical numerical simulation. Quantum error correcting codes are many-body quantum systems, and therefore simulating them in the presence of noise is in general challenging due to the exponential size of Hilbert space. However, quantum error correcting codes do have additional structure that generic quantum systems don’t have.

In this work we develop numerical tensor network methods to simulate quantum error correcting codes under various realistic types of circuit level noise. These simulations exploit the area law entanglement structure of these codes and allow the simulation of coherent noise and leakage, which cannot be studied with conventional Pauli simulations. The methods can be thought of as an extension of the methods for simulating surface-code error correction I had developed previously based on tensor networks, which could not be applied to full circuit level noise.

We have developed one dimensional methods based on matrix product states (MPS), a powerful ansatz for 1D systems. This has been applied to simulate realistic noise in a superconducting qubit implementation of a repetition code. Extensions of this method to thin surface codes is currently underway.

While we had originally attempted to develop simulation methods based on a 2D ansatz (PEPS), this proved quite challenging due to the numerical instabilities that appeared. We plan to revisit this problem once the 1D algorithm has been fully demonstrated (however this may fall outside the scope of the current Sakigake project).

Notes on collaborations

The projects described above are all collaborative efforts, leveraging talent from Japan and overseas. Project 1. Was a collaboration with researchers at Sydney University (David Tuckett, Chris Chubb, Steve Flammia, Stephen Bartlett) and IBM (Sergei Bravyi). Project 2. Was a collaboration with researchers at Yale (Shruti Puri, Shraddah Singh) and Sydney University (Arne Grimsmo, Ben Brown, David Tuckett). Project 3 is collaboration with fellow PRESTO researcher Hayata Yamasaki at Tokyo University, Yoshifumi Nakata (YITP, Kyoto University) and Shiro Tamiya (Tokyo University). Project 4. Is a based on a collaboration with David Poulin of Sherbrooke University (who sadly passed away in June 2020). Project 5 is a collaboration with Hidetaka Manabe (Kyoto University), who is the main researcher on this project, and fellow PRESTO researcher Yasunari Suzuki.

3. 今後の展開

I hope that the projects inspires numerous developments in the field of quantum error correction and tensor network methods. While tensor network methods are often used in other fields, such as high energy physics or condensed matter physics, their application to quantum error correction has, to now, been lacking. I have demonstrated here a number of ways that tensor networks may help us overcome the challenges posed by noise in quantum computers. I believe that there are potentially many further applications and improvements to these methods that could lead to further breakthroughs in the field. This could also encourage researchers from other fields to join in the effort to build a quantum computer.

Personally, I have developed many collaborations during my PRESTO project, which I hope to maintain in the future. In March 2023 I will hold a workshop at YITP in order to gather many of the current researchers to work out the next steps necessary to make quantum error correction (and quantum computing) practical. There are a number of directions of future research that can build off some of the results of this PRESTO project, especially relating to practical implementation of biased noise qubits and random quantum codes that I plan to continue working on.

It is challenging to specify a precise time at which these developments will lead to social implementation, since this relies a lot on experimental breakthroughs (which are hard to predict). However, I would hope that with some of the methods developed here for error correction will significantly speed up the development of universal quantum computers, such that we could have a quantum computer of practical use within the next two decades.

4. 自己評価

I believe that the original goals of this project have largely been addressed by the work I have done. The planned outcomes were numerical methods to study the effect of noise on quantum information processing, and practical methods to deal with it. I believe that by producing these outcomes, I have made contributions that have helped the research community understand how to deal with noise in current quantum computing architectures.

There were some subjects which I had originally planned to work on but didn't in the end. These include correlated noise and neural-network based numerical methods. I don't think this is a major problem since, in place of these, I worked on other topics that I thought were more pressing, such as random coding (which was not in my original proposal).

In terms of overall impact on the field I seem to have generated quite a lot of interest in these topics since the start of this project. For instance, I have given invited talks at Yale and Tokyo University about applications of tensor network methods to error correction.

The published work on biased noise appears to have been well received by the research community. In total the papers have received about 140 citations as of November 2022. I have given multiple invited talks on the paper about Kerr-cat qubits and the XZZX code. One big development was that Amazon's new quantum computing team is now focussing on a biased noise architecture.

The numerical techniques I have developed have provided a new perspective for simulating quantum systems and performing error correction. Most of the tensor network techniques are quite simple, and I expect there is significant room for improvement, as well as for new applications of these methods to other areas. Overall, I think that the techniques I have developed may help speed up the development of quantum computers, and therefore bring the societal benefits of quantum computers closer to reality.

5. 主な研究成果リスト

(1)代表的な論文(原著論文)発表

研究期間累積件数:4 件

1. A. S. Darmawan, B. J. Brown, A. L. Grimsmo, D. K. Tuckett, and S. Puri, Practical quantum error correction with the XZZX code and Kerr-cat qubits, PRX Quantum
We propose a new scheme for quantum error correction. Numerical evidence suggests this scheme achieves thresholds greatly surpassing conventional surface code schemes.
2. D. K. Tuckett, A. S. Darmawan, C. T. Chubb, S. Bravyi, S. D. Bartlett, and S. T. Flammia Tailoring surface codes for highly biased noise, Phys. Rev. X

We demonstrate how small modifications to the surface code can greatly impact its performance when the noise is strongly biased.
3. S. Singh, A. S. Darmawan, B. J. Brown, and S. Puri, High-fidelity magic-state preparation with a biased-noise architecture, Phys. Rev. A
We show how a resource intensive subroutine of fault-tolerant quantum computation (magic state distillation) can be performed significantly more efficiently when the noise is biased.

（2）特許出願

（3）その他の成果（主要な学会発表、受賞、著作物、プレスリリース等）