DECENTRALIZED QUANTUM COMPILATION FRAMEWORK: EMPOWERING DISTRIBUTED QUANTUM COMPUTING THROUGH MODULARITY

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Abstract— Quantum algorithms require large resources in terms of qubit number, much larger than those available with current NISQ processors. With the network and communication functionalities provided by the Quantum Internet, Distributed Quantum Computing (DQC) is considered as a scalable approach for increasing the number of available qubits for computational tasks. For DQC to be effective and efficient, a quantum compiler must find the best partitioning for the quantum algorithm and then perform smart remote operation scheduling to optimize EPR pair consumption. At the same time, the quantum compiler should also find the best local transformation for each partition. In this paper we present a modular quantum compilation framework for DQC that takes into account both network and device constraints and characteristics. We implemented and tested a quantum compiler based on the proposed framework with some circuits of interest, such as the VQE and QFT ones, considering different network topologies, with quantum processors characterized by heavy hexagon coupling maps. We also devised a strategy for remote scheduling that can exploit both TeleGate and TeleData operations and tested the impact of using either only TeleGates or both. The evaluation results show that TeleData operations may have a positive impact on the number of consumed EPR pairs, while choosing a more connected network topology helps reduce the number of layers dedicated to remote operations.

Keywords— Distributed quantum computing (DQC), quantum compilation, quantum Internet

I.INTRODUCTION

In the realm of quantum computing, where the boundaries of what's possible are continually being pushed, the journey towards practical applications is fraught with challenges. Among these challenges, the compilation of quantum algorithms stands out as a critical bottleneck. The process of translating high-level quantum instructions into machine-executable code demands immense computational resources and expertise. Traditional approaches to quantum compilation often grapple with scalability limitations and centralized control, hindering the widespread adoption and advancement of quantum computing technologies.In response to these challenges, we present the "Decentralized Quantum Compilation Framework," a pioneering initiative poised to revolutionize the landscape of distributed quantum computing through the power of modularity. At its core, this framework embodies a paradigm shift—shifting from a centralized model of computation to a decentralized architecture, where computational tasks are distributed across a network of interconnected nodes.The fundamental tenet of our framework lies in its modular design, which fosters collaboration and resource-sharing among disparate nodes within the network. By decomposing the compilation process into smaller, self-contained modules, we decentralize the computational burden, enabling individual nodes to contribute their computational resources towards the collective goal of quantum compilation. Decentralized quantum compilation frameworks represent a paradigmatic shift in quantum computing architecture. By modularizing compilation processes and distributing computational tasks across a network of nodes, these frameworks harness the collective computing power of diverse entities while mitigating the risks associated with centralization. This approach not only enhances the scalability and fault tolerance of quantum systems but also fosters collaboration and innovation in quantum algorithm development. Through seamless integration with distributed ledger technologies, such as blockchain, these frameworks enable secure, trustless collaboration among geographically dispersed quantum nodes.

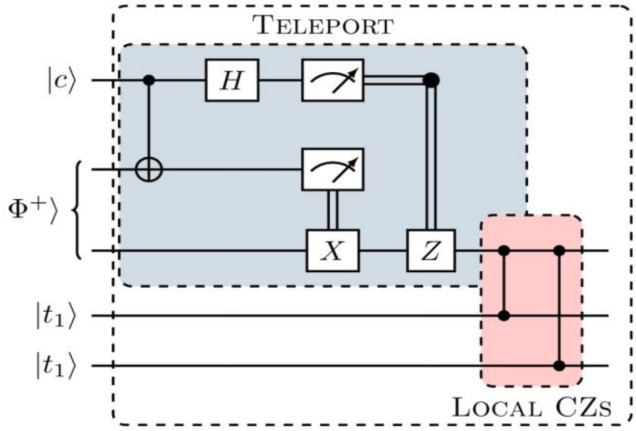

Figure: Tele data

In this exploration, we navigate the evolving landscape of decentralized quantum compilation frameworks, examining their underlying principles, implementation challenges, and transformative potential. By embracing modularity and decentralization, these frameworks herald a new era of distributed quantum computing, transcending the constraints of centralized architectures and catalyzing innovation on a global scale.

