# Minerva: Enhancing Quantum Network Performance for High-Fidelity Multimedia Transmission

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## ABSTRACT

Quantum networks have the potential to transmit multimedia data with high security and efficiency. However, ensuring high-fidelity transmission links remains a significant challenge. Current work mainly focuses on selecting high-fidelity link transmissions for single packages, neglecting the link allocation problem for multi-package transmissions. This limitation leads to reduced scalability in the practical applications of quantum networks. In addition, when selecting a single link, existing methods can easily fall into the exploration and exploitation dilemma, given various fidelity distributions. To address this issue, this paper proposes a new framework that selects high-fidelity link transmission for multiple tasks through median elimination to estimate fidelity and transmission strategies, thereby improving the application scalability of quantum networks. To optimize the transmission of multimedia chunks in a quantum network, we can employ the scheduling strategy to maximize the cumulative profit of chunk transmissions while considering the fidelity of the links and the overall network utilization. Through extensive experiments, our proposal demonstrates significant advantages. Compared to the randomized method, *Minerva* reduces bounce number and execution time by 12% ∼ 28% and 8% ∼ 32%, respectively, while improving average fidelity by 15%. Compared with the uniformly distributed method, our approach decreases bounce number by 24% ∼ 30% and execution time by 8% ∼ 32% and enhances average fidelity by 11% ∼ 21%.

## CCS CONCEPTS

• **Information systems → Multimedia streaming**; • **Networks → Data path algorithms**.

## KEYWORDS

Quantum network and links, multimedia transmission, multi-armed bandit, quantum fidelity

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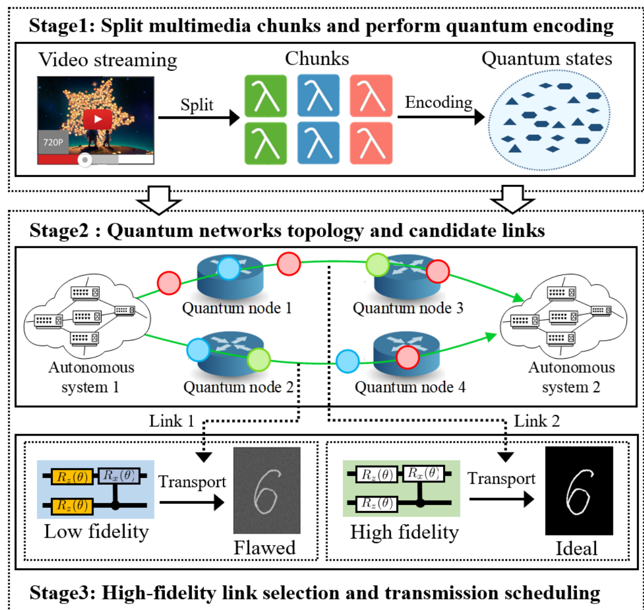


**Figure 1: Illustrative explanation of Minerva framework.**

## 1 INTRODUCTION

Quantum networks [12, 17, 32] herald a new era in networking, facilitating applications that were previously deemed impossible using classical means, achieving unique cryptographic advantages by exploiting quantum mechanics, such as quantum cryptography [5], quantum teleportation [11], Quantum Key Distribution (QKD) [16], and Quantum Internet-of-Things (QIoT) [31]. In the realm of multimedia [34], the integration of quantum networking holds significant promise for transformative applications. Leveraging the unique properties of quantum communication, such as superposition and entanglement, can revolutionize various aspects of multimedia processing, storage, and distribution [23].

A quantum network consists of quantum nodes, quantum channels, quantum repeaters, entanglement sources, measurement devices, and classical communication channels [2, 22]. The transmission process involves generating and distributing entangled qubit pairs, encoding and sending qubits through quantum channels, and using techniques like quantum teleportation for long-distance communication. Entanglement swapping [25] and purification [26] extend and improve the quality of entanglement, while classical communication handles measurement results and control signals to complete the quantum information transfer [13]. Quantum networks utilize entangled photons for key generation and employ quantum repeaters [22, 30] to overcome inherent limitations of optical fiber transmission, thereby achieving long-distance transmission of quantum states. This capability is particularly advantageous for multimedia streaming services, where high-quality, low-latency transmission is essential.

In the context of multimedia transmission, quantum networks offer a novel approach to enhance the security and integrity of data transfer. Figure 2 illustrates a typical pipeline where multimedia data, such as video streams, are first segmented into multiple chunks. These chunks are then subjected to quantum encoding, a process that encodes the information into quantum states for transmission over the quantum network. Given a specific quantum network topology, each quantum state of the data chunk can be transmitted over different links. However, due to the fragility of quantum information, quantum bits (or qubits) can easily decoherence through interactions with the environment. For example, imperfect entangled pairs and physical operations may lead to transmission failure during the establishment of long-distance entanglement. Typically, in addition to standard metrics like throughput and delay, a key metric is called *fidelity* [24]. Fidelity is a quantum metric with no classical equivalents and is used to quantify the quality of an expected quantum state. To cope with this, it is desirable to transmit over links that maintain high fidelity, while also considering transmission efficiency. In cases where the optimal links with high fidelity are not available or are congested, it may be necessary to utilize suboptimal links with lower fidelity to ensure the continuity of transmission.

