Computer Science

Capstone Report - Spring 2022

Explore Quantum Teleportation Algorithms with Cloud-based Quantum Computers

Xinyao Han,
Yile Xu

supervised by
Tim Byrnes, Olivier Marin

Preface

This is a Computer Science capstone paper on exploring the cutting-edge topic quantum computation, with a focus on how a specific quantum algorithm – quantum teleportation could advance classic computer science problems in distributed systems and benchmarking the performance of the IBM quantum processor using on-chip quantum teleportation with post selection. The two authors are Xinyao Han, a Computer Science major student, and Yile Xu, a Computer Science and Interactive Media Art double major student.

This project is inspired by the promise of quantum computing to deliver a huge leap forward in computational speed compared with conventional computers. In this paper, we will examine in detail the contribution of quantum teleportation in solving distributed system problems.

Acknowledgements

In this section, we would like to sincerely thank everyone who helps us out throughout 2022 when we are doing this capstone. It's a challenging and inspiring experience for both me and Yile, not only for the tough topic itself, but the situation we find ourselves in, when my flight back to Shanghai got cancelled in early January and had to conduct this capstone online throughout this semester, and when Yile experienced the severe lockdown in Shanghai during late March to May. With those difficulties, we managed to explore this brand new and cutting-edge topic, examine thoroughly quantum computing and present what we've accomplished in this paper.

We would like to thank Professor Olivier Marin who mentor us along the way, guide us on drafting the scope of research questions and narrowing down our analysis, give us useful feedback, and mentally support us in times of difficulty.

We would like to thank Professor Tim Byrnes who supervise us on this deep and arduous topic, answer our questions patiently, give us useful feedback and suggestions, and direct us to the correct path in uncertainty.

We would like to thank Marek Narożniak, who is Prof.Byrnes's Ph.D student. He is very meticulous and always willing to offer help when we have questions, and answer them in a timely and devoted manner. We would not be able to finish this capstone without his advice and guidance.

We would like to thank our friends, who always support us in out difficult times during 4 year of college experience. We have created many precious memories, laughter and tears during these four years. Such good times will always shine in the memory.

Abstract

This paper focuses on the cutting-edge quantum computation algorithm, quantum teleportation, and prepare the ground for using quantum Internet to solve distributed system problems. The 3-qubit on-chip quantum teleportation algorithm is simulated and implemented with IBM quantum processor with post selection, customized state preparation and 4 different corrections. Fidelity is used as measurement methods to analyze the performance.

Keywords

Quantum Computation; Quantum Teleportation; Quantum Internet; Quantum Computer; IBM Quantum Processor; Distributed System; 3-qubit; Correction; Fidelity; Capstone; Computer Science; NYU Shanghai

Contents

1 Introduction

Quantum computing, harnessing the phenomena of quantum superposition and entanglement, can be expected to deliver a huge leap forward in computational speed compared with conventional computers [1]. In 2017, constant-depth quantum circuits proved to surpass their classical counterparts [2]. This marks the first time quantum algorithms have theoretically surpassed classical computing, revealing the potential of quantum computing as a field. The computing power is realized with the help of quantum computers. Until recently, quantum computers have only been a theoretical construct, however, the innovation of quantum simulators and emulators makes cloud-based quantum computers easily accessible through networks, making it a practical possibility for basic users to test quantum algorithms performances and utilize the potential of quantum computing.

Among quantum computing algorithms, as an advanced algorithm transmitting information using the quantum state change of two distant entities, Quantum Teleportation occupies a groundbreaking place [3]. It plays an important role in transmitting information with its completely secure transmission property and long distance information transmission capability [4].

Moreover, its connectivity in networks brought a realistic foundation and enabled the vision of quantum internet, provided with a distributed computational power that greatly exceeds that of the classical internet via creating a quantum network with nodes and entangled quantum states to connect [5, 6]. Quantum Internet connects quantum information processors and will achieve unparalleled capabilities that are provably impossible with classical information. It provides a distributed computational power that greatly exceeds that of the classical internet and thus serves as the key strategy to enable distributed quantum systems [7]. Quantum internet greatly assists distributed system problems such as the task of byzantine agreement.

Quantum teleportation and quantum Internet are promising contributors to possible distributed system problems on networks. In this paper, we choose to examine in detail the fundamentals of the quantum Internet – the quantum teleportation algorithm. We chose the quantum teleportation algorithm due to its huge potential as well as the implementation constraints. Because the quantum internet is based on a quantum network and thus not feasible on a single quantum computer [8]. We implemented the quantum teleportation algorithm with cloud based quantum computers IBM quantum processor and analyzed its contribution in solving contemporary problems in distributed systems.

