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Energy Efficient Quantum Entanglement Generation Optimizing Resource Utilization in Large Network

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***Abstract*—Quantum networks are set to transform distributed communication and computation. However, achieving energy efficiency and resource optimization in large-scale networks is notably challenging because of the complexity of creating and routing quantum entanglement. This study presents a new quantum routing framework, Quantum Fidelity-Energy Optimized Routing (QFER), which dynamically balances energy use and fidelity loss to improve entanglement generation in diverse quantum networks. It employs a multiobjective optimization strategy that considers fidelity degradation, energy efficiency, and success probability, considering device variability, network traffic, and coherence limits. Real-time path optimization enables effective entanglement creation and optimal resource use in multi-hop networks. This approach significantly improves network scalability, throughput, and energy efficiency, supporting the development of resilient and sustainable quantum Internet frameworks that can meet the needs of advanced quantum communication systems.**

***Index Terms*—Quantum Entanglement, Quantum Communication, Quantum Routing, Routing Framework.**

I. Introduction

Quantum networks have revolutionized secure communication, distributed computation, and QKD [1]. Quantum entanglement [2] [3] permits unique correlations between quantum states over long distances in these networks. Entanglement is essential for quantum applications like secure data transmission and teleportation [4]. Implementing quantum networks in large-scale applications is challenging due to sensitive entangled states, operational limitations, and resource-intensive routing [4].

Maintaining entanglement fidelity over long distances is a major difficulty in large-scale quantum networking [5]. Decoherence, photon loss, and ambient noise degrade entanglement fidelity exponentially, making long-distance quantum communication uncertain and resource-intensive [6]. While quantum repeaters [4] expand communication range by switching entanglement at intermediate nodes, they also increase synchronization difficulty and energy consumption. Quantum error correction and entanglement purification use more resources. Coherence time limitations in quantum memory require precise coordination to prevent fidelity deterioration and entanglement loss [5].

A. *Energy Consumption in Quantum Networks:*

Unlike classical networks, where energy usage is primarily associated with data transmission and computation, quantum networks consume energy for entanglement generation, storage, maintenance, and error correction.

Establishing and sustaining network entanglement requires energy-intensive operations:

- Entanglement Generation: Quantum nodes need energy to create entangled photon pairs, with resource demands altering based on hardware efficiency and environmental conditions.
- To extend entanglement across long distances, quantum repeaters must switch and purify entangled states, which requires extra energy for measurement, quantum memory operations, and classical signal exchange.
- Quantum error correction approaches, which reduce noise and decoherence, increase energy costs due to redundant qubit encoding and repetitive syndrome measurements.
- Quantum networks use conventional signals for synchronization, entanglement verification, and routing decisions. Quantum devices' classical overhead and hardware inefficiencies (such as poor quantum memory and photon detectors) increase energy consumption.

Different quantum device memory coherence times, noise thresholds, and entanglement formation rates affect network routing decisions. Many quantum routing systems assume network parts are homogeneous and static. Because these methods don't account for quantum networks' dynamic nature, they waste energy, allocate resources poorly, and decrease network performance. Existing routing frameworks ignore energy efficiency, which is essential for large-scale quantum networks.

This research introduces the adaptive and scalable QFER framework for quantum entanglement routing that optimizes energy consumption, fidelity maintenance, and success probability. The framework uses real-time network circumstances like device heterogeneity, traffic fluctuations, and quantum coherence constraints to find optimal routes. QFER optimizes resource use, energy costs, and network scalability by integrating these aspects into a routing scheme.

QFER explicitly describes the stochastic and temporal nature of entanglement creation while making energy-efficient routing decisions, unlike conventional routing methods. Through comprehensive simulation tests, the proposed framework improves energy economy, throughput, and fidelity preservation, making it a crucial enabler for next-generation quantum Internet infrastructures.

Different quantum device memory lifetimes and noise thresholds affect network routing decisions. Routers sometimes assume all network elements are homogeneous and unchangeable. These methods cannot account for the dynamic nature of real-world quantum networks, resulting in wasteful resource allocation, energy use, and performance. Energy efficiency, which is necessary for the long-term functioning of large quantum networks, is often overlooked.