In this paper, we propose Minerva[1], to enhance quantum network performance for high-fidelity multimedia transmission. Specifically, we formalize the quantum fidelity estimation and link selection as a best-arm identification problem and leverage median elimination [6] to estimate fidelity and select the optimal quantum link for each multimedia chunk transmission. To optimize the transmission of multimedia chunks in a quantum network, we can employ the scheduling strategy to maximize the cumulative profit of chunk transmissions while considering the fidelity of the links and the overall network utilization. This paper makes these contributions:

- We carefully examine the constraints associated with the application of quantum networks in multimedia transmission, particularly the selection of high-fidelity links and the implementation of dynamic allocation strategies.
- Specifically, we first abstract the quantum network topology into multiple candidate links, and then we design a tailor-made link selection algorithm for Minerva based on the median elimination of the best-arm identification problem. Meanwhile, the profit of each multimedia chunk transmission is modeled to implement a dynamic allocation strategy.
- Through extensive experiments, *Minerva* demonstrates significant advantages. Compared to the randomized method, *Minerva* reduces bounce number and execution time by 12% ∼ 28% and 8% ∼ 32%, respectively, and improves average fidelity by 15%. When compared with the uniformly distributed method, our approach decreases bounce number by 24% ∼ 30% and execution time by 8% ∼ 32% and enhances average fidelity by 11% ∼ 21%.

[1]Minerva is the Roman goddess associated with wisdom, justice, victory, and other aspects including arts, trade, and strategy.

## 2 BACKGROUND AND RELATED WORK

### 2.1 Quantum Network

Quantum networks represent an emerging paradigm in the field of quantum information science, leveraging the principles of quantum mechanics to enable secure and efficient communication. Unlike classical communication networks, quantum networks offer the potential for ultra-secure communication protocols, including Quantum Key Distribution (QKD) [16] and quantum teleportation [11], which are immune to eavesdropping and interception due to the inherent uncertainty and no-cloning properties of quantum systems. The architectural framework of quantum networks is designed to facilitate efficient communication among quantum nodes, which form the backbone of the quantum internet. *Quantum nodes*, the fundamental units of a quantum network, utilize quantum communication links to transmit quantum bits (qubits). These links can be optical fibers, free-space optical links, or other quantum channels based on various transmission media. A pivotal feature of quantum networks is the ability to establish connections between distant quantum nodes through quantum entanglement. That is *quantum nodes* process and transmit quantum information via *quantum links*, while *entanglement swapping* extends entanglement across nodes to facilitate long-distance communication.

The key component of quantum network architecture is quantum nodes, which serve as the fundamental building blocks for information processing and transmission. These nodes typically consist of quantum processors capable of manipulating quantum states, quantum memories for storing quantum information, and quantum interfaces [9, 10, 12] for interfacing with external quantum systems. Quantum links [3, 19] form the backbone of quantum communication networks, facilitating the transmission of quantum information between nodes. These links often comprise optical fibers or free-space channels, where quantum states encoded on photons are transmitted over varying distances. However, the fidelity of quantum states transmitted through these links is susceptible to quantum noise (*e.g.,* decoherence), leading to information loss and degradation. Entanglement swapping [13, 35] is a key technique for long-distance quantum communication within quantum networks. This method enables two quantum nodes to "swap" entangled states through a series of operations and an intermediary node, thereby creating a direct quantum correlation between them. This approach circumvents the limitations of direct qubit transmission, such as losses and noise, and also circumvents the challenges posed by the quantum no-cloning theorem.

Basic quantum mechanics principles include the uncertainty principle, measurement collapse, and the no-cloning theorem. The uncertainty principle prevents eavesdroppers from intercepting quantum information undetected, the measurement collapse enables eavesdropping attempts to be detected, and the no-cloning principle prevents unauthorized access by prohibiting faithful copying of quantum states. These principles ensure the security of quantum communication systems. As quantum networks evolve, researchers have proposed diverse quantum network architectures. For instance, Kozlowski *et al.* [13] proposed a quantum network protocol for end-to-end quantum communication, focusing on efficient entanglement generation. Their approach introduces an Entanglement Generation Switch (EGS), facilitating resource-sharing among multiple quantum nodes. Andrade *et al.* [4] focuses on characterizing channel noise with bit-flip in quantum networks using Network Tomography Protocols (NTP).

## 2.2 Quantum Noise and Average Fidelity

Current quantum computing is in the Noisy Intermediate-Scale Quantum (NISQ) era, where noise is an inherent feature [27]. Quantum noise arises from various sources, including thermal fluctuations, electromagnetic radiation, and material imperfections in the quantum hardware. These interactions introduce fluctuations that couple the quantum system to its surroundings, resulting in the entanglement of the system with the environmental states and the subsequent loss of quantum coherence. Quantum noise poses a significant challenge in quantum communication, leading to the loss of quantum coherence and degradation of fidelity. Arising from interactions with the environment, quantum noise causes quantum states to become entangled with their surroundings, rendering them susceptible to information loss and corruption.

In quantum networks, fidelity serves as a critical metric for assessing the quality of entanglement between nodes in quantum communication, quantifying the similarity between an actual quantum state and its desired target state. It ranges from 0 to 1, with a fidelity of 1 indicating perfect alignment with the ideal state. However, in practice in the NISQ era, quantum states are susceptible to defects and errors due to noise, resulting in fidelity values lower than 1, and fidelity below 0.5 is generally considered unavailable. Therefore, in order to ensure the realization of efficient transmission of quantum information, the estimated quantum fidelity is usually required to be above a certain threshold value, for instance, the threshold fidelity is around 0.8 for basic QKD [3].

