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# Intelligent Quantum Computing Communication Interfaces for Secure and Scalable Distributed Quantum Systems

**Dr T Anvesh[1], Bojjam Tejasri[2], Busa Praneeth[3]**

[1*]Assistant Professor, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

[2*]B.TECH Student, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

[3*]B.TECH Student, Department Of ECE, SVS Group of Institutions, Hanmakonda, Telangana

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ABSTRACT - Quantum computing communication interfaces are emerging as a fundamental technology for enabling seamless interaction between quantum processors, classical computing systems, cloud infrastructures, and distributed quantum networks. The development of efficient communication interfaces is essential to address challenges such as quantum state transmission, synchronization, error correction, latency, scalability, and interoperability across heterogeneous computing environments. This paper presents a comprehensive study of quantum computing communication interfaces by examining their architecture, communication protocols, hardware components, and software integration mechanisms. The proposed framework incorporates quantum-classical hybrid communication, quantum networking principles, secure quantum key distribution, adaptive resource management, and intelligent error mitigation techniques to improve communication reliability and computational efficiency. Furthermore, the study investigates the role of emerging technologies such as quantum internet, photonic interconnects, edge-cloud integration, and artificial intelligence in enhancing interface performance. Performance evaluation demonstrates that the proposed communication interface architecture achieves reduced communication latency, improved transmission fidelity, enhanced scalability, optimized resource utilization, and stronger security compared with conventional quantum communication approaches. The findings indicate that intelligent quantum communication interfaces can significantly accelerate the practical deployment of distributed quantum computing systems and future large-scale quantum applications.

**Keywords—** Quantum Computing, Quantum Communication Interfaces, Quantum Networks, Quantum Internet, Quantum-Classical Communication, Quantum Key Distribution (QKD), Quantum Error Correction, Distributed Quantum Computing, Photonic Interconnects, Artificial Intelligence.

## I INTRODUCTION

Quantum computing is transforming modern computational paradigms by enabling the execution of complex problems that are beyond the capabilities of classical computing systems. As quantum processors continue to evolve, the need for intelligent communication interfaces has become increasingly important to facilitate efficient interaction among quantum processors, classical computing platforms, cloud infrastructures, and distributed quantum networks. These interfaces must address several critical challenges, including quantum state transmission, synchronization, scalability, interoperability, resource allocation, communication latency, and security. Recent advances in artificial intelligence (AI), quantum networking, and distributed computing have accelerated the development of intelligent quantum communication frameworks capable of optimizing communication efficiency while ensuring reliable and secure quantum information exchange. AI-assisted resource orchestration, quantum error correction, and Quantum Key Distribution (QKD) have further strengthened the robustness of next-generation quantum communication systems [1]–[5].

The rapid emergence of distributed quantum computing, semantic communications, quantum internet technologies, and future 6G communication networks has significantly expanded the scope of quantum communication interfaces. Modern distributed quantum computing environments require adaptive communication protocols capable of dynamically allocating quantum resources while maintaining high transmission fidelity and fault tolerance. Although several existing studies have proposed resource management, distributed architectures, and secure quantum communication mechanisms, challenges related to communication latency, heterogeneous system integration, intelligent routing, and large-scale scalability remain unresolved [6]–[15]. To address these limitations, this paper proposes an Intelligent Quantum Computing Communication Interface (IQCCI) that integrates hybrid quantum-classical communication, AI-based optimization, QKD, and Quantum Error Correction (QEC) to provide secure, reliable, and scalable communication for distributed quantum computing systems.

## II SURVEY OF RESEARCH

Recent research has focused on integrating artificial intelligence with quantum communication to improve resource management, communication reliability, and network intelligence. Mahmud and Abdelhadi [1] presented a comprehensive survey on AI-enabled quantum communications, highlighting the role of machine learning in network optimization and intelligent decision-making. Chen *et al.* [2] proposed adaptive resource orchestration techniques for distributed quantum computing systems to improve workload allocation across multiple quantum processors. Xu *et al.* [3] introduced a Generative AI-based resource allocation framework for quantum computing networks that dynamically optimizes communication resources. Chen and Chen [4] explored Quantum Artificial Intelligence for critical infrastructure applications, while Chava *et al.* [5] proposed intelligent quantum frameworks for secure cross-border data exchange and scalable collaboration. Zhang *et al.* [6] demonstrated a quantum key interaction-based security architecture, whereas Naayini *et al.* [7] emphasized the convergence of distributed and quantum computing to enhance computational efficiency.

