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# Obstacles of Quantum Error Correction and Decoherence and Impact on Qubit Behavior

Dr.Shahebaz Ahmed Khan[1], Shaik Subhan Ali[2]
[1]Associate Professor, Computer Science and Engineering, Jayaprakash Narayan Engineering College, Hyderabad, India
[2]Assistant Professor, Avanthi Institute of Engineering &Technology, Hyderabad, India

***Abstract: The quantum computing theoretically serves as a path to many high-level complex problems, but suffers some profound challenges which become hurdles in its path to a practical scenario. It has deep rooted inexplicable and unsettled challenges like Quantum Error Correction (QEC), qubit instability and issues of quantum decoherence. One of the main obstacles in quantum computing is tenuousness of quantum information processing. The time limit and decoherence problem have been a long-term scientific barrier in the theory of quantum mechanics. The quantum behavior of a quantum computer is influenced and affected by the surroundings creating a 'race against time' causing errors in the quantum computations making later unreliable. The error correction requires resource overhead further causing the data processing complexities and so remains as a monumental issue. This paper discusses some major unresolved limitations and deficiencies of quantum computing to eliminate the hurdles, for a need to create a transformative potential technology in the era of quantum computing.***

***Index Terms: Decoherence, Quantum Error Correction, Race Against Time, Qubit Instability and Quantum Computation etc.***

## I. INTRODUCTION

Today despite its advances, the reliability, scalability and application of quantum computing is limited to some fundamental complexities struck with the engineering hurdles during its implementation. The time limit on quantum computations by the phenomenon of decoherence is a core challenge where the quantum behavior is modified and gradually allowing a quantum state to get transformed into a classical state. Any kind of perturbation like changes in temperature, sound vibrations, moisture density etc. can cause the quantum states to lose their property of qubit coherence and making the information stored to be lost. To perform quantum computations, the primary need is to maintain the quantum qubits in the desired states, which is a difficult task and a major challenge. The qubits store the information, these qubits are found in superposition of states by entangling each other allowing the parallel computation which makes quantum computers trillions of times faster than other classical machines. This idea is possible only when quantum coherence exists. The qubits are sensitive to various environmental and atmospheric factors like temperature, moisture, electromagnetic signals, noise or sound waves etc. On the other hand, the No Cloning theorem tells that the quantum operations are unitary linear transformations of various quantum states and so it is not possible to copy the unknown arbitrary states. This makes quantum computers sensitive to errors and so today, the quantum error correction is an area of active study by researchers in order to search the solutions without violating the No cloning theorem in parallel to the computation of the quantum qubits. In this era of theoretical quantum computing, a major task and challenge is to scale up the quantum computing machines to millions of qubits with good coherence and declining error rate simultaneously [1]. This is so complex that, whenever the count of qubits increases, the computational burden is more and so the error rate probability also increases. The tendency of decoherence in qubits causing to lose the quantum characteristics due to slight changes in environmental parameters sets a limit on time of computation demanding quantum error correction (QEC). This scenario restricts the practicality of promised quantum computer power in terms of super solving of many problems rested with limitations of computational ability of classical systems.

## II. QUBIT INSTABILITY AND DECOHERENCE

Decoherence refers to the phenomena of loss of quantum character from the qubits whenever the qubits interact with the surroundings and are influenced by environmental parameters though even slightly[2]. The information in quantum computers is stored in the form of qubits instead of bits. The qubits come into superposition states representing both 0 and 1 at a time. This means, the qubit can act as 0 and 1 simultaneously. When this situation occurs, the entanglement takes place with each other or among the qubits. The entanglement of qubits is responsible for parallel computation in quantum computing technology. In order to balance the properties and meet conditions required for efficient functioning of quantum systems, the quantum coherence is a pre-condition [3].

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Any quantum computer must be in a coherence to perform very minute calculations ranging from micro-nano seconds to milli-nano seconds. The power and depth of solving the problems by any algorithm in quantum boundary is limited by the constraint of coherence time of the qubits. To perform computations on qubits, the maintaining of qubits in their desired states is a complicated scenario. The quantum systems operate extremely at low temperatures; there can be thermal fluctuations and can lead to differences in qubit energy levels causing decoherence. Also, electromagnetic interference with the qubits can create disturbance in quantum states causing decoherence. One should also remember that, the operations and calculations of quantum computers are dependent on timed signals, any kind of minute noise perturbations can destroy the shape and timing of the pulses leading to unnecessary transitions and so decoherence occurs. Even grain boundaries and the presence of atomic vacancy can also invite unknown noise that can lead to decoherence. The loss of superposition makes the qubits to transform into a classical state and causes to lose the quantum behavior forms a decoherence state [4]. This further makes the system to decline the computational abilities which are provided by entanglement and superposition. The quantum information is lost gradually and the output computation remains meaningless and erratic. This is like a race against time situation; the errors should be eliminated at the pre occurrence of decoherence state [5]. There is a specific coherence time characteristic, where within the time limit the quantum information can be preserved.

