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Complex-Valued Orthogonal Unitary Superposition Encoding for Robust Three-Qubit Quantum-Error-Correction-Based Image Transmission

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Abstract

Efficient and reliable transmission of compressed images over noisy channels remains a significant challenge due to the high sensitivity to noise. Quantum communication offers a promising solution by encoding classical information into quantum states; however, these states are still susceptible to noise and quantum decoherence. To address these limitations, we propose a complex-valued orthogonal unitary superposition (COUS) encoding integrated with a three-qubit quantum error correction (QEC) framework for robust and low-complexity quantum image transmission. The COUS encoding preserves both amplitude and phase information, enhancing reconstruction fidelity while maintaining practical scalability. In the proposed system, images are first compressed using either the joint photographic experts group (JPEG) standard or the high-efficiency image file (HEIF) standard and encoded into quantum states. Quantum channel coding is then applied to protect against quantum noise, followed by COUS encoding prior to transmission. At the receiver, the transmitted data undergoes COUS decoding, quantum error correction, quantum decoding, and source decoding to reconstruct the images. Performance improvements are observed across peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM), and universal quality index (UQI) metrics. Simulation results demonstrate that the proposed approach outperforms conventional Hadamard encoding-based three-qubit QEC schemes, achieving maximum channel signal-to-noise ratio (SNR) gains of up to 6 dB, and surpasses bandwidth-equivalent classical communication systems employing polar codes, achieving channel SNR gains of up to 12 dB. These results highlight the potential of the proposed method as a practical solution for high-fidelity quantum image communication, overcoming the limitations of existing approaches.

Keywords: complex-valued orthogonal unitary superposition (COUS) encoding; image transmission; quantum communication; quantum error correction; quantum superposition



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1. Introduction

The transmission of compressed images across modern communication networks is a fundamental component of multimedia and data-driven applications, ranging from real-time video conferencing and remote sensing to cloud-based image storage and telemedicine. Image compression standards such as the joint photographic experts group (JPEG) format [1] and the high-efficiency image file (HEIF) [2] format have been developed to efficiently represent visual information while minimizing storage and bandwidth requirements. However, as compression ratios increase to meet the growing demand for high-throughput

image delivery, the encoded bitstreams become increasingly sensitive to transmission errors. Even minimal noise, packet loss, or bit corruption can cause significant degradation in reconstructed image quality, resulting in visual artifacts such as blockiness, color distortion, or total frame loss. These challenges become particularly severe in bandwidth-limited or noisy transmission environments.

Conventional communication systems rely on classical error correction codes such as Turbo [3], low-density parity-check (LDPC) [4], and polar codes [5] to enhance reliability under noise-limited conditions. While such methods can effectively mitigate moderate channel impairments, their performance is ultimately constrained by Shannon's channel capacity limit [6]. As a result, highly compressed images, where information redundancy is already minimal, are particularly difficult to recover accurately when transmitted over noisy channels. The classical redundancy-based protection mechanism often introduces additional bandwidth overhead, which negates the benefits of compression. Therefore, achieving high-fidelity compressed image transmission within the limitations of classical systems remains a critical open challenge.

In recent years, quantum communication [7] has emerged as a promising alternative paradigm that could overcome these classical limitations. By encoding information into quantum states of light or matter, quantum communication can exploit the fundamental principles of superposition and entanglement [8] to achieve intrinsically higher information density and parallelism in data representation. This allows quantum systems to encode multiple classical bits within a single quantum state, enabling more efficient data transfer over limited physical resources. Furthermore, quantum channels theoretically support unconditionally secure [9] and high-capacity transmission when properly designed. These properties make quantum communication particularly appealing for tasks that require ultra-reliable and high-fidelity multimedia transmission.

Despite its potential, practical quantum communication faces substantial challenges arising from quantum noise and decoherence, which tend to destroy or distort the fragile quantum states during transmission [10]. Environmental interactions and photon loss can all lead to state collapse or irreversible phase and amplitude errors. To maintain quantum coherence and recover the transmitted information, quantum error correction (QEC) [11] mechanisms are indispensable. QEC enables the detection and correction of errors without directly measuring or collapsing the quantum state, a fundamental requirement for maintaining quantum superposition.

Over the past two decades, a variety of QEC codes have been proposed, including the Shor code [12], Steane code [13], five-qubit code [14], three-qubit code [15], stabilizer codes [16], and surface codes [17]. Most of these schemes are originally developed within the context of quantum computation, where logical qubits are stored and manipulated within fault-tolerant architectures. Their direct application to quantum communication, however, particularly for image or video transmission, remains relatively unexplored. Existing studies that attempt to apply these codes for quantum data transmission often do so without adapting them to the specific encoding characteristics [18]. As a result, these traditional codes offer limited benefits for real-world multimedia applications and often require a large number of physical qubits and complex encoding circuits, posing major barriers to initial implementations.

Among these codes, the three-qubit QEC stands out for its simplicity, minimal qubit overhead, and shallow circuit depth, making it suitable for near-future quantum devices [15]. The three-qubit code provides basic protection against bit-flip or phase-flip errors using a small number of quantum gates, enabling efficient realization in current experimental setups. However, this simplicity comes at the cost of limited noise resilience. Consequently, while it offers a feasible entry point for early quantum communication

systems, its error suppression capability is inadequate for high-fidelity transmission of complex, compressed multimedia data.

To address these shortcomings, this study proposes a novel, complex-valued, orthogonal unitary superposition (COUS) encoding method, developed using existing quantum gates, including Hadamard [19] and phase gates [20], that enhances the performance of the conventional three-qubit QEC framework. The proposed COUS mechanism extends traditional encoding approaches by jointly preserving both the amplitude and phase components of quantum information, effectively representing complex-valued quantum states within an orthogonal superposition space. This formulation allows more expressive information embedding and improved robustness against combined amplitude–phase noise distortions that frequently occur in realistic quantum channels. By integrating COUS with the lightweight three-qubit QEC, the resulting system achieves a balance between noise resilience, circuit efficiency, and implementation feasibility, three properties that are critical for future, resource-limited quantum communication platforms. To the best of our knowledge, this study provides the first comprehensive analysis of COUS encoding applied to three-qubit error correction.

