# Noise Analysis on Topology-based Distributed Quantum Image Encoding

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***Abstract*—General quantum communication protocols are inherently vulnerable to unintended quantum channel noise, which can significantly degrade the quality of encoded images. In this work, we investigate the impact of quantum noise and the potential noise-mitigation capability of a non-local star-topology-based distributed quantum image encoding scheme. By fixing system parameters along two perspectives—the noise strength and the number of quantum nodes, we systematically analyze the behavior of noise propagation within the network. Our results demonstrate that the topology-aware distributed mechanism can be effectively exploited to enhance noise resilience in quantum image processing, thereby improving the robustness to noisy channel-related image degradations.**

***Index Terms*—quantum network topology, distributed quantum computation, quantum image encoding, quantum teleportation**

## I. INTRODUCTION

Previous studies have demonstrated that several quantum network topologies can violate n-locality inequalities [1, 2], thereby enabling the establishment of entanglement and the distribution of quantum states among multiple quantum computational nodes (Qnodes).

In prior work [3–5], we investigated noise behavior during the state-preparation stage for various quantum network topologies and demonstrated that distributed encoding mechanisms can effectively mitigate noise through a straightforward, centralized image-encoding approach. Beyond quantum image encoding, quantum network architectures have also shown promise in enabling quantum machine learning for complex decision-making tasks in practical engineering systems [6–8]. However, in those studies, the distribution and rearrangement processes within the proposed framework were classically implemented, leaving the influence of fully quantum communication mechanisms unexplored.

In this paper, we extend our previous framework by exploiting a quantum star-network topology that integrates quantum teleportation with amplitude-encoding-based quantum image representations. By explicitly embedding noise into the quantum teleportation channels, we propose and analyze a star-topology-based distributed quantum image encoding framework that integrates quantum teleportation and systematically investigates its noise resilience under noisy quantum channels.

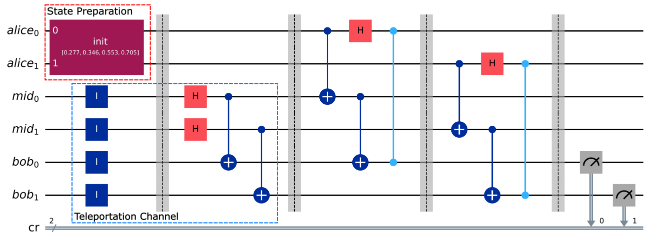

Fig. 1: Teleportation Circuit. A 2-qubit state teleportation example, where the red box indicates state preparation, and the blue box indicates the teleportation channel.

## II. APPROACH

### A. Image Encoding

We evaluate the impact of quantum noise on image data, as images constitute discrete signal representations whose degradation can be directly and intuitively observed. To this end, we adopt the amplitude encoding scheme for quantum image representation due to its resource efficiency, as it enables the encoding of $2^n$ classical data points using only $n$ qubits. Specifically, the resulting quantum state can be expressed as

$$\rho_{alice} = \sum_{i,j} c_{i,j} c_{i,j}^{*} \left| k \right\rangle \left\langle k \right|, \quad c_{i,j} = \frac{F_{i,j}}{\sqrt{\sum_{i,j} (F_{i,j})^2}}, \tag{1}$$

where $\rho_{alice}$ denotes the quantum state initialized by individual senders (Alice) in a teleportation context, and $F_{i,j}$ denotes the intensity value of the pixel located at coordinates $(i, j)$, $c_{i,j}$ represents the corresponding normalized amplitude coefficient, and $|k\rangle$ encodes the spatial position of the pixel on the computational basis.

### B. Teleportation-based Star Network Topology

The standard quantum teleportation protocol exploits a state-swapping mechanism arising from the joint action of Bell-state generation (BSG) and Bell-state measurement (BSM), as illustrated in Fig. 1. Within the density-operator formalism, the teleportation process can be expressed as [9]

$$\rho_{bob} = Tr_{alice,mid} \left\{ U_{tel} \rho_{alice} \otimes \rho_{en} U_{tel}^{\dagger} \right\}, \tag{2}$$

where $\rho_{en}$ represents the entangled resource shared between the intermediate node and receptors (Bob). In this work, the entangled resource is chosen as a maximally entangled Bell state, $\rho_{en} = |\Phi^+\rangle \langle\Phi^+|$, with $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$

A star network represents one of the most fundamental network topologies [10], characterized by a central hub that collects data from, or distributes data to, multiple isolated peripheral nodes. As illustrated in Fig. 2, each distributed node (Alice) shares an independent entangled state with the central hub (Bob) through an entanglement source $S_n$. As a database be partitioned into $n$ independent data blocks, $Alice = \{alice_0, alice_1, ..., alice_n\}$, Bob will gather the corresponding peripheral teleported state to combine as $\rho_{bob} = \rho_{bob_0} \otimes \rho_{bob_1} \otimes ... \otimes \rho_{bob_n}$.

