International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 6, Nov-Dec-2026, ISSN (Online): 2395-566X

Quantum Computing and Future Communications

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Abstract—Quantum computing and quantum communication are expected to shape the networks of the future. Quantum networks aim to transmit, store and process quantum information across separated nodes, which supports distributed quantum computing and quantum key distribution. However, an unknown quantum state cannot be copied, inspected, buffered or freely retransmitted, so the link-layer reliability mechanisms of classical communication cannot be applied directly. This paper presents a literature-based study of quantum computing and future communications drawn from two IEEE research works and the foundational literature they cite. It reviews quantum error correction, entanglement purification, quantum teleportation, encoded teleportation with code puncturing and a quantum-semantic image transmission system that combines a semantic autoencoder, a polar code and quantum superposition encoding. A general framework covering application, information protection, entanglement resources, link and network coordination is described. The paper discusses fidelity, logical error probability, latency, PSNR, SSIM, UQI and classification accuracy as evaluation measures, along with applications and challenges such as decoherence, transduction loss, resource overhead and simulation-only evidence. The reported gains should always be validated on realistic channels before real-world deployment.

Keywords—Quantum Computing, Quantum Communication, Quantum Networks, Entanglement Purification, Quantum Error Correction, Quantum Teleportation, Semantic Communication, Future Communications.

I. INTRODUCTION

Quantum networks aim to enable the transmission, storage and processing of quantum information across spatially separated nodes. They form the foundation for applications such as distributed quantum computing, in which several quantum processors collaborate on problems beyond a single device, and quantum key distribution (QKD), which uses quantum mechanics to provide information-theoretic security [1], [8], [14]. Quantum communication is therefore an important part of future communication systems, including wireless systems that integrate classical and quantum communication [4].

Classical link-layer protocols rely on bits that are fungible and cloneable, so the same packet can sit in a transmitter buffer, a coded packet and a retransmission queue. A qubit with an unknown state cannot be copied because of the no-cloning theorem [12], and measuring it generally disturbs it. Quantum resources are also volatile: stored qubits and shared entangled states decohere, and moving a qubit between matter memories and photons requires transduction, which can add loss and noise [1].

The objective of this paper is to study how reliable quantum links can be built and how quantum encoding can be combined with semantic communication, and to describe a general framework for evaluating such systems. The study emphasizes that a gain reported in simulation does not guarantee performance on real quantum hardware; this must be assessed for each application [1], [2].

Objectives and Scope

The main objectives are: (1) to understand why classical reliability mechanisms cannot be applied to unknown quantum states; (2) to study quantum error correction, entanglement purification and teleportation; (3) to describe a general workflow from the source data to the recovered output; (4) to identify suitable evaluation measures; and (5) to discuss applications, limitations and future improvements.

The scope includes Pauli and related noise models, Bell-diagonal entangled states, stabilizer and CSS codes, and a quantum-semantic image transmission pipeline evaluated by simulation. Physical hardware implementation, detailed repeater design and full network protocol design are outside the scope. No new experiment is claimed; the numerical results quoted are taken from the cited papers.

II. LITERATURE REVIEW

Abouamer et al. present a tutorial-style link-layer view of reliable quantum communication. They treat quantum error correction (QEC) as the analogue of forward error correction and entanglement purification as an ARQ-like mechanism, and use teleportation as the link abstraction that consumes shared Bell pairs and classical messages [1].

Jayasinghe et al. propose a quantum communication system for semantic image transmission in noisy vehicular networks. A semantic autoencoder produces a latent vector, a rate-1/2 polar code protects the bitstream, and a quantum

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encoder maps it to superposition states sent over a noisy quantum channel [2].

Abouamer et al. study latency-constrained encoded teleportation with punctured codes [3]. Popovski et al. address first-generation wireless systems that integrate classical and quantum communication [4], and Chehimi et al. propose a quantum semantic communication framework for resource-efficient quantum networking [5].

Quantum repeaters establish entanglement over shorter sublinks and join them by entanglement swapping [6]. Dahlberg et al. describe a link-layer protocol in which a higher layer requests entanglement and is notified of success or failure [7], and Wehner et al. describe the vision of the quantum Internet [8], and Illiano et al. survey its protocol stack [16]. The foundations are the purification protocols of Bennett et al. [9] and Deutsch et al. [10], the teleportation protocol [11] and the no-cloning theorem [12].

III. PROPOSED FRAMEWORK

1. System Overview

The proposed framework accepts source data, such as an image, as input. The data are semantically encoded, protected by a channel code and mapped to qubits. Quantum payloads are transferred either directly or by teleportation using purified Bell pairs, optionally protected by a CSS code. The receiver measures, decodes and reconstructs the data, and the result is evaluated by link-level and application-level measures. Only configurations that meet the fidelity, latency and resource requirements of the application are retained.