The QFER framework optimizes quantum entanglement formation in large networks in an adaptable and scalable manner. QFER uses a multi-objective optimization method to evaluate fidelity loss, energy consumption, and entanglement generation success. Real-time network factors including device variety, traffic variations, and coherence time constraints are used to dynamically find optimal paths. QFER ensures network resource efficiency, integrity, and scalability by integrating these variables into a routing design.

QFER openly displays quantum entanglement's probabilistic and temporal properties, enabling resilient and energy-efficient routing solutions. Simulations show that this framework improves energy economy, throughput, and network scalability, making it a strong candidate for next-generation quantum communication systems. QFER addresses the fundamental challenges of large-scale entanglement routing, laying the groundwork for quantum Internet designs that can support future quantum technology advances.

II. Related work

Entanglement lets particles share correlated quantum states across any distance, making data transport secure and efficient. Quantum networks are difficult to scale for practical, large-scale applications due to probabilistic entanglement generation, fidelity decay, and resource-intensive routing.

Long-distance quantum communication is hindered by the exponential fall in entanglement fidelity due to photon loss, decoherence, and ambient noise [7]. To overcome these issues, quantum repeaters have been proposed to enable entanglement swapping between intermediary nodes, extending communication lengths (Zeng2022multi, Azuma 2023quantum). Repeaters reduce distance-induced fidelity loss, but they also require synchronization of entanglement creation between nodes and fidelity loss reduction during swapping operations. Quantum memory' short coherence lengths require accurate temporal synchronization to avoid fidelity deterioration and ensure entanglement across numerous hops. The operational challenges make entanglement routing computationally complex and resource-intensive, especially in large networks where repeated linkage generation requires a lot of energy.

Quantum entanglement routing research has grown due to these efforts. In their 2019 study, Cacciapuoti et al. compared quantum networks to conventional networks, examining the constraints of quantum physics on networking topologies [8] [9] Their research focused on quantum system difficulties such the no-cloning theorem, probabilistic entanglement generation, and distance-dependent fidelity deterioration. Their publication offered a theoretical basis for quantum network architecture, but implementations that address these restrictions are still being researched.

Throughput optimization is a focus of quantum networking research. Zeng et al. (2022) developed a multi-entanglement routing method to maximize user pair success. [2]. They increased throughput under static network conditions by modeling routing as an integer linear programming (ILP) issue. Their model was too rigid to adapt to real-world, dynamic situations with changing network conditions, traffic volumes, and device capabilities. Energy efficiency, crucial for the evolution of large quantum networks, was disregarded, resulting in a significant design flaw.

Device heterogeneity is another quantum network problem. Gan et al. (2023) introduced the Synchronous Multi-Time-Slot (SynMts) paradigm, unifying heterogeneous devices [10] with varying quantum memory coherence [11] durations. Quantum networks can scale in heterogeneous device settings, since this strategy allowed sophisticated devices to generate prolonged entanglements while helping older devices with reduced coherence times. However, its benefits and planned scheduling procedures limited its adaptability to real-time network changes like traffic spikes and resource rivalry. Energy use and resource allocation were inefficient due to this limitation.

Recent studies have investigated energy-efficient quantum network designs. They focus on particular components like enhancing entanglement generation fidelity or reducing quantum storage decoherence. Limited energy efficiency solutions exist for the entire routing process, especially in large and heterogeneous quantum systems. Modern methods often use static optimization techniques, which are unsuitable for dynamic quantum networks with temporal variability [12]. Poor use of device heterogeneity, such as memory lifetimes, noise thresholds, and entanglement formation rates, wastes resources and limits network scalability.

Despite these achievements, contemporary research have several gaps. Limited adaptability, energy efficiency, and device diversity hinder large-scale quantum entanglement routing [2]. Innovative solutions are needed to enhance network performance, fidelity, and resource utilization for sustainable and scalable next-generation quantum networks [8].

III. Proposed Methodology

Large-scale quantum networks face energy efficiency, fidelity degradation, and routing scalability issues. The Quantum Fidelity-Energy Optimized Routing framework (QFER) uses multi-objective optimization and adaptive routing to optimize resource use and entanglement creation. Refer to 1 for the suggested framework.

