# Optimizing Quantum Internet Performance: A Game-Theoretic Approach to Quantum Teleportation


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***Abstract*—Quantum teleportation is a fundamental protocol enabling the transfer of quantum states between remote nodes without physical transmission. As the Quantum Internet evolves, optimizing quantum teleportation becomes crucial due to entanglement degradation, resource constraints, and network efficiency. This paper proposes a game-theoretic framework for managing quantum teleportation by modeling quantum nodes as rational agents competing or cooperating to maximize teleportation fidelity and entanglement utility. We introduce cooperative and non-cooperative game models, analyze Nash equilibrium strategies for teleportation efficiency, and propose a Shapley-value-based entanglement allocation for fair resource distribution. Our system model incorporates graph-theoretic representations of quantum networks, utility functions, and incentive mechanisms to encourage efficient teleportation strategies. A Qiskit-based simulation evaluates teleportation fidelity and resource efficiency, comparing game-theoretic strategies with classical resource allocation methods. Our findings demonstrate that game-theoretic approaches significantly enhance teleportation efficiency, entanglement utilization, and robustness in a dynamic Quantum Internet environment.**



***Index Terms*—Quantum teleportation, Quantum Internet, Game theory, Nash equilibrium, Shapley value, Quantum networks, Teleportation fidelity, Incentive mechanisms.**


## I. Introduction

NOW the Quantum Internet [1] represents a groundbreaking advancement in communication technology, enabling the interconnection of quantum devices [2] over long distances. Unlike classical networks, which rely on the direct transmission of bits, the Quantum Internet leverages quantum entanglement and teleportation to transfer quantum states securely and instantaneously. This unique capability paves the way for critical applications such as quantum-secure communication, distributed quantum computing [3] [4], and advanced quantum sensing. At the heart of these advancements lies quantum teleportation [5] [6], a fundamental protocol that allows quantum information to be transmitted between remote nodes without physically transferring quantum particles. This process relies on three key components: pre-shared entanglement between sender and receiver, Bell-state measurements, and classical communication to apply necessary corrections at the receiver's end.

However, implementing quantum teleportation in a real-world quantum network presents several challenges. Entanglement degradation due to decoherence limits the fidelity of transmitted quantum states, while resource constraints necessitate efficient allocation [7] of limited entangled qubits. Additionally, traditional classical network optimization techniques fail in a quantum setting due to the no-cloning theorem and the non-local nature of entanglement. These challenges necessitate novel strategies for managing entanglement resources and optimizing quantum teleportation across complex, dynamic quantum networks.

Game theory [8] [9] offers a promising approach to addressing these challenges by modeling quantum network nodes as strategic agents that make rational decisions to optimize teleportation efficiency. By incorporating non-cooperative, cooperative, and evolutionary game models, quantum teleportation can be optimized through Nash equilibrium [10] [11] strategies, incentive-driven cooperation, and fair entanglement allocation using Shapley values [12]. This paper explores these game-theoretic approaches, providing a robust framework for enhancing quantum teleportation reliability and efficiency in the evolving Quantum Internet.

## II. Literature Review

Quantum teleportation, first introduced by Bennett et al. in 1993, forms a foundational building block of quantum communication systems. It allows the transfer of an arbitrary quantum state between two parties using shared entanglement and classical communication, without physically transmitting the particle itself. This protocol is essential to the development of the Quantum Internet, where quantum states must be transmitted across large-scale, noisy networks. However, as networks scale, maintaining high-fidelity entanglement becomes increasingly difficult due to decoherence, entanglement degradation, and the no-cloning theorem. Classical methods of routing and resource allocation are inadequate in such environments, necessitating new models for dynamic optimization in quantum networks.

Recent research has explored the integration of game theory into quantum communication [13] [14] [15] to address strategic decision-making among quantum nodes. Game theory, a framework for modeling competition and cooperation among rational agents, has been successfully applied in classical networks for problems such as congestion control, routing, and resource allocation. In the quantum domain, researchers like Khan et al. (2019) and Bera et al. (2022) have begun to investigate how quantum nodes can be modeled as self-interested players competing for limited entanglement [16] [17] [18] resources. These studies demonstrate the feasibility of using non-cooperative game models to reach Nash equilibria where each node independently maximizes its utility, but often at the cost of global efficiency. Other work has emphasized cooperative strategies, employing tools such as Shapley values and coalition formation to ensure fairness and collective performance enhancement.