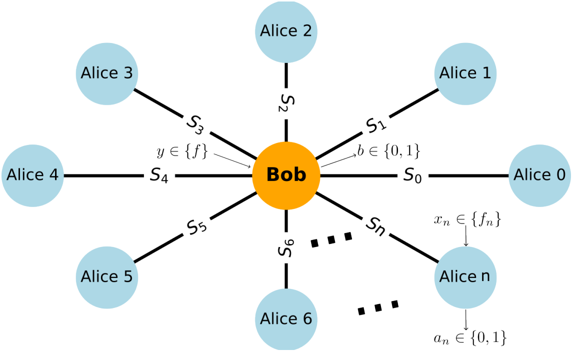

Fig. 2: Quantum Star Network Structure. $S_n$ represents the sources creating independent entanglements, $\{x, y\}$ and $\{a, b\}$ denotes the inputs and outputs of Qnodes, respectively. $f_n$ is the sub-data, where $n$ represents the $n^{th}$ divided block data.

In this work, we focus on a one-way teleportation architecture, in which the Qnodes act exclusively as senders. Each Qnode locally prepares and encodes its quantum state through a state-preparation circuit, after which the encoded state is teleported independently to the central hub. At the hub, local BSGs are employed for intermediate-node processing, followed by BSMs to complete the final state collection and reconstruction. This architecture naturally supports scalable distributed quantum image encoding while enabling a systematic analysis of communication-induced noise effects.

### C. Noise Analysis in Teleportation Process

Following the previous noise-analysis framework [3, 4], we distinguish two noise injection scenarios [9]: Input state and teleportation channel. The first scenario could be expressed as

$$\varepsilon(\rho_{bob}) = Tr_{alice,mid}\left\{U_{tel}\varepsilon(\rho_{alice}) \otimes \rho_{en}U_{tel}^{\dagger}\right\}. \tag{3}$$

Under this noise model, noise $\varepsilon(.)$ occurs at the input $x_n$ at each isolated node. In the present work, we extend this analysis by replacing the classical data-recovery process with a fully quantum communication channel, where noise arises intrinsically from the teleportation process itself. In this scenario, the noisy teleportation channel is modeled as

$$\varepsilon(\rho_{bob}) = Tr_{alice,mid}\left\{U_{tel}\rho_{alice} \otimes \varepsilon(\rho_{en})U_{tel}^{\dagger}\right\}, \tag{4}$$

where the noise channel $\varepsilon(.)$ acts on the state of the entangled resource shared between the intermediate node and Bob. To statistically evaluate the influence of quantum noise on image quality, we employ the Structural Similarity Index Measure (SSIM), which is widely used to quantify perceptual similarity between images.

## III. RESULTS

To implement the noisy communication channel, we employ the IBM Qiskit platform to simulate quantum circuits. In order to introduce controllable noise into the teleportation channel, as illustrated in Fig. 1, identity gates are inserted prior to the BSGs that initialize the entangled resource state $\rho_{en}$.

To simplify the analysis, we focus on the data re-gathering stage of the quantum star network, which constitutes the core of the communication process. We consider two experimental configurations. In the first experiment, the number of quantum nodes is fixed at 32 while the noise parameter is gradually increased. As shown in Fig. 3 (a), both amplitude damping and depolarization noise exhibit a similar monotonic degradation trend, leading to a gradual decrease in image quality as the noise strength increases. In contrast, phase damping introduces only a marginal effect on the teleportation channel, indicating a lower sensitivity of the encoded images to phase-related noise. The bit-flip noise channel exhibits non-monotonic behavior, with a minimum image quality at a noise parameter of approximately 0.6, followed by a slight recovery as the noise strength increases further.

In the second experiment, the noise parameter is fixed at 0.5, while the number of quantum nodes is progressively increased. The results, shown in Fig. 3 (b), indicate that the reconstructed image quality consistently improves with an increasing number of nodes. This trend is consistent with our previous observations [5], suggesting that the distributed mechanism retains its robustness even when noise is introduced directly into the quantum communication channel.

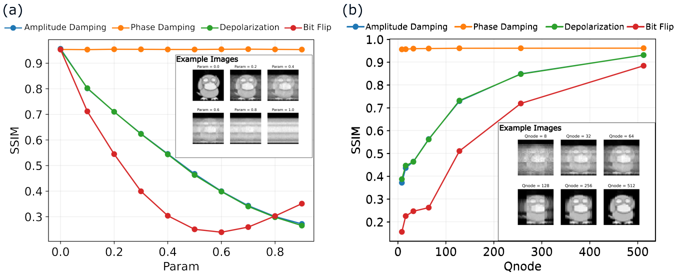

Fig. 3: (a) Noise behavior when increasing noise parameter (Param). (b) Noise mitigation after increasing quantum nodes (Qnode).

## IV. DISCUSSION

This paper builds upon our previous studies [3, 4]. We investigate the effects of quantum noise in a star-topology-based quantum network and demonstrate that teleporting quantum states through a controllable phase-damping channel provides a promising approach for noise-resilient quantum data communication. Furthermore, we examine the noise-mitigation capability of distributed quantum image encoding under noisy communication conditions. The results reveal behavior consistent with that observed in distributed mechanisms applied during the state-preparation stage, indicating that the proposed noise-resilient properties are not limited to a specific processing step. Instead, they suggest that topology-driven distributed mechanisms can be broadly leveraged to enhance robustness in quantum image encoding and quantum optical free-space communication frameworks [11]. However, the findings in this study are primarily empirical and based on direct observation. Moreover, the degree of noise resilience may vary across different quantum image representation schemes [3]. A more systematic theoretical investigation of these differences will be pursued in our future work.

**Acknowledgement**: We acknowledge support from startup funds provided by SMU.

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