The proposed Quantum Fidelity and Energy-aware Routing (QFER) Framework architecture is shown in Fig.1. The architecture has multiple interconnected components to improve quantum network performance. The Fidelity Calculator, Energy Estimator, and Success Probability Evaluator comprise

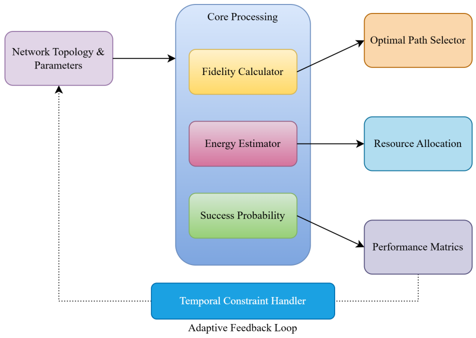

Fig. 1. QFER Framework Architecture

the Core Processing Unit. Modules optimise routing based on network topology and parameter inputs.

The Temporal Constraint Handler dynamically adjusts routing to real-time network conditions for adaptive feedback control. The Optimal Path Selector finds optimal quantum communication paths using fidelity, energy, and success probability. Resource Allocation and Performance Metrics modules manage quantum resources and evaluate system efficiency. The suggested architecture uses an integrated, feedback-driven approach to increase quantum communication reliability and efficiency.

A. Problem Definition

A quantum network is modeled as a graph $G = (V, E, W)$, where, V, Set of quantum nodes capable of entanglement generation and management. E, Set of quantum channels between nodes. W, The weights assigned to edges $e_{i,j} \in E$, representing metrics such as distance, noise, and fidelity decay. The problem involves finding an optimal path P^* between a source node e and a destination node d such that,

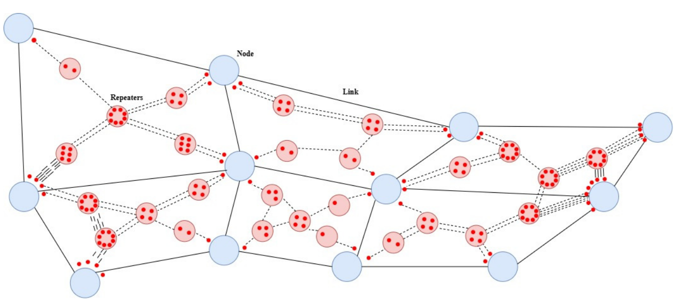

Fig. 2. Demonstrating the development and adaptive reconfiguration of entangled quantum connections inside a network, facilitating effective path optimization for quantum information transmission.

B. Contribution

- Enhance the end-to-end fidelity $F(P)$ of the entangled state.
- Optimize the success probability $P_s(P)$ for generating entanglement throughout the path.

$$P^* = arg \max_{P \in \mathrm{P}(s,d)} (\omega_1 F(P) - \omega_2 E(P) + \omega_3 P_s(P)) \quad (1)$$

Where, $P(s,d)$, Set of all feasible paths from s to d. $\omega_1, \omega_2, \omega_3$, Weights representing the relative importance of fidelity, energy, and success probability.

C. Theoretical Model

The QFER framework relies on an extensive mathematical model that assesses routing metrics at both the edge and path levels.

1) Edge-Level Metrics:

a) Fidelity Decay (F_{ij}): Fidelity decays [13] exponentially with distance and noise along the channel e_{ij}. The fidelity is defined as

$$F_{ij} = F_0 \cdot e^{-\lambda d_{ij}} \cdot (1 - \eta_{ij}) \quad (2)$$

where, F_0 Initial fidelity of the entangled pair. λ Fidelity decay constant. d_{ij} Distance between nodes i and j. η_{ij} Noise and channel loss factor.

b) Energy Consumption (E_{ij}): The energy required to establish an entanglement [14] link between nodes i and j is

$$E_{ij} = E_0 + \alpha d_{ij} + \beta F_{ij}^{-1} \quad (3)$$

where, E_0 Base energy cost for entanglement generation. α Energy coefficient for distance. β Penalty for lower fidelity (inverse proportionality to fidelity).

