Efficiency of Distributed Myopic Routing in a Quantum Memory-Free Network

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***Abstract*—Entanglement routing in quantum networks is a crucial step toward building secure and scalable quantum communication systems. Due to the unique properties of quantum information, this routing task is more complex than its classical counterparts. In this study, we evaluate the impact of local myopic decision-making on network performance, offering an alternative to a centralized approach. We analyze real-world network topologies by extracting different subgraphs and statistically examining how the efficiency of myopic routing varies with the number of nodes in each cluster. Using a custom reward–cost-based objective function, we compare the performance of both myopic and globally optimal routing strategies. Our results show that the efficiency of the myopic routing is generally low; however, it improves as the number of nodes increases. This hints at the necessity of at least some level of centralized coordination, but overall seems to imply that local decision-making mechanisms can be efficient enough, which paves the road for the scalable design of quantum networks.**

***Index Terms*—Quantum communications; Myopic routing; Memory-free quantum network; Distributed routing.**

I. Introduction

Quantum networks are envisioned as the foundation of a future "quantum Internet," allowing quantum computers and sensors to communicate in ways impossible with classical networks [1], [2]. This has driven global efforts to build quantum communication infrastructures, from large-scale initiatives to industrial prototypes.

Central to these networks is distributing entangled qubit pairs (Bell pairs) between distant nodes, essential for protocols like quantum teleportation, distributed quantum computing, and device-independent security. Entanglement serves as the key resource in quantum networking, comparable to bandwidth in classical systems [3], [4]. However, creating and sustaining high-fidelity entanglement is challenging due to vulnerability of qubits to loss and decoherence, which worsen over distance and time. Quantum repeaters and memory devices are needed to store qubits and perform entanglement swapping, extending links over multiple hops [5], [6]. Without memory at intermediate nodes, end-to-end entangled links must form simultaneously, making long-distance distribution exponentially hard.

These issues highlight the importance of network topology and node capabilities, as connectivity and storage directly affect entanglement rate, fidelity, and latency. Classical networking has used game theory to analyze resource allocation, routing, and incentives in distributed systems, modeling how agents make strategic decisions for stable, efficient outcomes [7], [8]. Applying game theory to quantum networks is promising, especially for challenges like entanglement distribution, routing, and topology control [9]. Nodes can act as autonomous agents, adapting behaviors (such as relaying entanglement or allocating memory) to optimize utilities like fidelity or delivery time. Recent studies show how combining game theory and quantum strategies can improve link fidelities, reduce latency, and contrast eavesdropping in entanglement distribution games [10], [11].

This paper explores the problems related to the inability of nodes in quantum communication memory-free networks to store quantum information. In this case, hot potato routing emerges as a natural and necessary strategy, as we consider a scenario where qubits cannot be buffered without introducing decoherence or requiring costly quantum memory and therefore are forwarded immediately upon arrival. This leads to a scenario where each node, upon receiving quantum information, must decide in real-time which neighbor to forward it to [12].

This connects our analysis to the classic investigations of hot potato routing, traditionally used in IP networks to minimize storage needs and simplify routing decisions, especially in high-throughput or low-buffer environments [13]. Its adaptation to quantum networks is supported by proposals with quantum repeater chains or near-term quantum autonomous systems. Studies often model this behavior using probabilistic forwarding, Markov decision processes, or game theory to account for routing trade-offs under strict temporal and fidelity constraints [14], [15].

In particular, we investigate the efficiency of myopic forwarding as opposed to a centralized decision based on the resulting long-term result of the hot potato passing, solved as the steady-state distribution of probabilistic routing. To quantify the goodness of the resulting forwarding decision, we assume that nodes are driven by a forwarding cost and a reward based on the proximity the information is eventually found in the network, both based on link distance (but having different impacts). Our results serve to assess the need for centralized coordination in quantum networks, as opposed to a fully distributed management [16]–[18].