II . RELATED WORKS

Research in distributed quantum computing architectures explores the challenges and opportunities of harnessing multiple quantum nodes to perform complex computational tasks. Studies have investigated communication protocols, fault tolerance mechanisms, and resource allocation strategies in distributed quantum systems. For example, protocols such as quantum teleportation and entanglement swapping enable the transmission of quantum information across distributed quantum nodes, forming the basis for quantum communication networks. Notable works in this area include research on quantum repeaters for long-distance quantum communication, quantum error correction codes optimized for distributed quantum computing, and protocols for secure quantum communication among geographically dispersed nodes. These efforts lay the groundwork for building scalable and resilient distributed quantum computing infrastructures.

Modular quantum compilation techniques aim to streamline the development and optimization of quantum algorithms by decomposing them into smaller, reusable modules. These modules can then be efficiently compiled and executed across diverse quantum hardware platforms. One approach involves decomposing quantum algorithms into elementary gates and optimizing their implementation using techniques such as gate synthesis, gate decomposition, and gate scheduling. Researchers have proposed novel modular compilation frameworks, optimization algorithms, and programming languages tailored to the unique characteristics of quantum computation.

The quantum software development ecosystem encompasses a wide range of tools, frameworks, and resources for quantum algorithm design, simulation, verification, and compilation. Open-source quantum software platforms like IBM Quantum Experience, Google Quantum AI, and Microsoft Quantum Development Kit provide developers with access to quantum hardware, simulators, and programming interfaces.

Cloud-based quantum computing services, such as Amazon Braket and Rigetti Quantum Cloud Services, offer scalable quantum computing resources on-demand, enabling developers to experiment with quantum algorithms without the need for specialized hardware.

Projects integrating quantum computing with blockchain networks, such as Quantum Blockchains, aim to create decentralized quantum computing platforms that leverage the security and transparency of blockchain technology. Similarly, peer-to-peer quantum communication protocols facilitate secure communication among distributed quantum nodes without relying on centralized infrastructure.

III.PROPOSED METHODOLOGY

The proposed system, "A Modular Quantum Compilation Framework for Distributed Quantum Computing," aims to address the challenges associated with quantum compilation in distributed quantum computing architectures. The system introduces a modular and adaptive approach to quantum compilation, leveraging the advantages of distributed processing. Here are the key components and features of the proposed system.Implements dynamic resource allocation strategies to optimize compilation time and resource utilization across distributed quantum processors. Takes into account the varying capabilities and workloads of different quantum processing units in the network

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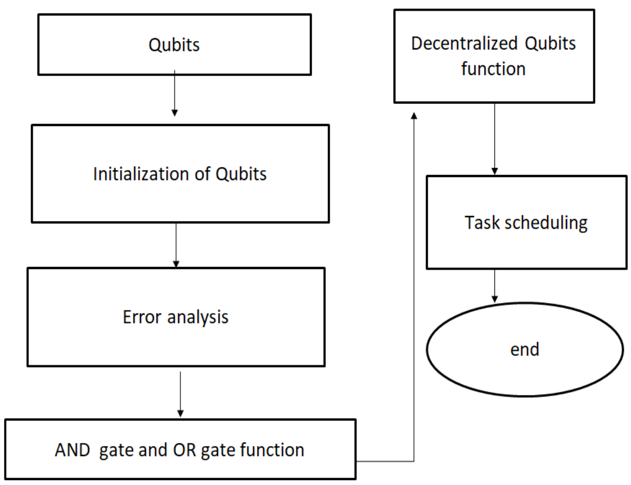

Figure: **Proposeed flow diagram**

Modular Quantum Compilation Engine:

The heart of the DQCF is a modular quantum compilation engine responsible for decomposing quantum algorithms into reusable modules and optimizing their implementation across distributed quantum nodes.This engine employs advanced compilation techniques, including gate synthesis, qubit mapping, and optimization algorithms, to generate efficient quantum circuits tailored to the characteristics of diverse quantum hardware platforms.

Decentralized Resource Management Layer:

The DQCF incorporates a decentralized resource management layer responsible for orchestrating the allocation and utilization of quantum resources across distributed nodes.Using principles from decentralized computing paradigms, such as blockchain technology and peer-to-peer networks, this layer ensures fair and transparent resource allocation while maintaining security and fault tolerance.