2. System Architecture

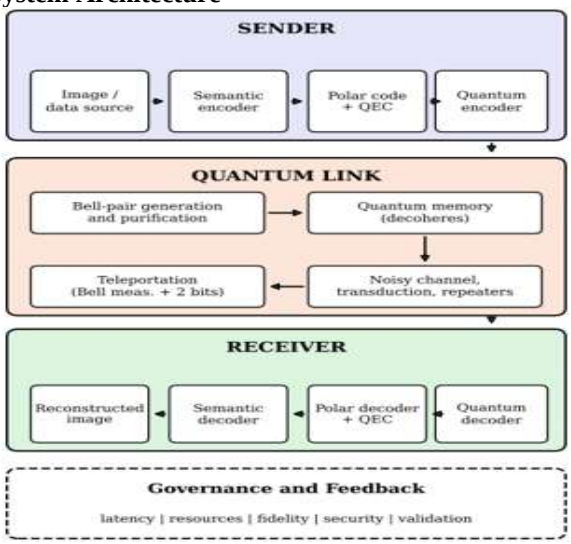

Fig. 1. General architecture of the proposed quantum communication framework for future networks.

3. Working Procedure

First, the source data are selected from an authorized public dataset such as CIFAR-10 or MNIST. Second, a semantic encoder compresses the data to a latent vector, which is converted to bits and protected by a rate-1/2 polar code. Third, the bits are mapped to qubits and superposition states by a Hadamard gate. Fourth, for payloads that must be teleported, raw Bell pairs are generated and purified, and the number of rounds is chosen by raw-pair quality, memory lifetime, classical-coordination time and the deadline. Fifth, each qubit of an encoded codeword is teleported using one Bell pair. Finally, the receiver measures and decodes the data, and the output is evaluated using fidelity, logical error probability, PSNR, SSIM, UQI and classification accuracy.

IV. QUANTUM TECHNIQUES FOR FUTURE COMMUNICATIONS

1. Qubits and Noise Models

A qubit is a unit vector $|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$ with $|\alpha|^2+|\beta|^2=1$. Measurement gives an outcome with a probability set by the Born rule and projects the state, so a single measurement does not reveal α and β. Noise is modelled by the Pauli channel, which applies the error X^aZ^b with probability p_{ab}, and its special case, the depolarizing channel [1]. The system in [2] also uses bit-flip, phase-flip, amplitude-damping and phase-damping noise.

2. Quantum Error Correction

QEC encodes a logical qubit into a larger code space. The redundancy is created by structured quantum correlations, not by copying, and syndrome measurements reveal information about errors without revealing the encoded state. A stabilizer code with n−k independent generators is an [[n,k,d]] code, limited by the quantum Singleton bound $2d \le n-k+2$. Examples are the [[3,1,3/1]] repetition code, which corrects one bit flip but not phase flips, and the [[5,1,3]] code, which corrects any single-qubit error. For CSS codes the numbers of correctable X and Z errors are $t_X=\lfloor(d_X-1)/2\rfloor$ $t_Z=\lfloor(d_Z-1)/2\rfloor$ [1].

3. Entanglement Purification

The basic entanglement resource is the Bell pair $(|00\rangle+|11\rangle)/\sqrt{2}$, called one ebit when ideal. Local operations and classical communication cannot create entanglement, so noisy pairs are improved by purification. A noisy pair has fidelity $F = p_{00}$, and distillation is possible only if $F > 1/2$. In BBPSSW [9] and DEJMPS [10], a bilateral CNOT is applied to a data pair and a check pair, the check pair is measured in the Z basis, and the data pair is kept only if the outcomes match. Entanglement pumping keeps one data pair and uses little memory, but reaches a fidelity fixed point below one for generic noise. Hashing uses one-way

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communication on many pairs and has a positive yield only if the entropy of the state is below one; for Werner states the threshold is F ≈ 0.8107 [1].

4. Quantum Teleportation

Teleportation transfers an unknown qubit using one Bell pair and two classical bits: Alice performs a Bell measurement, sends the two bits, and Bob applies the corresponding Pauli correction [11]. All four outcomes are equally likely and reveal nothing about the state, and since Bob needs the classical bits, teleportation does not allow faster-than-light communication. With an imperfect Bell pair, the Pauli error of the pair is transferred to the teleported qubit, so purification changes the effective channel [1].

5. Encoded Teleportation and Puncturing

In encoded teleportation, each physical qubit of an n-qubit codeword is teleported using one Bell pair, so coding helps only if its gain exceeds the extra acquisition time and decoherence. Puncturing a mother CSS code gives shorter related codes, for example [[17,1,5/5]], [[13,1,3/5]] and [[8,1,3/3]], to adapt to the latency budget [1], [3].

6. Quantum-Semantic Encoding

In [2], a convolutional autoencoder produces a 512-element latent vector, which is converted to bits, protected by a polar code [15], mapped to |0⟩ and |1⟩, and transformed into superposition states by a Hadamard gate. The receiver measures with projective operators, decodes the polar code and reconstructs the image with the semantic decoder.

V. DATASETS, MODELS AND NOISE SETTINGS

The image system in [2] is evaluated on CIFAR-10 (60,000 RGB images of size 32×32×3 in 10 classes) and MNIST (28×28 grayscale images). The semantic encoder has two convolutional layers with 32 and 64 filters of size 3×3, max-pooling, a 4096-element flatten layer and a 512-element dense bottleneck. Training uses 100 epochs, a batch size of 12, the Adam optimizer with a learning rate of 0.001 and binary cross-entropy loss.