Average fidelity is a key metric for measuring the effect of quantum noise on quantum channels and the reliability of quantum communication. It is defined as the average overlap between the actual final state of a quantum system and the intended target state after undergoing a quantum operation or evolution. The average fidelity is a measure of how well a quantum channel preserves the quantum information and is crucial for assessing the performance of quantum networks. There are existing research works based on fidelity estimation, Ruan [29] proposes a fidelity estimation protocol for entanglement among remote nodes without consideration of quantum measurement errors.

## 2.3 Network Benchmarking

Helsen *et al.* [9] proposed a network benchmarking method that is robust to state preparation and measurement errors, allowing for efficient and accurate estimation of link fidelity regardless of how the quantum links are formed. Network benchmarking [9] is essential for characterizing quantum networks and ensuring their reliability and performance. It adapts the random benchmarking protocol specifically for quantum networks, aligning with their unique characteristics and theoretical foundations [2]. It involves measuring the average fidelity of quantum entanglement links and identifying the optimal operating parameters for a quantum network. This method is particularly relevant for quantum networks where the fidelity of established entangled links is unknown a priori, and uniform estimation of all links can be costly, especially in networks with numerous links.

Let us consider a quantum network composed of $N$ nodes, each capable of generating and sharing entangled pairs of qubits. The network is modeled by a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ represents the set of nodes and $\mathcal{E}$ represents the set of entangled links between nodes. Each link $e_{i\to j} \in \mathcal{E}$ is associated with a noise channel $\mathcal{N}_{i\to j}$ that characterizes the quantum noise and decoherence effects along the communication path between nodes $i$ and $j$. The average fidelity $F_{i\to j}$ of the entangled link $e_{i\to j}$ is defined as the average overlap through the noise channel $\mathcal{N}_{i\to j}$. Mathematically, it is given by [9]:

$$F(\mathcal{N}_{i\to j}) = \int d\psi \, \mathrm{Tr}[\mathcal{N}_{i\to j}(|\psi\rangle\langle\psi|)|\psi\rangle\langle\psi|] \tag{1}$$

Helsen *et al.* [9] introduces the network benchmarking aims to estimate the average fidelity $F_{i\to j}$ for each link $e_{i\to j}$ by performing a series of quantum state tomography measurements. This process requires the transmission of multiple copies of entangled pairs and the subsequent analysis of the measurement outcomes to deduce the properties of the noise channel $\mathcal{N}_{i\to j}$. In practice, network benchmarking is often limited by the availability of quantum resources and the inherent noise in the system. Therefore, efficient benchmarking protocols are designed to minimize the number of required measurements while still providing accurate estimates of the network's performance. The resilient network benchmarking technique is capable of precisely determining the single quantum link fidelity, which includes two-node and multi-node link versions. Recent advancements in network benchmarking include Liu *et al.* [18] propose the Quantum Border Gateway Protocol (QBGP) for entanglement routing across multiple Quantum Internet Service Providers (QISPs), integrating network benchmarking with the top-K arm identification problem. Building upon network benchmarking [9], Liu *et al.* [19] develop LINKSELFIE, an online link selection algorithm integrating concepts from online learning to reduce computation and speed up fidelity estimation by eliminating low-fidelity quantum links.

In conclusion, the field of quantum network architecture and quantum link selection is rapidly evolving, with ongoing research focused on developing scalable, efficient, and robust protocols for quantum communication. As quantum networks transition from theoretical constructs to practical implementations, the continued advancement of these foundational concepts will be essential for realizing the full potential of quantum technologies.

# 3 PROBLEM SPACE AND FORMULATION

In this section, we formalize the problem of the quantum network transmission model, the constraints and optimization goals.

### 3.1 Quantum Network Transmission Model

We consider a task allocation system denoted as $\mathcal{S} = (\mathcal{D}, \mathcal{L})$, where $\mathcal{D}$ represents the multimedia dataset to be transmitted (which can be decomposed into $m$ quantum states for distribution), and $\mathcal{L}$ represents the available quantum links. Specifically, $\mathcal{D} = \{d_1, d_2, ..., d_m\}$ constitutes a complete multimedia dataset, while $\mathcal{L} = \{l_1, l_2, ..., l_n\}$ denotes the available $n$ quantum links. This study assumes that the multimedia dataset $\mathcal{D}$ is divided into $m$ quantum states for distribution, with each quantum state requiring a certain transmission time. To focus on multiple quantum states allocation, we do not delve into the effects of switch throughput [7], the simultaneous transmission of multiple tasks. Thus, we assume that a quantum link $l_i$ can only transmit one quantum state $d_j$ at a time. This implies that concurrent transmission of two quantum nodes is not considered, aligning with the previous research [9, 19].

### 3.2 Constraints and Optimization Goals

Once the task allocation within the quantum network transmission model is determined, the quantum states of the data chunks will be transmitted. Three metrics are used to measure the efficiency of execution: average transmission time, the number of bounces, and average transmission fidelity. Our goal is to achieve high-fidelity quantum state transmission with as low transmission time and fewer bounces as possible. Achieving high-fidelity transmission while minimizing transmission time involves a trade-off process. To address this trade-off, we formulate a dynamic optimization objective function that balances these metrics. We define three components of the cost model:

**(i) Average Fidelity**:

$$Fidelity = \frac{1}{m}\sum_{i=1}^{m} Fidelity(d_i) \tag{2}$$

where $Fidelity(d_i)$ represents the average fidelity of transmitting the $i^{th}$ data chunk, computed using the average fidelity formula derived from network benchmarking.

