High Fidelity Qubit Mapping for IBM Q

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Existing quantum computer processors have topological limitations on the execution of CNOT gates. Moreover, the degree of operational imperfection differs according to qubits. Mapping qubit variables to processor has a strong influence on the feasibility and fidelity on the current processors. In this research, we defined simple error model S_{est} using Randomized Benchmarking and compared it with the result of executing the circuit with IBM Q20. The result shows S_{est} is enough high accuracy for CNOT path selection.

Ⅰ. Introduction

The number of qubits in the processor of a quantum computer is increasing day by day **[J. Q. You]**. As a result, the necessity of considering the computer architecture is increasing. Fig.1 shows an example of Quantum Computer Architecture.

We are focusing on Qubit Mapping which map Logical Qubit in a code to Physical Qubit on processors. Mapping of qubits should be optimized in order to deal with large-scale and large amount of code.

In Qubit Mapping for existing quantum computers, there are several following problems.

1. It is difficult to generate the entangled state in any physically non-adjacent qubits on the processor. In fact, all processors created by IBM are limited in the use of CNOT gates. Fig. 2. shows the topology of IBMQ20 tokyo. The nodes are qubits and the edges means whether programmer can execute CNOT (Controlled-X) gate or not.
2. Error rates of each qubit are not equal.

We have created tools for performing similar mapping in prior work **[Ishizaki2011] [choi2011]**. That work dealt with non-neighboring qubits, but not gate polarity.

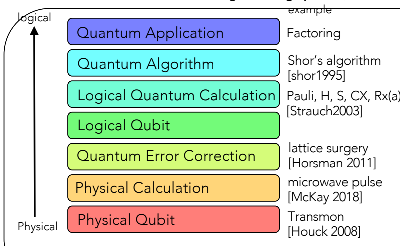

FIG. 1. Quantum Computer Architecture

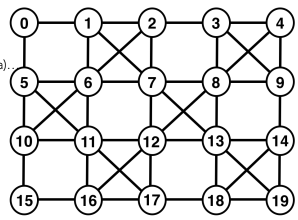

FIG. 2. Topology of IBMQ20 Tokyo

Ⅱ. Definition of our problem

Our goal:

Compare analytic simple error model with the reality of the machine.

This will enable error aware qubit mapping.

For the goal, we need to:

1. Characterize the machine
2. Create an **estimate of circuit success probability**
3. Compare to the reality of the machine
4. incorporate into **compilation process**; **Pan et al., (QOPTER)**

Ⅲ. Randomized Benchmarking and Success Probability

(1) Randomized Benchmarking

Randomized Benchmarking (RB) is a way to show how close the quantum state is to the desired state. By changing the number of gates to be executed and executing it multiple times, it is possible to obtain the value of the gate error as the attenuation factor. At this time, it is necessary to select gates from the gate set forming a dense space.

IBM has published the results of IBM Q20 Tokyo's Randomized Benchmarking to members of IBMQ Network HUB (a kind of joint research team). Fig. 3. is a procedure of RB.

In this case, they defined clifford gates $C_n = \{U : UP_nU^\dagger = P_m\}$ as gate set (P is a pauli gate in this case).

(2)Error model and success probability

In this research, we used the error model that we can assume that the error can be divided into 3 groups. It is shown in Fig. 4.

a). Error accompanying gate operation of single qubit: Single-Qubit Gate error(G)

b). Error accompanying operation on multiple qubits: Bi-Qubit gate error(B)

c). Error accompanying state preparation and measurement: SPAM error(S)

Using this error model we defined Estimated Success Probability S_{est} for quantum circuit. This is simple total ride. ε_i is one of **G**, **B**, and **S**.

$$S_{est} = \prod_i (1 - \varepsilon_i)$$

Also, we call S_{act} as fidelity of result value.

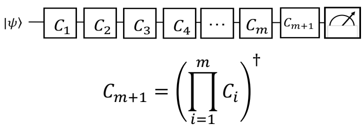

FIG. 3. Randomized Benchmarking

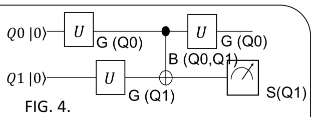

FIG. 4.
(a)Single-Qubit Gate error,
(b)Bi-Qubit Gate error,
and (c)SPAM error

Ⅳ. Problems

For simple, we have thinking about two problem.

(1)Path selection

Suppose a programmer want to use CNOT gate from a qubit to other qubit at a distance. In many case, programmer can select CNOT path (passing qubit) as shown in Fig. 5. We tried path selection using S_{est} for 2-4 hops CNOT paths such as Fig. 6. We have ran at the all not crossing pair of 2-4 hops path which is starting and end at same qubit and "shortest" at that qubits. The result is shown in Fig. 7. **We were able to choose a good pass with accuracies of 70% for 2hops, 66.6% for 3hops, and 62.5% for 4hops. It can be use for compilation.**

However, the value S_{est} itself is not correlate strongly with S_{act} as shown in Fig. 8.

