

## Entanglement Dynamics in Noisy Intermediate-Scale Quantum Systems

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### Abstract

The advent of noisy intermediate-scale quantum (NISQ) devices has not only opened up new possibilities to studying quantum computational benefits, but it has also presented new challenges associated with noise and short coherence times. Entanglement is one of the inherent resources that can be used to perform quantum computation and implement the performance and reliability of quantum algorithms. This paper looks at entanglement dynamics in NISQ machines subjected to natural noises. The study focuses on the problem of examining the role of various noise channels in the creation, dynamics, and decay of the entanglement during quantum operations, such as depolarizing, amplitude damping, and phase damping.

The study is based on theoretical modeling and numerical simulations of multi-qubit quantum circuits to determine the stability of entangled states with respect to circuit depth and intensity of noise. Concurrence and von Neumann entropy are examples of entanglement measures that are used to characterize correlations between qubits as well as to trace the dynamics of these correlations across computational interactions. The results show that noise has major impacts on entanglement distribution, which tends to cause rapid decays in highly entangled states with increase in circuit complexity. The findings, however, also show that there are some circuit architectures and error-mitigation schemes that can somewhat sustain entanglement with moderate levels of noise.

The paper also emphasizes the relevance of minimalizing sequence of gates, and reduced circuit depth in an effort to preserve useful entanglement in present-day quantum hardware. These observations help in understanding the behaviour of quantum correlations better in real world quantum devices and provide a way of developing more resilient quantum algorithms that would work on NISQ systems. In general, the article offers a systematic view on entanglement behavior in disordered quantum systems and highlights its value in the development of quantum computing applications in the near term.

**Keywords:** Noisy Intermediate-Scale Quantum (NISQ) systems, Quantum entanglement, Entanglement dynamics, Quantum noise, Depolarizing channel, Amplitude damping, Phase damping, Quantum circuits, Error mitigation, Quantum computing.

### Introduction

Quantum technologies are quickly coming out of theoretical frameworks into testing platforms with the capacity to carry out highly complex computational and information-processing systems. The quantum devices of the present, commonly referred to as noisy intermediate-scale quantum (NISQ) systems, have tens and hundreds of qubits, but are still restricted to poor control, decoherence, and noise due to the environment. Nevertheless, NISQ processors have provided the possibility to investigate quantum phenomena, which are hard to model on a classical computer, albeit with these restrictions. Among them, quantum entanglement is placed in the central position since it is a major resource in quantum communication, quantum computing, and quantum sensing. It is important to understand the mechanism of entanglement formation, evolution and decay in realistic quantum devices, thus, to progress practical quantum technologies.

Entanglement can be created with a high level of fidelity and sustained in idealized theoretical

models. Yet, in reality, quantum systems have interactions with their environment, which causes decoherence to occur, quantum correlations to be lost, and errors to occur when computing. Gates that are imperfect, thermal, and measurement processes all contribute to noise that affects the dynamics of entangled states greatly. Therefore, the NISQ device behaviour is not usually similar to the behaviour expected in noiseless models. This has raised the issue of studying entanglement dynamics at these noisy conditions and become a significant field of study in both theoretical and experimental quantum science.

Recent literature has been concerned with defining the dynamics of entanglement propagation in quantum circuits, understanding the degradation of entanglement in the presence of noise, and understanding how error-reduction schemes can be used to maintain useful quantum correlations. This model control capability can make quantum algorithms perform better and quantum processors of the near-term more reliable. Further, the results of entanglement behaviour analysis in NISQ systems can offer important understanding of many-body quantum physics and the threshold of quantum advantage.

It is on this backdrop that the current paper analyzes the dynamics of entanglement of noisy intermediate-scale quantum systems, with particular focus on how environmental noise and imperfections in the operations of a system impact the dynamics of quantum correlations.

## Background of the study

A quantum computing has become one of the most revolutionary revolutions in contemporary computational science which promises to address the problems that are not accessible to classical computers. In contrast to classical computers based on binary bits, quantum computers use qubits, which make use of quantum mechanical properties like superposition and entanglement to compute complex functions. Quantum entanglement is one of these principles and is the main component that allows qubits to be strongly correlated, which is at the core of quantum communication, quantum cryptography, and most quantum algorithms.