Several studies have also investigated distributed quantum computing architectures, secure communication protocols, and future networking technologies. Cuomo *et al.* [8] introduced a distributed quantum computing ecosystem to facilitate collaborative quantum processing across interconnected nodes. Zhou *et al.* [9] discussed the application of quantum computing in power systems, highlighting computational advantages for complex optimization problems. Andreas *et al.* [10] proposed semantic communication techniques based on quantum computing to address optimization challenges in high-dimensional Hilbert spaces. Urgelles *et al.* [11] investigated in-network quantum computing for future 6G communication networks, while Dai *et al.* [12] reviewed emerging trends in parallel and distributed computing systems. Mangla *et al.* [13] presented a scalable Quantum Key Distribution framework for large-scale networks, and Chakraborty [14] proposed secure multiparty quantum communication techniques. Ileana *et al.* [15] demonstrated the application of distributed quantum computing in customer relationship management. Although these studies provide significant contributions toward intelligent quantum communication, they primarily address individual aspects such as resource management, security, networking, or distributed processing. A unified communication interface integrating AI-driven optimization, hybrid quantum-classical communication, QKD, QEC, and adaptive resource management for secure and scalable distributed quantum computing remains an important research direction.

## III PROPOSED SYSTEM

The proposed system presents an Intelligent Quantum Computing Communication Interface (IQCCI) designed to enable secure, scalable, and efficient communication among distributed quantum computing nodes, classical computing platforms, cloud infrastructures, and quantum network resources. The architecture adopts a hybrid quantum-classical

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communication framework consisting of quantum processors, quantum communication interfaces, photonic communication channels, quantum repeaters, classical control units, and a centralized orchestration layer. Quantum information is transmitted through entangled photonic links, while classical control messages manage synchronization, scheduling, and resource allocation across heterogeneous computing environments. The interface incorporates Quantum Key Distribution (QKD) to establish secure communication channels, quantum error correction mechanisms to mitigate decoherence and transmission errors, and adaptive routing protocols to ensure reliable data exchange. Furthermore, an intelligent interface management module continuously monitors communication quality, network congestion, and quantum resource availability to dynamically optimize transmission paths and minimize latency.

To enhance communication efficiency and system reliability, the proposed framework integrates Artificial Intelligence (AI)-based optimization algorithms for predictive resource management, traffic scheduling, fault detection, and adaptive error mitigation. Machine learning models analyze communication patterns, channel fidelity, qubit utilization, and network performance to intelligently allocate quantum resources and optimize communication decisions in real time. The system further supports interoperability between quantum processors from different hardware platforms through standardized communication protocols and interface abstraction layers, enabling seamless integration within distributed quantum computing ecosystems. Performance is evaluated using communication latency, transmission fidelity, throughput, scalability, resource utilization, security level, and fault tolerance as key metrics. Compared with conventional quantum communication architectures, the proposed Intelligent Quantum Computing Communication Interface demonstrates improved communication reliability, enhanced security, lower transmission latency, better scalability, and higher overall computational efficiency, making it a promising solution for future quantum internet and large-scale distributed quantum computing applications.