The channel combines bit-flip, phase-flip, depolarizing, amplitude-damping and phase-damping noise, with the total error probability set from the channel SNR and split among the five types by random weights. Four systems are compared at equal bandwidth: C-SEMANTIC (classical, BPSK), Q-JPEG, C-JPEG and Q-SEMANTIC. The evaluation is a mathematical simulation of the noise models, not a quantum simulator or hardware [2]. The link-layer study in [1] uses an ion-trap memory with T_1=1.14 s and T_2=0.5 s and a classical coordination latency of 10 ms to show the limits of purification.

VI. PERFORMANCE EVALUATION

A quantum communication system should be assessed from both link-level and application-level perspectives, because a single figure can hide the cost in latency and resources.

1. Link-Level Metrics

For a Bell-diagonal pair, fidelity is $F = p_{00}$. For BBPSSW with two Werner pairs of equal fidelity F, the output fidelity is [1]

$$F' = [\, F^2 + (1/9)(1-F)^2 \,] \,/\, [\, F^2 + (2/3)F(1-F) + (5/9)(1-F)^2 \,] \qquad (1)$$

which exceeds F for 1/2 < F < 1. As an illustration computed from (1), F = 0.55 gives F′ ≈ 0.560 after one round. For encoded teleportation with a CSS code, with $q_X = p_X + p_Y$ and $q_Z = p_Z + p_Y$, the logical error probability is approximated by [1]

$$P_L \approx 1 - P_{succ,X} P_{succ,Z} \quad (2)$$

where $P_{succ,X}$ is the probability of at most t_X errors among n qubits and $P_{succ,Z}$ is defined likewise. Other measures are the purification success probability, the surviving fraction of pairs and the hashing yield.

2. Application-Level Metric

Image systems are evaluated by PSNR, SSIM, UQI and CNN classification accuracy, where at least 90% accuracy is called "Classified" [2]. The total channel error probability is mapped from the SNR as

$$\varepsilon_{tot} = \min [\, 1,\, 1 / (1 + 10^{SNR/10}) \,] \qquad (3)$$

3. Reported Results

In [2], Q-SEMANTIC reaches a PSNR of up to 28.55 dB, an SSIM of up to 0.7996 and a UQI of up to 0.7836. CNN classification stays above 90% accuracy at SNRs as low as 6 dB, compared with about 9 dB for C-SEMANTIC and about dB for classical JPEG, and the authors report an approximate 3 dB gain with p ≤ 0.001 below 9 dB. In [1], the useful gain of purification saturates because each round adds decoherence time.

4. Latency and Resource Efficiency

The number of Bell pairs, qubits, purification rounds and the end-to-end latency relative to the application deadline should also be reported, because an additional purification

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round is useful only if its gain remains after the extra waiting time [1].

Applications

Reliable quantum links support distributed quantum computing and QKD [1]. Quantum-semantic image transmission is proposed for advanced driver assistance, autonomous navigation, object detection, traffic analysis and vehicle-to-everything communication [2]. Quantum repeaters and link-layer protocols support the quantum Internet [6]–[8]. Wireless systems that integrate classical and quantum communication [4] and quantum semantic communication frameworks [5] target future networks. In every case, the system should be validated against domain requirements before deployment.

Challenges and Limitations

Unknown quantum states cannot be copied or retransmitted, so reliability depends on QEC, purification and teleportation. Stored pairs lose fidelity while waiting for classical messages, so more purification rounds do not always help [13]. Purification consumes many noisy pairs to produce fewer good ones, and an n-qubit codeword needs n Bell pairs. Transduction between matter qubits and photons adds loss and noise [1].

The analysis in [1] assumes Pauli noise, independent and identically distributed pairs and an approximate separate treatment of X and Z errors. The results of [2] come from mathematical modelling of noise, not quantum hardware, do not use QEC, and use small images, and the complexity and latency advantages are stated qualitatively. Therefore, fidelity, latency, resource use and application quality should be evaluated together.

Future Scope

Future work may integrate low-complexity QEC codes into the semantic system, investigate multi-qubit encoding and video transmission, and choose purification depth, code and puncturing jointly under latency and memory constraints [1]–[3]. Multipartite and localized purification of graph states, adaptive quantum-channel strategies, hybrid quantum-classical processing, and network-level coordination with repeaters and link-layer interfaces are further directions. Validation with quantum simulators or hardware will remain important before quantum communication is used in high-impact applications.

VII. CONCLUSION

Quantum computing and quantum communication open new possibilities for future communication systems, from distributed quantum computing and secure communication to robust image transmission in noisy vehicular networks. The reviewed works show that reliability can be rebuilt for uncopyable quantum information by using QEC and purification, with teleportation turning qubit transfer into the consumption of entanglement and classical bits [1], and that quantum encoding combined with semantic communication improved image quality at low SNR in simulation [2]. Reliable use requires more than a high figure in simulation: fidelity, latency, resource cost and validation on realistic channels must all be considered.

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