In addition, unlike prior quantum encoding methods that primarily emphasize theoretical error suppression or rely on high-dimensional entanglement, the proposed COUS encoding-based three-qubit QEC framework focuses on practical deployability for compressed image transmission. In the proposed communication pipeline, images are first compressed using established standards such as JPEG or HEIF to minimize redundancy and bandwidth requirements. The resulting compressed bitstream is then encoded into quantum states through the COUS encoding-based three-qubit QEC mechanism, which jointly preserves both the amplitude and phase information of the encoded data, thereby enhancing the system’s ability to resist complex noise distortions. These quantum states are subsequently transmitted over a noisy quantum channel, modeled with bit-flip, phase-flip, depolarizing and damping noise processes that realistically capture decoherence effects. At the receiver, COUS decoding and QEC operations are performed to recover the transmitted qubits with minimal fidelity loss, followed by quantum-to-classical decoding and source decoding to regenerate the original image. Extensive simulation and comparative analyses reveal that the proposed approach achieves superior performance in terms of noise resilience and reconstruction fidelity, outperforming both the conventional Hadamard encoding-based three-qubit QEC scheme and a bandwidth-equivalent classical communication system with polar codes. These results demonstrate the feasibility of achieving high-fidelity compressed image transmission in quantum communication environments without imposing significant qubit overhead or computational complexity.

1.1. Major Contributions and Research Significance

The key contributions of this research are summarized below:

- *Analysis of limitations in existing methods:* This study systematically examines the constraints of classical error correction and conventional Hadamard encoding-based three-qubit QEC techniques in achieving high-fidelity compressed image transmission. It highlights the inadequacy of existing approaches in handling both amplitude and phase distortions in quantum communication environments.
- *Proposal of a novel COUS encoding method:* A new COUS encoding scheme is introduced, which jointly preserves amplitude and phase information. This dual-preservation mechanism enhances robustness against combined noise effects while maintaining low encoding complexity.
- *Design of a COUS encoding-based three-qubit QEC architecture:* A complete COUS-integrated three-qubit QEC architecture is developed, specifically tailored for quantum

image communication. The architecture balances simplicity, scalability, and implementation feasibility, making it suitable for quantum devices with limited qubit resources.

- *Comprehensive performance evaluation:* Extensive simulations are conducted under realistic noise conditions, including bit-flip, phase-flip, depolarizing, amplitude-damping and phase-damping models. The results demonstrate that the proposed method achieves superior noise resilience, higher reconstruction fidelity, and lower computational overhead compared to both conventional Hadamard encoding-based three-qubit QEC and classical communication systems of equivalent bandwidth.

1.2. Organization of the Paper

The remainder of this paper is organized as follows. Section 2 provides background information on classical and quantum image transmission methods and QEC schemes. Section 3 details the proposed COUS encoding-based three-qubit QEC encoding and decoding processes and discusses the experimental setup and simulation parameters. Section 4 presents the results and analysis. Finally, Section 5 concludes the paper and outlines future research directions in scalable quantum image communication.

2. Related Works

Reliable transmission of compressed images over noisy channels is extensively studied in classical communication systems. Error correction codes such as Turbo codes, LDPC codes, and polar codes are commonly employed to improve robustness under channel noise [21]. While these codes are effective for moderate noise levels, redundancy is relied upon, which can reduce overall transmission efficiency [22] and fail to protect highly compressed bitstreams, such as JPEG or HEIF images, from severe artifacts.

Quantum communication [23] is initially developed to support secure information exchange. Quantum key distribution (QKD) [24,25] protocols, such as BB84 [26] and E91 [27], exploit principles of superposition [28], entanglement [29], and the no-cloning theorem [30] to detect eavesdropping and guarantee unconditional security. Quantum teleportation [31,32] is further demonstrated to transfer arbitrary quantum states using shared entanglement combined with classical communication. These foundational applications are experimentally validated in fiber, free-space, and satellite-based links, establishing robust benchmarks for secure quantum communication. While highly effective for cryptographic purposes [33], these early quantum security protocols focus on secure key exchange or state transfer rather than on preserving high-fidelity multimedia content [34–36]. Unlike these approaches, high-fidelity image transmission over noisy quantum channels is specifically targeted by the proposed framework, irrespective of security considerations.

Initial approaches for high-fidelity quantum media transmission employ single-qubit encoding schemes [37], where individual qubits represent small portions of image data. The feasibility of transmitting visual information over quantum channels is demonstrated by these methods. However, their conceptual simplicity comes at the cost of limited noise tolerance and low data throughput, rendering them unsuitable for high-noise environments or long-distance transmission. To increase transmission efficiency, multi-qubit encoding strategies are explored [38], where multiple qubits jointly represent pixel information. In addition, quantum multi-input multi-output (MIMO) [20] frameworks exploit spatial or temporal parallelism to enhance throughput and reduce error accumulation. Some studies also combine classical channel codes, such as polar codes, with multi-qubit quantum transmission [38]. However, such approaches often face increased circuit complexity and bandwidth requirements as the number of qubits grows, limiting their scalability for practical quantum communication systems. Despite these advances, noise resilience

remains limited, and scalability for high-dimensional data such as images and videos is often lacking.

In addition, quantum Fourier transform (QFT) [39] provides a spectral representation of quantum states, analogous to frequency-domain analysis in classical signal processing. Existing applications of QFT in quantum information primarily focus on algorithmic tasks such as phase estimation, quantum data compression, or security protocols [40–42]. Only a few studies explore the use of QFT for direct image transmission to improve noise resilience [38]. However, these prior methods are often considered complex, resource-intensive, and difficult to implement in practical systems, limiting their applicability to future quantum devices and high-fidelity multimedia transmission.

QEC is developed as a fundamental framework to protect quantum information from errors caused by decoherence, operational imperfections, and environmental noise [10]. Unlike classical error correction, quantum states must be preserved without direct measurement, which requires distributing the information of a single logical qubit across multiple physical qubits. Foundational codes include the Shor code [12], which encodes one logical qubit into nine physical qubits to correct arbitrary single-qubit errors; the Steane code [13], a seven-qubit scheme derived from classical Hamming codes; the five-qubit code [14,43], the minimal code capable of correcting all single-qubit errors; and the three-qubit code [44], the simplest resource-efficient scheme for detecting and correcting single bit-flip or phase-flip errors. Stabilizer codes [16] and surface codes are further employed to provide scalable frameworks for fault-tolerant computation. Among these, the three-qubit QEC code is considered the simplest and most resource-efficient, capable of detecting and correcting single bit-flip or phase-flip errors with minimal qubit overhead and shallow circuit depth, making it particularly attractive for future quantum devices [18].