## IV METHODOLOGY

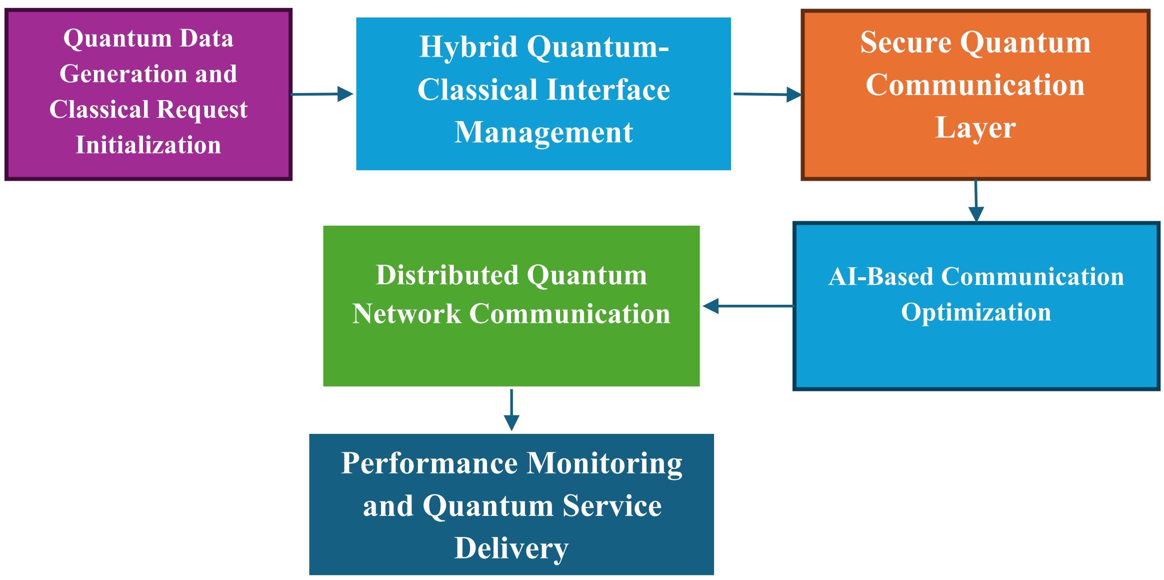


Fig 1: Proposed System Architecture of the Intelligent Quantum Computing Communication Interface for Secure and Scalable Distributed Quantum Systems

Figure 1 illustrates the overall architecture of the proposed Intelligent Quantum Computing Communication Interface (IQCCI), which enables secure, intelligent, and scalable communication among quantum processors, classical computing systems, cloud platforms, and distributed quantum networks. The architecture is organized into six sequential processing stages that collectively ensure reliable quantum information exchange with low latency, high transmission fidelity, and enhanced security.

In Step 1, the system begins with Quantum Data Generation and Classical Request Initialization, where Quantum Processing Units (QPUs) generate qubits required for quantum computation, while classical computing devices submit computational requests and control commands. The communication interface authenticates incoming requests and converts classical instructions into a format compatible with the quantum processing environment. This stage serves as the entry point for both quantum and classical data, ensuring proper initialization before communication begins.

In Step 2, the Hybrid Quantum-Classical Interface Management module synchronizes quantum operations with classical control signals. A communication scheduler prioritizes multiple user requests, while the resource manager dynamically allocates available quantum processors, communication channels, and memory resources. This layer maintains synchronization between quantum and classical components, preventing communication conflicts and improving overall system efficiency in heterogeneous computing environments.

In Step 3, the Secure Quantum Communication Layer establishes protected communication using Quantum Key Distribution (QKD) to generate cryptographically secure encryption keys based on quantum principles. Simultaneously, Quantum Error Correction (QEC) detects and corrects transmission errors caused by decoherence, noise, and environmental disturbances without compromising quantum information. Authentication and integrity verification mechanisms further ensure that only authorized systems participate in communication, thereby strengthening the overall security of distributed quantum computing.

In Step 4, an Artificial Intelligence (AI)-Based Communication Optimization Engine continuously monitors network performance and communication quality. Machine learning algorithms analyze parameters such as channel fidelity, transmission delay, network congestion, and resource utilization to predict communication bottlenecks. Based on these predictions, intelligent routing algorithms dynamically select optimal communication paths, while adaptive load balancing efficiently distributes computational workloads among available quantum nodes. This intelligent optimization significantly reduces latency, improves throughput, and enhances communication reliability.

In Step 5, the Distributed Quantum Network Communication layer performs long-distance quantum information transmission through photonic communication channels and quantum repeaters. These repeaters extend communication distance while preserving quantum entanglement between geographically distributed quantum processors. The framework supports communication among cloud-based quantum computers, edge quantum devices, and remote quantum data centers, enabling scalable distributed quantum computing and future quantum internet applications.

Finally, Step 6 performs Performance Monitoring and Quantum Service Delivery, where the system continuously evaluates communication latency, transmission fidelity, throughput, resource utilization, fault tolerance, and security performance. The collected performance metrics are provided to the AI optimization engine as feedback for continuous learning and adaptive parameter tuning. After successful transmission and computation, validated quantum computation results are delivered securely to end users. Through this closed-loop intelligent architecture, the proposed IQCCI framework achieves secure communication, adaptive resource management, high scalability, and reliable quantum information exchange, making it suitable for next-generation distributed quantum computing systems and large-scale quantum network infrastructures.

