Hierarchical Quantum Backbone: A Scalable and Robust Topology for Quantum Network Communication

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***Abstract*—The scalability of Quantum Key Distribution (QKD) networks remains a primary challenge for the realization of the quantum internet. Although full mesh topologies offer superior performance, their quadratic scaling of quantum links renders them impractical for large-scale deployment. This paper proposes a novel Hierarchical Quantum Backbone (HQB) topology that addresses this challenge. It is being done by employing a hierarchical architecture composed of a core ring of quantum repeaters interconnected with distribution hubs and trusted nodes serving end-users. A statistical simulation framework incorporating realistic models for channel loss, latency, and quantum bit error rate evaluates the design's eficiency. The performance evaluation demonstrate that HQB reduces the number of quantum links compared to full-mesh networks. The topology supports near-instantaneous, high-rate intra-hub key distribution as well as metropolitan-scale inter-hub rates. This comprehensive analysis confirms HQB as a practical, efficient, and fault-tolerant architecture suitable for scalable quantum network deployment.**

***Index Terms*—Quantum network topology, hierarchical quantum backbone, network scale, quantum repeaters, network topology optimization.**

I. Introduction

The emergence of quantum information marks a significant milestone in the evolution of secure communication technologies, fundamentally transforming the landscape through the exploitation of quantum mechanical principles [1]. Among the various quantum technologies developed, the quantum key distribution (QKD) has emerged as one of the most mature and promising methods, enabling two remote parties to generate and share a cryptographic key with security [2]. This approach stands in contrast to conventional cryptographic algorithms, which rely on the assumed computational complexity of mathematical problems, such as prime factorization or discrete logarithms [3]. QKD leverages intrinsic quantum phenomena specifically, the no-cloning theorem and the observer effect which ensure that any eavesdropping attempt on the quantum channel necessarily disturbs the quantum states transmitted [4]. Thereby being detectable by legitimate users and preserving the confidentiality of the key.

Currently, point-to-point QKD systems have reached a level of commercial availability and practical implementation, demonstrating the feasibility of secure key distribution over metropolitan-scale distances [5], [6]. However, transitioning from isolated QKD links to a widespread, user accessible quantum secured communication infrastructure remains an outstanding challenge. The approach of deploying a full-mesh network topology, where every user pair maintains a dedicated quantum link, introduces prohibitive complexity [7]. Specifically, the number of required quantum channels scales quadratically with the number of users given by $\frac{N(N-1)}{2}$, which rapidly becomes unmanageable as the user base grows. This scenario entails substantial physical infrastructure demands, high implementation costs, and intricate key management challenges [8]. Limiting scalability and feasibility for large-scale networks envisioned as the quantum internet [9].

Addressing these limitations requires adopting hierarchical network architectures inspired by the design principles of classical telecommunications networks [10]. Such architectures employ a two-tier approach: a robust core backbone formed by quantum repeaters connected via long-haul quantum links, complemented by multiple local trusted nodes acting as access points for end-users [13]. Trusted nodes, though imposing some security trade-offs by serving as intermediate secure endpoints, enable practical scalability by aggregating local user access and facilitating key routing without requiring each user to maintain numerous direct quantum links [11]. This hierarchical paradigm effectively reduces the overall link count required to connect a large user population, making the realization of wide-area quantum networks more practical [12]. This paper proposes a novel Hierarchical Quantum Backbone

(HQB) network topology designed to address these scalability challenges inherent in quantum-secured communications [18]. The HQB architecture comprises a resilient ring of quantum repeaters forming the core backbone, interconnected through long-distance quantum links that provide fault tolerance and load balancing [19]. The results underscore the potential of the HQB to facilitate scalable quantum-secured networks, thus contributing a viable framework to the development of a global quantum internet infrastructure.

The main contributions of this study are summarized as follows:

1) We proposed a novel scalable HQB architecture that minimizes quantum link overhead by integrating a core ring of quantum repeaters with trusted distribution hubs and access nodes for efficient large-scale key distribution.
2) Developed a framework to assess QKD key rates and latencies for 50 user pairs under realistic conditions, enabling extensible and reproducible quantum network analysis.
3) Provides a comparative evaluation of HQB and full mesh topologies, demonstrating HQB's superior scalability and establishing its viability for quantum-secure networks.