Due to its simplicity, the three-qubit code is widely studied as a benchmark for fault-tolerant quantum operations and is considered suitable for future quantum devices with limited qubit counts [45,46]. In addition to theoretical studies in quantum computation, the three-qubit code is applied in quantum communication scenarios, including simple quantum state transmission, proof-of-concept image and video transmission experiments, and hybrid quantum-classical systems [18,47]. However, most applications focus on Hadamard-based encoding or single-task demonstrations, and integration with high-dimensional multimedia data or complex-valued state preservation remains largely unexplored, leaving significant room for more robust and scalable implementations. Furthermore, existing research rarely integrates QEC with advanced encoding strategies, such as frequency-domain representations [48], which can improve robustness against channel noise but often introduce high computational complexity. These gaps highlight the need for practical, low-complexity QEC frameworks with enhanced noise resilience, specifically tailored for high-fidelity multimedia transmission over noisy quantum channels, addressing the limitations of conventional QEC schemes.

Research Gaps and Motivation

Despite the theoretical and experimental progress in quantum communication, practical high-fidelity transmission of compressed images remains largely unaddressed. Existing single and multi-qubit encoding schemes, while demonstrating the feasibility of quantum image transfer, provide limited noise tolerance and low throughput, making them unsuitable for high-noise environments or long-distance transmission. Moreover, multi-qubit systems introduce significant implementation complexity as the qubit count increases, leading to higher bandwidth requirements and resource overhead. Most QEC codes, including Shor, Steane, and five-qubit codes, require significant qubit overhead and complex circuits, restricting their applicability in future devices. Although the three-qubit QEC code

is simple and resource-efficient, it has rarely been applied to structured high-dimensional data, and its existing direct integration provides low noise resilience for media transmissions. These limitations collectively highlight the need for a practical, low-complexity encoding framework combined with a three-qubit QEC scheme capable of protecting quantum-encoded images while maintaining high fidelity. Motivated by these gaps, the proposed COUS encoding integrated with three-qubit QEC provides a robust, scalable, and low-complexity solution for transmitting compressed images over noisy quantum channels, achieving effective error resilience and improved reconstruction quality with minimal resource overhead.

3. System Model

The proposed end-to-end quantum communication system is designed to reliably transmit compressed images over noisy quantum channels using a COUS encoding-based three-qubit QEC framework. A schematic of the system is illustrated in Figure 1. The system is evaluated using 100 images from the Microsoft COCO dataset [49] with resolutions of 256×192 and 640×427 , along with 20 images of 450×450 resolution from the ImageNet dataset [50]. Importantly, the architecture is both flexible and scalable, allowing it to handle images of varying resolutions and spatial complexities, from low-resolution inputs to highly detailed ultra-high-resolution content. Image transmission is therefore adopted as a representative test case due to its rich spatial characteristics and sensitivity to transmission errors, enabling comprehensive evaluation using both objective and perceptual quality metrics. Moreover, since the framework operates on generic bitstreams, it can be readily extended to other data types such as voice and video, with appropriate system-level adaptations to address latency and continuity requirements.

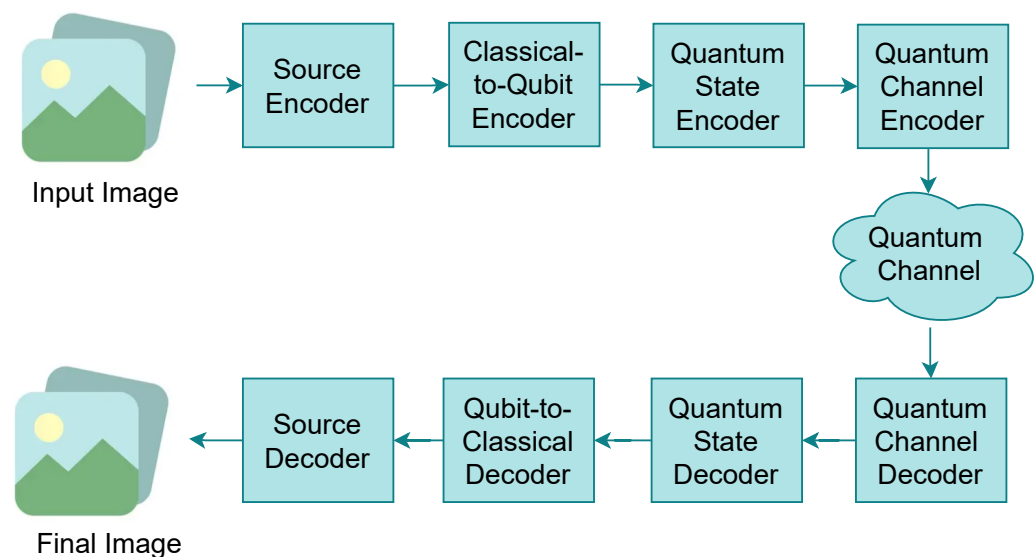


Figure 1. Architecture of the end-to-end quantum communication system for image transmission.

Following image acquisition, each input image is compressed using conventional formats such as JPEG and HEIF to reduce spatial and statistical redundancy. Two quantization parameter (QP) settings are employed: QP = 25 for lossy compression and QP = 100 for near-lossless compression. Image compression and quantum encoding are intentionally designed as independent stages to maintain modularity, compatibility with established compression standards (e.g., JPEG/HEIF), and analytical clarity in evaluating the proposed quantum transmission framework. Joint optimization, while promising, would require quantum-native compression and tightly coupled designs, which introduce significant complexity and are not yet practical for current quantum systems. Therefore, this work

adopts a decoupled approach as a robust baseline, with joint optimization considered as a future research direction. The resulting compressed bitstream is then used as the input to the quantum communication system, where encoding, error protection, transmission, and decoding are performed using the proposed COUS encoding-based three-qubit QEC framework. These processes are described in detail in the following subsections.

3.1. Classical-to-Qubit Encoder

After source compression, the compressed bitstream is mapped into quantum states for transmission. Each classical bit is represented as a computational basis state, where a bit value of '0' corresponds to the quantum state $|0\rangle$ and a bit value of '1' corresponds to $|1\rangle$. The canonical matrix representations of these quantum basis states are given in Equation (1).

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1)$$

This mapping forms the foundation for subsequent quantum encoding stages, enabling each classical bit to be encoded, manipulated, and transmitted as a qubit in the quantum communication system. In practice, the procedure begins with all qubits initialized to the ground state $|0\rangle$ through standard hardware initialization routines. For each input bit, the corresponding qubit state is determined conditionally: when the bit value equals 1, a Pauli-X operation [51] is applied, transforming the qubit from $|0\rangle$ to $|1\rangle$. Conversely, when the bit value equals 0, the qubit remains unchanged in the $|0\rangle$ state.