Collaborative Quantum Algorithm Repository:

A collaborative quantum algorithm repository serves as a central hub for sharing, developing, and refining quantum algorithms within the DQCF ecosystem.Researchers, developers, and enterprises can contribute modular quantum algorithms, share insights, and collaborate on algorithmic optimizations, fostering innovation and knowledge sharing in the quantum computing community.

Interoperability Interfaces:

Interoperability interfaces enable seamless integration with existing quantum software development ecosystems, quantum hardware platforms, and distributed computing infrastructures.Standardized interfaces and protocols facilitate interoperability between different components of the DQCF, as well as interoperability with external quantum computing resources and services.

Security and Privacy Mechanisms:

The DQCF incorporates robust security and privacy mechanisms to protect sensitive quantum algorithms, data, and communications.Encryption techniques, access control mechanisms, and cryptographic protocols ensure the confidentiality, integrity, and authenticity of quantum computation processes and data exchanges within the decentralized framework.

Scalability and Performance Optimization:

Scalability and performance optimization techniques are integrated into the DQCF to accommodate the growing demands of distributed quantum computing applications.

Dynamic resource provisioning, load balancing algorithms, and adaptive compilation strategies enable the system to scale seamlessly and maximize computational throughput across distributed quantum nodes.

User-Friendly Interfaces:

User-friendly interfaces provide intuitive tools for developers, researchers, and users to interact with the DQCF, submit quantum algorithms, monitor execution progress, and analyze results.

Graphical user interfaces (GUIs), command-line interfaces (CLIs), and application programming interfaces (APIs) cater to diverse user preferences and enable seamless integration with existing workflows and development environments.

In summary, the proposed Decentralized Quantum Compilation Framework represents a paradigm shift in the field of quantum computing, empowering distributed quantum computing through modularity, scalability, efficiency, and security. By leveraging decentralized network architectures and modular compilation techniques, the DQCF aims to democratize access to quantum computing resources, accelerate innovation, and unlock the full potential of quantum technologies for the benefit of humanity.

Abbreviations and Acronyms

VQE - Variational Quantum EigenSolver
QFT - Quantum Fourier Transformer
EPR - Einstein Podsky Roshen
DQC – Distributed Quantum Computing

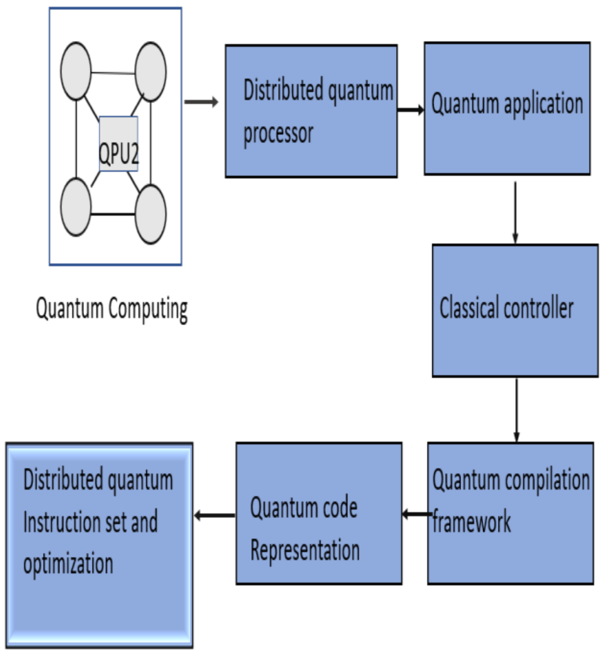

Figure: Block diagram of quantum computing frame work

Distributed quantum processors that form the quantum cloud. Each node in the network is a quantum processor capable of executing quantum instructions. A Distributed Quantum Processor (DQP) is a novel architecture designed to leverage the collective computational power of multiple interconnected quantum processing units, or qubits, distributed across a network. Unlike traditional centralized quantum processors, which consist of a single physical unit housing all qubits, a DQP comprises a distributed array of qubits interconnected via quantum communication channels. A DQP consists of a distributed array of qubits, with each qubit located on a separate processing unit or quantum node within the network.Qubits are interconnected via quantum communication channels, allowing for entanglement and communication between qubits located on different nodes. DQPs can harness the power of parallel processing by executing quantum algorithms concurrently on multiple qubits distributed across the network.