Our main contribution in this work is:

1. **We benchmark the performance of the IBM quantum processor using on-chip quantum teleportation with post selection.**

2. **We build 3 qubit quantum teleportation algorithms on IBM quantum processor with our own state preparation and applied 4 different corrections.** We build our own state preparation, make four versions of the circuit by changing different combination of the X and Z gates.

3. **We simulate the performance of quantum teleportation using simulator and implement teleportation on quantum computer.** We simulate all versions of the circuit and gather all the measurements, implement some post processing and exclude all the outcomes where wrong correction is applied to gather results.

4. **We systematically test the performance using fidelity and analyze the results.**We performed a rotation on the basis of the state we are teleporting. We use 4000 runs each to measure the state in simulation and we use 500 runs each to test the results and analyze their standard deviation and mean.

We believe our work brings insights into the Quantum Teleportation algorithm in analyzing its performance with post selection and different corrections, which helps formulating a solid ground into future work on building the quantum Internet and solves distributed system problems.

2 Related Work

2.1 Basic Concepts

2.1.1 Quantum Bit

Quantum bit, or *qubit* for short, is a tangible physical resource and realized as physical systems. In quantum language, qubits are treated as abstract mathematical objects for the generalization of quantum computation. To understand qubit, we compare it with a classical bit. A classical bit has a state of either 0 or 1, and a qubit has a state of either $|1\rangle$ or $|0\rangle$. A qubit is a linear combination or superposition of the two classical values: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ [1]. The state of $|1\rangle$

and $|0\rangle$ are *computational basis states*, and the numbers α and β are complex numbers. However, we can't determine the value of α and β and thus cannot determine the quantum state of a qubit.

2.1.2 Superposition and Entanglement Measures

Superposition *Superposition* is the linear combinations of states [1]. In physics, a qubit could exist in a continuum of states between $|1\rangle$ and $|0\rangle$, which is the superposition of $|1\rangle$ and $|0\rangle$.

Entanglement *Entanglement*, as a physical resource, is fundamental in quantum computation and quantum information. It refers to the physical phenomenon that two particles remain connected when seperated apart after they become entangled [1]. These two particles behave as one composite entity regardless of their distance in space [9].

2.1.3 Quantum Logic Gates

Quantum gates performs information processing respectively.

Controlled-NOT gate (CNOT) CNOT gate has two input qubits, the control qubit and the target qubit. It's a generalization of the classical *XOR* gate.

Hadamard gate It's one of the most useful quantum gates, can be interpreted as a 'square-root of *NOT* gate. This gate operates on one qubit at a time.

2.1.4 Quantum Computation

Quantum computation refers to the quantum mechanics that the system uses to accomplish information processing tasks [1]. Classical computation uses a bit as a classical unit of computation. while quantum computation uses a qubit as the unit of computation.

2.1.5 Quantum Teleportation

Quantum Teleportation is an advanced information transmission technique. According to the no-cloning theorem, making an exact copy of unknown quantum states is prohibited. Quantum teleportation uses two classical bits and an entangled qubit pair to transfer states. It is the ability to transmit the quantum state of an entity using classical bits and to reconstruct the exact quantum state at the receiver, even without a quantum communications channel [1]. It requires both classical and quantum channels, where the classical channel transmits the results generated by the Bell measurement, and the quantum channel is used for unitary transformation [3]. Quantum teleportation emphasizes the interchangeability of different resources in quantum mechanics.

The theory of quantum teleportation is stated as follows:

Two remote parties *Alice* and *Bob* share a qubit pair in a prior entangled state, A and B. Ideally, Bell pair $|\psi\rangle = \frac{1}{2}(|00\rangle + |11\rangle)$ is used to ensure maximally entanglement [10]. As input, *Alice* performs Bell detection giving another qubit $|\psi\rangle$ whose state is assumed to be unknown, projects both of her qubits into one of the Bell states and sends the result as classical bits to *Bob* [10]. *Bob* then can applies the Bell states result to recover the original input state of the qubit $|\psi\rangle$ and thus achieve the transmission [10].

A more detailed study of quantum teleportation including its algorithms, architecture and formulas will be presented in *Section 3*.

2.1.6 Quantum Internet

Built upon a quantum network with nodes and entangled states to connect the nodes, *quantum internet* is a distributed set of quantum nodes mutually connected over a network capable of allocating qubits and entangled states between locations [5, 11]. It is supposed to provide distributed computational power that greatly exceeds that of its classical counterpart [7].