The efficiency of a myopic approach is found to be, depending on the topology, between 40% to 80% of the optimal centralized routing. While this obviously suggests that some further coordination among nodes than a pure myopic approach is needed, we are able to obtain some interesting insights. First of all, this efficiency gap does not seem to be insurmontable, and some targeted coordination for critical topologies is probably sufficient to alleviate it significantly. Moreover, the efficiency increases as the number of nodes becomes larger, which seems to suggest that a distributed myopic forwarding with some local coordination may be a good scalable solution.

The rest of this paper is organized as follows. In Section II, we discuss the related literature. Section III presents our investigation. We show numerical results in Section IV, and we conclude in Section V.

II. Related Work

Entanglement routing is essential for scaling quantum networks, but poses significant challenges due to the inherent properties of quantum information and constraints imposed by quantum mechanics [4].

In recent years, this problem has attracted considerable attention, leading to the development of various protocols and algorithms aimed at addressing it. A dynamic entanglement routing is presented in [16], leveraging stream processing to optimize entanglement distribution within quantum networks. However, practical deployment still faces challenges, particularly in resource allocation, error handling, and computational efficiency—areas that the authors plan to explore further. In [19], the authors introduces a novel entanglement routing (ER) protocol for quantum networks, to jointly utilize multiple paths to route entanglement more efficiently across the network—an approach that contrasts with conventional protocols that typically focus on a single optimal path.

In [20], the authors address a gap in the literature by investigating the limitations caused by the scarce availability of entangled photon sources (EPS). To enhance the throughput of quantum networks in entanglement routing, they propose the use of all-optical switching. However, while promising, this approach introduces substantial implementation costs in practical network deployments. In [17], the authors investigate the challenge of quantum entanglement routing with the dual objective of maximizing both the number of quantum user pairs and their anticipated data throughput.

In [21], the authors introduce novel models, metrics, and algorithms for entanglement routing that operate on arbitrary network topologies. This approach stands in contrast to previous studies, which primarily focused on fixed structures such as ring, star, or mesh topologies. However, their approach only partially tackles the imbalance between limited entanglement resources and high request demands, which can result in network congestion. In [22], the authors propose a greedy entanglement routing (ER) algorithm tailored for grid-topology quantum networks, taking into account physical constraints like the limited coherence time of quantum memory. Although the algorithm effectively boosts end-to-end entanglement rates by aggressively leveraging available network resources, it suffers from poor resource efficiency. This is because it tends to exhaust all resources within a localized region to serve a single source-destination (S-D) pair.

In [15], [18], [23], the authors investigate multipath routing strategies. However, these approaches either select each path in isolation without coordinating with others or restrict selection to completely disjoint paths—those that share no common links. Such strategies can be fragile; if even a small number of links fail, it can disrupt or delay entanglement generation across all selected paths.

Optimizing long-term behavior in quantum networks may be achieved through centralized or distributed decision-making methods designed to improve entanglement distribution. In a centralized decision-making approach, a single control entity makes decisions based on global knowledge of the entire network. This allows for system-wide optimization strategies, potentially maximizing the efficiency of entanglement distribution and long-term network performance. However, centralized architectures come with notable limitations. The performance of centralized routing algorithms is significantly influenced by the underlying network topology [24]. Additionally, in large-scale quantum networks, nodes cannot access global information quickly due to latency in the classical communication layer. This contradicts the assumption made in some existing studies that global knowledge is readily available. These delays hinder the responsiveness and adaptability of centralized systems [12]. In contrast, distributed decision-making involves each node making decisions independently based on its local information and interactions with neighboring nodes. This approach avoids the bottlenecks and single points of failure inherent in centralized systems, offering greater scalability and robustness. While distributed algorithms may not always achieve globally optimal solutions, they are more practical for dynamic or large-scale quantum networks where timely access to global state information is not feasible. Thus, distributed strategies are increasingly being considered as promising solutions for scalable and resilient entanglement distribution.