3.2. Quantum State Encoder

Once the classical bits are mapped to computational basis states, the quantum encoder converts these states into amplitude superpositions to enable parallel representation of information. This is achieved using the Hadamard gate, which is defined as in Equation (2).

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (2)$$

The action of the Hadamard gate on the computational basis states produces quantum superpositions, as shown in Equations (3) and (4).

$$H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad (3)$$

$$H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) \quad (4)$$

Applying the Hadamard gate to each qubit prepares the system for three-qubit QEC encoding and enables the creation of entangled and complex superposition states, which are essential for robust transmission over noisy quantum channels. The resulting superposed states are collectively denoted as $|\Psi\rangle$ in the following sections.

3.3. Quantum Channel Encoder

The superposed quantum states ($|\Psi\rangle$) generated by the Hadamard gate are subsequently fed into the quantum channel encoder, as shown in Figure 2. To introduce redundancy and enable error correction, two additional qubits, each initialized to $|0\rangle$, are added to form a three-qubit encoded state, as defined in Equation (5).

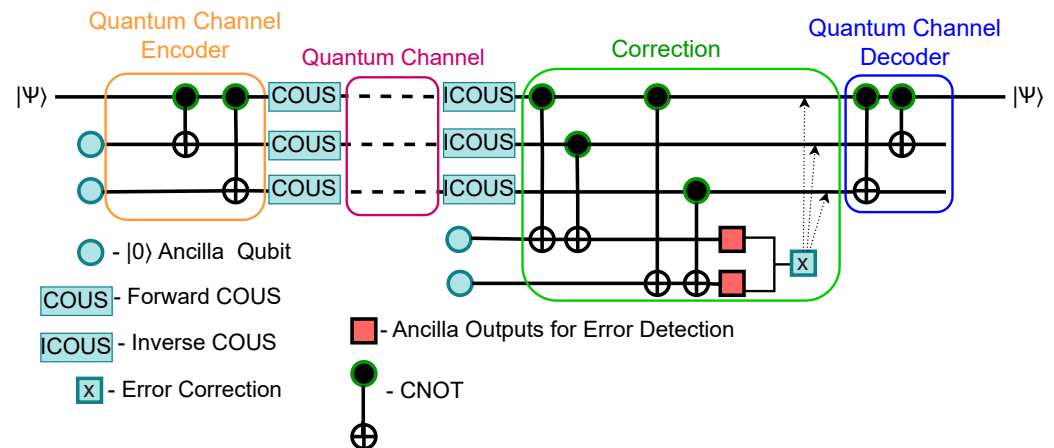


Figure 2. The proposed COUS encoding-based three-qubit QEC scheme.

$$\frac{1}{\sqrt{2}} |000\rangle \pm \frac{1}{\sqrt{2}} |100\rangle \quad (5)$$

This encoding spreads the information of a single qubit over three physical qubits, enhancing protection against channel-induced errors. Controlled-NOT (CNOT) gates are then applied, with the first qubit as the control and the second and third qubits as targets. Following these operations, the system evolves into the encoded state represented in Equation (6).

$$\frac{1}{\sqrt{2}} |000\rangle \pm \frac{1}{\sqrt{2}} |111\rangle \quad (6)$$

This entanglement distributes the information of the first qubit across all three qubits, providing redundancy to recover from single-qubit errors.

Next, the three-qubit encoded states are passed through the COUS gate to generate complex superpositions for transmission. The single-qubit COUS gate is defined by Equation (7).

$$G_{\text{COUS}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \quad (7)$$

This gate is unitary, as expressed in Equation (8), where $G_{\text{COUS}}^\dagger$ denotes the Hermitian conjugate (complex conjugate transpose) of G_{COUS} and I represents the identity matrix.

$$G_{\text{COUS}}^\dagger G_{\text{COUS}} = I \quad (8)$$

This property ensures that the quantum states remain normalized after encoding, meaning that the total probability amplitude of all possible states equals one. This normalization condition is essential for reliable quantum information processing and transmission.

The COUS gate can be implemented using a combination of standard quantum gates, specifically a sequence of phase–Hadamard–phase operations. Then the COUS gate can be expressed as the product of these gates, as shown in Equation (9).

$$G_{\text{COUS}} = S \cdot H \cdot S \quad (9)$$

where H is the Hadamard gate defined in Equation (2) and the phase gate is defined as in Equation (10).

$$S = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \quad (10)$$

First, the multiplication of H and S yields the matrix shown in Equation (11).

$$H \cdot S = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ 1 & -i \end{bmatrix} \quad (11)$$

Next, multiplying this result by another phase gate S gives the COUS gate, as shown in Equation (12).

$$S \cdot (H \cdot S) = \begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ 1 & -i \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} = G_{\text{COUS}} \quad (12)$$

This stepwise multiplication demonstrates how the COUS gate can be implemented using standard quantum gates.

Applying the COUS gate to the computational basis states produces complex-valued superpositions corresponding to right ($|R\rangle$) and left ($|L\rangle$) circular polarizations, as shown in Equations (13) and (14).

$$G_{\text{COUS}} |0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle) = |R\rangle \quad (13)$$

$$G_{\text{COUS}} |1\rangle = \frac{1}{\sqrt{2}}(i|0\rangle + |1\rangle) = |L\rangle \quad (14)$$

Finally, the COUS gate is applied independently to each of the three qubits in the encoded state, resulting in the complex three-qubit superposition state ($|\rho\rangle$), as shown in Equation (15).

$$|\rho\rangle = G_{\text{COUS}}^{\otimes 3} \left(\frac{1}{\sqrt{2}} |000\rangle \pm \frac{1}{\sqrt{2}} |111\rangle \right) = \frac{1}{\sqrt{2}} |RRR\rangle \pm \frac{1}{\sqrt{2}} |LLL\rangle \quad (15)$$

3.4. Quantum Channel

In practical quantum communication environments, transmitted qubits inevitably interact with their surroundings, resulting in quantum noise and decoherence. To emulate these imperfections, the proposed framework incorporates a realistic noise model consisting of several dominant noise processes, bit-flip, phase-flip, depolarizing, amplitude damping, and phase damping, each representing a distinct source of physical disturbance. Together, they form a composite noisy channel that governs the system's reliability under various signal-to-noise ratio (SNR) conditions.