2.1.7 IBM Quantum Processor

IBM Quantum Processor is a circuit-based commercial quantum computer, introduced by IBM in January 2019. It allows the general public to access cloud-based quantum computing services with its online platform. In this paper, we implement quantum algorithms using this cloud quantum computer.

2.2 Literature Review

2.2.1 Contribution of Quantum Computing in Distributed Systems

To see how quantum computing can help in speeding up distributed network algorithms, [12] analyzes the lower bond of some fundamental network problems such as graph optimization and verification problems. By introducing the Server model and Quantum Simulation Theorem, [12] provides a connection between distributed algorithms and communication complexity and it carries the harness in the standard two party communication complexity to quantum distributed computing. Based on their detailed analysis of the lower bounds for those problems, quantum computing and communication does not help in substantially speeding up distributed algorithms compared to the classical setting [12]. We turned our attention to quantum teleportation.

2.2.2 Applying Quantum Teleportation to Distributed Systems

The nature of quantum teleportation as a transmission method determines several possible applications in the field of distributed systems. Since quantum teleportation utilizes shared prior quantum entanglement to transmit messages between the source and receiver, long-distant superluminal transmission might be considered to reduce latency. Besides, its connectivity in networks makes multi-node quantum networks feasible, and thus might provide distributed computational power that surpasses the classical one.

Failure in achieving super-luminal transmission Even though quantum teleportation utilizes shared entanglement to transmit messages, it doesn't mean that its transmission merely depends on the entanglement and thus can reach beyond the speed of light. During transmission, a classical communication channel is also needed for passing the classic bit results from the source to the receiver. As a result, quantum teleportation cannot achieve superluminal transmission due to this limitation: classical messages sent through classical communication channels are restricted to transmitting at the speed of light [13].

Distributed computational power via Quantum Internet Quantum teleportation, as a transmission method, uses shared prior entangled qubits along with a classical bits communication channel to transmit quantum information. This process enables the implementation of distributed quantum applications [8] via creating a quantum network with nodes and entangled states to connect the nodes [11]. Among these applications, quantum internet has been envisioned as the key to largely scale up the number of qubits [8] and is supposed to provide distributed computational power that greatly exceeds that of the classical internet [7]. Thus quantum teleportation is regarded as the key strategy to enable distributed quantum computing [14]. Even though quantum networking technologies are still in an early stage of research and development [8], practical devices have been implemented as a realistic foundation for quantum internet and revealed the great potential of further implementation [5].

3 Solution

We implemented the quantum teleportation algorithm with cloud based quantum computers IBM quantum processor to shed lights on its application.

3.1 3-qubit Quantum Teleportation Algorithm

As denoted in *Section 2*, the basic solution for the 3-qubit quantum teleportation algorithm is first create entangled bell pair between sender (Alice) and receiver (Bob), then Alice apply CNOT gate with the qubit carrying message and the entangled qubit in her side, then she send the result as 2 classic bit to Bob, and Bob will perform correction according to the result and retrieve the original quantum state of the qubit sent by Alice[1].

In detailed, the processes work as follow: Suppose the quantum state to be teleported is $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, and the entangled bell pair qubit is $|\beta_{00}\rangle$. The original input to the circuit would be:

$|\psi_{stateincircuit}\rangle = |\psi\rangle\,|\beta_{00}\rangle = \frac{1}{\sqrt{2}}[\alpha|0\rangle(|00\rangle + |11\rangle) + \beta|1\rangle(|00\rangle + |11\rangle)]$

Then, Alice applies CNOT gate to her qubits, $|\psi\rangle$ as control and $|\beta_{00}\rangle$ as target.

$|\psi_{stateincircuit}\rangle = \frac{1}{\sqrt{2}}[\alpha|0\rangle(|00\rangle + |11\rangle) + \beta|1\rangle(|10\rangle + |01\rangle)]$

After this, Alice applies Hadamard gate to her qubit $|\psi\rangle$.

$|\psi_{stateincircuit}\rangle = \frac{1}{2}[\alpha(|0\rangle + |1\rangle)(|00\rangle + |11\rangle) + \beta(|0\rangle - |1\rangle)(|10\rangle + |01\rangle)]$

$|\psi_{stateincircuit}\rangle = \frac{1}{2}[|00\rangle(\alpha|0\rangle + \beta|1\rangle) + |01\rangle(\alpha|1\rangle + \beta|0\rangle) + |10\rangle(\alpha|0\rangle - \beta|1\rangle) + |11\rangle(\alpha|1\rangle - \beta|0\rangle)]$

Here the equation is breaks down into 4 terms. And each term represent a circumstance which require its own correction process. The correspondence between Alice's measurement result and the quantum state is as follow:

$00 \longmapsto |\psi_3(00)\rangle \equiv [\alpha|0\rangle + \beta|1\rangle]$

$01 \longmapsto |\psi_3(01)\rangle \equiv [\alpha|1\rangle + \beta|0\rangle]$

$10 \longmapsto |\psi_3(10)\rangle \equiv [\alpha|0\rangle - \beta|1\rangle]$

$11 \longmapsto |\psi_3(11)\rangle \equiv [\alpha|1\rangle - \beta|0\rangle]$

Refer to this correspondence, Bob can apply corresponding corrections to his entangled qubit to recover the original quantum state from Alice. For instance, if the measurement result is 00, Bob doesn't need extra correction process to receive the quantum state send by Alice; if the measurement result is 01, Bob needs to apply X-gate for correction process to recover the state; if the measurement result is 10, Bob needs to apply Z-gate for correction process to recover the state; And it the measurement result is 11, both X-gate and Z-gate is required in the correction process to recover the state[1].

3.2 3-qubit Quantum Teleportation Circuit

Among quantum teleportation circuit, 3-qubit quantum teleportation protocol is widely used in the actual implementation of the circuit. Under 3-qubit quantum teleportation, the first qubit refers to an arbitrary state, which is to be teleported, and the second qubit and third qubit are in a Bell state. In this capstone, we tear down the detailed process of building a 3-qubit quantum teleportation circuit can be teared down into 6 steps:

Step 1: Set up the overall structure of the circuit. In our context, we need 1 quantum register to store the qubit, 2 classical registers (crz, crx) to store the projection result regarding the different state of X and Z in different register, and an additional classical register (crq) to store the qubit received after correction and reverse rotation processes for the post-selection to work properly.

Step 2: Initialize the qubit that is meant to be sent. In our case, qubit q_0 will be teleported.

Step 3: Create bell pair to entangle qubits q_1 and q_2. This includes putting qubit q_1 into quantum state $|+\rangle$, and we then apply a CNOT gate with qubit q_1 as control and qubit q_2 as target.

Step 4: Apply a CNOT gate with qubit q_0 as control and qubit q_1 as target. Then apply a Hadamard gate to qubit q_0.

Step 5: Till this step, the projection process completes. We measure qubit q_0 and qubit q_1 and store their results as a classic bit in the classic bit registers (crz, crx) that we created in step 1.

Step 6: According to the projection result stored in the classic bit register, 4 different types of correction will be applied in the circuits. The 4 possible results are: 00, 01, 10, and 11 and each result has different implications. Firstly, if the result is 00, it means no correction need to be applied for this teleportation process and there's no extra work is needed. Secondly, if the result is 01, it indicates that we need to apply the X-gate for the correction. Thirdly, if the result is 10, it means that a Z-gate instead is needed for correction. Finally, if the result is 11, we apply both X-gate and Z-gate for the correction process.

At this point, the 3-qubit quantum teleportation circuit is properly implemented in IBM quantum processor, and our next step is to analyze the Quantum Teleportation algorithm's performance regarding different correction methods.

3.3 Fidelity: the Measurement Method

In order to systematically analyze the Quantum Teleportation algorithm's performance and help to formulate a solid ground for future work, we need to introduce a concept called fidelity as our measurement method before our analysis.

By definition, in the quantum world, especially in areas regarding quantum information theory, "fidelity" is commonly used as an evaluation methodology to measure the "closeness" of two quantum states. It's denoted as:

$F(\rho, \sigma) = (\mathrm{tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}})^2$, where ρ and σ are density operators.

In our context of quantum teleportation, subcategory of quantum information transmission as we mentioned above, the density operators ρ and σ represent different quantum states. Therefore, here the fidelity help determines whether the qubit has been teleported accurately and thus can be utilized as the quantitative analysis of overall performance.

However, due to implementation constrains that the IBM quantum processor is not able to provide us with the raw data of the generated quantum states, we shift our solution to testing the fidelity by performing a rotation on the basis of the state that is teleported and examine the number of times that this state was measured. Our criteria is that if the teleported state after state preparation is reversed to be $|0\rangle$, this teleportation is considered as successful.

With this in mind, circuits were built to achieve both quantum teleportation and the fidelity test processes by combining the teleportation circuits and the reverse rotation operation.

In the actual implementation stage, we implemented quantum circuit simulators to conduct sufficient simulation to confirm the authentic of the algorithm theoretically, and we then test the result on actual quantum computer to measure its fidelity.

3.4 Correction Types, Post Selection and Fidelity Analysis

Since the actual correction processes are determined by the projection outcome stored in the classic bits, each correction process for each qubit sent can be various. Therefore, we choose to implement different versions of circuits based on different corrections and apply post-selection after retrieving the dataset to ensure all the corrections are applied properly.