c) Success Probability, P_{ij}: The probability of successfully establishing an entanglement link [15] is

$$P_{ij} = p_s \cdot e^{-\delta d_{ij}} \cdot (1 - \eta_{ij}) \quad (4)$$

where, P_s Baseline success probability of the channel. δ Probability decay constant over distance.

d) Temporal Constraints: Quantum memory imposes a strict coherence time T within which operations must be completed. The effective fidelity [16] after considering time is

$$F_{ij}^{\text{eff}} = \min(F_{ij}, 1 - \frac{t(P)}{\tau}) \quad (5)$$

where, $t(P)$ is the accumulated time along the path P,

2) Path-Level Metrics:

a) Cumulative Fidelity $(F(P))$: Fidelity along a multi-hop path $P = v_1, v_2, ...v_n$ with $n-1$ edges [2] is given by

$$F(P) = S^{n-2} \cdot \prod_{i=1}^{n-1} F_{v_i v_{i+1}} \quad (6)$$

where, S, Success rate of entanglement swapping.

b) Entanglement regeneration (E_r): Entanglement regeneration refers to the process of re-establishing entanglement between intermediate nodes when an existing link fails or degrades below a threshold. This typically includes:

Entanglement swapping energy cost: When a repeater node performs Bell-state measurement (BSM) to transfer entanglement, it consumes energy for qubit operations.

Quantum memory refresh energy: If a repeater needs to store entangled qubits while waiting for an incoming pair, it consumes energy to maintain coherence.

Additional entanglement generation: If the original entanglement fails (e.g., due to fidelity degradation), the system attempts a new entanglement generation cycle, increasing energy use.

$$E_r = \gamma + \lambda t + \rho(1 - F_{\text{swap}}) \tag{7}$$

where γ is the fixed energy cost of performing an entanglement swap, λt is the energy cost of keeping qubits coherent for duration t (memory cost), and $\rho(1 - F_{\text{swap}})$ represents the energy penalty for lower swap fidelity, where ρ is a scaling factor.

c) Total Energy ($E(P)$): Energy consumption along the path is the sum of edge energy and regeneration costs

$$E(P) = \sum_{i=1}^{n-1} \left(E_{v_i v_{i+1}} + k \cdot E_r \right) \tag{8}$$

where k is the number of entanglement swaps along the path and E_r is the energy required for entanglement regeneration.

d) Overall Success Probability, $P_s(P)$: The cumulative probability of successful entanglement generation is

$$P_s(P) = R \cdot \prod_{i=1}^{n-1} P_{v_i v_{i+1}} \tag{9}$$

where R accounts for reliability factors such as node availability and operational stability.

e) Path Score: The score of a path [17] P integrates fidelity, energy, and success probability

$$\text{Score}(P) = \omega_1 F(P) - \omega_2 E(P) + \omega_3 P_s(P) \tag{10}$$

IV. Performance Evaluation & Discussion

The results demonstrate the framework's energy efficiency, fidelity preservation, and scalability in massive quantum networks. Below are detailed analyses and graphs for each relevant measure.

Simulations were conducted on an Intel Core i7-12700K processor (12 cores, 20 threads, 3.60 GHz) with 32 GB DDR4 RAM and Ubuntu 24.04.1 LTS operating system. NumPy, Pandas, and Matplotlib were simulation libraries for Python 3.8. The quantum network simulator was proprietary and developed on QuNetSim. To replicate real-world quantum network settings, heterogeneous edge features like fidelity decay factors and noise levels were used.

1) Energy Efficiency vs Path Length: The findings demonstrate that energy consumption increases somewhat with longer pathways due to increased costs associated with greater distances and fidelity penalties (Fig. 3). The graph demonstrates a linear link between energy usage and path length, consistent with the energy data.