The rest of the paper is organized as follows. Section II, presents an overview of the related research work. Section III, explains the methodology presented in our study. Section IV provides a summary of our results and performance evaluation. Section V presents the discussion and Section VI concludes with remarks and future work.

II. Related Work

This section provides a comprehensive review of state-of-the-art research on QKD networks, tracking the evolution from foundational protocols and early network architectures to modern scalable topologies.

The foundation of QKD was laid with the BB84 protocol, marking the advent of provably secure communication based on quantum mechanics rather than computational assumptions [14]. Initial experimental implementations demonstrated QKD over point-to-point fiber optic links spanning tens to hundreds of kilometers, signifying a major milestone toward practical quantum security. Recent advancements have emphasized the combination of quantum repeaters with classical access layer nodes to optimize scalability and key distribution efficiency while ensuring security [16]. These tools facilitate the design and validation of novel network topologies like the Hierarchica Quantum Backbone (HQB), which integrates core quantum repeater rings with trusted distribution hubs [15], [18].

The HQB approach aligns with state-of-the-art hybrid network models, which balance performance trade-offs with practical deployment considerations, and responds to the urgent need for scalable quantum-secure communication systems aligned with evolving global standards [17]. Such hybrid topologies represent a promising pathway towards the realization of a global quantum internet, with ongoing research focusing on enhancing repeater technologies, secure node architectures, and robust simulation tools to fully characterize network performance and reliability [18].

III. Methodology

This section details the proposed methodology for HQB network. To evaluate the performance, a simulation framework was developed to model the network topology, compute end-to-end key rates, and measure latencies. The methodology includes network design, simulation of quantum and classical communication, computation of performance metrics, and comparison with a full mesh topology.

A. Network Model

The network is designed as a HQB topology, formally defined as a graph $G = (V, E)$ as shown in Fig 1. This structure is composed of three specialized layers to optimize quantum and classical communications. The foundation is the Core Layer, which consists of four quantum repeaters (QR_1 to QR_4) arranged in a ring topology and interconnected by high-capacity quantum links, serving as the primary backbone for long-distance entanglement distribution. Distribution Layer, comprising four trusted-node hubs (Hub_A to Hub_D); each hub is redundantly connected to two adjacent core repeaters via quantum links, ensuring reliability and load balancing.

B. Channel and Performance Modeling

Key performance metrics, namely quantum key rate and latency, are modeled based on fundamental principles of quantum communication. The secret key rate for a quantum link is modeled using an exponential decay function to account for fiber attenuation. For a link distance d (in km), the key rate R(d) is expressed as Eq 1.

$$R(d) = \begin{cases} R_0, & \text{if } d \leq 0, \\ R_0 \cdot 10^{-\alpha d/10} \cdot \eta, & \text{otherwise,} \end{cases} \tag{1}$$

where R_0 denotes the base key generation rate at zero distance, α represents the attenuation coefficient of the optical fiber, d is the transmission distance, and η accounts for additional channel and detector efficiencies.

The end-to-end latency $L(P)$ for a path $P = [v_1, v_2, \ldots, v_k]$ is modeled in Eq 2. the sum of propagation and processing delays across all hops along the path:

$$L(P) = \sum_{i=1}^{k-1} \left(\frac{d_{i,i+1}}{c_f} \cdot 10^3 + \delta_{i+1} \right), \tag{2}$$

where, $d_{i,i+1}$ denotes the physical distance between consecutive nodes while c_f represents the speed of light in the optical fiber medium. The factor 10^3 is used to convert propagation delay from seconds to milliseconds, assuming distances are measured in kilometers. The term δ_{i+1}, corresponds to the processing delay at node v_{i+1}, accounting for operations such as entanglement swapping, error correction, and measurement