To be specific, we implement 4 version of circuits with different correction, including one with X-gate and Z-gate correction, one with only X-gate correction, one with only Z-gate correction, and one without both correction.

For the post selection process to work properly, we need to extract the X-gate and Z-gate indicators stored in the classic bits and also retrieve the qubit quantum state after the correction and the reverse rotation operation. In order to achieve these, we create an extra classic bit register parallel to the former ones and store the qubit quantum state after correction and reverse operation.

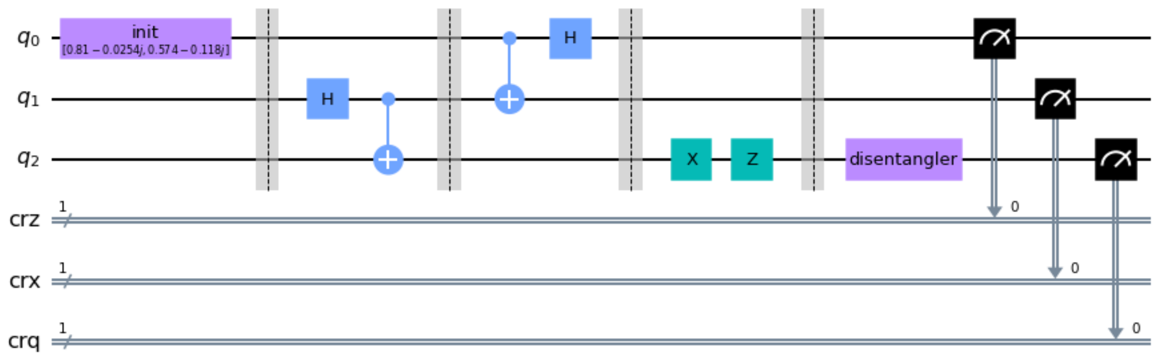

Figure 1: Quantum teleportation circuit with correction type X and Z, the label "disentangle" represent the inverse rotation process of the initial gate

After the circuits accomplished their jobs, we then applied post selections on each dataset for filtering purpose and left only the qubit data that would go through properly corrections. After the post-selection process, we calculated the mean and the standard deviation of the results, and then plotted the fidelity of all of these 4 versions of circuits separately, which will be discussed in detail in *Section 4*.

4 Results and Discussion

4.1 Theoretical Fidelity Analysis with IBM Quantum Simulator

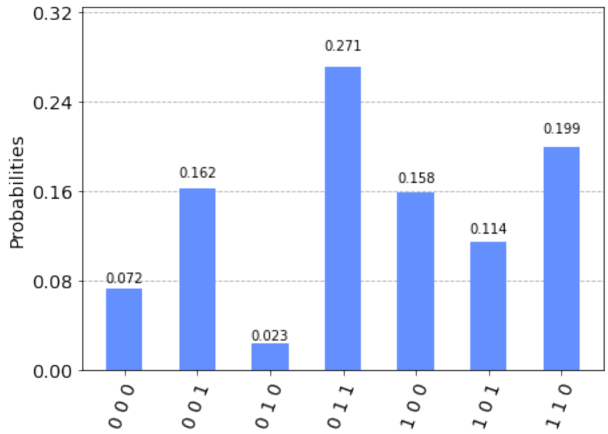

Figure 2: The fidelity with correction type X and Z over 4000 runs on IBM Quantum Simulator

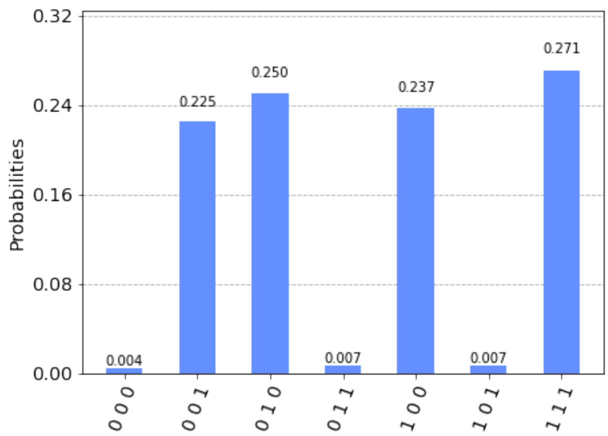

Figure 3: The fidelity with correction type X over 4000 runs on IBM Quantum Simulator