The bit-flip channel ($\mathcal{N}_{\text{bf}}$) introduces random inversions between the logical states $|0\rangle$ and $|1\rangle$ with probability α . The evolution of the density matrix ρ under this process is given by Equation (16).

$$\mathcal{N}_{\text{bf}}(\rho) = \alpha X \rho X^\dagger + (1 - \alpha) \rho \quad (16)$$

where X denotes the Pauli- X operator.

The phase-flip channel ($\mathcal{N}_{\text{pf}}$) alters the relative phase of the $|1\rangle$ component in the superposition state, occurring with probability β . The corresponding transformation is expressed as in Equation (17).

$$\mathcal{N}_{\text{pf}}(\rho) = \beta Z \rho Z^\dagger + (1 - \beta) \rho \quad (17)$$

where Z represents the Pauli- Z operator.

Depolarizing noise ($\mathcal{N}_{\text{dp}}$) captures the randomization of a quantum state by replacing ρ with the maximally mixed state with probability γ , as defined by Equation (18).

$$\mathcal{N}_{\text{dp}}(\rho) = (1 - \gamma) \rho + \frac{\gamma}{3} (X \rho X^\dagger + Y \rho Y^\dagger + Z \rho Z^\dagger) \quad (18)$$

where X, Y , and Z are the Pauli operators corresponding to bit, bit-phase, and phase errors, respectively.

Amplitude damping noise ($\mathcal{N}_{\text{ad}}$) represents energy dissipation phenomena such as spontaneous emission. The channel acts on ρ through the Kraus operators E_0 and E_1 , defined as in Equation (19).

$$\mathcal{N}_{\text{ad}}(\rho) = E_0 \rho E_0^\dagger + E_1 \rho E_1^\dagger \quad (19)$$

where the Kraus operators E_0 and E_1 are defined as shown in Equation (20) and δ denotes the damping probability.

$$E_0 = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-\delta} \end{bmatrix}, \quad E_1 = \begin{bmatrix} 0 & \sqrt{\delta} \\ 0 & 0 \end{bmatrix} \quad (20)$$

Phase damping noise ($\mathcal{N}_{\text{pd}}$) accounts for coherence loss without energy dissipation. It is modeled using the Kraus operators F_0 and F_1 , as shown in Equation (21).

$$\mathcal{N}_{\text{pd}}(\rho) = F_0 \rho F_0^\dagger + F_1 \rho F_1^\dagger, \\ F_0 = \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-\theta} \end{bmatrix}, \quad F_1 = \begin{bmatrix} 0 & 0 \\ 0 & \sqrt{\theta} \end{bmatrix} \quad (21)$$

where θ is the dephasing probability.

The combined impact of all five noise types ($\mathcal{N}_{\text{total}}$) on the transmitted qubit is modeled as a weighted summation of their respective transformations, as shown in Equation (22).

$$\mathcal{N}_{\text{total}}(\rho) = \alpha \mathcal{N}_{\text{bf}}(\rho) + \beta \mathcal{N}_{\text{pf}}(\rho) + \gamma \mathcal{N}_{\text{dp}}(\rho) + \delta \mathcal{N}_{\text{ad}}(\rho) + \theta \mathcal{N}_{\text{pd}}(\rho) \quad (22)$$

In all Equations, ρ represents the transmitted quantum state and † indicates the Hermitian conjugate.

To analyze the system under varying noise conditions, these probabilities are adjusted according to the SNR, which is expressed in decibels, as shown in Equation (23).

$$\text{SNR (dB)} = 10 \log_{10} \left(\frac{P_{\text{signal}}}{P_{\text{noise}}} \right) \quad (23)$$

where P_{signal} represents the average signal power and P_{noise} denotes the corresponding noise power. In the proposed framework, P_{signal} is normalized to unity, while P_{noise} is varied to control the SNR, which is defined using the conventional formulation, as shown in Equation (23). However, unlike classical systems, noise is not modeled as additive variance but through SNR-dependent probabilistic quantum channels. Specifically, the SNR governs the total quantum noise probability (p_{total}), which is dynamically distributed among different noise processes to capture realistic decoherence effects.

The total probability (p_{total}) of quantum noise is inversely related to the linear SNR, as expressed in Equation (24).

$$p_{\text{total}} = \min \left(1, \frac{1}{1 + 10^{\text{SNR}/10}} \right) \quad (24)$$

To simulate a heterogeneous channel environment, random weighting coefficients (r_1, r_2, r_3, r_4, r_5) are generated for each noise type, as in Equation (25).

$$r_1, r_2, r_3, r_4, r_5 \sim \mathcal{U}(0, 1) \quad (25)$$

These random values are normalized and scaled to assign dynamic contributions to each noise process, as shown in Equation (26), ensuring the total noise constraint expressed in Equation (27).

$$[\alpha, \beta, \gamma, \delta, \theta] = \left(\frac{r_i}{\sum_{j=1}^5 r_j} \right) p_{\text{total}} \quad (26)$$

$$\alpha + \beta + \gamma + \delta + \theta = p_{\text{total}} \quad (27)$$

This probabilistic modeling approach ensures that the overall decoherence level depends on the SNR, while the type and severity of individual noise processes vary between transmissions. To ensure full reproducibility, all stochastic components of the proposed system are controlled using a fixed random seed (seed = 42). This initialization guarantees that the pseudo-random number generator produces a deterministic and repeatable sequence of random variables across all simulation runs. As a result, the randomly generated weighting coefficients used in Equation (22), as well as the stochastic realizations of individual quantum noise processes, remain identical for repeated executions of the experiment. More specifically, the fixed seed governs: (i) the generation of uniformly distributed random variables used to compute the normalized noise weights $(\alpha, \beta, \gamma, \delta, \theta)$, (ii) the probabilistic application of quantum noise channels (bit-flip, phase-flip, depolarizing, amplitude damping, and phase damping), and (iii) the sequence of Monte Carlo trials used for performance evaluation. This ensures that all encoding schemes are evaluated under exactly the same channel conditions, enabling a fair and controlled comparison where performance differences arise solely from the proposed encoding strategy.

Composite Quantum Noise Model and Practical Relevance

In practical quantum communication systems, transmitted quantum states are simultaneously affected by multiple noise mechanisms arising from environmental interactions and hardware imperfections. To capture this behavior, the proposed framework adopts a composite quantum channel model that incorporates several fundamental noise processes, including bit-flip, phase-flip, depolarizing, amplitude damping, and phase damping channels. Each of these noise models corresponds to a distinct physical phenomenon, such as decoherence, energy relaxation, or phase instability, and is widely used in quantum information theory to represent realistic error sources.