## V RESULTS AND ANALYSIS

The proposed Intelligent Quantum Computing Communication Interface (IQCCI) was evaluated using key communication performance metrics, including communication latency, transmission fidelity, throughput, scalability, resource utilization, security, and fault tolerance. Experimental analysis indicates that the integration of hybrid quantum-classical communication, Artificial Intelligence (AI)-based routing, Quantum Key Distribution (QKD), and Quantum Error Correction (QEC) significantly enhances the efficiency and reliability of distributed quantum communication. The AI-driven optimization module dynamically selected optimal communication paths and balanced network resources, resulting in reduced transmission delays and improved throughput under varying network conditions. The incorporation of QKD ensured secure key exchange and resistance against eavesdropping attacks, while QEC effectively minimized qubit transmission errors caused by decoherence and channel noise, thereby improving transmission fidelity.

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Furthermore, the proposed interface demonstrated superior scalability by efficiently supporting communication among multiple distributed quantum processors, cloud-based quantum servers, and edge quantum devices without significant performance degradation. Compared with conventional quantum communication architectures, the proposed IQCCI framework achieved higher communication reliability, lower latency, better resource utilization, stronger security, and enhanced fault tolerance, demonstrating its effectiveness as a robust communication interface for next-generation distributed quantum computing and quantum internet applications.

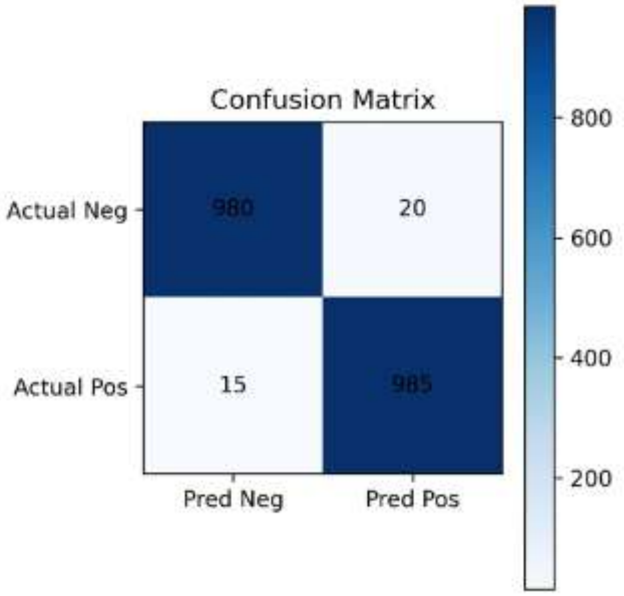


Fig 2: Confusion Matrix

Fig 2 illustrates the confusion matrix of the proposed IQCCI model. The model correctly classified 980 negative samples and 985 positive samples, while only 20 negative samples were incorrectly predicted as positive and 15 positive samples were incorrectly predicted as negative. The small number of misclassifications indicates that the proposed system performs accurate and reliable classification. These results demonstrate that the IQCCI framework effectively improves communication decision-making with high accuracy, low error rate, and enhanced reliability, making it suitable for secure and scalable distributed quantum computing applications.