In [10], the authors conduct a comparative analysis of classical and quantum game-theoretic approaches to optimize entanglement distribution in quantum networks. They propose a game-based framework evaluated through two distinct network scenarios, where network nodes (players) determine their strategies based on key performance metrics such as latency, fidelity, and entanglement rate. Simulation results demonstrate that in both scenarios quantum strategies outperform their classical counterparts, particularly by providing a favorable trade-off between reduced latency and enhanced fidelity. Overall, the findings highlight the potential of game theory as a powerful tool for addressing core challenges in quantum networks, including routing, topology inference, and resource allocation.

In contrast to the existing literature, in this study we evaluate the efficiency of myopic routing across different network topologies. We focus on specific subgraphs, and we investigate how the efficiency of myopic routing varies with their size in terms of number of nodes. This approach enables us to systematically analyze the relationship between local decision-making and network performance under different structural configurations.

This study makes the following key contributions to the literature:

- **Evaluation of Myopic Routing Efficiency Across Realistic Topologies:** Unlike previous studies that focus on global or game-theoretic routing strategies, this work provides a quantitative evaluation of myopic (local) routing efficiency across two distinct and realistic quantum network topologies.
- **Subgraph-Based Cluster Analysis:** We systematically partition each network into smaller subgraphs (clusters) and analyze how the efficiency of myopic routing changes with the number of nodes in each cluster, offering a fine-grained view of local decision dynamics.
- **Formalized Reward-Cost Objective Function:** A novel objective function is proposed to capture the trade-off between proximity-based reward and transmission cost, enabling a unified comparison between globally optimal and myopic (local) strategies.
- **Comparison Between Centralized and Decentralized Strategies:** By comparing the optimal forwarding policy (F_{opt}) with the myopic strategy (F_{myopic}), we quantify the performance gap and highlight the trade-offs associated with decentralization in routing decisions.
- **Statistical Robustness Through Large-Scale Sampling:** The evaluation is conducted over 10,000 simulation instances per topology, and 95% confidence intervals are derived using percentile-based analysis, ensuring statistically reliable and interpretable results.
- **Scalability-Oriented Framework:** The proposed methodology is lightweight and scalable, making it suitable for analyzing routing performance in large-scale or memoryless quantum networks where global coordination is impractical.

III. Proposed Model

In our study, we define a customized reward-cost-based objective function to evaluate the effectiveness of different routing strategies. This function is designed to capture both the impact of individual (selfish) decisions made by each node and the overall network-wide efficiency.

A. Objective Function

Each routing strategy is evaluated based on a dedicated objective function composed of two key components:

- **Proximity reward:** Encourages the long-term localization of Bell pairs in nearby nodes, promoting efficient spatial distribution.
- **Transmission cost:** Represents the total cost associated with the paths traversed by the bell pairs across the network links.

In our study, the objective function is formulated as follows [25]:

$$f = -\text{reward} + \text{cost}\,.$$

The reward is computed using the high powers of the transition matrix $P = \{P_{ij}\}$, which defines the forwarding probabilities between nodes. By repeatedly squaring this matrix, we approximate the steady-state distribution that reflects the long-term behavior of the routing policy - i.e., the probability that a Bell pair will reside at a given node after many forwarding steps.

B. Optimal (Centralized) and Myopic (Decentralized) Solutions

Optimal cost (F_{opt}) is obtained by numerically minimizing the objective function over all feasible probability distributions, i.e., all valid P matrices. This represents a centralized approach where all nodes coordinate their forwarding probabilities globally in order to minimize the total cost across the entire network.

Myopic cost (F_{myopic}) corresponds to a decentralized strategy in which each node forwards to its least costly neighbor based solely on local information. That is, each p_{ij} is nonzero only for the link with the lowest individual transmission cost from node i. This approach ignores the long-term impact of forwarding decisions and does not account for the global network behavior. While it may yield locally optimal outcomes, it can result in suboptimal overall performance.

We represent the forwarding strategy with a stochastic matrix $P = \{p_{ij}\}$, where p_{ij} is the probability that node i forwards the bell pair to node j. The transmission cost for each link is represented by a matrix $C = \{c_{ij}\}$, where c_{ij} is the cost from node i to node j.