**(ii) Cost Time**:

$$Time\_Cost = \frac{1}{m}\sum_{i=1}^{m}(Trans\_Time(d_i)+Estimation\_Time(d_i)) \tag{3}$$

where $Trans\_Time(d_i)$ denotes the transmission time of the $i^{th}$ data chunk, and $Estimation\_Time(d_i)$ denotes the estimation fidelity time of the $i^{th}$ data chunk.

**(iii) Bounce Number**: it is the process of applying a random Clifford operation on the state from the source node and sending it to the target node, which then performs the same operation and returns it to the source node.

Therefore, the goal of this study is to achieve a balance between transmission fidelity, time overhead, and bounce number based on user-specified trade-off coefficients.

## 4 DESIGN OF MINERVA

### 4.1 Modeling Quantum Network Links

Consider a network topology consisting of $N$ nodes, where each node represents a critical point within the network, such as a quantum router, a quantum switch, or a quantum repeater. The nodes are interconnected through a set of candidate links that form the communication pathways between the nodes. Let $C$ denote the connection relationship between various nodes, which are potential connections that can be established based on the network's design and requirements. The connectivity between nodes is represented by an adjacency matrix $V$, where $V_{ij}$ is a binary value indicating the presence (denoted as 1) or absence (denoted as 0) of a direct link between node $v_i$ and node $v_j$. The set of all candidate links can be described as $\{c_k\}_{k=1}^{C}$, where each $c_k$ represents a unique link between a pair of nodes.

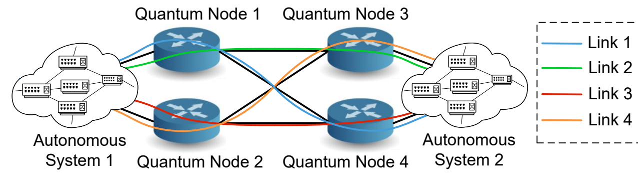


**Figure 2: Quantum network topology and candidate links.**

Given the network topology with $N$ nodes and node connection relationship $C$, we can systematically identify all possible candidate links by performing a unique preorder traversal of the nodes. This method ensures that for each node $v_i$ in the topology, we visit all its predecessors before visiting the node itself, thus generating a sequence of node visits that respects the directed edges without forming any cycles. The process of generating candidate links can be outlined as follows:

- Start at an initial node $v_s$ and mark it as visited.
- For the current node $v_i$, iterate through its adjacent nodes $v_j$ in the adjacency matrix $V$.
- If $v_j$ has not been visited, perform a preorder traversal on $v_j$ and mark it as visited.
- Record the sequence of visited nodes, corresponding to a unique network path.
- Repeat the traversal for all unvisited nodes until all nodes have been visited.

By traversing the network in this manner, we can enumerate all unique paths between nodes, which can be considered candidate links. For instance, Figure 2 shows a quantum network topology with 4 nodes between autonomous system 1 and autonomous system 2. It contains 4 candidate links represented by "blue", "green", "red", and "orange" respectively.

### 4.2 Quantum Link Selection Policy

To select high-fidelity quantum links, a vanilla design [9] refers to performing fidelity measurements on all possible candidate links. However, this is inefficient and unnecessary. Therefore, we identify quantum link selection as a multi-armed bandit problem [18, 19] and leverage the median elimination algorithm [6] to efficiently find the high-fidelity link. Specifically, the median elimination algorithm is grounded in the concept of statistical confidence intervals and is tailored to identify an $\varepsilon$-optimal arm with high probability while minimizing the number of trials required [8]. The algorithm operates by iteratively sampling each arm of the bandit and calculating the median of the empirical rewards. In each iteration, the

**Algorithm 1** Median Elimination Algorithm in Minerva

1: Initialize the set of quantum links $\mathcal{L}$ and calculate the expected rewards $p_i$ for each link $l_i \in \mathcal{L}$.
2: Set the parameters $\varepsilon > 0$ and $\delta > 0$ which determine the desired accuracy and confidence level, respectively.
3: **while** $|\mathcal{L}| > 1$ **do**
4: Calculate the sampling time $Num = \frac{4}{\varepsilon^2} \log\left(\frac{3}{\delta}\right)$
5: **for** each link $l_i \in \mathcal{L}$ **do**
6: Sample link $l_i$ $Num$ times to obtain the reward $\hat{p}_i$.
7: **end for**
8: Calculate the median empirical reward $\bar{p}$.
9: **for** each link $l_i \in \mathcal{L}$ **do**
10: **if** $\hat{p}_i < \bar{p}$ **then**
11: Eliminate link $l_i$ from set $\mathcal{L}$.
12: **end if**
13: **end for**
14: Update $\varepsilon = \frac{3}{4}\varepsilon$; $\delta = \frac{1}{2}\delta$
15: **end while**
16: **return** the remaining link in set $\mathcal{L}$ as the optimal link.

arm with the lowest empirical reward below the median is eliminated from further consideration. This process continues until an arm that is likely to be $\varepsilon$-optimal is identified, as per the Probably Approximately Correct (PAC) learning framework [6].

The key to the median elimination algorithm's efficiency lies in its ability to reduce the number of necessary samples by eliminating sub-optimal arms early in the process. This not only conserves resources but also accelerates the convergence to an optimal policy. As shown in Algorithm 1, the median elimination algorithm iteratively selects the optimal option from a set of choices by sampling each option, calculating the median reward, and eliminating options with empirical rewards lower than the median. This process continues until only one candidate link remains.