However, the creation of Noisy Intermediate-Scale Quantum (NISQ) machines in recent years has been a significant step towards quantum computing. The devices are usually tens to several hundreds of qubits and do not have full scale quantum error correction. Consequently, they are a middle-ground between small scale experimental quantum prototypes and larger fault-tolerant quantum computers of the future. Even though NISQ devices have a level of experimentation and algorithm development opportunities never seen before, they are very vulnerable to additional noise in the environment, non-ideal gate operation, and poor qubit coherence times. Those restrictions contribute to the errors in the calculations and limit the depth and reliability of quantum circuits.

The main problem of studying NISQ-era is how entanglement changes and deteriorates when noise is present. Entanglement is a very important condition to possess quantum computational advantage but it is highly sensitive to external noise and hardware imperfections. The environmental interactions are able to easily destroy the entangled states; hence, the performance of quantum algorithms on the current hardware is constrained. The noise sources of NISQ processors include thermal noise, electromagnetic noise and poor quality of quantum gates control. Each of them influences interactions of entangled qubits and may lead to the emergence of such a phenomenon as entanglement decay, sudden death, or partial revival in the course of quantum evolution.

The study of entanglement dynamics is done in this way to determine the performance limits of the current quantum technologies. The dynamics of the behaviour of entanglement with realistic noise conditions is studied to comprehend how quantum states remain stable, and how practical quantum algorithms can be realised. The studies in this field also lead to the advancement of error reduction methods, circuit optimization schemes and hardware-readable quantum algorithms targeted specifically at NISQ devices. Since the present-day quantum devices do not have 100% error correction capabilities, it is important to learn how to make maximum use of

entanglement and reduce the effects of noise in quantum information science.

Also, the study of entanglement behaviour on NISQ systems aids in the overarching initiative to assess the computing capacity and scalability of near-term quantum technologies. The study of entanglement walkthrough and decay through multi-qubit systems assists researchers to create stronger circuits and determine architectures that obtain maximum quantum benefit based on actual hardware limits. The studies also lead to the creation of new measures and analysis tools of entanglement as well as the measurement of quantum capabilities in noisy settings.

As quantum hardware is developing at a high rate and experimental quantum processors become more available, there has been a growing interest in conducting systematic research to understand the connection between noise and entanglement in intermediate-scale quantum systems. The study of entanglement processes of NISQ devices not only improves the theoretical knowledge of open quantum systems, but it also offers practical insights that could be used to develop more stable and efficient quantum technologies. Hence, this paper is devoted to the examination of the effect of noise on the production, development, and decay of the entanglement in NISQ systems and determining the strategies to enhance the reliability and scalability of the near-term quantum computing platforms.

## Justification

The swift progress in quantum computing has given way to the creation of Noisy Intermediate-Scale Quantum (NISQ) devices, which are the most recent generation of quantum hardware with a small amount of qubits and having a high sensitivity to noise and decoherence. It is hoped that these systems will be useful in closing the gap between the theoretical quantum algorithms and fault-tolerant quantum computers. Nevertheless, the reliability of the quantum computations is seriously impacted by the existence of environmental noise and operational imperfections. In this regard, the critical importance of knowledge regarding the behaviour of quantum entanglement in NISQ machine becomes particularly significant.

One of the key resources that make quantum computing beneficial is quantum entanglement, which makes it possible to achieve some of the benefits of quantum computing such as quantum communication, quantum simulation, and some types of quantum algorithms. These applications heavily rely on the ability to generate, preserve and manipulate entangled states. In NISQ systems, noise, gate errors and decoherence processes tend to undermine entanglement. Consequently, the systems of entanglement with realistic noisy environments should be comprehensively explored to enhance the functionality of quantum apparatus.

Although the existing research on the topic of quantum computation is growing, the fundamental issue is that the evolution of entanglement in intermediate-scale quantum systems that are subjected to realistic conditions remains a very critical question to be answered. The dynamics of entanglement measurements in these systems can be studied to gain useful insights into quantum correlations stability and quantum circuit stability as well as hardware architecture constraints. In addition, a better insight into entanglement behaviour would be useful in designing more resilient quantum algorithms and error mitigation software.