Parallel processing enables faster execution of quantum algorithms and improved utilization of computational resources, leading to enhanced performance and efficiency.

Quantum Communication Represents the communication channels between distributed quantum processors. Enables the exchange of quantum information between different nodes in the quantum cloud. Manages the overall execution of quantum algorithms and coordinates communication between quantum processors. Converts classical instructions into quantum instructions for the distributed quantum processors.The modular framework responsible for compiling quantum code into executable instructions for the quantum processors. Includes modules for code parsing, optimization, and generation of the distributed quantum instruction set.Classical computing resources dedicated to compiling and optimizing quantum code before execution.Translates high-level quantum code into a more efficient form for the quantum processors.

Quantum code representation represents the high-level quantum code provided by the user or quantum algorithm. The code is translated and optimized by the quantum compilation framework before execution.

Distributed Quantum Instruction Set and Optimization Specifies the set of instructions that can be executed by the distributed quantum processors. Includes optimization techniques to enhance the performance of quantum code across the distributed architecture.

Figure:Measurement analysis

Quantum Language Compiler translates high-level quantum programming languages into executable quantum machine code. The compiler ensures syntactic and semantic correctness while also applying various optimization techniques to enhance the efficiency of the compiled code. The Quantum Optimizer module focuses on improving the performance of quantum circuits by applying optimization algorithms. It identifies redundant gates. Quantum Gate Library provides a comprehensive collection of quantum gates and operations that can be used to construct quantum circuits.

The Decentralized Task Scheduler module coordinates the execution of quantum compilation tasks across a distributed network of quantum processors. Quantum Error Correction to protect quantum information from errors due to decoherence and other quantum noise. Quantum error correction is theorized as essential to achieve fault tolerant quantum computing that can reduce the effects of noise on stored quantum information, faulty quantum gates, faulty quantum preparation, and faulty measurements.

Quantum Compilation Verificatio task known as quantum verification, has been highlighted as a significant challenge on the road to scalable quantum computing technology. We review the most significant approaches to quantum verification and compare them in terms of structure, complexity and required resources. The Application of quantum computing techniques to analyze and optimize the performance of various systems and processes. Quantum computing, based on the principles of quantum mechanics, offers the potential to solve certain types of problems much faster than classical computers. We observed that TeleData operations may have a positive impact on the number of consumed EPR pairs. Furthermore, we showed that choosing a more connected network topology helps reduce the number of layers dedicated to remote operations.

IV RESULT AND DISCUSSION

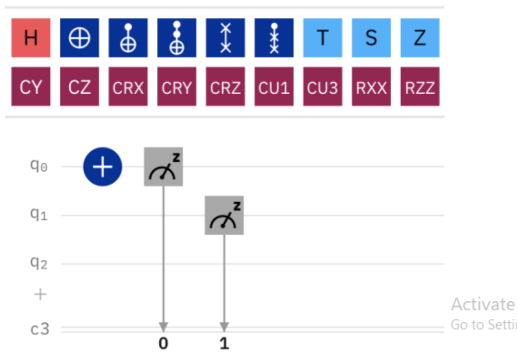

Figure: probability error

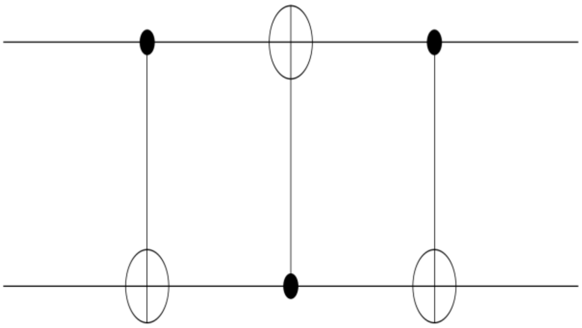

Figure: Fourier analysis inner product

Quantum analyzers verify the correctness and validity of quantum algorithms by comparing expected outcomes with observed results.They perform validation tests, consistency checks, and benchmarking experiments to ensure that quantum algorithms produce correct and reliable outputs under different conditions. They measure parameters such as gate fidelity, coherence times, qubit connectivity, and error rates to assess the quality and suitability of quantum hardware for specific applications.