Specifically, the samples number required is bounded by $\frac{4}{\varepsilon^2} \log\left(\frac{3}{\delta}\right)$ (line 4 in Algorithm 1), matching the bound derived by the previous work [20]. This bound reflects the trade-off between the number of samples required and the desired level of accuracy and confidence. Then, we aim to find the median fidelity $\mu$ of the link set $\mathcal{L}$. Let $l_{\text{fid}}^{(i)}$ be the fidelity of the link $l_i$. To calculate the median fidelity $\mu$, we first sort the $l_{\text{fid}}^{(i)}$ in ascending order:

$$l_{\text{fid}}^{(1)} \leq l_{\text{fid}}^{(2)} \leq \ldots \leq l_{\text{fid}}^{(N_l)} \tag{4}$$

where $N_l$ is the total number of links in $\mathcal{L}$. If $N_l$ is odd, the median $\mu$ is the value of the middle element:

$$\mu = l_{\text{fid}}^{(\frac{N_l+1}{2})} \tag{5}$$

If $N_l$ is even, the median $\mu$ is the average of the two middle elements:

$$\mu = \frac{1}{2}(l_{\text{fid}}^{(\frac{N_l}{2})} + l_{\text{fid}}^{(\frac{N_l}{2}+1)}) \tag{6}$$

The sampling and elimination process is repeated until a single quantum link is retained or until the remaining quantum link is sufficiently optimal (within $\epsilon$ of the best performance). The remaining quantum link can be selected as the optimal transmission link.

## 4.3 Multimedia Chunk Profit Modeling

In the context of quantum networks, the task allocation involves distributing $k$ multimedia chunks between two quantum nodes using $n$ available quantum links. Each quantum link is characterized by the fidelity $F_i$ and the cost time $C_i$, which represent the reliability and the time required to transmit a multimedia chunk, respectively. Moreover, the number of bounces $B_i$ refers to the required bounces for estimating the link fidelity. The optimization goal is to allocate the multimedia chunks across the quantum links to maximize the overall performance, defined by the profit function:

$$\text{Profit} = \alpha \times \text{Fidelity} - \beta \times \log(\text{Cost Time}) - \gamma \times \log(\text{Bounces}) \tag{7}$$

where $\alpha$, $\beta$, and $\gamma$ are weights that reflect the relative importance of fidelity, cost time, and bounce num in the specific quantum network application, respectively.

Mathematically define the problem, let $\mathcal{M} = \{m_1, m_2, \ldots, m_k\}$ be the set of multimedia chunks and $\mathcal{L} = \{l_1, l_2, \ldots, l_n\}$ be the set of quantum links. The transmission policy $\mathcal{P}$ is a mapping from $\mathcal{M}$ to $\mathcal{L}$, *i.e.*, $\mathcal{P} : \mathcal{M} \to \mathcal{L}$. The fidelity $F_i$, cost time $C_i$, and bounce number $B_i$ for each quantum link $l_i$ are considered to guide optimization direction. The optimization problem can be formulated:

$$\begin{aligned} &\text{Maximize:} \\ &\sum_{m_i \in \mathcal{M}} \left(\alpha \times F_{\mathcal{P}(m_i)} - \beta \times \log(C_{\mathcal{P}(m_i)}) - \gamma \times \log(B_{\mathcal{P}(m_i)})\right) \\ &\text{Subject to: } \mathcal{P}(m_i) \in \mathcal{L} \text{ for all } m_i \in \mathcal{M} \end{aligned}$$

## 4.4 Multimedia Chunk Transmission Strategy

**Initialization.** The algorithm with the initialization of the multimedia chunk set, denoted as $\mathcal{M}$. A set of parameters, $\alpha$, $\beta$, $\gamma$, $\mathcal{L}$, and $\mathcal{M}$, is defined to govern the allocation process. (i) The quantum links $\mathcal{L}$ (which could include multiple repeaters) are established to facilitate the transmission of data. (ii) The algorithmic parameters, involve $\alpha$, $\beta$, and $\gamma$, are configured. (iii) The set of multimedia chunks destined for allocation is initialized and represented as $\mathcal{M}$.
**Iterative Allocation.** The allocation procedure is executed iteratively for each multimedia chunk $m_i$ within the set $\mathcal{M}$.

- An empty set of links is initialized for the allocation of multimedia chunk $m_i$.
- Calculating the initial profit for each available link, taking into account the potential allocation of $m_i$.
- The link with the maximal initial profit will be identified and selected.
- Data chunk $m_i$ is allocated to the chosen link $l_i$.
- Updating the fidelity, cost time, and bounce number information for the allocated link.
- The profit for all links is recalculated in light of the updated parameter states.
- This iterative process is reiterated until all multimedia chunks are effectively allocated.

**State Maintenance and Allocation Termination.** During the link selection, the computation of fidelity is performed incrementally and in real-time to mitigate preliminary computational expenditures. Concurrently, the cost time and bounce number are incremented as chunks are transmitted across the allocated links. Fidelity is dynamically assessed during the link selection process to adapt to the latest link status. The cost time and bounce number are recorded as chunks traverse through the allocated links. The allocation process is terminated upon the successful allocation of all multimedia chunks to quantum links. Meanwhile, the allocation strategy will be outputted, detailing the assigned links and their corresponding multimedia chunks.