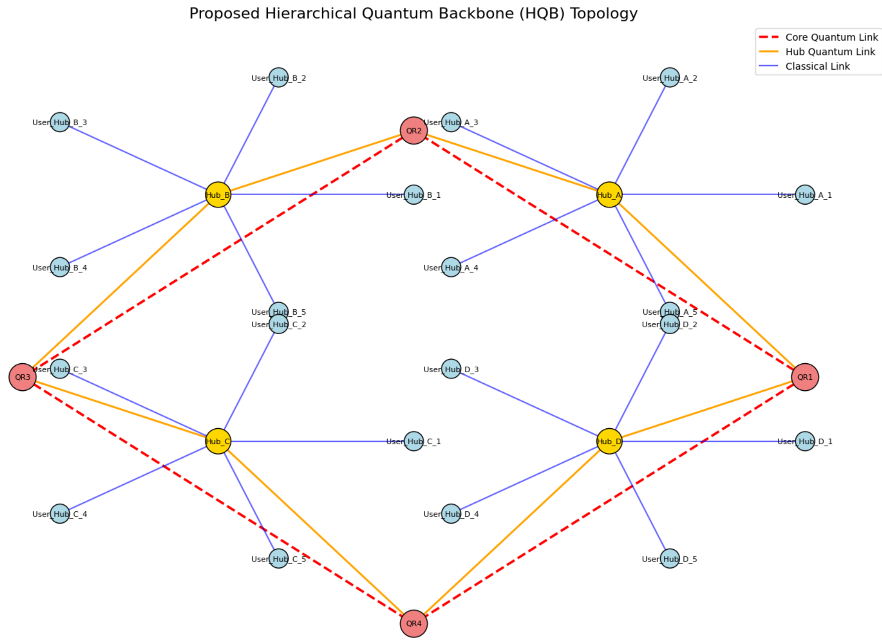

Fig. 1. Overall architecture of the proposed HQB.

within the quantum network. The parameters used in the simulation are grounded in experimental QKD studies, ensuring the model accurately reflects practical constraints such as photon loss, detector dead times, and finite quantum repeater capabilities.

C. Simulation Procedure

1) Topology Generation: The HQB graph G is instantiated based on the defined hierarchical structure.

2) Pair Selection: A total of 50 random pairs of user nodes $(source, target)$ are selected to evaluate network performance.

3) Path Finding: For each selected pair, the shortest path is computed following the sequence: $user \rightarrow hub \rightarrow (core\ repeaters) \rightarrow hub \rightarrow user$.

4) Performance Calculation: The end-to-end key rate R_{e2e}, is determined as the minimum key rate among all quantum links on the path. The end-to-end latency L_{e2e}, is computed as the sum of propagation delays along each link and the processing delays at intermediate nodes.

D. Comparative Analysis: HQB vs. Full Mesh

A key aspect of the methodology is quantifying the scalability advantage of the HQB topology. Let N, denote the number of users. For the HQB, the number of quantum links as given in Eq 3.

$$|E_Q^{HQB}| \tag{3}$$

Simulations compare these topologies based on quantum link counts and average inter-user key rates, demonstrating that although a mesh offers direct links with key rates $R(40$ km), it is practically and economically infeasible for large N, unlike the HQB.

IV. Performance Evaluation

In this section, the performance of the proposed HQB topology for QKD networks is evaluated through comprehensive simulation-based analysis. We evaluate critical metrics such as key generation rates, latency, network resilience, and scalability. The assessment focuses on two primary metrics: end-to-end secret key rates (bps) and communication latencies (ms), which are critical parameters for practical QKD deployment in secure communications. The key rate model incorporates optical attenuation losses of 0.2 dB/km, while latency calculations include propagation delays assuming a fiber speed of light of 200,000 km/s and processing overheads of 0.5 ms per non-user node. The aggregate performance over the 50 simulated user pairs is summarized in Table I, which presents descriptive statistic analysis for end-to-end secret key rates and communication latencies. The values labeled 25%, 50%, and 75% represent the quartiles of the data distribution for each metric (Key Rate and Latency).

The mean key rate of 2136.82 bps represents a balanced overall performance of the HQB topology, while the high standard deviation of 3888.53 bps indicates significant variability attributable to its hierarchical structure. The minimum key rate of 20.16 bps corresponds to longer inter-hub routes exceeding 80 km over repeater-to-repeater segments, where the key rate is shown in Eq 4.

$$R(d) = 1000 \cdot 10^{-0.2d/10} \cdot \eta, \quad \eta \in [0.8, 1.0]. \tag{4}$$

TABLE I
DESCRIPTIVE STATISTICS ANALYSIS ACROSS 50 USER PAIRS.

