An investigation into quantum decoherence reduction techniques

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1. Abstract

Quantum computing can help make progress in many fields. This potential can transform the world. One of the biggest problems in quantum computing is the quantum decoherence in quantum circuits. Quantum decoherence makes things difficult to manipulate data and store data. Because qubits are essentially losing information because of quantum decoherence. The aim of this paper is to collect data from existing research and experiments and analysing them by architecture, qubit and circuit design and other techniques not mentioned here in order to list their strengths and weaknesses in their methods. Two major architecture has been investigated which are superconducting or ion trap. The author presents the different decoherence reduction techniques as well as his own general framework which can be used on almost all architectures in order to reduce decoherence. The results show that ion trap has the potential for general use such as at home where there is no need for industrial or specialised applications and superconducting has the potential for industrial or specialised applications. The results indicate that each methods and architectures are suitable for different purposes. Which means that people should continue to research and develop products with variety of methods and there is no one size fits all.

2. Introduction

Quantum computing has the potential to change everything about how our world works. They can help us in building new medicine (Solenov, 2020) and simulating movements of atoms in order to better understand them (Popkin, 2020).

There have been several superconducting and ion trap circuits which have been successful in manipulating qubits in order to perform simple calculations. These circuits are the building blocks of quantum computers. They are like classical computer in a sense that they have gates. Despite recent progress in coherence times which can go up to 0.1 microsecond (Solenov, 2020), decoherence due to noise from the circuit and external environment severely hinders these circuits for development of quantum processor. Even with small number of qubits, the decoherence affects the computation significantly because decoherence cannot allow computation to take place more than average of few microseconds. The error rate is linear to decoherence time.

There has been lots of studies done and more and more people are researching this topic but compared to other subjects, it is still very lacking in data. There are gaps in literature, and most are outdated.

In this research, the author presents the different techniques that can be used to reduce decoherence time in circuits. There is also general framework that can be applied to most architectures in order to reduce decoherence.

The author presents to you the results of each techniques and analyse how effective they are in reducing decoherence. He will also analyse the techniques and their effectiveness based on their practicality. Techniques must be easily do able without huge cost associated. The aim is to collect data and list their strength and weaknesses. This can be used to quickly identify which architectures are better for which purposes. The author hopes that this will also get the core concepts across to the broad audience and so that it may accelerate the development of quantum computers.

The paper is organised as follows. In section 2, the author goes into the details of the problems. In section 3, the research aim of this papers. In section 4, the details of the research objective. Section 5 is for scope of this research. Section 6 is details of literature review. In Section 7, the author describes the research methodology and their process. Section 8 is the results and discussions about their use. In Section 9, the author will conclude the paper. In section 10, there are references which have been used throughout this paper.

2.1 Problem Background

Compared to other fields, quantum computing is being researched by very few people. There are wide gaps in research and there is no generalised research being done. General in this context means something that can be applied universally in quantum computing, something that can be understood by broader audience. One of the biggest problems in quantum computing is the decoherence. Decoherence happens when a qubit is affected by external energy (Bacon, 2003). It could be observing the qubit to make calculations, or it can be radio waves or magnetic fields. There are many techniques for reducing quantum decoherence but none of them provides enough protection for qubits so the computation time can be of longer time. There have been few experiments which were successful in decoherence time of 30 minutes using ion trap architecture however, it is still in very early phase (Colin D. Bruzewicz, 2019).

2.2 Research Aim

The aim of this research is to get data from other research and experiments and analyse them to list their strength and weaknesses. This will fill the research gap of general data that can be used in order to quickly make decisions in the development of quantum computer. This paper can be used to choose which architecture may be the most suitable for their situation. This paper also aims to accelerate the development of quantum computing by having general data and concepts understandable to broad audience.

2.3 Research Objectives

i. To help fill research gap of quantum decoherence reduction techniques
ii. To analyse different techniques to find out their effectiveness
iii. To understand the practical uses of different techniques

2.4 Scope

The scope of this research is quantum decoherence in quantum computing.

i. Focus on two main architecture ion trap and superconducting.
ii. Different qubit types are not considered

3. Literature Review

This section reviews the literatures and the techniques used to reduce quantum decoherence. It will reveal gaps in the literature and advantages and disadvantages of each technique.

This section will begin with introduction to quantum decoherence. Its history and motivations for reducing decoherence. Then there will be analysis of each technique with advantages and disadvantages. And lastly, each technique will be investigated by their effectiveness and practicality.