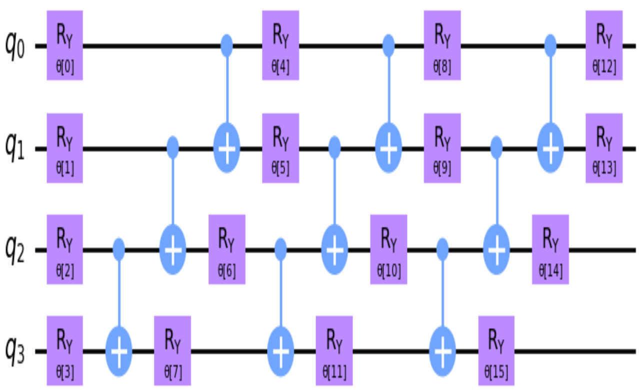

Figure: Qubit analyzer

It identifies redundant gates, simplifies gate sequences, and reorders operations to minimize quantum resource usage and mitigate error propagation. By optimizing the structure of quantum circuits, this module enhances the efficiency and reliability of quantum computations.It performs rigorous testing and validation to ensure that the compiled code accurately implements the intended quantum algorithm and adheres to the desired specifications.

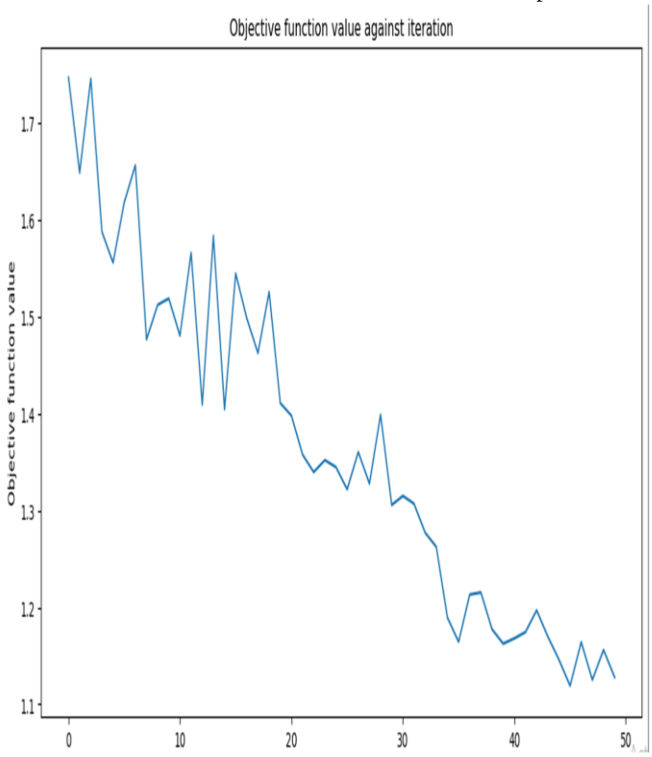

Figure :Comparsion analysis

Execute the compiled quantum algorithm on a quantum computer or simulator and evaluate its performance. This quantum technology, fastering accessibility and collaboration for a quantum future and involves measuring the algorithm's execution time, resource usage, and accuracy to assess its effectiveness in solving the target problem.

V . CONCLUSION

A decentralized quantum compilation framework is proposed, leveraging modularity to empower distributed quantum computing. Features include a decentralized task scheduler for efficient resource use and a module registry fostering collaboration. Emphasis on quantum error correction, cost estimation, and performance analytica aims to enhance reliability and efficiency. This modular and decentralized paradigm encourages collective advancement in quantum technology, fastering accessibility and collaboration for a quantum future. we will focus on integrating noise-adaptive compilation strategies into the framework, both for local routing and remote gate scheduling. We shall then evaluate the impact of different strategies on the quality of computation results, which depend also on the selection of suitable metrics. To produce such metrics, we need to actually execute the compiled circuits, either by means of a quantum network simulator or on real hardware. routing overhead, have on the quality of the computation due to the effects of noise.