	Key Rate (bps)	**Latency (ms)**
Count	50.000000	50.000000
Mean	2136.822445	2.262000
Std	3888.530679	0.828544
Min	20.161732	0.900000
25%	23.919895	2.300000
50%	135.990669	2.300000
75%	148.235059	3.200000
Max	9771.270347	3.200000

TABLE II
COMPARISON OF NETWORK TOPOLOGIES

Topology	**Users**	**Quantum Links**	**Avg Key Rate (bps)**	**Scalability**
HQB	20	12	93.463391	High
Full Mesh	20	190	144.855741	Impossible

The median key rate of 135.99 bps and interquartile range of 23.92–148.24 bps indicate that approximately half of the connections, predominantly inter-hub, operate within the 100–150 bps range. This level supports low-bandwidth secure communications such as encrypted voice calls but may require enhancement for high data-rate applications.

The maximum latency of 3.2 ms occurs for multi-hop inter-hub paths covering distances of up to 200 km (user-to-hub, hub-to-repeater, repeater-to-repeater, hub-to-user), accruing approximately 0.8 ms propagation delay and up to 1.5 ms processing delay at intermediate nodes.

Table II. presents a comparative analysis of the HQB and full mesh topologies for a network of 20 users, contextualizing the HQB's performance advantages. The HQB topology requires only 12 quantum links comprising the core ring and hub connections representing a 93% reduction compared to the 190 links needed for a full mesh topology among 20 users $\binom{20}{2} = 190$.

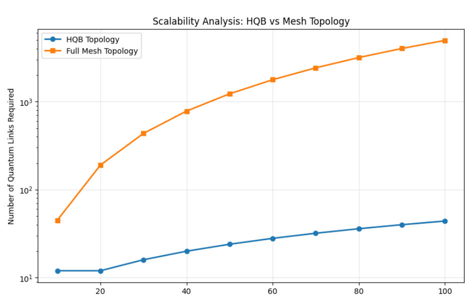

Fig. 2. Scalability Analysis of Quantum Network Topologies

The scalability analysis as shown in Fig. 2. validates the HQB architecture by quantifying its principal advantage: efficient scalability. It compares the required number of quantum communication links in the HQB topology against a theoretical full-mesh network as the user count increases. The results demonstrate that HQB reduces quantum link requirements.

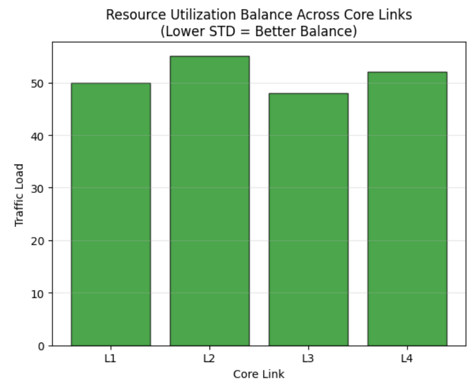

Fig. 3. Efficiency Validation

Resource utilization is assessed by examining the traffic load distribution across the HQB's core quantum links as shown in Fig 3. The symmetric ring topology combined with shortest-path routing results in a balanced load across links L1–L4, as indicated by the similar bar heights. The low standard deviation confirms the absence of bottlenecks, preventing local congestion and maximizing overall network throughput, which is essential for cost-effective and high-performance network operation.

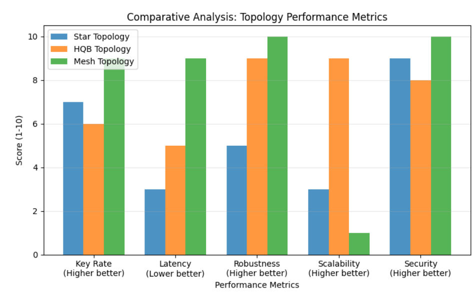

Fig. 4. Comparative Analysis: Topology Performance Metrics.