### *A. Quantum Error Correction and Challenges*

Quantum Error Correction (QEC)is a crucial strategy and algorithmic technique to eliminate the errors and reduce the decoherence. The error correction enables the quantum computers to execute large scale complex calculations and become fault tolerance. The Quantum Error Correction (QEC) detects the errors and fixes these errors without destroying the quantum information preserved. The idea of QEC is such that, it works by encoding a single logical qubit into some large count of qubits by using some error correction code adding redundancy. The added redundancy opens the doors for a quantum system to detect and correct the errors so that a system can become meaningful and reliable. The errors are detected first by using some special measurements called syndrome measurements. The syndrome measurements are applied on physical qubits without measuring the logical qubits so as to detect the area and presence of errors [6]. Later, taking the results of syndrome measurements, a correction is applied to the detected qubits with errors so as to bring back these qubits in their original state.

Similar to classical Error Correction Codes, The Quantum Error Correction codes are implemented in a three-step process. The first step is error detection, the second is error deduction, and the final step is error correction. From this, it is to be known that, every Quantum Error Correction circuit must possess all of these three components. Due to the limitations laid by No Cloning theorem, the encoding of the state |ψi in quantum computations is done by applying CNOT gates to prepare the logical state [7]. Quantum Error Correction has many uses but is not essentially required in classical computing, where as it is very essential in terms of computations in large scale quantum computing. There are various Error Correction algorithms like Shor Code, Surface Code, Steane's Code, Toric Code, Bacon-Shor Codes, Flag Cubit Code and Stabilizer Code etc. which can enable large scale quantum computation by allowing the quantum systems to grow in size without any issue of noise. To protect and preserve the quantum information from the problems of gate errors and decoherence, to make the quantum computers fault tolerance and scalable, these algorithms make use of multiple qubits for encoding of a single logical qubit. But there are some fundamental challenges in Quantum Error Correction because of large significant overhead and so still QEC execution remains a hurdle in quantum systems. The measurement problems, uniqueness of the errors and No Cloning theorem are some special challenges which make QEC far more difficult than classical error correction.

### *B. QEC Overhead and Bottlenecks*

The Quantum Error Correction invites a significant overhead, where some hundreds of physical qubits are required to represent a single logical qubit. To create a single logical qubit, there can be a need of thousands or ten thousand of physical qubits in quantum computations. Sometimes, thousands of physical qubits are required to form a single logical qubit. Due to this gap in ratio of qubits, there can be a direct ratio conflict between reliability and scalability [8]. The scaling of a quantum system to millions or trillions of qubits needs a classical system to be capable of refining some enormous amounts of data that can range to more than 1000 terabytes per second. Another problem is that the time frame for QEC code execution, where it should be always deterministic and executed with in less than 1 nano or micro second in order to overcome the delays which can further cause unpredictable errors. Besides, the hardware specific challenges of scaling, multi-dimensional scaling issues, resource gaps etc. are also the reasons that work as bottlenecks during Quantum Error Corrections. Anyhow, the adaptation of existing classical error correction techniques for quantum computing is a complication due to the No Cloning theorem [9] [10]. This theorem interdicts and forbids the making of duplicate copies of qubits, which is quite possible and allowed in terms of classical bits.

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## III. NO CLONING THEOREM AND QUANTUM STATES

A quantum state can represent information about the quantum environment. The classical information is extracted by measuring the system, but it can only be probabilistic. If again a state is measured, it extracts the different information, as a consequent scenario the quantum states are measured large number of times in order to gain more information about the qubit quantum states. This is known a quantum state tomography. The quantum measurement is probabilistic, so each measurement can have different results with approximations. Due to this, a quantum state cannot be determined precisely and so it cannot be recreated precisely or copied and cloned exactly. However, by measuring a quantum state some thousands of times, the state can be determined by tomography with approximate accuracy. In addition to this, the qubit measurements are subject confined to the constraints of qubit measurements, failing which can cause the collapse of wave function resulting in the destruction of the quantum states.

We can only prepare infinite copies of quantum states but cannot precisely copy the quantum states due to limitations of no cloning theorem. Generally, we use a common error correction technique called check pointing in classical systems. This check pointing makes a backup value of the current state and so even if it gets corrupted in future, we can avoid the computation from the scratch and can resume it from the check point [11]. This is not allowed in quantum computing because we cannot copy the random states or arbitrary qubit values. So, the error correction in quantum computing is still a key area of research.