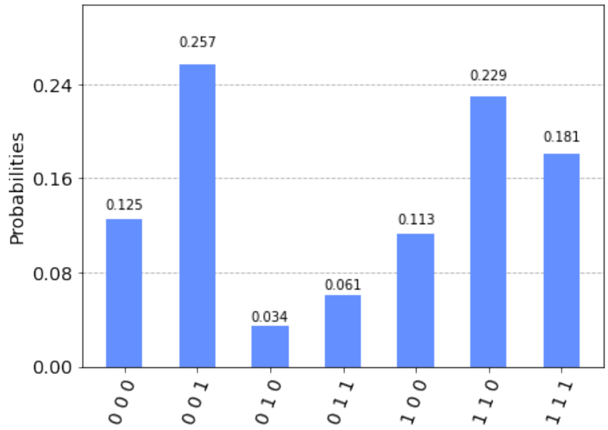

Figure 4: The fidelity with correction type Z over 4000 runs on IBM Quantum Simulator

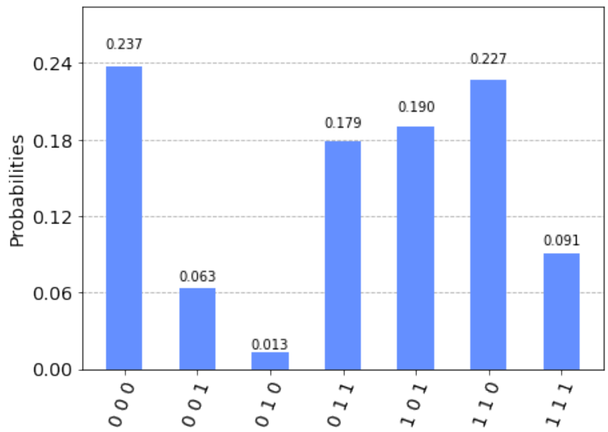

Figure 5: The fidelity with correction type None over 4000 runs on IBM Quantum Simulator

The above 4 figures above demonstrated the fidelity results of all 4 versions of the circuits with different correction types on IBM Quantum Simulator: correction with both X-gate and X-gate, correction with only X-gate, correction with only Z-gate, and circuit without correction respectively. They help simulate the quantum teleportation circuits and ensure the correctness of the circuit design, help to build solid foundation for the fidelity test on future IBM Quantum Process.

The X-axis of the graph is composed of different combinations of 3 numbers. They are listed to represent the projection results stored in the classic bit and the qubit quantum state after the teleportation and the reverse rotation process. In our case, the first number represent the quantum state of the transmited qubit went through correction and reverse rotation operator, the second number indicate whether this qubit has went through X-gate correction, and the third number indicate whether this qubit has went through Z-gate correction.

For the correction type X and Z, the qualified pillar after post-selection would be "0 1 1" and "1 1 1", which represent the circumstance where the qubit went through X-gate and Z-gate and reversed back to $|0\rangle$ and $|1\rangle$. As denoted in the figure, the possibility of the pillar "0 1 1" is greater than 0 and the possibility of the pillar "1 1 1" is 0, this indicates that after went through X-gate and Z-gate, all of the qubit were reversed back to $|0\rangle$, and thus represent the absolute fidelity of the circuit with correction type X and Z theoretically.

The other 3 correction types work similar. For the correction type X, the qualified pillar after post-selection would be "0 1 0" and "1 1 0", which represent the circumstance where the qubit went through X-gate and reversed back to $|0\rangle$ and $|1\rangle$. As denoted in the figure, the possibility of the pillar "0 1 0" is greater than 0 and the possibility of the pillar "1 1 0" is 0, this indicates that after went through X-gate, all of the qubit were reversed back to $|0\rangle$, and thus represent the absolute fidelity of the circuit with correction type X theoretically. For the correction type Z, the qualified pillar after post-selection would be "0 0 1" and "1 0 1", which represent the circumstance where the qubit went through Z-gate and reversed back to $|0\rangle$ and $|1\rangle$. As denoted in the figure, the possibility of the pillar "0 0 1" is greater than 0 and the possibility of the pillar "1 0 1" is 0, this indicates that after went through Z-gate, all of the qubit were reversed back to $|0\rangle$, and thus represent the absolute fidelity of the circuit with correction type Z theoretically. For the circuit without correction, the possibility of the pillar "0 0 0" is greater than 0 and the possibility of the pillar "1 0 0" is 0, which represent the absolute fidelity of the circuit without correction theoretically.

At this point, the theoretical fidelity analysis on IBM Quantum Simulator is all done and be ready to move forward to the benchmarking experiments on IBM Quantum Processor.