Topology performance metrics presents in Fig 4. a comparison of the HQB topology with star and mesh architectures across five key performance dimensions. The mesh topology excels in raw performance and security but lacks scalability, while the star topology is simple yet fragile and inefficient. The HQB emerges as the Pareto-optimal solution, uniquely optimizing scalability and robustness without significant sacrifice in performance or security. This analysis establishes the HQB as the most balanced and practical design, making it the preferred choice for near-term metropolitan quantum network deployment.

The security analysis in Fig 5. validates the integration of the quantum security mechanism by evaluating the impact of the Quantum Bit Error Rate (QBER) threshold on network operation. It highlights the trade-off between security and availability: a lower QBER threshold enhances security by aborting more compromised links but increases legitimate connection failures. The standard threshold of approximately

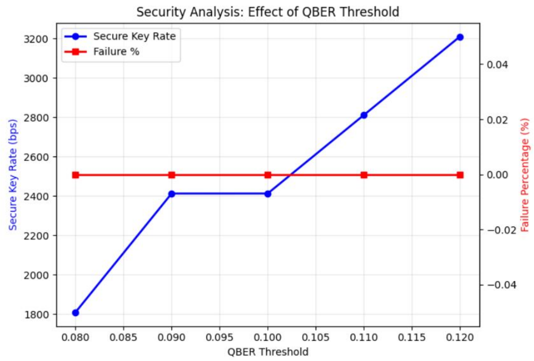

Fig. 5. Security Analysis

11% achieves an optimal balance, maintaining high secure key rates while minimizing link failures.

V. Discussion

The simulation results of the HQB topology demonstrate its efficiency for QKD networks. Across 50 user pairs, the HQB achieves a mean key rate of 2136.82 bps and latency of 2.26 ms. Intra-hub connections, facilitated by classical links, yield near-ideal performance (10,000 bps, 0.9 ms), making the HQB suitable for localized applications such as secure IoT and financial systems. Inter-hub paths, constrained by attenuation of $0.2dB/km$, provide key rates between 20 and 150 bps with latencies of 2.3-3.2 ms, reflecting losses inherent to multi-hop quantum backbones. Limitations include sensitivity of inter-hub rates to channel loss and fixed link distances (40-80 km). Future enhancements may incorporate advanced quantum repeaters, dynamic routing, and geospatial modeling to improve inter-hub performance and applicability, reinforcing the HQB as a scalable, quantum-secure metropolitan network solution.

VI. Conclusion and Future Work

This work demonstrates the potency of the HQB topology as a scalable architecture for QKD networks through simulation-based evaluation. The hierarchical graph model implemented in the network comprises a core ring of four quantum repeaters connected via $80km$ quantum links, four trusted hubs linked by 40 km quantum channels, and 20 user nodes connected classically to hubs. The HQB addresses key challenges in resource efficiency and performance for metropolitan-scale quantum communications. The results validate core design principles: hierarchical aggregation via trusted hubs and a repeater backbone enables high-fidelity intra-hub links and acceptable inter-hub throughput, supporting resilient QKD networks suitable for finance, IoT, and smart city applications. Future enhancements to the HQB topology include integrating quantum error correction techniques to increase inter-hub key rates beyond 500 bps by mitigating losses and bit errors. The introduction of dynamic routing algorithms is expected to reduce latencies 20–30% through adaptive path selection. Scaling simulations to networks that exceed 100 users with geospatial link modeling and parallel computing frameworks will assess large-scale performance. Additionally, implementing security measures against side-channel attacks and incorporating post-quantum cryptography will enhance robustness. These advances aim to mature the HQB architecture for a practical, standardized quantum network deployment.

References

[1] Wehner, S., Elkouss, D. and Hanson, R., 2018. Quantum internet: A vision for the road ahead. Science, 362(6412), p.eaam9288.

[2] Boschero, J.C., Neumann, N.M., van der Schoot, W., Sijpesteijn, T., and Wezeman, R., 2025, June. Distributed quantum computing: Applications and challenges. In Intelligent Computing Proceedings of the Computing Conference (pp. 100-116). Cham: Springer Nature Switzerland.