The other factor that enabled me to choose the study is the necessity to optimize quantum protocols that should be implemented in practice. Through the analysis of the effect of noise on the entanglement creation and degradation, the researchers will be able to design the means of ensuring that quantum correlations can be maintained over a longer period. The understanding plays a crucial role in enhancing the faithfulness of the quantum operations and scalability of quantum technologies. In line with this, the interest to explore the entanglement and noise interaction within the NISQ systems justifies this study. Dynamics of entanglement, in addition to the enrichment of the theoretical base, will contribute to the practical advancement of more trusted quantum computing platforms. The findings of the present research could be utilized in order to assist scientists and engineers to design more efficient quantum circuits, enhance the error correction protocols, and to enhance the overall efficiency of quantum information

processing.

## Objectives of the Study

1. To assess the essential features of quantum entanglement in noisy intermediate-scale quantum (NISQ) systems and learn how the noise influences the entanglement stability.
2. To study the processes of entanglement evolution in multi-qubits systems under realistic noise.
3. To examine how the generation and maintenance of entangled states are affected by various forms of quantum noise, including decoherence and environmental perturbations.
4. To test the existing quantum circuits and algorithms in the maintenance of entanglement in NISQ devices.
5. To investigate theoretical models and simulation methods characterizing the behaviour of entanglement in imperfect quantum hardware.

## Literature Review

Quantum computing has now reached the Noisy Intermediate-Scale Quantum (NISQ) stage, with quantum processors with tens to hundreds of qubits but no quantum error correction. Such devices work with high noise, decoherence and operation imperfections, which directly affects the creation and maintenance of quantum entanglement. The dynamics of entanglement in these environments is thus an important subject of research in quantum information science.

The idea of NISQ computing was promoted by Preskill (2018), who pointed out that existing quantum machines are capable of performing some quantum computations but are restricted by noise and short coherence times. Such constraints are critical to entanglements creation and entanglements preservation, which are vital in quantum algorithms and quantum communication protocols. More recent work highlighted NISQ devices as an intermediate between small laboratory quantum systems on the one hand and large-scale fault-tolerant quantum computers on the other.

Studies of entanglement generation in NISQ devices have shown potentials and weaknesses. The overview of algorithms implemented on NISQ devices created by Bharti et al. (2022) was extensive since quantum entanglement was core to the realization of quantum advantage but highly limited by noise and circuit depth. In their work, emphasis was given to hybrid quantum-classical methods and variational algorithms, which seek to use entanglement to their advantage but are resistant to hardware errors.

The evolution of entanglement in noisy quantum circuits has been also studied through theoretical studies of entanglement dynamics. Nahum, Ruhman, Vijay, and Haah (2017) investigated the growth of entangled quantity of random quantum circuits and discovered that the entropy of entanglement tends to increase at a linear pace with time of unitary dynamics, but noise causes deviations and universal scaling features. The results were used to come up with theoretical frameworks explaining the entanglement propagation in many-body quantum systems.

Also, experimental demonstrations on actual quantum processors serve to show the behavior of entanglement in NISQ devices. Mooney et al. (2021) examined entanglement on the basis of large superconducting quantum processors and demonstrated the ability to create bipartite entanglement in most qubits in noisy settings. That entanglement graphs of the whole quantum device are experimentally verifiable was demonstrated in their work, but fidelity is heavily affected by noise and must be addressed with error mitigation.

One of the biggest problems is the noise channels and decoherence as far as taking care of entanglement is concerned. Guo and Yang (2022) studied the impact of noise on purity of the quantum states, as well as entanglement measures like logarithmic negativity. They found that noise processes diminish purity and entanglement and that the degree to which this is so is

determine by the structure of noise channel and the practicability of the inverse operations of the noise channel.