Quantum decoherence is a loss of information in quantum bits. Particles are described by wave function in quantum mechanics. They are probabilistic and it explains various quantum effects which one of them are decoherence. A definite phase is necessary to observe the quantum states. However, this phase needs to be perfectly isolated which is impossible because in order to observe the quantum states, there is a need to externally affect the phase. Decoherence was first introduced in 1970 by a German physicist Heinz-Dieter Zeh (Zeh, 1970). As the observation changes the phase, it can be viewed as loss of information by an external effect (Bacon, 2001). As decoherence are loss of information, it is hard to do computations while information is lost somewhere. This created motivations to reduce quantum decoherence as much as possible in order to reduce error rates and to also allow more and longer computation to take place.

Some techniques for reducing quantum decoherence

In 2011, Californian researchers were able to predict and control environmental decoherence by using magnetic molecule called iron-8 molecule (University of British Columbia, 2011) (Jablonski, 2011). However, they didn't tell much details about the experiment, the decoherence time, the architecture they used. This shows a gap in the research and the data available for further development. It is not possible to state the advantages and disadvantages without much data.

Katarzyna Roszak, Radim Filip & Tomáš Novotný has shown that decoherence could be controlled by decoherence itself (Katarzyna Roszak, 2015). By changing the system environment interaction, which is responsible for the decoherence of qubits, they can cancel out the decoherence in qubits theoretically. This research does not provide details on which architecture was used. It also says that they only support few picoseconds and have considered the Hamiltonian free evolution which is solely of pure dephasing type. The author also talks about other relaxation such as exciton occupation and radiative relaxation. This is very experimental and since it supports only few picoseconds, it is hard to find advantages for this technique.

Matthew Otten and Stephen K. Gray decided to combine many results into one to remove any errors (Matthew Otten, 2019). The idea is that errors can occur in different parts in different calculation even if they are computing the same thing. They proposed that if they combine many small quantum computers to compute one problem and combine all of them together, they can compute almost the same time as one big quantum computer but with much less errors. This is a practical and effective technique that can almost reduce the error rate to 0 as long as they use many quantum computers to compute one problem. The disadvantage is that it could get expensive because of the need for many quantum computers or many computations of one problem.

A group of researchers has confirmed that trapped ion can have much better accuracy and coherence times of 50 seconds (Colin D. Bruzewicz, 2019). They were able to achieve this at room temperature and without magnetic field shielding or other techniques. This is not a technique but more of an architecture. This is the most effective and practical solution yet. It is cost effective, more portable and modular compared to superconducting architecture. On the topic of decoherence, trapped ion is far ahead than superconducting. Since this is an architecture, it can be used with other techniques. The disadvantages is that it is a lot slower than superconducting.

In conclusion to this section, there are a massive gap in the literature. There are data missing and most are theoretical papers. There are not many techniques on reducing quantum decoherence besides shielding them better and cooling them down to the lowest temperature possible. The ion trapped computer is very good compared to superconducting, but they are slower as well.

4. Research Methodology

As discussed in section 1, the problem is that decoherence does not allow computation to take place in quantum computer. The biggest problem that causes decoherence is heat. The temperature must be as low as possible to have the best coherence times regardless of architecture. This is due to way quantum mechanics work. Other causes are noises such as radiation or magnetic fields. The two solutions the problems are to reduce the noise. Such as lowering temperature or having better shielding. And a solution that is not affected by errors. Such as performing multiple computations for one problem and stitching them together or detecting and correct errors (Shor, 1995).

4.1 Research Framework

This section gives some details on research method used.

First step was to pre-process and select literatures which are relevant to this topic.

Second step was to research general quantum reduction techniques which were not specific to certain architecture. As shown in section 6, most of the techniques does not tell which architecture the technique belongs to.

Third step was to research superconducting specific techniques to reduce quantum decoherence. The author assumes that some techniques in the general category are for superconducting based on the information that ion trap can operate fairly well at room temperature.

Fourth step was to research ion trap specific techniques. There are so far no techniques specific to ion trap.

Fifth step was to evaluate different techniques.

4.2 Gantt Chart

	25/04/2020	03/05/2020	06/05/2020	07/05/2020	11/05/2020
Research					
Literature review					
Analysis					
Writing					
Submission					

Table 1 Gantt chart

4.3 Data Collection Strategy

There are no datasets on this topic at the moment. The author had to manually search the internet for this topic, combine them all together and analyse them.

5. Results and Discussion

As stated in previous sections, the aim of this research is to compile and evaluate different quantum decoherence reduction techniques. In this section, the author will detail how the different techniques can help and be used for practical purposes.