The total cost function is given as:

$$f(P, C) = -R(P, C) + \sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij} \cdot c_{ij} \tag{1}$$

where $R(P, C)$ is the proximity reward, and the second term is the expected transmission cost across the entire network.

To calculate $R(P, C)$, we compute the steady-state distribution matrix S by raising the matrix P to a large power (e.g., P^{8192}). This approximates the long-term behavior of the forwarding process, i.e., the probability that a bell pair originating from node 1 reaches node j in the long run.

The reward is then calculated as:

$$R(P, C) = \sum_{j=1}^{n}\sum_{i=1}^{n} S_{1j} \cdot (d_{\text{max}} - c_{ji}) \tag{2}$$

where d_{max} is the maximum transmission cost in the matrix C. This formulation ensures that forwarding to nodes with lower cost yields a higher reward.

The **optimal forwarding policy** is found by minimizing $f(P, C)$ under stochastic constraints on P (i.e., each row of P sums to 1, $p_{ii} = 0$, and $0 \leq p_{ij} \leq 1$). This yields a solution denoted by F_{opt}, representing the minimum achievable total cost.

In contrast, the **myopic strategy** does not consider long-term effects or the global cost structure. Each node simply forwards the bell pair to its immediate neighbor with the lowest cost:

$$p_{ij} = \begin{cases} 1, & \text{if } j = \arg\min_{k \neq i} c_{ik} \\ 0, & \text{otherwise} \end{cases}$$

This strategy minimizes only the local transmission cost at each step, without accounting for where the bell pairs might eventually end up. The cost associated with this myopic forwarding strategy is denoted as F_{myopic}.

We define the **efficiency** of the myopic strategy relative to the optimal strategy as:

$$\text{Efficiency} = \frac{F_{\text{myopic}}}{F_{\text{opt}}} \tag{3}$$

Since both cost values are positive, the efficiency lies in the range $[0, 1]$. Higher values indicate that the myopic approach performs close to the global optimum.

In our study, we conducted a statistical analysis to more reliably evaluate the effectiveness of different routing strategies across various subgraph sizes K. For each value of K, we randomly sampled 200 different subgraphs and computed efficiency scores. This process was repeated 50 times, resulting in a total of 10,000 scenarios evaluated for each topology. These repetitions helped reduce the impact of random fluctuations and increased the statistical robustness of our findings. For each K, we computed the mean efficiency and additionally derived confidence intervals to quantify the variability in the results. Specifically, we adopted a percentile-based approach, calculating the 2.5$^{\text{th}}$ and 97.5$^{\text{th}}$ percentiles across repetitions to obtain a 95% confidence interval. This statistical framework allows us not only to assess the average performance but also to visualize the uncertainty around the measurements, leading to a more comprehensive and reliable analysis of routing strategy performance.

IV. Simulation Results

Our evaluation is conducted over five different topologies, which are summarized along with their characteristics in Table I [26].

Fig. 1 reports the efficiency of myopic routing in different subnetworks of K nodes extracted from the five topologies. We choose values of K in $\{8, 10, 20\}$. On the x-axis, we display the standard deviation of the link lengths, which is mildly indicative of the efficiency as distributed myopic routing is apparently slightly better as the network is more diverse. Additionally, this parameter enables the visual separation of the topologies, as apparently the link lengths are significantly different across all of them. The most interesting trend is that the efficiency of myopic forwarding improves with increasing K, which we attribute to a better compensation of looping effect in relatively larger networks.