Figure 1 below illustrates the No Cloning Theorem. Here it is stated that, a copy machine is able to clone the states |0 and |1, but it provides the incorrect output for the superposition state |0+|1, saying that no pure and perfect cloning can exist.

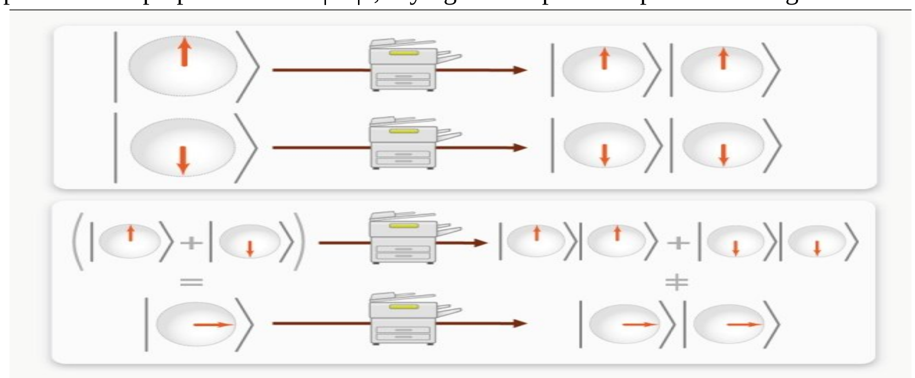

Fig. 1 No Cloning Illustration

It is a proposition that quantum information can be transmitted without breaking the theorem of No Cloning. Quantum teleportation makes the possibility of transferring quantum information from one point to another one by enabling entanglement of qubits. We are in a need of exact quantum information, but No Cloning theorem stands as a challenge here. In order to understand No Cloning theorem, let us start with a common Hilbert space of two quantum states [12]. This means the two states must have same number of qubits. Now, let us assume that the quantum system has some information that has to be copied exactly. Now, create a duplicate precise copy of that information on the other quantum system without perturbing the preserved information of the earlier or first quantum qubit. This gives two same copies of qubits. This can be proved by contradiction.

Let us be with an assumption that, there is a unitary matrix Z capable of cloning the arbitrary quantum states.

At first we have two quantum arbitrary states namely $| X\rangle \otimes |Y\rangle$

Now we need to clone the first vector and it gives $| X\rangle \otimes |X\rangle$

To do this we make use of matrix Z

Where, $Z(| X\rangle \otimes |Y\rangle) = | X\rangle \otimes |X\rangle$

Now, when the second time the cloning is to be done then, we find the following result.

$Z(| V\rangle \otimes |Y\rangle) = | V\rangle \otimes |V\rangle$

We should know two things here that, the unitary matrices conserve inner products first and secondly, we should be aware of how the inner products between multi qubit states are calculated.

$(| p\rangle \otimes |q\rangle) . (| s\rangle \otimes |t\rangle) = \langle p | s\rangle\langle s | t\rangle$

Now prior to cloning, let us take the inner product

$(| X\rangle \otimes |Y\rangle) . (| V\rangle \otimes |Y\rangle) = \langle X | V\rangle\langle Y | Y\rangle$

After, cloning we will get $(| X\rangle \otimes |X\rangle) . (| V\rangle \otimes |V\rangle) = \langle X | V\rangle\langle X | V\rangle = (\langle X | V\rangle)2$

Here, Z has conserved the inner products we have $\langle X | V\rangle = (\langle X | V\rangle)2$

This means there can be only two solutions finitely, either 0 or 1. i.e,

$<X \mid V> = 0$ or $<X \mid V> = 1$

This is a contradiction that either means both X or V cannot be arbitrary.

The further simplification can prove that; it is not possible to create the desired exact copy.

## IV. FUTURE DIRECTION AND OTHER CHALLENGES

Quantum Error Correction and coherence encounter various obstacles which are in a requirement resolution to solve and fix the fault tolerant and qubit behavior in large scale quantum computer. Addressing these issues is a crucial research step for the execution of complex computations with a reduced error rate. Some of the prevalent impediments like error characterization, noise modeling, scalability, resource overhead, implementation complications in error coding techniques etc. require a universal function that can reliably compute the quantum operations. Sophisticated techniques of machine learning and deep learning are deployed to optimize the performance and reliability in error correction coding mechanisms to achieve fault tolerant quantum computations.