Algorithm 1 Quantum Fidelity-Energy Optimized Routing (QFER)

Input: Graph G, source node s, destination node d, parameters $(F_0, E_0, \lambda, \alpha, \beta, \delta, \tau)$, weights $(\omega_1, \omega_2, \omega_3)$
Initialize priority queue Q with $(s, F_0, 0, 1, [s])$, where F_0 is the initial fidelity.
while priority queue Q is not empty **do**
  Dequeue the path (i, F, E, P_s, P) from Q with the highest score.
  if $i = d$ **then**
    Return: Path P^* with the highest score.
  end if
  for each edge (i, j) connected to node i **do**
    Compute edge fidelity: $F_{ij} = F_0 \cdot e^{-\lambda d_{ij}} \cdot (1 - \eta_{ij})$
    Compute edge energy: $E_{ij} = E_0 + \alpha d_{ij} + \beta F_{ij}^{-1}$
    Compute success probability: $P_{ij} = p_s \cdot e^{-\delta d_{ij}} \cdot (1 - \eta_{ij})$
    Update effective fidelity: $F_{ij}^{\text{eff}} = \min(F_{ij}, 1 - \frac{t(P)}{\tau})$
    Compute path score:
$$\text{Score}(P \cup \{j\}) = \omega_1 F_{ij}^{\text{eff}} - \omega_2 E_{ij} + \omega_3 P_{ij}$$
    if score improves **then**
      Enqueue $(j, F, E, P_s, P \cup \{j\})$ into Q
    end if
  end for
end while

$$E_{ij} = E_0 + \alpha d_{ij} + \beta F_{ij}^{-1} \tag{11}$$

The findings demonstrate that QFER significantly decreases energy consumption while managing the necessary costs of multi-hop routing.

2) Fidelity vs Path Length: The fidelity graph demonstrates an exponential decrease in fidelity as path length increases (Fig. 4), reflecting the cumulative impact of fidelity degradation and noise along multi-hop paths. This aligns with the fidelity model.

$$F_{ij} = F_0 \cdot e^{-\lambda d_{ij}} \cdot (1 - \eta_{ij}) \tag{12}$$

The results indicate that QFER can maintain acceptable fidelity levels throughout multi-hop paths, making it suitable for large networks.

3) Success Rate vs Noise Levels: The success rate declines as noise levels increase, as shown in the graph, confirming the probabilistic nature of entanglement formation (Fig. 5). The decline in success rate corresponds with the expected trend indicated by the model.

$$P_{ij} = p_s \cdot e^{-\delta d_{ij}} \cdot (1 - \eta_{ij}) \tag{13}$$

despite this drop, QFER sustains high success rates in moderate noise circumstances, demonstrating resilience to channel deficiencies.

4) Throughput vs. Traffic Load: The throughput graph indicates a small decrease in the entanglement generation rates as the traffic load increases (Fig. 6). This signifies the expected penalty resulting from increased competition and resource utilization. QFER efficiently manages traffic by constantly enhancing route selection, maintaining throughput close to its maximum.

5) Scalability: Energy Consumption vs. Number of Nodes: The scalability analysis confirms that energy usage rises logarithmically with the number of nodes, aligning with the concept (Fig. 7).

$$F(P) = S^{n-2} \cdot \prod_{i=1}^{n-1} F_{v_i v_{i+1}} \tag{14}$$

Fig 8 shows the optimal routing path in a quantum network, shown as nodes (A, B, C, D, E, and F) connected by entangled links. Quantum Fidelity and Energy-aware Routing (QFER) dynamically finds the best path based on fidelity, energy efficiency, and success probability. The illustrated channel is the best quantum information transfer mechanism for minimal decoherence and resource efficiency.

QFER uses adaptive routing to enhance speed while meeting network restrictions to increase quantum communication dependability. This shows the framework's ability to make smart routing decisions in complex quantum networks.

QFER scales effectively with network size and maintains energy efficiency in huge networks, making it suited for future quantum Internet architectures.

Figure 9 compares quantum routing systems using a radar chart, evaluating energy efficiency, fidelity, success rate, scalability, and throughput. Compared to conventional routing approaches (red), the Quantum Fidelity and Energy-aware Routing (QFER) Framework (blue shade) performs better across all criteria.

QFER has high fidelity and success rates, boosting quantum communication's credibility. The architecture is ideal for large quantum networks due to its energy efficiency and scalability. Its improved throughput proves its quantum resource optimization. Comparing QFER to traditional quantum routing algorithms shows its advantages.