4.2 Fidelity Analysis on IBM Quantum Processor

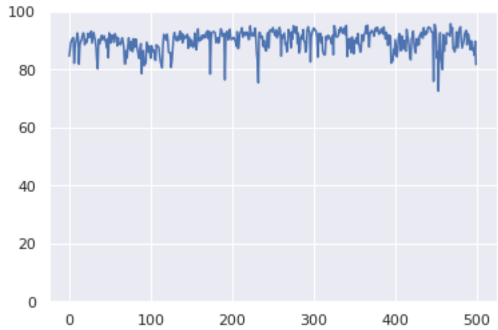

Figure 6: The fidelity with correction type X and Z over 500 runs on IBM Quantum Processor

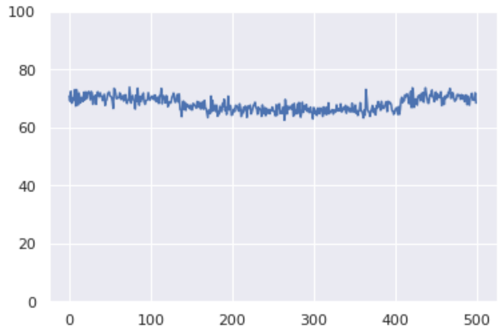

Figure 7: The fidelity with correction type X over 500 runs on IBM Quantum Processor

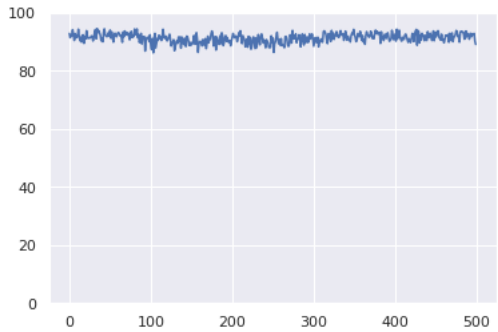

Figure 8: The fidelity with correction type Z over 500 runs on IBM Quantum Processor

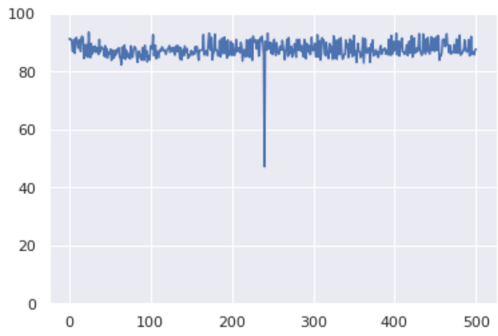

Figure 9: The fidelity with correction type None over 500 runs on IBM Quantum Processor

Fidelity Analysis		
Correction Type	Mean	Std
X and Z	89.912	3.504
X	68.157	2.468
Z	91.309	1.603
None	87.530	2.925

Table 1: Comparison of fidelity between different correction types

These 4 figures above demonstrated the fidelity results of all 4 versions of the circuits with different correction types on IBM Quantum Processor: correction with both X-gate and X-gate, correction with only X-gate, correction with only Z-gate, and circuit without correction. They help benchmark the performance of the IBM quantum processor using on-chip quantum teleportation with post-selection.

To analyze the results, based on theoretical analysis, the outcomes without X-gate and Z-gate will have the least deep circuit, which is just the teleportation itself. Moreover, the deeper the circuit, the more time will be needed for the noise and decoherence to accumulate. Inferring from this theory, the fidelity result of the circuit without correction gate should be the highest, and the result of the circuit with both X-gate and Z-gate should be lower than those with only one correction gate either X-gate or Z-gate.

We then turn to comparing these four different results, which fit largely the conjecture. The correction type with both X-gate and Z-gate implemented has larger standard deviation (3.504) then the one with either X-gate (2.468) and Z-gate (1.603), and also surpass the one without correction (2.925). However, judging from the plots, it seems like the X-gate is much noisier than the Z-gate. One possible explanation is that this phenomenon might be caused of how those gates are physically implemented in the IBM quantum processor.

Also, considering the fact that single qubit gate fidelity is supposed to be very high, it would seem strange that the fidelity would drop so much with an extra gate of either X-gate or Z-gate. After external research and consultation with supervisor, one possible explanation is that this phenomenon has more to do with the measurement methods. For example, IBM quantum processor has a poor reputation with its readout fidelity, which may partially explain this phenomenon. Any kind of conditional operation would be affected by IBM quantum processor.

5 Conclusion

Quantum teleportation, as a progressive quantum computation algorithm, paves the way for building the quantum Internet, which has the potential to solve contemporary distributed system problems, especially in network. In this paper, we thoroughly examine this algorithm by conducting simulation and then implementing it on cloud quantum computer: IBM quantum processor. We benchmark the performance of quantum teleportation the using on-chip IBM quantum processor with post selection.