Technique	Advantages	Disadvantages
Control environmental decoherence using magnetic molecule	Potential to significantly reduce decoherence.	There are not enough data to consider this seriously
Control decoherence with decoherence	Cost effective method to reduce decoherence	Only works on Hamiltonian free evolution currently. Doesn’t consider other types of relaxation.
Combine many results into one	Potential to almost get rid of errors. Potential to be used with many architectures.	Can cost significant amount of money because it requires multiple quantum computer.
Trapped ion computer	Can operate at room temperature. Does not need extra shielding.	Slower than other architecture.

Table 2 Advantages and disadvantages of each technique

As you can see in the table, there are not many techniques currently available to reduce decoherence. Most are still experimental or purely theoretical such as controlling decoherence with decoherence and using magnetic molecule to control decoherence. The clear winner here is trapped ion computer which is not a technique but architecture itself.

Although trapped ion computer is the winner in terms of decoherence and error rates, other techniques and architectures could be better suited for certain applications.

Architecture/architecture with technique	Potential uses
Superconducting	Industrial, large companies which require fast processing speed and can afford the higher maintenance cost and cooling cost.
Ion trap	Home or amateur use. Does not require much maintenance because of no cooling and allows for the operation under room temperature.
Superconducting with combining many results into one	Industrial or large companies where accuracy is the priority. It will have fast processing speed and high accuracy. Will have very high cost too.
Ion trap with combining many results into one	Home or amateur user but with better accuracy.

Table 3 Effectiveness and practicality of different techniques and architectures

As you can see in the table above, different techniques and architectures can be used for different purposes. Only one technique was considered because it has been tested and seems to work with both architectures. Other techniques do not have enough data or only very limited uses.

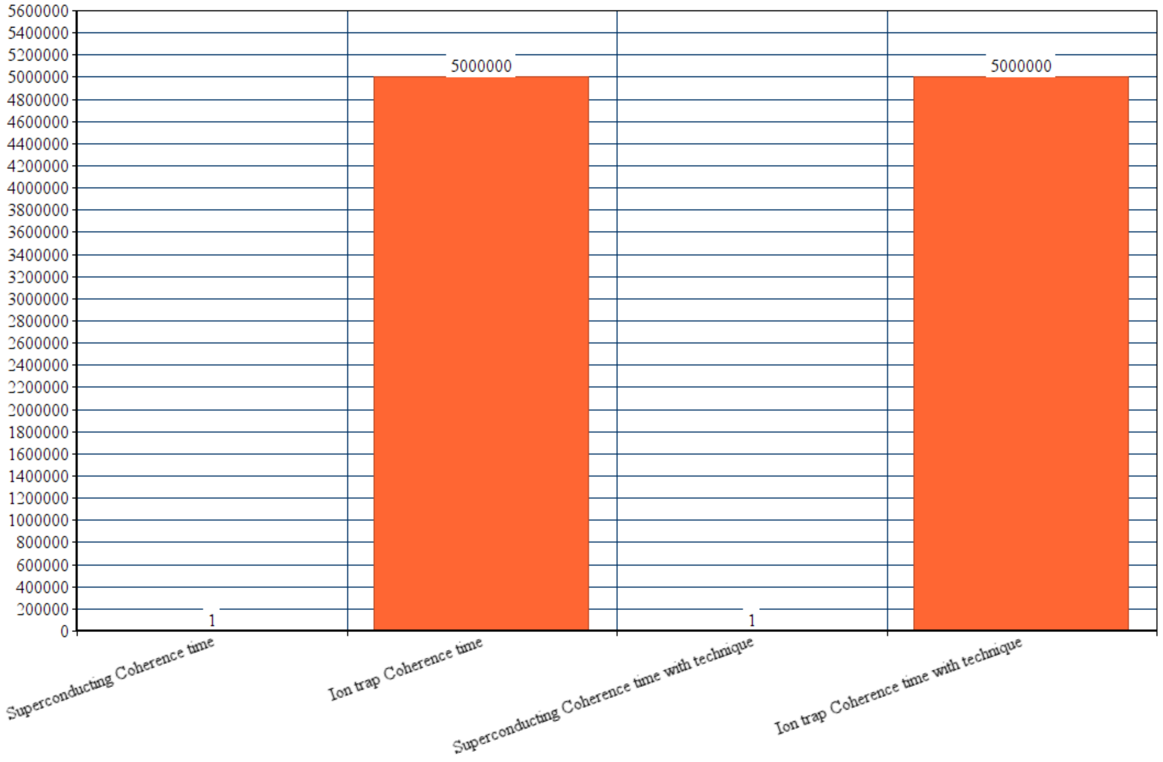

Figure 1 Showing the difference of coherence time. It is as extreme as it seems.