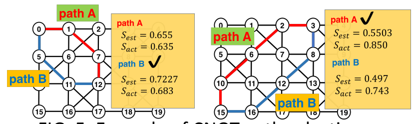

FIG. 5. Example of CNOT path selection for 3hops and 4hops

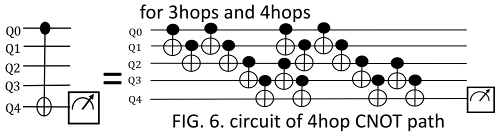

FIG. 6. circuit of 4hop CNOT path

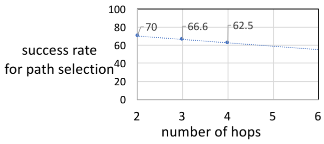

FIG. 7. Success rate for path selection with S_{est}

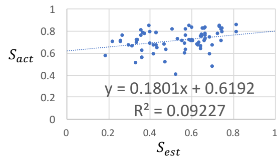

FIG. 8. Relation between S_{est} and S_{act}

(2)Three body problem

Suppose there are three qubit in a processor and all qubit are connected(can use CNOT between two) each other such as Fig. 9. On that qubits, we can run **circuit A** in Fig. 10. In reality, many qubits have connection limitations like Fig. 11. In that case, we cannot run circuit A, but we can run equivalent circuits such as **circuit B, C, and D** in Fig.12. The number of CNOT gate of circuit C is less than B and D, mainly circuit C can get high fidelity, however if B12 — Bi-qubit-error between Q1 and Q2– is really bigger than B01, circuit B is the best way. And also it can be said that if B01 is really bigger than B12, circuit D is the best way. This is shown in Fig. 13.

We tried to select circuit which fidelity will be high from circuit B,C, and D using the S_{est}.

Result

We could select the best path for only 8 times in 20 times. S_{est} is not good enough to select circuits from B, C, and D.

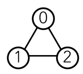

FIG. 9. Three qubits

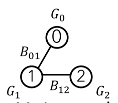

FIG. 11. Incompletely connected qubits

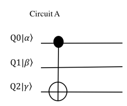

FIG. 10. Circuit for CNOT

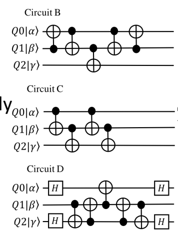

FIG. 12. Equivalent Circuits

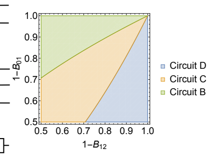

FIG. 13. best circuit

Ⅴ. Conclusion

S_{est} is easy to calculate and enough useful for CNOT path selection. Otherwise, the number itself is not so much correlated to actual fidelity. Accuracy decreases as the number of qubit increases.

Ⅵ. Future Works

Use Other Error Model and compare the accuracy.

- use T1, T2 & time for execute gate
- leakage, crosstalk
- Divide errors
  Decoherence , Dephasing, and Unitary

Acknowledgements

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[J. Q. You] J. Q. You and Franco Nori, **Superconducting Circuits and Quantum Information**, Phys. Today 58 (11), 42 (2005) .
[Ishizaki2011] Kaori Ishizaki, An algorithm for optimizing movement of quantum variables on arbitrary physical qubit structures, Bachelor's thesis, Keio University (In Japanese)
[Choi2011] Choi, Byung-Soo and Van Meter, Rodney, On the Effect of Quantum Interaction Distance on Quantum Addition Circuits, J. Emerg. Technol. Comput. Syst, August 2011, 7, 3, 1550-4832, 11-17
[shor1995] Peter W. Shor , Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer, arXiv:9508027 [quant-ph]
[Strauch2003]Frederick W. Strauch, Philip R. Johnson, Alex J. Dragt, C.J. Lobb, J.R. Anderson, F.C. Wellstood, **Quantum logic gates for coupled superconducting phase qubits**, arXiv:0303002 [quant-ph]
[Horsman2011]Clare Horsman, Austin G. Fowler, Simon Devitt, Rodney Van Meter, **Surface code quantum computing by lattice surgery**, arXiv:1111.4022 [quant-ph]
[McKay2018]David C. McKay, Thomas Alexander, Luciano Bello, Michael J. Biercuk, Lev Bishop, Jiayin Chen, Jerry M. Chow, Antonio D. Córcoles, Daniel Egger, Stefan Filipp, Juan Gomez, Michael Hush, Ali Javadi-Abhari, Diego Moreda, Paul Nation, Brent Paulovicks, Erick Winston, Christopher J. Wood, James Wootton, Jay M. Gambetta, **Qiskit Backend Specifications for OpenQASM and OpenPulse Experiments**, arXiv:1809.03452[quant-ph]
[Houck2008] A. A. Houck, J. A. Schreier, B. R. Johnson, J. M. Chow, Jens Koch, J. M. Gambetta, D. I. Schuster, L. Frunzio, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, **Controlling the Spontaneous Emission of a Superconducting Transmon Qubit**, Phys. Rev. Lett. 101, 080502
[Dawson2005]Christopher M. Dawson, Michael A. Nielsen, **The Solovay-Kitaev algorithm,** arXiv:0505030 [quant-ph]
[IBMQ2018] IBM, **Quantum devices and simulators** , accessed 2018/11/4 https://www.research.ibm.com/ibm-q/technology/devices/
[Knill2007]E. Knill, D. Leibfried, R. Reichle, J. Britton, R. B. Blakestad, J. D. Jost, C. Langer, R. Ozeri, S. Seidelin, D. J. Wineland, **Randomized Benchmarking of Quantum Gates,** arXiv:0707.0963[quant-ph]