More recent advancements have introduced evolutionary game theory and reinforcement learning into quantum network management. These models enable nodes to adapt strategies based on past performance, enhancing robustness in dynamic environments. Literature also highlights the potential for integrating quantum-specific metrics, such as entanglement fidelity and teleportation success probability, directly into the utility functions of game-theoretic models. Despite these advances, a fully unified framework combining teleportation protocols, entanglement optimization, and multi-agent strategic behavior remains underdeveloped. This gap motivates our research, which aims to systematically design and simulate a game-theoretic model for quantum teleportation using cooperative and non-cooperative strategies, while evaluating its effectiveness in terms of fidelity, fairness, and entanglement efficiency across a distributed quantum network.

## III. SYSTEM MODEL AND PROBLEM FORMULATION

### ■ Quantum Network Representation

A quantum network can be represented as a graph:

$$G = (V, E) \tag{1}$$

where:

- $V$ represents the **set of quantum nodes**.
- $E$ represents the **set of entangled links** connecting these nodes.

Each entangled link $e_{ij} \in E$ has an associated **fidelity** $F_{ij}$ that measures the quality of entanglement between nodes $i$ and $j$. The fidelity of an entangled state $\rho$ with respect to a Bell state $|\Phi^+\rangle$ is defined as:

$$F(\rho) = \langle \Phi^+ | \rho | \Phi^+ \rangle \tag{2}$$

1) Entanglement Swapping in the Network
If two quantum nodes, A and C, wish to establish entanglement but do not have a direct connection, an intermediary node B can perform a **Bell-state measurement (BSM)** on its qubits and communicate the result classically. This process extends entanglement across the network.
If node A is entangled with node B ($F_{AB}$) and node B is entangled with node C ($F_{BC}$), then after **entanglement swapping**, the fidelity of the new entanglement link A–C is:

$$F_{AC} = F_{AB} \cdot F_{BC} \tag{3}$$

This fidelity degradation affects the overall **teleportation success probability**.

### ■ Game-Theoretic Model for Quantum Teleportation

Each quantum node behaves as a self-interested agent that seeks to maximize its utility for teleportation. The decision-making process is framed as a strategic game.

1) Utility Function for Teleportation
Each node $i$ selects an entanglement allocation strategy $s_i$ to maximize its utility function:

$$U_i(s_i, s_{-i}) = \sum_{j \in N(i)} F_{ij} \cdot P_{ij} - C(s_i) \tag{4}$$

where:

- $P_{ij}$ is the **probability of successful teleportation** between nodes $i$ and $j$.
- $C(s_i)$ represents the **cost** associated with using entanglement resources.
- $N(i)$ is the **set of neighboring nodes** of $i$.

A rational node aims to maximize $U_i$ while ensuring a high teleportation success rate.

2) Nash Equilibrium Condition
A Nash Equilibrium (NE) is reached when no node has an incentive to unilaterally change its strategy:

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*) \quad \forall s_i, i \in V \tag{5}$$

This equilibrium ensures that no quantum node can improve its teleportation efficiency without affecting others.

### ■ Cooperative Game Model for Resource Allocation

1) Coalition Formation Among Quantum Nodes To improve teleportation efficiency, nodes can cooperate by forming coalitions where they share entanglement resources fairly. The fairness of resource allocation is determined using Shapley Values.
2) Shapley Value for Fair Entanglement Distribution

In a cooperative game, the Shapley Value provides a fair distribution of benefits among coalition members. The Shapley value for node $i$ in a coalition $S$ is:

$$\phi_i = \sum_{S \subseteq V \setminus \{i\}} \frac{|S|!(|V| - |S| - 1)!}{|V|!} \left( U(S \cup \{i\}) - U(S) \right) \tag{6}$$

where:

- $U(S)$ is the total teleportation utility of the coalition $S$.
- $U(S \cup \{i\})$ represents the utility when node $i$ joins the coalition.

This method ensures fair allocation of entanglement resources among cooperating nodes.