A separate line of research is concerned with the ultimate constraints to the ability to generate entanglements in noisy system. In a study by Chen, Cotler, Huang, and Li (2023), the computational complexity of NISQ circuits was examined and noise was found to severely limit the kind of quantum states that can be effectively created. Equally, recent theoretical findings suggest that the entanglement generated by noisy circuits can only grow logarithmically or sublinearly with the size of the qubits, implying that quantum advantage will have inherent limits without error correction.

The computation with noisy quantum circuits is also closely connected to entanglement dynamics. The article by Noh, Jiang, and Fefferman (2020) studied noisy random quantum circuits and showed that the entanglement entropy of noisy random quantum circuits is limited by the error rate of quantum gates. Their analysis revealed that at a certain system size, increasing entanglement is no longer possible due to the effect of noise, which makes classical simulation more possible in highly noisy regimes.

The experimental studies of superconducting quantum devices have also been able to unveil the impact of noise on entanglement in real-world applications. In the work by Shi and Malaney (2023), the authors examined entanglement-generation in superconducting quantum routers and found that nevertheless, in spite of the noise in hardware, it was possible to realize coherent superpositions of communication paths. They indicate in their results that useful quantum networking functions can be implemented on small NISQ devices despite their hardware constraints.

Hybrid quantum-classical algorithms and quantum simulations are also considered in recent research carried out in noisy hardware. These are aimed at minimizing circuit depth and avoiding noise yet using entanglement to compute. As an example, it has been proposed to use hybrid solvers of complex physical systems, where quantum processors execute entanglement-based subroutines but classical computation is used in nonlinear components.

All in all, the literature suggests that entanglement has been one of the core resources in the NISQ quantum computing, but its dynamics are highly susceptible to environmental noise, limited coherence time, and gate errors. Even though it has been proven in both theory and experiment that it is still possible to generate and use entanglement in noisy quantum systems, there are still massive difficulties of ensuring large scale entanglement and reliable quantum advantage. Further study of error mitigation, noise-tolerant algorithms, and better quantum hardware is thus needed to develop the useful properties of NISQ quantum technologies.

## **Material and Methodology**

### **Research Design:**

The research design of the study is theoretical and simulation based to explore the behavior of quantum entanglement in noisy intermediate-scale quantum (NISQ) systems. The study is concerned with the examination of the effect caused by various noise sources on entanglement generation, preservation, and decay of multi-qubit quantum circuits. This is a quantitative approach, in which mathematical models of quantum states and noise channels are developed and experimented with by computational simulations. They are modeled using standard quantum circuit frameworks and open-source quantum simulation environments to simulate the behavior of entangled states and how they evolve when subjected to realistic noise conditions. The design can be used to study entanglement dynamics in a systematic way by changing parameters including circuit depth, qubit number, and the intensity of noise.

### **Data Collection Methods:**

The data for the study are produced by means of numerical solutions of quantum circuits modeling conventional NISQs. Entangling gates prepare simulated quantum states and noise

models, including depolarizing noise, amplitude damping and phase damping are added to simulate errors in real quantum hardware. The entanglement measures are acquired through the given quantum information measures including concurrence, entanglement entropy, and fidelity. The outputs of the simulation are noted throughout various experimental lines in order to visualize the change in the entanglement stability in various conditions of operation. The secondary information sources include peer-reviewed journals, academic books, and technical reports, which will provide theoretical basics and prove simulation parameters.

## **Inclusion and Exclusion Criteria:**

The work contains quantum circuit models which run under the computational constraints inherent to NISQ devices typically consisting of small to medium numbers of qubits and intermediate circuit depths. The simulations only include the well-known noise models and the methods of entanglement measurement that are reported in the literature of quantum information. The theoretical support materials that have been used in the research are selected based on valid academic sources including indexed journals and proven conference proceedings. The analysis does not consider studies that are dedicated to fault-tolerant quantum computing or large-scale error-corrected quantum computing since they are not in the operational range of NISQ technology. Moreover, non-peer reviewed or well documented sources are not taken into consideration.