Figure 1 Shows the coherence time in microseconds. As you can see, there is extreme difference between superconducting and ion trap. The coherence time doesn't change because its average is fixed. It could fluctuate during computation however; it is outside the scope.

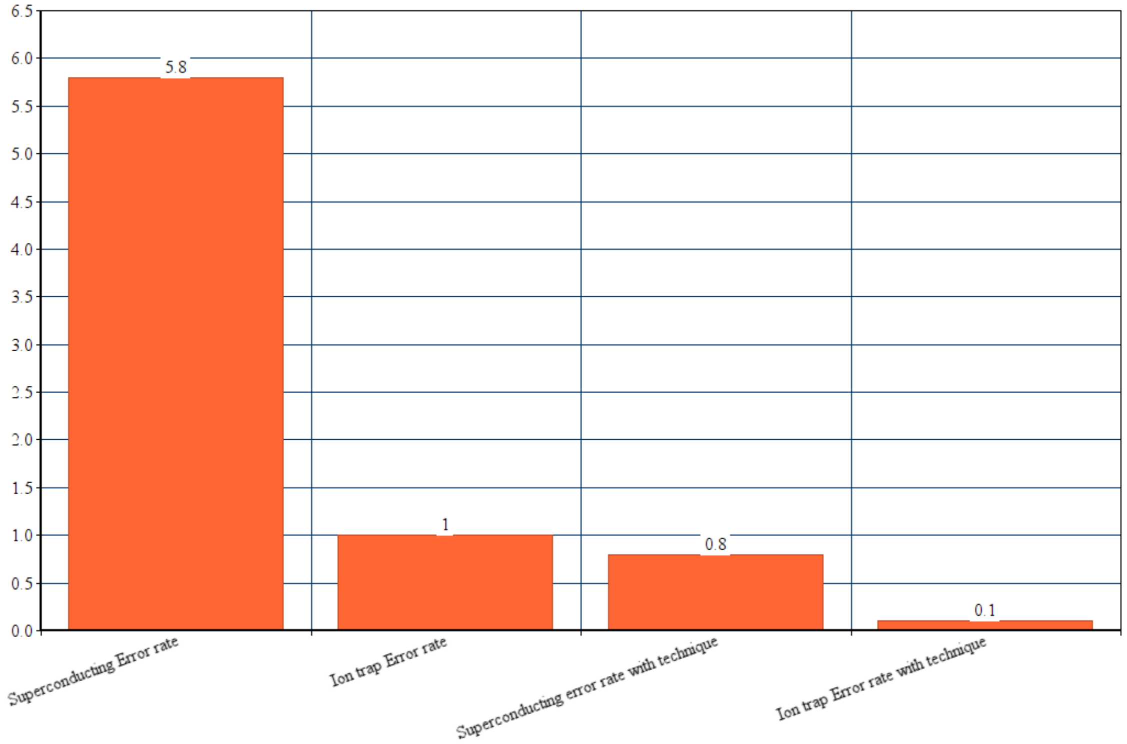

Figure 2 Showing the error rate of each architecture without and with technique.

Figure 2 shows the error rates. As you can see, the superconducting has the most error rate and ion trap has lower error rate. Using the technique mentioned above allows the error rate to come down a lot more. Especially on superconducting, the error rate is significantly reduced.

6. Conclusion

Quantum computing can be revolutionary. However, because of the issues mentioned such as decoherence, it is very difficult to develop a useful quantum computer. The cause of decoherence is external noise. It can be heat, radiation or magnetic fields. Qubits lose information due to decoherence and this makes longer computation almost impossible. Decoherence can be thought of as equivalent of signal deterioration in classical sense.

To solve this issue, this research has gathered available techniques in reducing quantum decoherence. The first method is using magnetic module to control environmental decoherence. It has potential to control all the decoherence but there is not enough data to know if it is practical. The second method is Controlling decoherence with decoherence. It is a cost-effective method however; it only works on Hamiltonian free evolution and it does not consider other types of relaxation. So, it is not practical. The third method is Combining many results into one. This is a practical method because it can significantly increase accuracy and it can be used with many quantum architectures. However, it is very costly as it requires multiple computation or multiple quantum computers. The fourth method is to use ion trap computer which by architecture, allows it to operate at room temperature and less shielding than superconducting. However, it is slower than superconducting.

This research has contributed as below:

i. Fill missing research gap of quantum decoherence reduction techniques
ii. Find different uses for different quantum architecture
iii. Analyse the effectiveness of each techniques

Recommendation for future work:

i. Creating industry specific quantum architecture and techniques
ii. Research tolerable error rate for home use quantum computer

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