In this work, we choose to build the most widely applied 3-qubit quantum teleportation algorithm with customized state preparation and 4 different corrections. Firstly, we simulate the performance of quantum teleportation with post processing and receive the teleported qubit correctly by excluding the results with wrong correction. Secondly, We use fidelity as measurement methods to measure the performance of quantum teleportation on IBM quantum processor. Those different combinations of X-gate and Z-gate influence the fidelity result of the quantum teleportation algorithm, with that of the circuit without correction gate being the highest. In general, the performance of quantum teleportation in environment with noise and decoherence is exciting and promising with the highest average fidelity being 91.3%.

We believe this paper provides a detailed analysis over the quantum teleportation algorithm, which helps formulating a solid ground into future work on building the quantum Internet and solves distributed system problems. We do need to expand our work to examining quantum Internet when it becomes feasible to build quantum network using quantum teleportation in the future to solve distributed system problems. Given implementation constrains of single cloud quantum computer, we could only focus on quantum teleportation on distributed system problems.

Regarding the implementation and examination of quantum teleportation, we could extend our work in the following ways:

Firstly, from a theoretical perspective, the focus of this paper is on 3-qubit quantum teleportation algorithm. This could be extended to generalizations of the quantum teleportation. Future work will be needed to find and test new circuits and perform the more generalized teleportation readily and then run on the actual quantum computer.

Secondly, from a implementation perspective, future work will need to control the IBM quantum processor backend. In this paper, the implementation uses the least busy backend on IBM quantum processor, which includes the situation of switching to different backend when the job queue is impacted by other cloud users. We've made some efforts on examining this issue, while this situation depends largely on the scheduling algorithm IBM quantum processor uses and we can't control over, which probably will impact the fidelity results. We are not sure about whether there's this impact while we can't rule out this possibility. If IBM quantum processor provide designated backend in the future,we would be able to conduct the implementation on single backend and control the variables.

Thirdly, further research regarding the abnormal phenomenon in our result and discussion section are needed. We need to be more aware of the possible impact of IBM Quantum processor and other possible reasons.

References

[1] M. Nielsen and I. Chuang, "Quantum computation and quantum information, 10th anniversary edition," 01 2010.

[2] S. Bravyi, D. Gosset, and R. Koenig, "Quantum advantage with shallow circuits," *Science*, vol. 362, 04 2017.

[3] R. Bera, *Quantum Cryptography and Quantum Teleportation*, 03 2020, pp. 1–16.

[4] T. Liu, "The applications and challenges of quantum teleportation," *Journal of Physics: Conference Series*, vol. 1634, p. 012089, 09 2020.

[5] V. R. R. Valivarthi, S. Davis, C. Pena, S. Xie, N. Lauk, L. Narváez, J. Allmaras, A. Beyer, Y. Gim, M. Hussein, G. Iskander, H. Kim, B. Korzh, A. Mueller, R. Rominsky, M. Shaw, D. Tang, E. Wollman, C. Simon, and M. Spiropulu, "Teleportation systems toward a quantum internet," *PRX Quantum*, vol. 1, 07 2020.

[6] H. J. Kimble, "The quantum internet," *Nature*, vol. 453, pp. 1023–1030, 2008.

[7] S. Pirandola and S. Braunstein, "Physics: Unite to build a quantum internet," *Nature*, vol. 532, pp. 169–171, 04 2016.

[8] A. J. G. Abelém, G. Vardoyan, and D. F. Towsley, "Quantum internet: The future of internetworking," 2020.

[9] R. Wolf, "Quantum communication and complexity," *Theoretical Computer Science*, vol. 287, pp. 337–353, 09 2002.

[10] S. Pirandola, J. Eisert, C. Weedbrook, A. Furusawa, and S. Braunstein, "Advances in quantum teleportation," *Nature Photonics*, vol. 9, 05 2015.

[11] S. Sazim and I. Chakrabarty, "A study of teleportation and super dense coding capacity in remote entanglement distribution," *The European Physical Journal D*, vol. 67, 10 2012.

[12] M. Elkin, H. Klauck, D. Nanongkai, and G. Pandurangan, "Can quantum communication speed up distributed computation?" *Proceedings of the Annual ACM Symposium on Principles of Distributed Computing*, 07 2014.

[13] C. Williams, *Explorations in Quantum Computing*, 01 2011.

[14] M. Caleffi, A. S. Cacciapuoti, and G. Bianchi, "Quantum internet: from communication to distributed computing!" 09 2018, pp. 1–4.