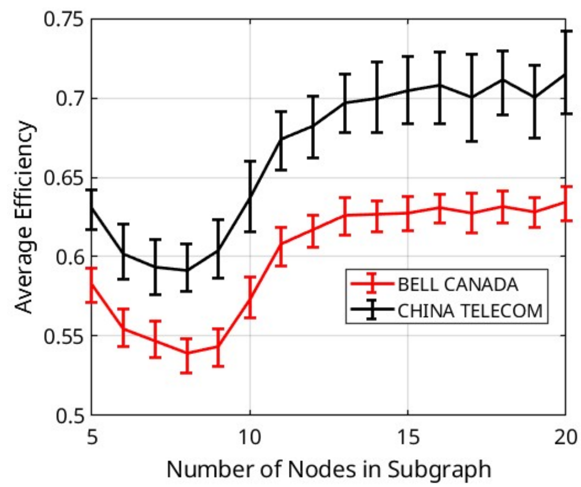

Fig. 2. Impact of Subgraph Size on Routing Efficiency for Bell Canada and China Telecom Topologies. Average efficiency increases with the number of nodes per subgraph, indicating improved performance with richer local connectivity. Error bars represent standard deviation across subgraph samples.

To get a better detail on this point, we report in Fig. 2 the effect of increasing the subnetwork size on the routing efficiency for two distinct topologies: Bell Canada and China Telecom, reported with 95% confidence intervals. As the number of nodes in the subgraphs increases from 5 to 20, both topologies exhibit an upward trend in efficiency, with China Telecom consistently outperforming Bell Canada. The improvement is more pronounced beyond 10 nodes, suggesting that larger subgraphs offer more alternative paths and flexibility for proximity-aware routing.

V. Conclusion and Future Works

In this study, we evaluated the efficiency of myopic routing strategies across various quantum network topologies by partitioning them into subgraphs of increasing size. Our results show a clear trend: as the cluster size increases, the efficiency of myopic routing significantly improves. This indicates that local decision-making strategies perform better when applied over larger structural units within the network.

These findings suggest that the structural granularity of the network - specifically, the size of subgraphs - plays a crucial role in the performance of decentralized routing protocols. Therefore, understanding and controlling the partitioning scale may serve as a design lever for improving entanglement distribution efficiency in memory-free quantum networks.

Our current work considers static clustering schemes with uniform cluster sizes. In future research, we plan to explore adaptive mechanisms where cluster sizes are determined dynamically based on network conditions, such as congestion, entanglement availability, or physical distance metrics [27].

Additionally, it would be valuable to investigate hybrid routing strategies that combine local myopic decisions with limited

TABLE I
TOPOLOGY CHARACTERISTICS

Topology	Number of Nodes	Number of Edges	Average Length	Standard Deviation of the Length
Bell Canada	48	65	720.08	$1.001\text{x}10^3$
China Telecom	42	66	911.97	567.47
Surfnet	50	73	30.79	20.20
BT Asia Pacific	51	66	270.44	264.07
IRIS USA	51	64	53.40	34.14