## 5 EVALUATION

### 5.1 Experiment Setup

**Testbed.** We conduct simulations of quantum networks using the NetSquid library with the network benchmarking [9]. If not otherwise stated, each experiment is run 20 times by default and the average results are reported. The simulations are performed on a machine equipped with an Intel(R) Core(TM) i7-9700 CPU @ 3.00GHz and 32GB RAM.

**Multimedia Chunk Sizes.** As for the multimedia chunk size, we adopt the representative network traces [28] involving 460 traces from Norway's 3G HSDPA, which is also widely used in the evaluation of previous work about streaming media transmission [1, 21, 33]. We randomly sample from those traces as the size of each multimedia chunk.

**Quantum Network Settings.** Due to limitations imposed by current NISQ-era quantum technologies [14], we utilize simulated quantum states to represent our multimedia chunk data. We simulate three scales, *i.e.,* $\{5, 10, 20\}$ for quantum link set $\mathcal{L}$, and the number of multimedia chunks in each group $\mathcal{M}$ refers to $\{20, 50, 80, 100\}$. The used bounce length set refers to [1, 2, 3, 4], which is consistent with previous work [18, 19]. The default configuration is the depolarizing noise model. We consider more noise models in § 5.5.

**Transmission Algorithm Baselines.** Three methods are used for comparison. (i) *Random:* Transmission allocation is randomly distributed across quantum links, without consideration for fidelity or cost time. (ii) *Uniform:* Allocation is conducted uniformly, ensuring an equal number of transmissions across all quantum links, independent of their characteristics. (iii) *Greedy:* Utilizes a greedy algorithm that prioritizes transmission through quantum links with the highest fidelity, aiming to maximize the overall system performance based on the individual link quality. Furthermore, to ensure that the bounce number is on the same scale as cost time and fidelity, we divide the bounce number by $5 \times 10^4$ and set the base of the logarithmic function in the profit function to 10, and the parameters $(\alpha, \beta, \gamma)$ are set to (1, 0.25, 0.25) in our scheme.

### 5.2 Transmission Performance Evaluation

In this section, we evaluate Minerva's transmission performance compared to three baseline strategies, employing a fixed number of data chunks denoted by $\mathcal{M} = 100$. The experimental result is shown in Table 1, which presents the statistical results across 100 chunks of multimedia quantum states. Metrics such as "Bounces ($\times 10^4$)", "Cost time", "Fidelity", and "Profit" denote the statistical bounce number of quantum links, the statistical transmission time, the average fidelity of quantum links, and the overall profit, respectively. We assess these metrics across three distinct strategies: *Random*, *Uniform*, *Greedy*, and our proposed method (*Minerva*), test over quantum link configurations $\mathcal{L} = \{5, 10, 20\}$.

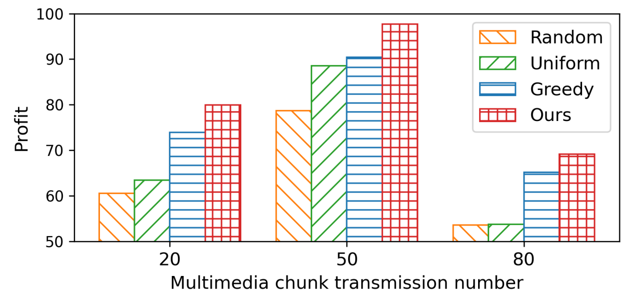


**Figure 3: Profit calculation for different multimedia chunk sizes with quantum links $\mathcal{L} = 30$.**

Overall, the Random strategy exhibits the poorest profit performance due to its disregard for the intrinsic characteristics of quantum links. It consistently yields the highest bounce numbers but correspondingly the lowest profit, especially evident with increased quantum link counts. This indicates the inefficiency of random allocation, failing to capitalize on higher fidelity links. Conversely, the Uniform strategy, distributing transmissions evenly across all links, demonstrates more consistent performance across different link counts. While uniformly distributed methods generally incur lower execution times, they sacrifice fidelity and need higher bounce numbers, resulting in a profit that is not high enough. The Greedy strategy, prioritizing links based on individual fidelity, shows notable improvement over baseline approaches, and it tends to realize higher fidelity and substantial profit across. However, because the greedy strategy selects the link with the highest current fidelity, and due to the fluctuations in noise, the current optimal link is not necessarily the global optimal link. Therefore, it is inferior to our median elimination method, our Minerva always retains the top half of the links, avoiding the exploration and exploitation dilemma of the optimal arm and increasing the probability of finding the globally optimal link.

Minerva consistently outperforms baseline methods across all evaluation metrics, achieving low computation times and bounce numbers while maximizing fidelity and profit. This underscores its ability to effectively navigate the trade-offs among these influencing factors. In summary, our results highlight the efficacy of our *Minerva* method in optimizing quantum data chunk transmission. Strategic selection of quantum links based on fidelity and cost-time characteristics significantly outperforms traditional random and uniform distribution strategies, as well as the Greedy approach, particularly in scenarios with higher quantum link counts.