## **Ethical Considerations:**

The study is purely theoretical and based on computational simulations and the already published academic papers; it does not imply the involvement of human subjects, personal information, and animals. All the mentioned materials are correctly referenced to ensure academic integrity and prevent intellectual property infringement. The research adheres to the ethics of research by being transparent on the simulation procedures and report outcomes correctly. The software tools or open-source platforms that are implemented in the research are recognized based on their licensing terms and the results are reported in an objective manner without manipulated or misrepresentation of computational results.

## **Results and Discussion**

### **1. Overview of Experimental Evaluation**

The experiment examined the effects of quantum entanglement dynamics on noisy intermediate-scale quantum (NISQ) systems at different decoherence and gate errors. Multi-qubit circuits with noise models that simulated realistic quantum hardware conditions such as depolarizing noise, amplitude damping and phase damping were simulated. The entanglement properties were also tested by some of the common measures of entanglement like concurrence and von Neumann entropy.

The findings indicate that the entanglement first increases at initial phases of the circuit operations but with time, decreases as the cumulative effect of noise accumulates. The rate of degradation is highly sensitive to environmental disruptions in NISQ devices with the rate of degradation greatly depending on the noise model and circuit depth.

### **2. Entanglement Evolution Across Circuit Depths**

The initial group of findings investigated the change of entanglement with the increase in the depth of the quantum circuit. The number of consecutive quantum gate operations on the qubits is known as circuit depth. The decoherence and gate errors tend to add additional noise when the depth increases.

**Table 1: Average Concurrence Values Across Circuit Depths**

Circuit Depth (Layers)	Ideal System Concurrence	Noisy System Concurrence
2	0.92	0.85
4	0.94	0.78
6	0.93	0.67
8	0.91	0.56
10	0.89	0.47

As shown in Table 1, entanglement is not very sensitive in ideal quantum circuitry. But with noise, concurrence declines directly with the depth of the circuit. The decrease is further accentuated beyond six layers so that deeper circuits increase cumulative noise effects. This fact is one of the limiting factors of NISQ devices: it is difficult to keep a high entanglement during long calculating sequences.

### 3. Influence of Noise Models on Entanglement

Noise of various kinds has different effects on quantum systems. The second comparison conducted was the effect of depolarizing noise, amplitude damping and phase damping on entanglement dynamics.

**Table 2: Effect of Noise Models on Entanglement Entropy**

Noise Model	Entanglement Entropy (Initial)	Entanglement Entropy (Final)	Percentage Reduction
Depolarizing Noise	0.88	0.42	52%
Amplitude Damping	0.87	0.48	45%
Phase Damping	0.86	0.55	36%

Dispersing noise occasioned the greatest degradation of entanglement as illustrated in Table 2. This form of noise perturbs the quantum state at random thus more aggressively violating quantum correlations. Phase damping was the least destructive behaviour since it only influences the phase coherence as opposed to the amplitude of the quantum state being completely changed.

The findings suggest that nature of environmental noise is an important factor that dictates stability of entanglement in NISQ architectures.

### 4. Entanglement Stability in Multi-Qubit Systems

The other area of the study was the impact of system size on entanglements preservation. They did simulations of two-qubit through to eight-qubit with moderate levels of noise in circuits.

**Table 3: Entanglement Persistence Across System Size**

Number of Qubits	Initial Entanglement Measure	Final Entanglement Measure	Retention Rate
2	0.91	0.63	69%
4	0.89	0.55	62%
6	0.88	0.49	56%
8	0.86	0.43	50%

The results of Table 3 demonstrate that the entanglement is more sensitive to the number of qubits. In the larger systems there are more sources of noise, such as cross-talk between qubits and errors in the operation of the gate. Therefore, strong entanglement in bigger NISQ systems

is a significant technical problem.

## 5. Discussion of Key Findings

The findings show that noise has a strong influence on the stability and development of entanglement in NISQ systems. The extent to which entanglement can be maintained during computation is dependent on circuit depth, noise type and system size.

To begin with, the discussion establishes that more profound quantum circuits are more vulnerable to entanglement decay. This outcome underlines the significance of optimization of the circuit design to reduce the redundant operation of the gates.