■ **Optimization of Entanglement Distribution**

The global objective is to optimize the allocation of entanglement resources across the quantum network. We define a global teleportation utility function as:

$$U_{global} = \sum_{i \in V} U_i(s_i, s_{-i}) \tag{7}$$

To maximize this, we solve the optimization problem:

$$\max_{\{s_i\}_{i \in V}} U_{global} \quad \text{subject to: } \sum_{i \in V} C(s_i) \leq C_{max} \tag{8}$$

where $C_{max}$ is the total resource budget.

- Proof of Optimal Strategy Existence

By the Lagrange Multiplier Method, we define:

$$L(s, \lambda) = U_{global} - \lambda \left( \sum_{i \in V} C(s_i) - C_{max} \right) \tag{9}$$

Solving:

$$\frac{\partial L}{\partial s_i} = 0 \quad \Rightarrow \quad \frac{\partial U_i}{\partial s_i} = \lambda \frac{\partial C(s_i)}{\partial s_i} \tag{10}$$

This ensures an optimal trade-off between teleportation efficiency and entanglement cost.

■ **Evolutionary Game Theory for Dynamic Networks**

In dynamic quantum networks, nodes learn and adap their strategies over time. The adaptation follows evolutionary dynamics, where successful strategies propagate while inefficient ones diminish.

- Replicator Dynamics for Quantum Teleportation

The evolution of strategy $s_i$ follows replicator equations:

$$\frac{ds_i}{dt} = s_i \left( U_i(s_i, s_{-i}) - \bar{U} \right) \tag{11}$$

where $\bar{U}$ is the average utility in the network.
At equilibrium, $\frac{ds_i}{dt} = 0$, which implies:

$$U_i(s_i, s_{-i}) = \bar{U} \tag{12}$$

This ensures network-wide efficiency over time.

## IV. PROPOSED MECHANISM

### A. *Overview of the Proposed Mechanism*

Quantum teleportation in the Quantum Internet is constrained by limitations in entanglement resources, fidelity degradation, and inefficient routing strategies. Our proposed mechanism leverages game-theoretic approaches to dynamically optimize quantum teleportation by modeling quantum nodes as self-interested agents that interact strategically.

The primary objectives of our mechanism are:

- Optimize entanglement allocation through utility maximization.
- Enhance teleportation fidelity using cooperative game-theoretic strategies.
- Adapt to network dynamics via evolutionary game theory.

We model teleportation as a multi-agent game where nodes decide on resource allocation, entanglement swapping, and teleportation strategies based on strategic interactions.

### B. *Quantum Entanglement Resource Allocation Game*

Quantum teleportation requires pre-shared entangled qubits. In large-scale quantum networks, nodes compete for limited entanglement resources.

*1) Game-Theoretic Formulation:* We define the **Quantum Resource Allocation Game (QRAG)** as follows:

- **Players:** Quantum nodes $i \in V$.
- **Strategies:** Allocation of quantum entanglement resources $s_i$.
- **Utility Function:** A measure of teleportation success based on fidelity and resource consumption.

Each node selects a strategy $s_i$ that determines how it allocates entanglement resources to its neighboring nodes. The utility function of node $i$ is given by:

$$U_i(s_i, s_{-i}) = \sum_{j \in N(i)} F_{ij} \cdot P_{ij} - C(s_i) \tag{13}$$

where:

- $P_{ij}$ is the probability of successful teleportation between nodes $i$ and $j$.
- $C(s_i)$ is the cost function associated with entanglement consumption.

Each node maximizes its utility while ensuring high teleportation fidelity.

*2) Nash Equilibrium Condition:* A **Nash Equilibrium (NE)** is a strategy profile where no node can improve its utility by unilaterally changing its strategy:

$$U_i(s_i^*, s_{-i}^*) \geq U_i(s_i, s_{-i}^*) \quad \forall s_i, i \in V \tag{14}$$

At Nash Equilibrium, each quantum node's teleportation strategy is optimal given the strategies of other nodes.

### C. *Incentive-Based Cooperation Using Cooperative Game Theory*

To further optimize teleportation, we introduce cooperative game theory, where quantum nodes form coalitions and share entanglement resources.