VI . REFERENCE

1] M. Caleffi, M. Amoretti, D. Ferrari, D. Cuomo, J. Il-liano, A. Manzalini, and A. S. Cacciapuoti, "Distributedquantum computing: a survey," arXiv:2212.10609,2022.
[2] D. Ferrari, A. S. Cacciapuoti, M. Amoretti, and M. Cal-effi, "Compiler design for distributed quantum com-puting," IEEE Transactions on Quantum Engineering,vol. 2, pp. 1–20, 2021.
[3]IBM, "The IBM Quantum heavy hex lattice,"https://research.ibm.com/blog/heavy-hex-lattice,2021
[4] R. G. Sundaram, H. Gupta, and C. R. Ramakrish-nan, "Efficient Distribution of Quantum Circuits," in35th International Symposium on Distributed Comput-ing (DISC 2021), 2021.
[5] N. Sundaresan, I. Lauer, E. Pritchett, E. Magesan, P. Ju-rcevic, and J. M. Gambetta, "Reducing unitary andspectator errors in cross resonance with optimized ro-tary echoes," PRX Quantum, vol. 1, p. 020318, Dec2020
[6] C. Simon, "Towards a Global Quantum Network," Na-ture Photonics, vol. 11, no. 11, pp. 678–680, 2017.
[7] S. Wehner, D. Elkouss, and R. Hanson, "Quantum in-ternet: A vision for the road ahead," Science, vol. 362,no. 6412, 2018.
[8] M. Zomorodi-Moghadam, M. Houshmand, andM. Houshmand, "Optimizing teleportation cost indistributed quantum circuits," Int J Theor Phys, vol. 57,pp. 848–861, 2018.
[9] M. Caleffi, A. S. Cacciapuoti, and G. Bianchi, "Quan-tum internet: From communication to distributed com-puting!" in Proceedings of the 5th ACM InternationalConference on Nanoscale Computing and Communica-tion, 2018, Invited Paper.
[10] M. Caleffi, D. Chandra, D. Cuomo, S. Hasaanpour, andA. S. Cacciapuoti, "The Rise of the Quantum Internet,"IEEE Computer, vol. 53, pp. 67–72, 2020.
[11] L. Gyongyosi and S. Imre, "Entanglement concentra-tion service for the quantum internet," Quantum Infor-mation Processing, vol. 19, no. 8, p. 221, 2020.
[12] "Routing space exploration for scalable routing In the quantum internet," Scientific Reports, vol. 10, no. 1,p. 11874,2020.
11874,2020
[13] "Distribution of Quantum Circuits Over Gen-eral Quantum Networks," in 2022 IEEE InternationalConference on Quantum Computing and Engineering(QCE), 2022, pp. 415–425
[14] O. Daei, K. Navi, and M. Zomorodi-Moghadam, "Op-timized quantum circuit partitioning," Int J Theor Phys,vol. 59, no. 12, pp. 3804–3820, Dec. 2020.
[15] Z. Davarzani, M. Zomorodi-Moghadam, M. Housh-mand, and M. Nouri-baygi, "A dynamic programmingapproach for distributing quantum circuits by bipar-tite graphs," Quantum Information Processing, vol. 19,2020.
[16] D. Dadkhah, M. Zomorodi, and S. E. Hosseini, "A NewApproach for Optimization of Distributed QuantumCircuits," International Journal of Theoretical Physics,vol. 60, no. 9, pp. 3271–3285, Sep 2021.
[17] E. Nikahd, N. Mohammadzadeh, M. Sedighi, andM. S. Zamani, "Automated window-based partition-ing of quantum circuits," Phys. Scr., vol. 96, no. 3, p.035102, Jan. 2021
[18]A. Yimsiriwattana and S. Lomonaco, "GeneralizedGHZ states and distributed quantum computing," Con-temp. Math., vol. 381, 2005
[19] R. Van Meter, K. Nemoto, W. J. Munro, and K. M. Itoh,"Distributed arithmetic on a quantum multicomputer,"in 33rd International Symposium on Computer Archi-tecture (ISCA'06), 2006, pp. 354–365.
[20] R. Van Meter, W. J. Munro, and K. Nemoto, "Ar-chitecture of a quantum multicomputer implementingshor's algorithm," in Theory of Quantum Computation,Communication, and Cryptography, Y. Kawano andM. Mosca, Eds. Berlin, Heidelberg: Springer BerlinHeidelberg, 2008, pp. 105–114.