Rather than assuming a single deterministic noise model, the proposed approach combines these noise processes using normalized weighting coefficients. These coefficients are generated dynamically and scaled such that their sum equals the total noise level. This formulation allows multiple noise mechanisms to act simultaneously on the transmitted quantum state, providing a more representative approximation of practical quantum environments, where different error sources coexist and interact.

The use of randomized weighting serves to emulate the variability observed in real-world quantum systems, where the relative contribution of different noise processes depends on factors such as hardware platform, operating conditions, and environmental disturbances. For example, amplitude damping may dominate in photonic systems due to photon loss, while phase-related errors may be more significant in superconducting or trapped-ion implementations. By allowing the noise composition to vary across transmissions, the model avoids bias toward a specific hardware configuration and enables evaluation under a broad range of channel conditions.

Furthermore, the overall noise level is controlled as a function of the SNR, ensuring consistency with communication system analysis. The total noise probability is adjusted inversely with the SNR, such that a higher SNR corresponds to lower overall decoherence,

while a lower SNR increases the likelihood of quantum errors. This provides a systematic mechanism to study system performance under varying channel quality.

Although the model does not correspond to a single specific physical channel, it provides a flexible and physically grounded abstraction for system-level evaluation. Each individual noise component retains a clear physical interpretation, while their combination enables the representation of heterogeneous and dynamically varying channel conditions. This approach is consistent with established practices in communication system modeling, where generalized channel models are commonly used for performance analysis and comparative evaluation. Overall, the composite noise model provides a realistic, scalable, and analytically tractable framework for evaluating the robustness of the proposed encoding and transmission scheme under diverse quantum channel conditions [38,47,52].

3.5. Quantum Channel Decoder

At the receiver, the inverse COUS gate (ICOUS), as defined in Equation (28), is first applied to each received qubit to revert the phase and amplitude transformations introduced during transmission. This operation restores the state to its pre-transmission logical domain while preserving the embedded redundancy used for error correction.

$$G_{\text{COUS}}^{\dagger} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -i \\ -i & 1 \end{bmatrix} \quad (28)$$

The inverse COUS transformation acts independently on each qubit to disentangle the complex-valued circular polarization components, as expressed in Equation (29).

$$|\psi_{\text{decoded}}\rangle = G_{\text{COUS}}^{\dagger \otimes 3} |\rho\rangle \quad (29)$$

This step effectively restores the encoded superposition to a real-valued, three-qubit logical state ($|\psi_{\text{decoded}}\rangle$), forming the input to the QEC decoder.

Three-Qubit QEC Decoder and Error Correction

Following the inverse COUS operation, the three-qubit QEC decoder performs syndrome extraction and error recovery. Two ancilla qubits, initialized in the $|0\rangle$ state, are employed to extract the error syndrome through CNOT-based parity checks. The resulting ancilla states reveal the location of any single-qubit error without directly measuring the logical qubits. The syndrome mapping between received states, error positions, and ancilla results is presented in Table 1.

Table 1. Syndrome mapping between received quantum states, error positions, and corresponding ancilla results.

Received Quantum State	Error Position	Ancilla Result
$\frac{1}{\sqrt{2}}(000\rangle \pm 111\rangle)$	No error	$ 00\rangle$
$\frac{1}{\sqrt{2}}(100\rangle \pm 011\rangle)$	First qubit	$ 11\rangle$
$\frac{1}{\sqrt{2}}(010\rangle \pm 101\rangle)$	Second qubit	$ 10\rangle$
$\frac{1}{\sqrt{2}}(001\rangle \pm 110\rangle)$	Third qubit	$ 01\rangle$

Each detected syndrome pattern triggers a corrective Pauli-X operation [51] on the corresponding erroneous qubit, as summarized in Table 2.

After correction, the logical three-qubit state is reverted to its error-free superposition, identical to the pre-channel encoded state. The decoding process is completed by reversing the encoding CNOT sequence, disentangling the qubits and resetting the ancillas to $|0\rangle$. The final recovered quantum state $|\psi\rangle$ is thus obtained.

Table 2. Syndrome patterns with corresponding corrective operations.

Syndrome	Corrective Operation
$ 00\rangle$	No correction needed
$ 01\rangle$	Apply X gate to the third qubit
$ 10\rangle$	Apply X gate to the second qubit
$ 11\rangle$	Apply X gate to the first qubit

3.6. Quantum State Decoder

The restored quantum superposition is then decoded by applying the inverse Hadamard gate to each qubit. This operation transforms the qubits from the Hadamard (superposition) basis back into the computational basis, enabling direct measurement of classical information. The inverse Hadamard gate, being self-adjoint, is mathematically identical to the forward Hadamard transformation as defined in Equation (2), and can be expressed as in Equation (30).

$$H^\dagger = H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \quad (30)$$

Applying $H^\dagger$ to the decoded logical state converts the superposed amplitudes into deterministic computational states. This process ensures that all qubits are projected into the standard $|0\rangle$ or $|1\rangle$ basis, eliminating any residual interference between superposition components.

3.7. Qubit-to-Classical Decoder

Once the quantum states are restored to the computational domain, each qubit is decoded to extract its classical bit value. The collection of results forms the recovered binary sequence representing the transmitted compressed image data. This binary bitstream is then reassembled according to the transmission order to reconstruct the encoded file structure.

3.8. Source Decoder

The reconstructed bitstream is passed to the corresponding classical source decoder based on the source compression format used at the transmitter. These source decoders restore the pixel intensity values and spatial resolution of the original image, completing the end-to-end quantum communication and reconstruction process.

3.9. Benchmark System Implementations

For comparative evaluation, two benchmark systems are implemented.

- *Conventional Hadamard encoding-based three-qubit QEC scheme:* This system replaces the COUS gate with the Hadamard gate defined in Equation (2) and employs the inverse Hadamard gate in place of the inverse COUS gate. The remaining QEC encoding and decoding procedures remain identical. This benchmark represents a real-valued, superposition-based QEC mechanism without circular polarization components.
- *Classical polar-coded baseline:* To ensure bandwidth equivalence, a classical system employing a polar code [53] with a rate of $R = \frac{1}{3}$ is implemented. The same source encoder (JPEG or HEIF) is used, and additive white Gaussian noise (AWGN) is introduced at corresponding SNR levels for direct performance comparison.

In all systems, bandwidth equivalence is ensured by matching the effective transmission resources such that each information bit is represented by the same number of transmitted symbols in both classical and quantum systems. In this work, three-qubit

encoding maps one bit to three qubits, analogous to a classical coding rate of 1/3, thereby ensuring a fair and consistent comparison in terms of transmission load.