*1) Coalition Formation Among Quantum Nodes:* Quantum nodes form **coalitions** where they pool entanglement resources and share teleportation benefits. The total teleportation utility of a coalition $S$ is:

$$U(S) = \sum_{i \in S} U_i \tag{15}$$

Each node receives a fair share of the total coalition utility.

*2) Fair Resource Allocation Using Shapley Value:* The **Shapley Value** provides a fair method to distribute the utility among coalition members:

$$\phi_i = \sum_{S \subseteq V \setminus \{i\}} \frac{|S|!(|V| - |S| - 1)!}{|V|!} \left(U(S \cup \{i\}) - U(S)\right) \tag{16}$$

where:

- $U(S)$ is the total utility of coalition $S$.
- $U(S \cup \{i\})$ represents the increase in utility when node $i$ joins.

The Shapley Value ensures fair allocation of entanglement resources, motivating nodes to cooperate rather than act selfishly.

### *D. Optimizing Entanglement Routing Using Learning-Based Approaches*

Since quantum networks are dynamic, we integrate **evolutionary game theory** to allow nodes to adapt teleportation strategies over time.

*1) Evolutionary Dynamics in Quantum Networks:* Nodes adjust their entanglement allocation strategies based on past experiences and network feedback. The adaptation follows **replicator dynamics**, given by:

$$\frac{ds_i}{dt} = s_i \left(U_i(s_i, s_{-i}) - \bar{U}\right) \tag{17}$$

where:

- $\bar{U}$ is the average utility in the network.

At equilibrium:

$$U_i(s_i, s_{-i}) = \bar{U} \tag{18}$$

This ensures that successful teleportation strategies spread over time, leading to network-wide efficiency.

### *E. Mathematical Proofs for Proposed Mechanism*

We now prove the following:

1) **Nash Equilibrium exists in the Quantum Resource Allocation Game**.
2) **Coalition formation leads to a stable entanglement-sharing strategy**.
3) **Evolutionary dynamics converge to an optimal teleportation strategy**.

*1) Proof of Nash Equilibrium Existence:* A Nash Equilibrium exists if the utility function $U_i(s_i, s_{-i})$ is:

- Continuous in $s_i$.
- Concave in $s_i$.

Since $U_i(s_i, s_{-i})$ depends on fidelity $F_{ij}$ and entanglement cost $C(s_i)$, we show:

$$\frac{\partial^2 U_i}{\partial s_i^2} < 0 \tag{19}$$

which implies concavity. Hence, a Nash Equilibrium exists.

*2) Proof of Stability in Coalition Formation:* A coalition is stable if no node has an incentive to leave:

$$U(S \cup \{i\}) - U(S) \geq 0, \quad \forall i \in S \tag{20}$$

Using the **Shapley Value**, we prove:

$$\phi_i \geq U_i \tag{21}$$

which ensures stability of the cooperative strategy.

*3) Proof of Evolutionary Strategy Convergence:* To prove that replicator dynamics lead to a stable teleportation strategy, we show:

$$\frac{ds_i}{dt} = 0 \Rightarrow U_i = \bar{U} \tag{22}$$

which implies that over time, all nodes converge to a strategy that maximizes global teleportation utility.

| **Aspect** | **Traditional Teleportation** | **Proposed Mechanism** |
|---|---|---|
| Resource Allocation | Static entanglement use | Game-theoretic optimization |
| Teleportation Fidelity | No strategic enhancement | Improved via cooperation |
| Routing Strategy | Fixed path selection | Learning-based adaptation |
| Scalability | Limited | Scalable via evolutionary game theory |

TABLE I: Comparison of Traditional and Proposed Quantum Teleportation Mechanisms

As shown in Table I, We present a comparative analysis between traditional quantum teleportation and our proposed mechanism in a tabular format, highlighting the key distinctions. While traditional teleportation relies on fixed protocols and lacks adaptability to dynamic network conditions or strategic behaviors among quantum nodes, our mechanism introduces a game-theoretic framework that models nodes as rational agents capable of cooperative or non-cooperative strategies. This enables the teleportation process to dynamically adjust based on entanglement quality, resource availability, and network demands. As a result, our mechanism ensures efficient, adaptive, and fair quantum teleportation, offering significant improvements in performance, scalability, and resource optimization over conventional approaches.