### 5.3 Comparison of Transmission Profit under Different Multimedia Chunk Groups

We investigate the profit performance of various multimedia chunk transmission sizes under a fixed number of quantum links $\mathcal{L} = 30$, as depicted in Figure 3. The profit metric is plotted against the number of transmitted multimedia chunks for four distinct algorithms:

**Table 1: Performance evaluation of multimedia quantum data chunks ($\mathcal{M}$ = 100) across various numbers of quantum links. Among them, the unit of "Bounces" number refers to $10^4$.**

| Links | Link scales $\mathcal{L}$ = 5 | | | | Link scales $\mathcal{L}$ = 10 | | | | Link scales $\mathcal{L}$ = 20 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Method | Bounces | Cost time | Fidelity | Profit | Bounces | Cost time | Fidelity | Profit | Bounces | Cost time | Fidelity | Profit |
| Random | 75.23 | 35.33 | 0.82 | 38.86 | 84.53 | 16.57 | 0.85 | 48.82 | 83.21 | 8.67 | 0.83 | 54.02 |
| Uniform | 88.54 | 20.75 | 0.85 | 45.87 | 85.97 | 10.89 | 0.80 | 48.19 | 86.19 | 5.44 | 0.81 | 56.70 |
| Greedy | 73.16 | 40.68 | 0.90 | 45.63 | 71.74 | 18.62 | 0.92 | 56.33 | 72.89 | 11.98 | 0.93 | 61.95 |
| **Ours** | **65.61** | 38.36 | **0.95** | **52.45** | **64.68** | 21.91 | **0.97** | **60.69** | **59.86** | 9.65 | **0.96** | **69.43** |

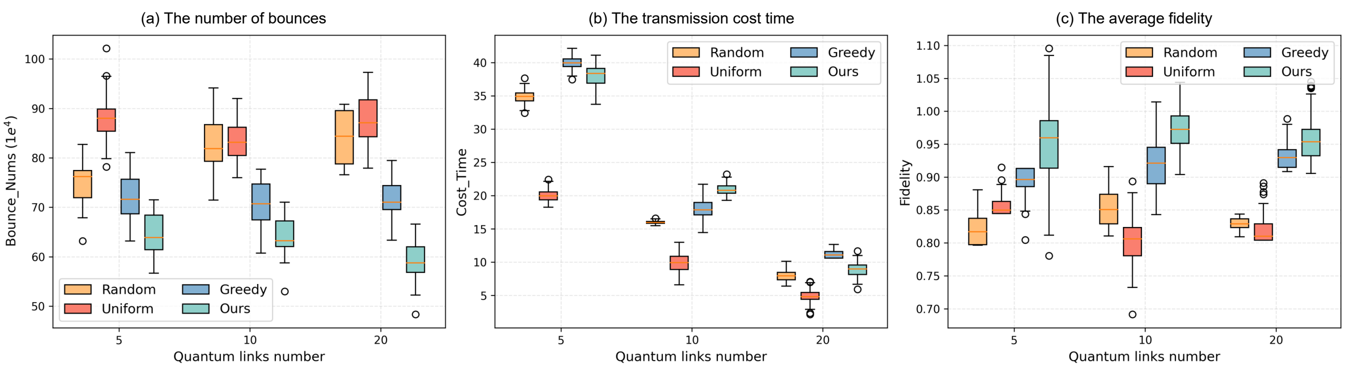


**Figure 4: The detailed results of different quantum links with multimedia chunk size $\mathcal{M}$ = 50.**

Random, Uniform, Greedy, and our proposed method Minerva (referred to as "Ours"). The overall profit exhibits an initial increase followed by a decline as the number of transmitted packets varies from 20 to 50 and then to 80. This trend suggests that with a fixed number of quantum links, the system gradually approaches the upper limit of its data transmission capacity as the chunk increases, without considering the parallel transmission of multiple packets.

Specifically, the Random and Uniform algorithms demonstrate relatively lower profit performance across varying transmission chunks. Their profit increment is modest with increasing transmission numbers, reflecting the stochastic nature of these approaches. In contrast, the Greedy algorithm showcases significant profit enhancement, particularly at lower transmission chunks, leveraging the highest fidelity links for rapid profit growth. However, as the transmission chunk increases, the rate of profit growth appears to diminish, indicating a potential saturation point where further exploitation of high-fidelity links yields diminishing returns. Our algorithm consistently outperforms the others, achieving the highest profit across all transmission chunks. Its optimized selection and allocation of quantum links afford a substantial profit advantage over alternative strategies. The steep ascent of the profit trend line for the Ours algorithm underscores its efficiency and effectiveness in managing multimedia chunk transmissions. In summary, the experimental results presented in Figure 3 emphasize the superior profit-maximizing capability of our proposed algorithm for multimedia chunk transmissions based on given quantum links.

## 5.4 Detailed Profit Analysis

To delve into the variation of profit's constituent elements across different quantum links, namely *bounce number*, *cost time*, and *fidelity*, we conduct tests on multimedia chunk size ($\mathcal{M}$ = 50) packets under three scenarios of quantum link counts $\mathcal{L} = \{5, 10, 20\}$. The experimental outcomes are depicted in Figure 4 (a)-(c).

**Number of Bounces.** Subfigure (a) illustrates the bounce number, measured in units of $10^4$. The observed trend is generally: *Uniform > Random > Greedy > Ours*. This ordering becomes more pronounced with increasing quantum links, as our algorithm exploits larger optimizable spaces compared to others.

**Cost Time.** From subfigure (b), it's evident that overall data transmission time decreases notably with increasing quantum links. Regarding the change in transmission time for each set of quantum links, the ordering typically follows: *Uniform < Random < Ours < Greedy*. The uniform distribution, prioritizing speed over transmission quality, achieves the shortest execution time, with ours slightly behind but ensuring transmission quality.

**Fidelity.** Subfigure (c) demonstrates that although Uniform evenly distributes tasks, it overlooks transmission quality, resulting in the lowest average fidelity. Minerva consistently outperforming other baseline methods, as quantum link counts increase, fidelity generally trends upwards. The performance of Random depends on the fidelity of the sampled links, leading to instability.