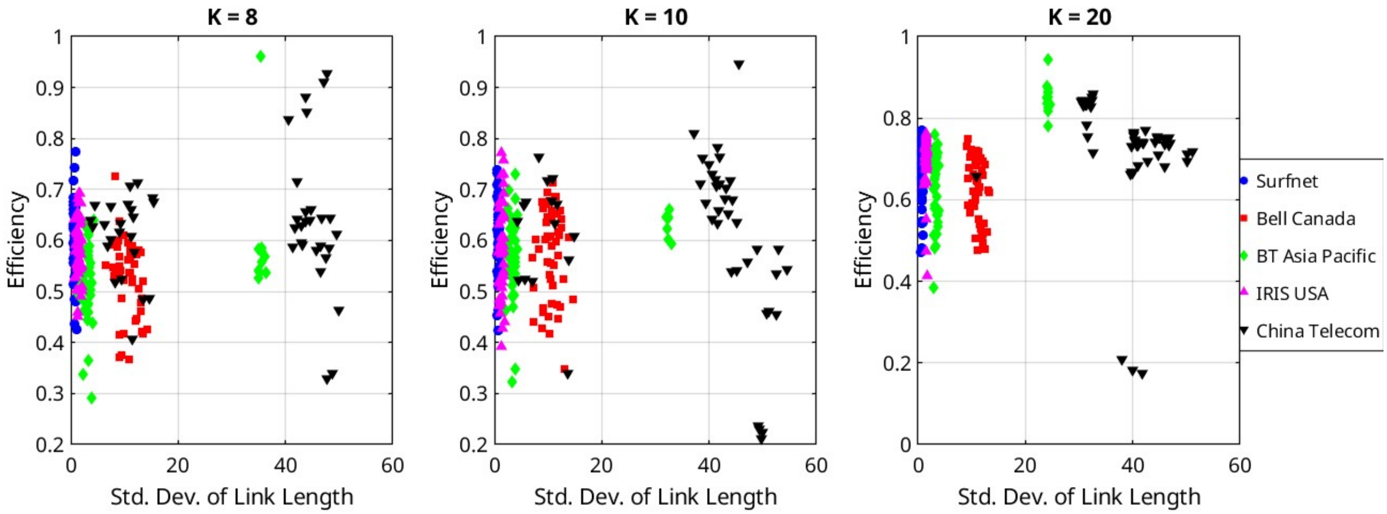

Fig. 1. Efficiency versus standard deviation of link length for five different network topologies (Surfnet, Bell Canada, BT Asia Pacific, IRIS USA, and China Telecom) under three different subgraph sizes (K = 8, 10, 20). Each marker represents a subgraph; variations in efficiency and spatial distribution of links are observed as K increases.

global coordination, especially in medium-sized clusters where purely local strategies may still suffer from inefficiencies [15], [17]. Finally, evaluating the robustness of myopic routing under link failures or dynamic request loads remains a promising direction for further analysis.

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REFERENCES

[1] H. J. Kimble, "The quantum internet," *Nature*, vol. 453, no. 7198, pp. 1023–1030, 2008.

[2] S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: A vision for the road ahead," *Science*, vol. 362, no. 6412, p. eaam9288, 2018.

[3] M. Ghadimi, L. Badia, B. Njoku, R. Bassoli, and F. H. Fitzek, "Assessing the impact of entanglement on strategic choices in quantum communication networks," in *Proc. IEEE Fut. Netw. World Forum (FNWF)*, 2024, pp. 725–730.

[4] A. Abane, M. Cubeddu, V. S. Mai, and A. Battou, "Entanglement routing in quantum networks: A comprehensive survey," *IEEE Trans. Quantum Eng.*, vol. 6, p. 4100638, 2025.

[5] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, "Quantum repeaters: the role of imperfect local operations in quantum communication," *Phys. Rev. Lett.*, vol. 81, no. 26, p. 5932, 1998.

[6] K. Azuma, S. E. Economou, D. Elkouss, P. Hilaire, L. Jiang, H.-K. Lo, and I. Tzitrin, "Quantum repeaters: From quantum networks to the quantum internet," *Rev. Mod. Phys.*, vol. 95, no. 4, p. 045006, 2023.

[7] A. Buratto, A. Munari, and L. Badia, "Strategic backoff of slotted ALOHA for minimal age of information," *IEEE Commun. Lett.*, vol. 29, no. 1, pp. 155–159, 2025.

[8] Y. Jiang, J. Kang, D. Niyato, X. Ge, Z. Xiong, C. Miao, and X. Shen, "Reliable distributed computing for metaverse: A hierarchical game-theoretic approach," *IEEE Trans. Veh. Technol.*, vol. 72, no. 1, pp. 1084–1100, 2022.

[9] W. Saad, Z. Han, M. Debbah, A. Hjorungnes, and T. Basar, "Coalitional game theory for communication networks," *IEEE Signal Process. Mag.*, vol. 26, no. 5, pp. 77–97, 2009.

[10] I. Dey, N. Marchetti, M. Caleffi, and A. S. Cacciapuoti, "Quantum game theory meets quantum networks," *IEEE Wireless Commun.*, vol. 31, no. 4, pp. 90–96, 2024.