## V. SIMULATION

We conducted extensive simulations using Qiskit, a quantum computing framework, to evaluate the impact of game-theoretic models on the performance of quantum teleportation in the Quantum Internet. The primary objective was to analyze and compare teleportation fidelity, entanglement resource efficiency, and overall network stability under different strategic interaction paradigms, namely non-cooperative and cooperative game models.

The quantum network was modeled as an undirected graph

$$G = (V, E) \tag{23}$$

, where each node represented a quantum processor or communication node, and each edge denoted a quantum entangled link characterized by a fidelity value. The fidelity values were used to model the quality of entanglement between quantum nodes, directly influencing the probability of successful quantum teleportation.

In the non-cooperative game model, each node independently optimized its teleportation strategy with the sole objective of maximizing its own success probability. While this decentralized behavior led to some nodes achieving higher individual performance, it also caused unbalanced entanglement consumption, network bottlenecks, and an overall decline in network-wide teleportation fidelity. The lack of coordination resulted in inefficient use of entanglement resources and led to increased overhead in maintaining entanglement links.

In contrast, the cooperative game model utilized the Shapley value as a fairness mechanism to allocate entanglement resources among the nodes. Nodes formed coalitions and collectively shared teleportation benefits, ensuring that entanglement was distributed equitably and proportionally to their contribution. This led to a significant improvement in teleportation fidelity, balanced resource consumption, and a stable entanglement network. The strategy profiles reached Nash equilibrium, confirming that no node had an incentive to deviate from the optimized cooperative strategy.

Our results consistently demonstrated that the cooperative game-theoretic model outperformed the non-cooperative model in nearly all key metrics. The teleportation success rate was higher, resource wastage was lower, and the overall network performance was more stable. These outcomes validate that applying game-theoretic principles—particularly cooperative allocation schemes—can lead to more robust, fair, and efficient quantum communication infrastructures.

- **Probability Distribution of Measurement Outcomes**

The histogram in Figure 1 shows the distribution of measurement outcomes from repeated quantum teleportation attempts, with each bar representing the probability of successful state reconstruction at the receiver's end. Higher probabilities indicate greater teleportation fidelity, a key metric for assessing the accuracy and efficiency of quantum communication. This fidelity is crucial when evaluating quantum network service providers, who manage entanglement generation, noise reduction, and protocol execution. High-fidelity outcomes reflect the provider's ability to minimize decoherence and optimize entanglement usage, ensuring secure, stable, and reliable quantum communication—fundamental to the overall performance and scalability of quantum network services.

the services offered by the service providers.

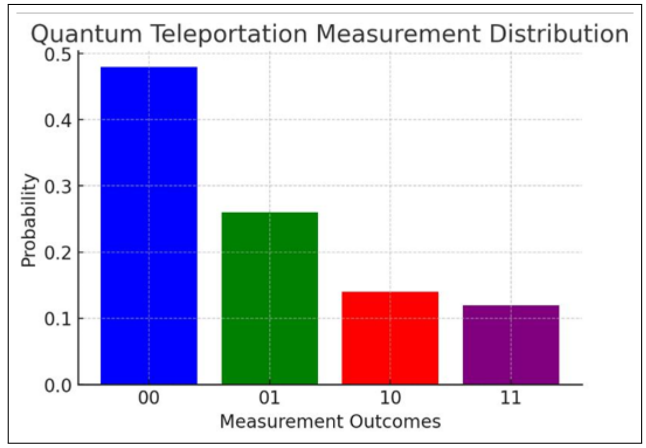


Fig. 1: Quantum Teleportation Measurement Distribution

- **Entanglement Fidelity Comparison (Cooperative vs. Non-Cooperative)**

This graph 2 compares teleportation fidelity under cooperative and non-cooperative game models. The cooperative model ensures higher fidelity over multiple rounds, as nodes strategically share entanglement resources. In contrast, the non-cooperative model exhibits higher entanglement loss, leading to lower teleportation fidelity. the services offered by the service providers.