Certain hybrid codes that combine the effective functions of different error correction codes are also being considered in some cases as a better solution for computation issues by the experts [13]. The conditions on a single quantum processing unit are very strict, emerging techniques in terms of decoherence elimination and reducing error correction issues need to connect the quantum computers of low power to overcome limitations on single chip systems. The frameworks like ARQUIN are focused on super conducting quantum devices which are interconnected to optical links by microwaves. ARQUIN pipeline is capable of simulating the large-scale quantum computers for a better computation of qubits

## V. CONCLUSION

The core issues of decoherence and Quantum Error Correction sets a limit on quantum computations and performance. These issues fundamentally stemmed from laws of quantum mechanics and physics derive the complexity by controlling the quantum phenomena. A long-term research goal is a need to fix the critical problems than the present-day imminent reality. The current qubit algorithms cannot actively and accurately shape the fundamental operations of error codes in quantum field. The paper underscores the technology of quantum computing remained constrained by serious unsolved limitations demanding an inter disciplinary work so that the promised potential by the quantum technology can be utilized. However, implementation of these methods to avoid decoherence is not an easy task due to the complexity of quantum systems. With exponential growth, the resources needed to execute error correction increases as the count of the qubits increase. Finally, without resolving and finding a permanent solution to decoherence hurdles and error correction codes, performance potentiality and computation of quantum computers remain as a long-term effort.

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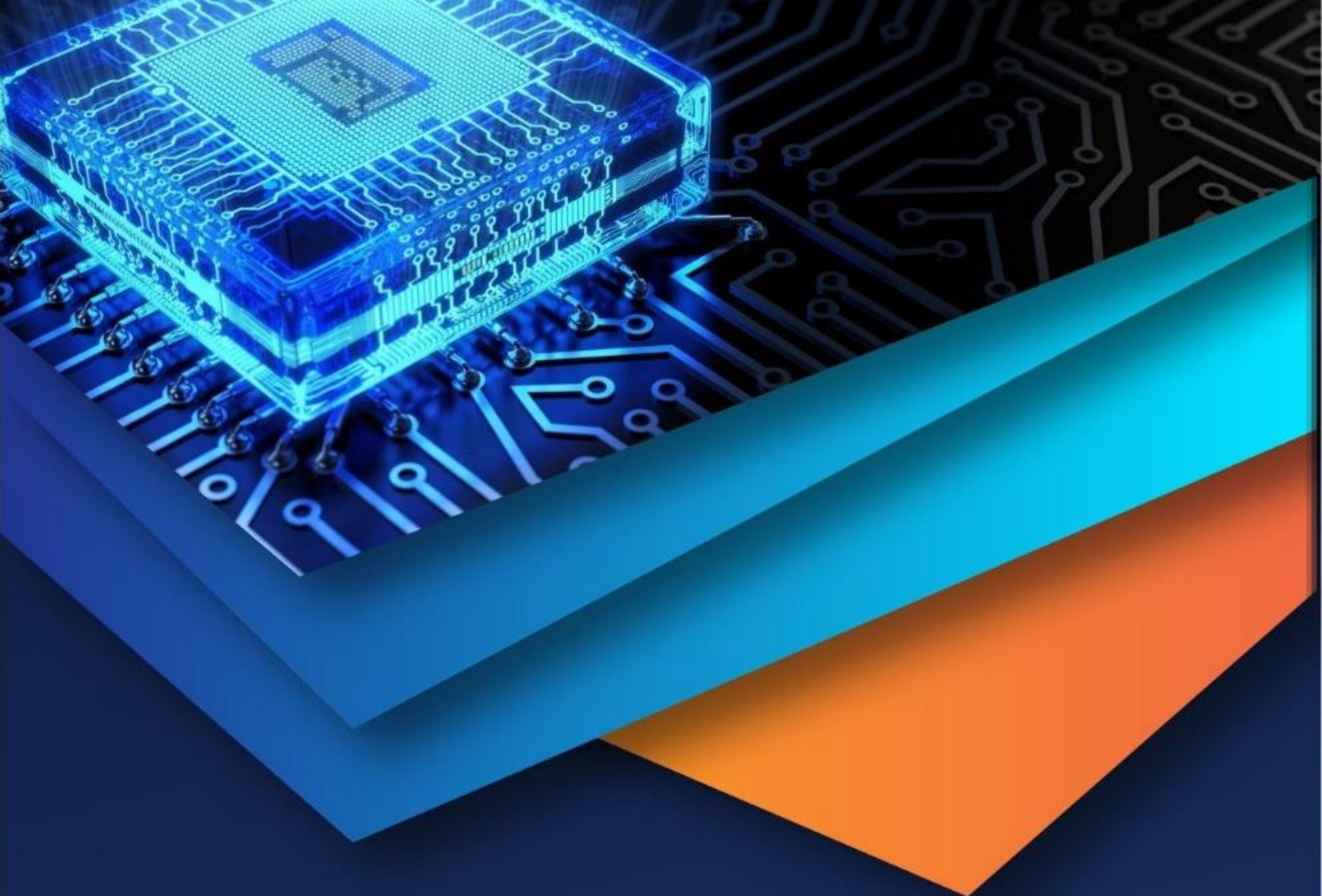

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