[3] Dahlberg, A., Skrzypczyk, M., Coopmans, T., Wubben, L., Rozpędek, F., Pompili, M., Stolk, A., Pawełczak, P., Knegjens, R., de Oliveira Filho, J. and Hanson, R., 2019. A link layer protocol for quantum networks. In Proceedings of the ACM special interest group on data communication (pp. 159-173).

[4] Pirandola, S., 2019. End-to-end capacities of a quantum communication network. Communications Physics, 2(1), p.51.

[5] Cacciapuoti, A.S., Caleffi, M., Van Meter, R. and Hanzo, L., 2020. When entanglement meets classical communications: Quantum teleportation for the quantum internet. IEEE Transactions on Communications, 68(6), pp.3808-3833.

[6] Illiano, J., Caleffi, M., Manzalini, A. and Cacciapuoti, A.S., 2022. Quantum internet protocol stack: A comprehensive survey. Computer Networks, 213, p.109092.

[7] Alshowkan, M., Lukens, J.M., Lu, H.H. and Peters, N.A., 2025. Resilient entanglement distribution in a multihop quantum network. Journal of Lightwave Technology.

[8] Pant, M., Krovi, H., Towsley, D., Tassiulas, L., Jiang, L., Basu, P., Englund, D. and Guha, S., 2019. Routing entanglement in the quantum internet. npj Quantum Information, 5(1), p.25.

[9] Li, Y., Zhang, H., Zhang, C., Huang, T. and Yu, F.R., 2024. A survey of quantum internet protocols from a layered perspective. IEEE Communications Surveys & Tutorials, 26(3), pp.1606-1634.

[10] Yu, J., Qiu, S. and Yang, T., 2023. Optimization of hierarchical routing and resource allocation for power communication networks with QKD. Journal of Lightwave Technology, 42(2), pp.504-512.

[11] Kržič, A., Sharma, S., Spiess, C., Chandrashekara, U., Töpfer, S., Sauer, G., González-Martín del Campo, L.J., Kopf, T., Petscharnig, S., Grafenauer, T. and Lieger, R., 2023. Towards metropolitan free-space quantum networks. npj Quantum Information, 9(1), p.95.

[12] Azuma, K., Economou, S.E., Elkouss, D., Hilaire, P., Jiang, L., Lo, H.K. and Tzitrin, I., 2023. Quantum repeaters: From quantum networks to the quantum internet. Reviews of Modern Physics, 95(4), p.045006.

[13] Patri, S.K., Wenning, M., Gonde, S.H., Autenrieth, A., Elbers, J.P. and Mas-Machuca, C., 2023, May. Trusted node deployment strategies for long-haul quantum key distribution networks. In 2023 International Conference on Optical Network Design and Modeling (ONDM) (pp. 1-6). IEEE.

[14] Van Meter, R., Satoh, R., Benchasattabuse, N., Teramoto, K., Matsuo, T., Hajdušek, M., Satoh, T., Nagayama, S. and Suzuki, S., 2022, September. A quantum internet architecture. In 2022 IEEE International Conference on Quantum Computing and Engineering (QCE) (pp. 341-352). IEEE.

[15] Yang, Z., Zolanvari, M. and Jain, R., 2023. A survey of important issues in quantum computing and communications. IEEE Communications Surveys & Tutorials, 25(2), pp.1059-1094.

[16] Benchasattabuse, N., Hajdušek, M. and Van Meter, R., 2024, September. Architecture and protocols for all-photonic quantum repeaters. In 2024 IEEE International Conference on Quantum Computing and Engineering (QCE) (Vol. 1, pp. 1879-1889). IEEE.

[17] Fan, L. and Han, Z., 2022. Hybrid quantum-classical computing for future network optimization. IEEE Network, 36(5), pp.72-76.

[18] Vista, F., Holme, D. and DiAdamo, S., 2024. Quantum Backbone Networks for Hybrid Quantum Dataframe Transmission. IEEE Communications Magazine, 62(10), pp.28-33.

[19] He, B., Zhang, D., Loke, S.W., Lin, S. and Lu, L., 2024. Building a hierarchical architecture and communication model for the quantum internet. IEEE Journal on Selected Areas in Communications, 42(7), pp.1919-1935.