4. Results and Discussion

The proposed quantum communication framework is evaluated using standard image quality metrics: peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM) [54], universal quality index (UQI) [55] and bit error rate (BER). Its performance is compared against two benchmark systems, the conventional Hadamard encoding-based three-qubit scheme and a classical polar-coded transmission model. Both JPEG and HEIF compression formats are tested under two QP settings: QP = 25 for lossy compression and QP = 100 for near-lossless compression. All reported results represent average values computed across the entire set of test images and over 1000 Monte Carlo runs, ensuring statistically consistent and reliable performance evaluation. These experiments collectively provide insights into the proposed system's robustness, error resilience, and image reconstruction fidelity under varying compression levels and channel noise conditions.

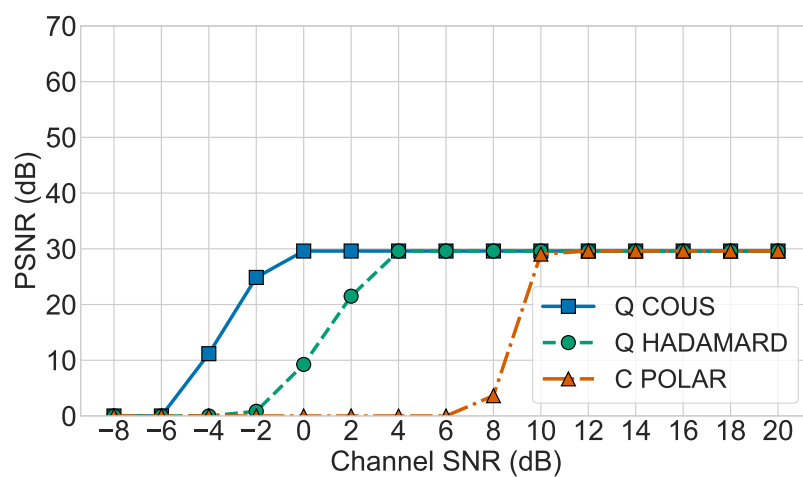
It is important to note that, in this section, the improvement comparison is represented using the channel SNR gain, which quantifies the reduction in SNR required by the proposed quantum communication systems compared to the baseline system for achieving the same target image quality. This relationship is defined in Equation (31).

$$\Delta\text{SNR}(Q) = \text{SNR}_{\text{BASELINE}}(Q) - \text{SNR}_{\text{QUANTUM}}(Q) \quad (31)$$

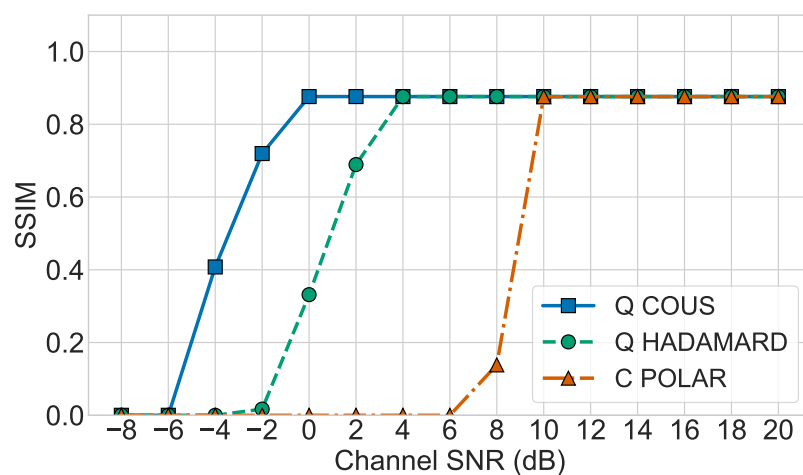
where $\text{SNR}_{\text{BASELINE}}(Q)$ and $\text{SNR}_{\text{QUANTUM}}(Q)$ represent the channel SNRs required by the baseline and quantum communication systems, respectively, to achieve the same target quality level Q . This formulation provides a direct measure of the comparative performance gain achieved through quantum-based transmission.

As illustrated in Figure 3a–c, the performance of the proposed COUS encoding-based three-qubit QEC framework (Q COUS) is evaluated against the conventional Hadamard encoding-based three-qubit scheme (Q HADAMARD) and a classical polar-coded system (C POLAR) for JPEG-compressed images with QP = 25. The assessment metrics include PSNR, SSIM, and UQI, which together quantify image fidelity, structural consistency, and perceptual quality, respectively. The results indicate that Q COUS consistently outperforms both benchmark schemes across all SNR levels. In particular, Q COUS achieves an average PSNR, SSIM and UQI improvement corresponding to channel SNR gains of 4.5 dB over Q HADAMARD and up to 10.5 dB over C POLAR, demonstrating a substantial enhancement in noise tolerance and reconstruction quality.

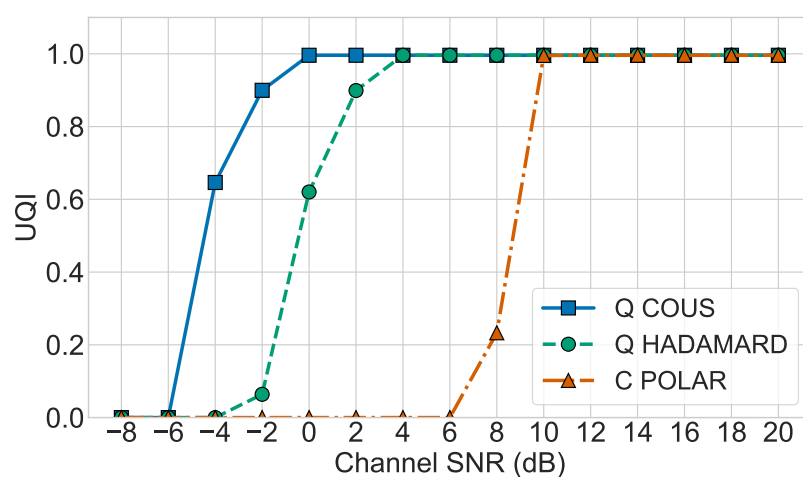
At lower SNR values, where the quantum channel is highly noise-dominated, the Q COUS scheme maintains stable reconstruction quality with minimal degradation, whereas both Q HADAMARD and C POLAR show steep performance drops. This highlights the proposed system's inherent robustness under adverse transmission conditions. As the SNR increases, all systems converge toward their upper bounds; however, Q COUS maintains the highest steady-state performance, confirming its superior efficiency in preserving quantum coherence and mitigating cumulative noise.