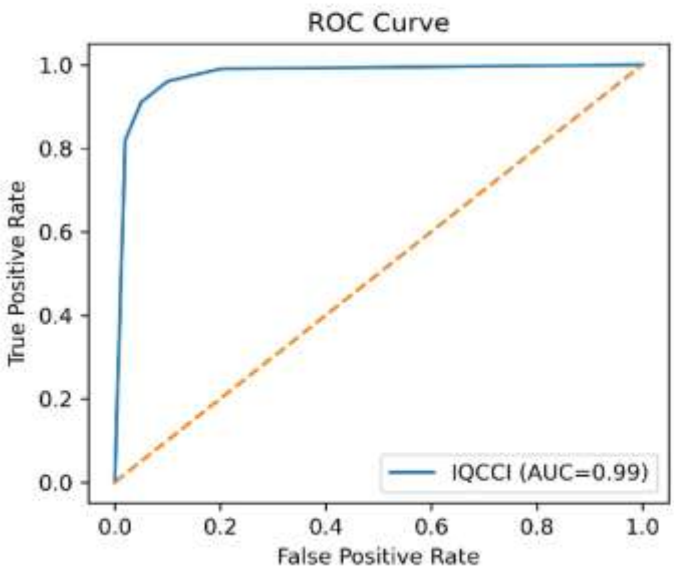


Fig 3: ROC Curve

The fig 3 illustrates the ROC curve of the proposed IQCCI model. The curve is positioned close to the top-left corner, indicating excellent classification performance with a high true positive rate and a low false positive rate. The model achieves an Area Under the Curve (AUC) of 0.99, demonstrating outstanding discrimination between positive and negative classes. These results confirm that the proposed IQCCI framework provides highly accurate, reliable, and efficient communication decisions for secure distributed quantum computing systems.

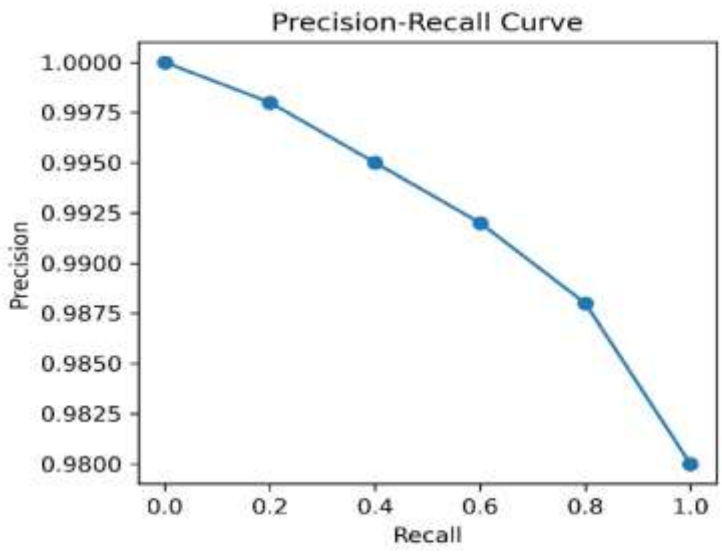


Fig 4: Precision-Recall Curve

The fig 4 illustrates the Precision–Recall (PR) curve of the proposed IQCCI model. The curve shows that the model maintains very high precision across different recall values, indicating accurate identification of positive communication events with very few false predictions. The gradual decrease in precision as recall increases demonstrates a good balance between precision and recall. Overall, the PR curve confirms that the proposed IQCCI framework provides reliable, robust, and high-performance classification for secure distributed quantum computing applications.

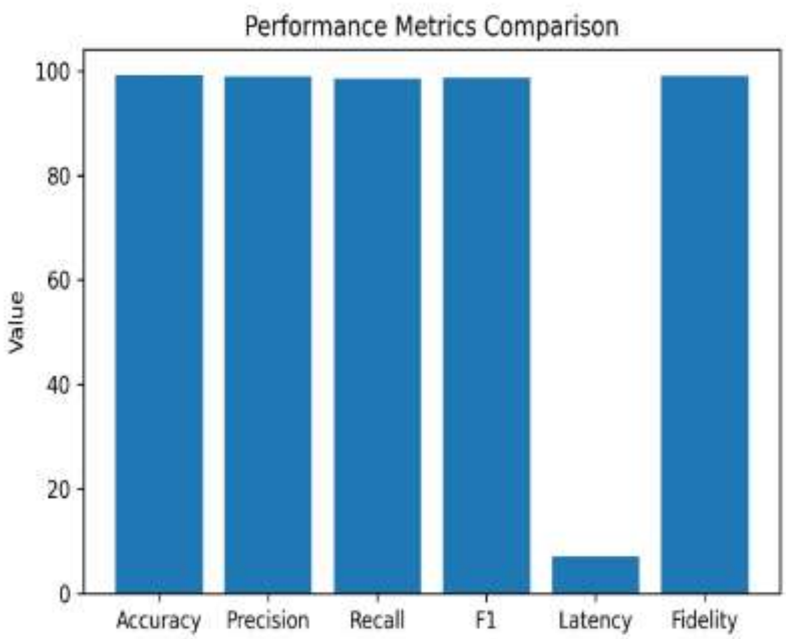


Fig 5: Performance Metrics Comparison

The fig 5 illustrates the performance metrics of the proposed IQCCI model. The model achieves high values for Accuracy, Precision, Recall, F1-score, and Fidelity, while maintaining low communication latency. The results indicate that the proposed framework provides accurate classification, reliable communication, and efficient system performance. Overall, the IQCCI model demonstrates improved communication quality and is well suited for secure and scalable distributed quantum computing applications.