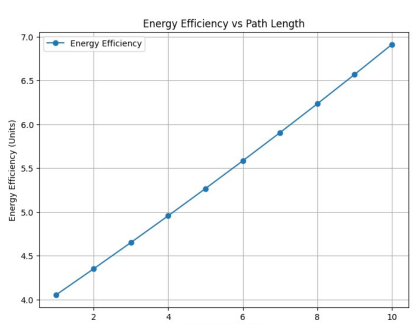

Fig. 3. Energy Efficiency vs Path length

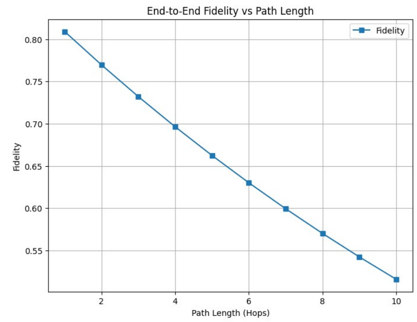

Fig. 4. End to End Fidelity vs Path Length

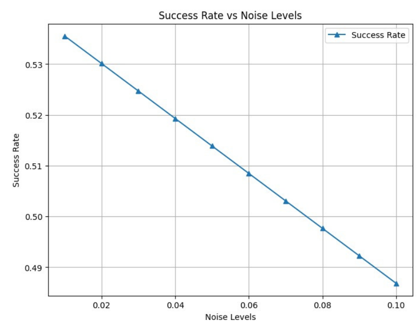

Fig. 5. Success Rate vs Noise Level

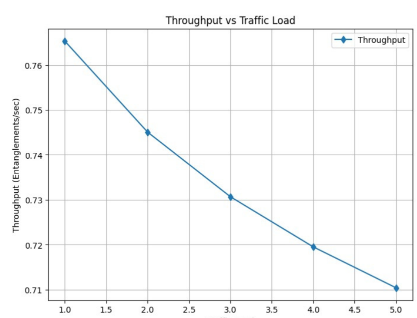

Fig. 6. Throughput vs Traffic Load

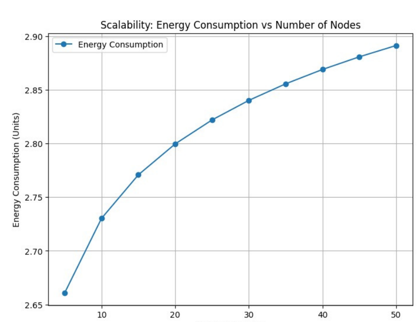

Fig. 7. Energy Consumption vs Number of Nodes

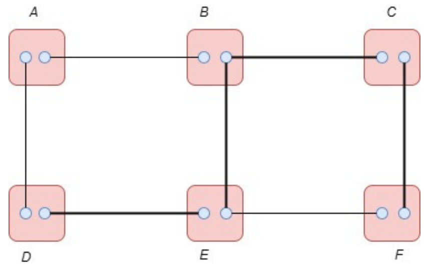

Fig. 8. Routing via Best Path

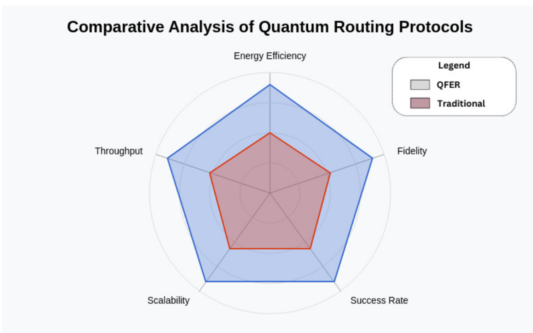

Fig. 9. Comparative Analysis

V. Conclusion

The proposed QFER system solves energy inefficiency, fidelity erosion, and scalability issues in large quantum networks. Using a multi-objective optimization model and a dynamic routing algorithm, QFER balances energy consumption, fidelity retention, and success rates across varied device capabilities. Simulations have reduced energy costs, maintained fidelity, and scaled well under different network conditions. Future research could use quantum error correction (QEC) to improve fidelity retention and reduce quantum decoherence. AI-driven adaptive routing could improve dynamic network decision-making in real time. QFER expansion for hybrid quantum-classical networking would assure classical-quantum communication system interoperability.

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