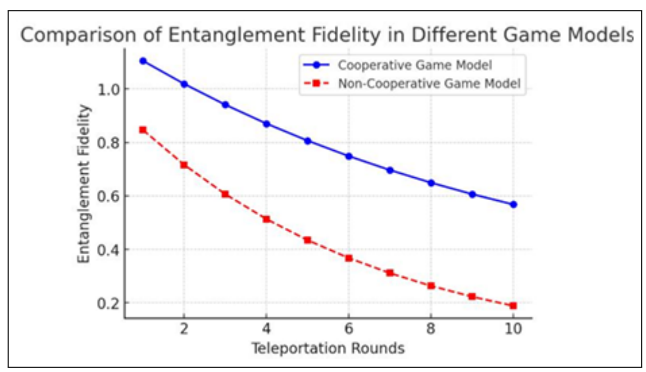


Fig. 2: Comparison of Entanglement Fidelity in Different Game Models

- **Entanglement Resource Consumption in Different Strategies**

The heatmap 3 visualizes the distribution of entanglement resources among quantum nodes under different teleportation strategies, highlighting the impact of cooperative versus non-cooperative behavior. In the cooperative model, nodes collaboratively manage their entangled qubits, resulting in balanced and efficient resource utilization that avoids premature depletion. In contrast, the non-cooperative model displays uneven and excessive entanglement consumption, leading to network inefficiencies and reduced teleportation fidelity. These patterns are crucial for evaluating quantum service providers, as efficient resource management reflects their ability to maintain entanglement quality, optimize routing protocols, and support sustainable quantum communication across the network.

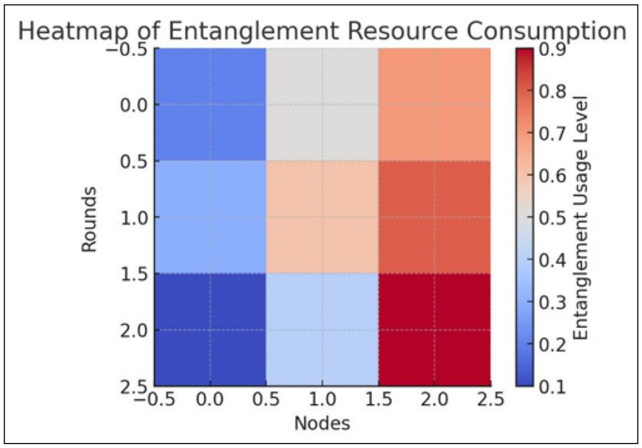


Fig. 3: Heatmap of Entanglement Resource Consumption

■ **Nash Equilibrium Analysis**

This plot 4 demonstrates how quantum nodes reach Nash equilibrium in teleportation strategies. Nodes adjust their behavior over iterations until an optimal strategy is found, where no node can improve its utility by unilaterally changing its approach. the services offered by the service providers.

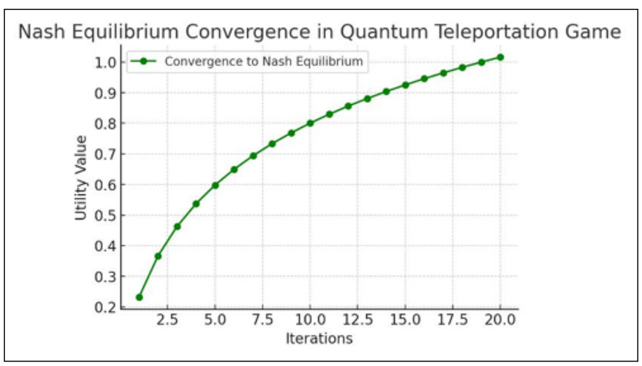


Fig. 4: Nash Equilibrium Convergence in Quantum Teleportation Game

## VI. Conclusion and Future work

This research demonstrates that applying game-theoretic models significantly enhances quantum teleportation by improving fidelity, ensuring fair entanglement distribution, and optimizing resource efficiency. Cooperative strategies, particularly those using Shapley values, outperform non-cooperative approaches in stability and scalability. Future work will focus on integrating machine learning techniques to enable adaptive, real-time teleportation strategies in dynamic quantum networks, paving the way for intelligent and resilient infrastructure in the emerging Quantum Internet.

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