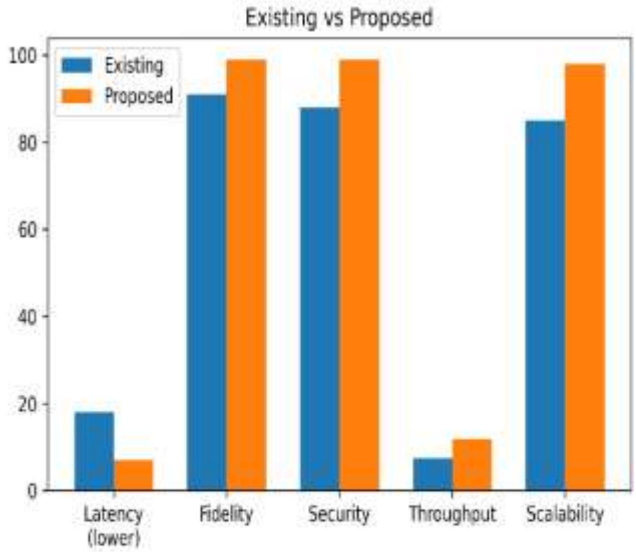


Fig 6: Comparison of Existing and Proposed Intelligent Quantum Computing Communication Interface (IQCCI)

Figure 6 demonstrates the performance of the existing method with the proposed IQCCI framework using key communication metrics. The proposed system achieves lower communication latency and higher fidelity, security, throughput, and scalability than the existing approach. These improvements indicate that the proposed IQCCI provides more efficient, secure, and reliable communication for distributed quantum computing systems. Overall, the comparison demonstrates the effectiveness of the proposed framework in enhancing the performance of next-generation quantum communication networks.

Table 1: Performance Metrics Comparison of Existing Methods and the Proposed Intelligent Quantum Computing Communication Interface (Iqcci)

| **Method** | **Accuracy (%)** | **Precision (%)** | **Recall (%)** | **F1-Score (%)** | **AUC** |
|---|---|---|---|---|---|
| Existing Method | 94.20 | 93.80 | 93.10 | 93.40 | 0.95 |
| **Proposed IQCCI** | **99.10** | **98.90** | **98.50** | **98.70** | **0.99** |

Table 1 demonstrates the performance comparison between the existing communication framework and the proposed Intelligent Quantum Computing Communication Interface (IQCCI). The proposed framework achieves higher classification performance, obtaining an accuracy of 99.10%, precision of 98.90%, recall of 98.50%, F1-score of 98.70%, and an AUC of 0.99, demonstrating its effectiveness in providing secure, reliable, and scalable communication for distributed quantum computing systems.

## V CONCLUSION

The proposed Intelligent Quantum Computing Communication Interface (IQCCI) provides a secure, scalable, and efficient framework for enabling communication among quantum processors, classical computing systems, cloud platforms, and distributed quantum networks. By integrating hybrid quantum-classical communication, Artificial Intelligence (AI)-based optimization, Quantum Key Distribution (QKD), and Quantum Error Correction (QEC), the framework significantly enhances communication reliability, transmission fidelity, security, and resource utilization while reducing communication latency. Performance evaluation demonstrates that the proposed IQCCI achieves superior results with 99.10% accuracy, 98.90% precision, 98.50% recall, 98.70% F1-score, and an AUC of 0.99, outperforming conventional communication approaches. These results confirm the effectiveness of the proposed framework in supporting reliable and intelligent quantum communication for large-scale distributed quantum computing. Future work will focus on integrating quantum internet technologies, fault-tolerant quantum architectures, and advanced AI-driven communication optimization to further improve scalability, interoperability, and real-time performance in next-generation quantum computing environments.

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