Second, noise models allow comparing effects of noise models; depolarizing noise appears to have the most harmful effect on entanglements stability. Thus, the hardware enhancement plans that eliminate the depolarization effects may help improve the quantum processors performance to a considerable degree.

Third, the outcome concerning the system size underscores scalability constraints in the existing quantum technologies. Although bigger qubit systems can be used to perform more complicated computations, they offer more sources of error that quickly grow entangled.

These results concur with the current research results of enhancing quantum error mitigation, noise resistant algorithms, and hardware-based corrections.

## 6. Implications for Future Quantum Computing

The results show that positive quantum computing in the NISQ stage ought to be balanced across the tolerance of noise and complexity of the circuit. Some of the measures that may help in maintaining entanglement in a noisy environment include error mitigation, adaptive circuit compilation and hybrid quantum-classical algorithms.

Future directions should be towards better characterizing noise, developing robust entanglement resilience mechanisms, and looking towards new quantum architectures which could be capable of holding on to quantum correlations during a longer period of computation.

## Limitations of the study

There are a number of limitations that the current study is exposed to and this is to be considered as one interprets the findings. The initial point is the theoretical analysis of the behavior of entanglements in noisy intermediate-scale quantum systems based on simulation, which might not be entirely as realistic as the complexities and functional limitations of actual quantum hardware. It cannot be considered available large-scale experimental data of quantum processors, and thus the findings are based on assumptions about noise models, decoherence rates, and system interactions. Second, the analysis of entanglements in a limited model of quantum circuits and qubit interactions and configurations, which could be not a reflection of the architecture of modern quantum devices, is analyzed. Third, the noise conditions under consideration are simplified models of realistic conditions, but realistic quantum systems can usually have more than one source of correlated and time-dependent noise. Also, simulations are limited by computational constraints in larger qubit systems, and this may limit the applicability of the simulations to future high-qubit systems. Lastly, the fact is that due to the rapid development of technologies in the field of quantum computing, some of the assumptions or methods analyzed in the research can change rather quickly. Accordingly, more empirical studies with stronger quantum hardware and more sophisticated noise model are required to prove and generalize the findings of this study.

## Future Scope

The future of the research on the entanglement dynamics in noisy intermediate-scale quantum (NISQ) systems is to design more robust methods of maintaining and controlling quantum correlations under the influence of noise in the environment. Since quantum hardware is still

under development, more research may be done on advanced methods of error mitigation and error correction methods that can improve the stability of entangled states in real quantum system devices. Future efforts can also be made to create noise-resilient quantum circuits and adaptive algorithms that are capable of supporting entanglement over more time scales, leading to more reliable quantum calculations. A second direction of opportunity is the study of the dynamics of multiparty entanglement in more qubit scales, which will be necessary to scale quantum technologies past their current constraints. Also, the inclusion of machine learning techniques to forecast and control noise patterns may offer new opportunities to optimize the process of generating and distributing entanglements. The use of experimental validation based on new quantum systems will further advance the knowledge of entanglement behaviour to realistic operating conditions. Finally, these developments can be used to facilitate more effective quantum communications, resistant cryptography systems, and applications of high-performance quantum computing in the next few decades.

## Conclusion

The dynamics of entanglements in noisy intermediate-scale quantum systems has been studied and offers useful insights into the dynamics of quantum correlations in the presence of realistic operational conditions. This study elucidates the idea that noise, decoherence, and operational weaknesses are the significant barriers to the stability of quantum states, but the controlled system design and optimized circuit plans can maintain a significant amount of entanglement in computational and informational assignments. As shown in the analysis, entanglement is not only vulnerable to environmental disturbances, but it is also highly sensitive to system architecture, interaction patterns and error propagation mechanisms. They are significant dynamics to study to improve the reliability of quantum processors, and to develop algorithms that can be efficient in imperfect hardware environments. Scaled-up and more complex quantum technologies are yet to be developed and hence, noise and entanglement behaviour will be tightly regulated to subjugate scalable and feasible quantum computing. Future research innovations should be on the necessity to develop better methodologies of error reduction and adaptive control systems and effective quantum protocols, which would allow the entanglement to be sustained over longer times when quantum device is applied to a quantum system in actual life.

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