[11] L. Badia, H. S. Duranoglu Tunc, A. C. Aka, R. Bassoli, and F. H. Fitzek, "Strategic interaction over age of information on a quantum wiretap channel," in *Proc. Eur. Wireless Conf.* VDE, 2023, pp. 388–394.

[12] H. S. Duranoglu Tunc, R. Bassoli, and F. H. Fitzek, "Distributed quantum routing with fidelity assurance in memory-free networks," in *Proc. IEEE Wirel. Commun. Netw. Conf. (WCNC)*, 2025, pp. 1–6.

[13] A. S. Acampora and S. I. Shah, "Multihop lightwave networks: a comparison of store-and-forward and hot-potato routing," *IEEE Trans. Commun.*, vol. 40, no. 6, pp. 1082–1090, 2002.

[14] L. Badia, M. Miozzo, M. Rossi, and M. Zorzi, "Routing schemes in heterogeneous wireless networks based on access advertisement and backward utilities for QoS support," *IEEE Commun. Mag.*, vol. 45, no. 2, pp. 67–73, 2007.

[15] Y. Zhao, G. Zhao, and C. Qiao, "E2E fidelity aware routing and purification for throughput maximization in quantum networks," in *Proc. IEEE Conf. Comp. Commun. (INFOCOM)*, 2022, pp. 480–489.

[16] L. Yang, Y. Zhao, H. Xu, L. Huang, and C. Qiao, "Dynamic entanglement routing based on stream processing for quantum networks," *IEEE/ACM Trans. Netw.*, 2024.

[17] Y. Zeng, J. Zhang, J. Liu, Z. Liu, and Y. Yang, "Entanglement routing design over quantum networks," *IEEE/ACM Trans. Netw.*, vol. 32, no. 1, pp. 352–367, 2023.

[18] C. Li, T. Li, Y.-X. Liu, and P. Cappellaro, "Effective routing design for remote entanglement generation on quantum networks," *npj Quantum Information*, vol. 7, no. 1, p. 10, 2021.

[19] J. Kim, H. Lee, J. Lee, and S. Lee, "Resource efficient link-set configuration (RELiC)-based entanglement routing," *IEEE Trans. Commun.*, vol. 73, no. 3, pp. 1726–1740, 2025.

[20] Q. Zhu, Y. Zhao, H. Xu, L. Huang, and C. Qiao, "Beyond entanglement routing: Source assignment and all-optical switching-based distribution," *IEEE/ACM Trans. Netw.*, vol. 33, no. 2, pp. 713–728, 2025.

[21] S. Shi and C. Qian, "Concurrent entanglement routing for quantum networks: Model and designs," in *Proc. ACM SIGCOMM*, 2020, pp. 62–75.

[22] M. Pant, H. Krovi, D. Towsley, L. Tassiulas, L. Jiang, P. Basu, D. Englund, and S. Guha, "Routing entanglement in the quantum internet," *npj Quantum Inf.*, vol. 5, no. 1, p. 25, 2019.

[23] E. Sutcliffe and A. Beghelli, "Multiuser entanglement distribution in quantum networks using multipath routing," *IEEE Trans. Quantum Eng.*, vol. 4, pp. 1–15, 2023.

[24] K. Chakraborty, F. Rozpedek, A. Dahlberg, and S. Wehner, "Distributed routing in a quantum internet," *arXiv preprint arXiv:1907.11630*, 2019.

[25] L. Badia and M. Zorzi, "On utility-based radio resource management with and without service guarantees," in *Proc. ACM Int. Symp. Model. Anal. Simul. Wireless Mobile Syst. (MSWiM)*, 2004, pp. 244–251.

[26] S. Knight, H. X. Nguyen, N. Falkner, R. Bowden, and M. Roughan, "The internet topology zoo," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 9, pp. 1765–1775, 2011.

[27] F. Guidolin, L. Badia, and M. Zorzi, "A distributed clustering algorithm for coordinated multipoint in LTE networks," *IEEE Wireless Commun. Lett.*, vol. 3, no. 5, pp. 517–520, 2014.