In summary, the experimental results across all three figures consistently highlight the effectiveness of our strategy in optimizing hop count and fidelity while minimizing cost and time. Our approach offers a robust and efficient algorithm for quantum link selection and task assignment. Conversely, the Random strategy performs poorly across all metrics, while Uniform achieves the shortest transmission time but sacrifices transmission quality. Though the Greedy algorithm shows some capacity improvement, a general greedy approach struggles to balance the three metrics optimally. These findings underscore the critical role of link selection and allocation strategy in quantum network optimization.

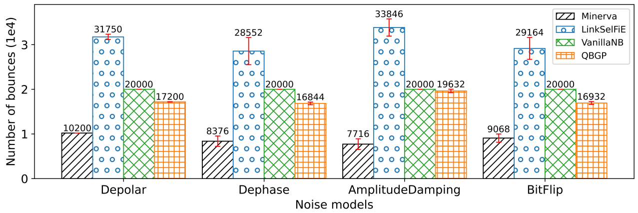


**Figure 5: The comparison results of different link selection algorithms under four noise models.**

## 5.5 Evaluation of Link Selection Policy

Since previous related work mainly focuses on the optimal link selection problem for single transmission, the link allocation strategy for multi-package transmission is not considered. In this section, we compare the performance of optimal link selection (*i.e.,* select one link) under four noise model types, we compare the performance of our Minerva with the three existing algorithms:

- *VanillaNB [9]:* The VanillaNB algorithm traverses all paths with the maximum number of explorations.
- *QBGP [18]:* This QBGP utilizes information gain and the successive elimination scheme to drop low-fidelity links.
- *LINKSELFIE [19]:* This LINKSELFIE abstracts the link selection problem as a Multi-Armed Bandit (MAB) problem and optimizes the number of times the arm is pulled and the elimination of low-fidelity judgment conditions.

Meanwhile, four noise models are considered to simulate quantum noise, including (i) the depolarizing noise model, (ii) the dephasing noise model, (iii) the amplitude damping noise model, and (iv) the bit flip noise model. We configure 10 candidate links with a bounce number list of [1, 2, 3, 4] (totaling 10 bounces for each exploration). The maximum exploitation times of each link is 200 times. Therefore, the VanillaNB traversal testing method requires $10 \times 200 \times 10 = 20,000$ bounces. The evaluation results are shown in Figure 5, under the four noise model tests, the performance ranking refers to Minerva (Ours) > QBGP > VanillaNB > LINKSELFIE. We use the median elimination method, which always remains the top half, thereby steadily reducing the bounce number and reliably finding the optimal link. VanillaNB uses a traversal method, resulting in a constant number of tests and high computational costs. QBGP uses information gain and the successive elimination method to reduce the number of bounces. It is worth noting that LINKSELFIE consumes more bounce numbers than VanillaNB. This is because LINKSELFIE can easily get stuck in the exploration-exploitation dilemma of the Multi-Armed Bandit (MAB) problem when encountering multiple similar target values [20]. This leads LINKSELFIE to repeatedly iterate among several candidates, making it difficult to select the optimal value.

# 6 DISCUSSION AND FUTURE WORK

## 6.1 Advantages of Quantum Networks

Quantum network transmission offers inherent security due to the fundamental principles of quantum mechanics, such as superposition, entanglement, and no-cloning (preventing eavesdropping). However, challenges such as Denial-of-Service (DoS) attacks still exist [15]. Mitigating these risks requires advancements in key distribution, error correction, network authentication, and post-quantum cryptography. Further research is crucial to optimize and integrate these protocols seamlessly into quantum network architectures. Addressing these challenges will unlock secure and reliable quantum multimedia transmission.

## 6.2 Practicality and Extensibility

Quantum network multimedia transmission has great potential to transform multimedia communication with improved security, fidelity, and bandwidth. However, practical challenges like infrastructure development, scalability, and cost must be addressed before it becomes widely adopted. Quantum-inspired heuristics and hybrid classical-quantum methods can offer viable solutions to scalability issues while accommodating the evolving network conditions. Our algorithm aims to adapt to the growing demands of multimedia networks, demonstrating good scalability over various link scales and diverse noise models.

## 6.3 Limitations and Future Works

This paper focuses on the chunk allocation problem in multi-link scenarios, and there are some limitations to our work. For instance, network topology is beyond the scope of this study, and future research could further investigate resource transmission issues related to network topology. Additionally, this paper examines four noise models, future work could explore the design of robust network transmission strategies and more efficient network protocols. Furthermore, investigating how to quantum-encode and decode multimedia data and transmit it over real quantum networks could be a promising area for future research.

# 7 CONCLUSION

In this paper, we study the multimedia data resource allocation problem in quantum networks. To solve this problem, we formalize quantum fidelity estimation and link selection as an optimal arm identification problem and design an efficient algorithm Minerva, a new framework for improving quantum network performance through link selection and transmission strategies, using median elimination to estimate the fidelity and to select quantum links for each multimedia block transmission. To optimize the transmission of multimedia blocks in a quantum network, we can employ a scheduling strategy to maximize the cumulative benefits of block transmission while considering link fidelity and overall network utilization. Simulation results show that Minerva can simultaneously guarantee a smaller bounce number and time overhead in different scenarios, while also achieving the highest average fidelity transmission and guaranteeing the quality of data transmission.

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