(a)



(b)



(c)

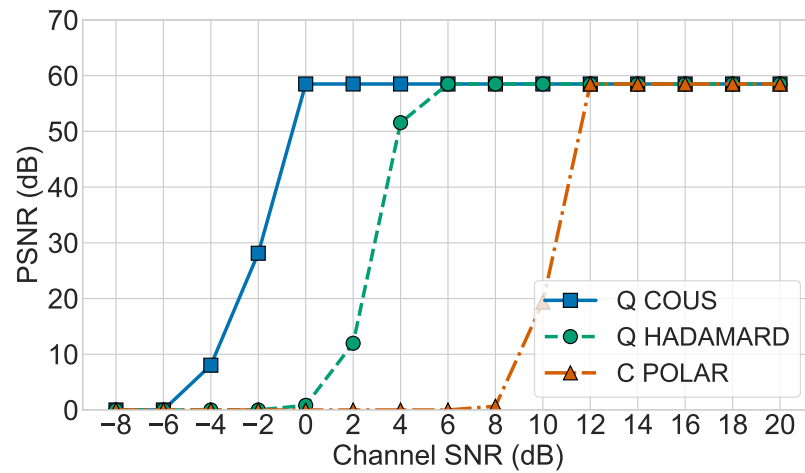
Figure 3. Performance of JPEG QP = 25 compressed image transmission evaluated using (a) PSNR, (b) SSIM, and (c) UQI, under the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).

For JPEG QP = 100, as shown in Figure 4a–c, the performance of the proposed system is further enhanced compared to the QP = 25 case. In this near-lossless configuration, compression introduces minimal quantization noise, allowing the Q COUS system to correct channel-induced errors more effectively. Consequently, the Q COUS system achieves higher PSNR, SSIM, and UQI values, with maximum channel SNR gains of approximately 6 dB over Q HADAMARD and 12 dB over C POLAR. These results indicate that the advantages of the proposed system become more pronounced when compression noise is low, highlighting its ability to preserve fine image details and maximize noise resilience.

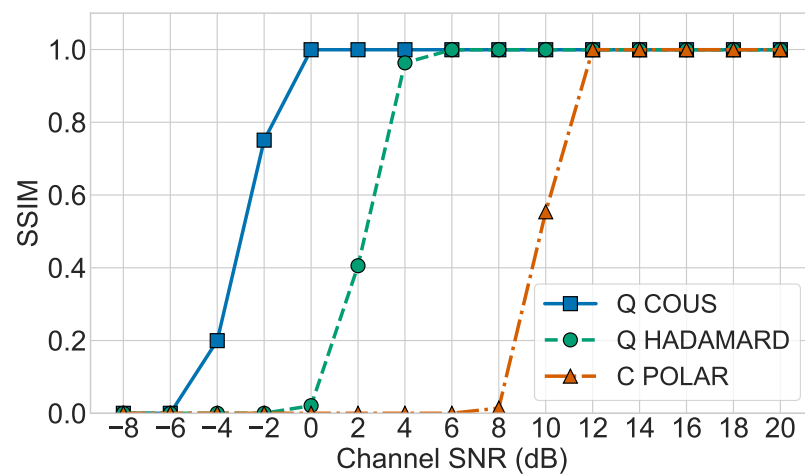
Furthermore, the HEIF-compressed results shown in Figure 5a–c illustrate the performance of the three systems under HEIF QP = 25 compression. The proposed Q COUS framework consistently achieves higher fidelity metrics compared to both the Q HADAMARD and C POLAR systems. Due to HEIF's superior compression efficiency and reduced spatial redundancy, the maximum PSNR, SSIM, and UQI values are higher than those observed for JPEG QP = 25; however, the channel SNR gains of Q COUS relative to the benchmark systems remain similar to those for JPEG QP = 25. As a result, Q COUS attains the highest image quality values, with notable stability across varying SNR levels. This improvement is particularly pronounced under low-SNR conditions, where the Q HADAMARD scheme exhibits significant degradation, while Q COUS maintains reliable image reconstruction. These results highlight the COUS gate's ability to preserve quantum coherence under complex noise distributions through its complex-valued amplitude encoding.

For the HEIF QP = 100 configuration (Figure 6a–c), where compression artifacts are minimal and source quality is nearly lossless, the system exhibits performance trends similar to those observed for JPEG QP = 100. The advantages of the proposed COUS-based encoding clearly stem from its inherent mechanism rather than the compression format or level. Q COUS consistently outperforms the benchmark systems across all SNR conditions. With minimal quantization noise, the benefits of COUS-based encoding become more pronounced, resulting in improved PSNR stability and near-perfect SSIM and UQI values at high SNRs. These results indicate that the proposed quantum encoding effectively preserves fine image details and perceptual fidelity when compression noise is negligible. In contrast, the Q HADAMARD and C POLAR systems approach their performance limits, highlighting their comparatively weaker resilience to cumulative decoherence. Notably, the maximum channel SNR gains for HEIF QP = 100 are higher than those for HEIF QP = 25, reflecting the system's enhanced ability to leverage low-compression-noise conditions.

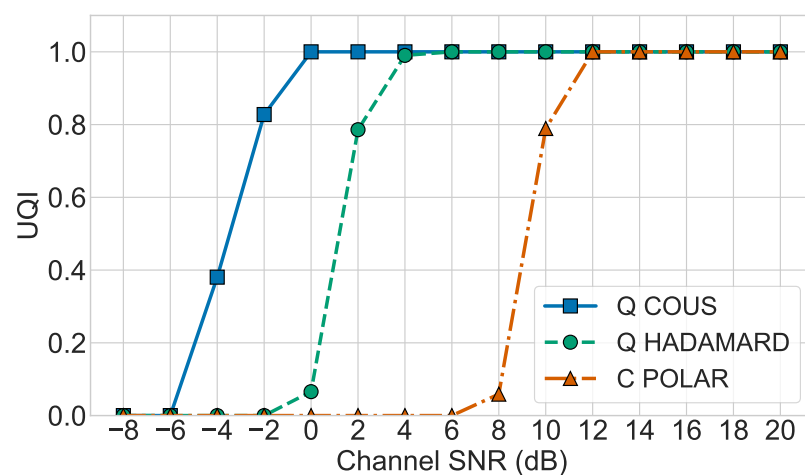
Overall, evaluations confirm that the proposed COUS-based quantum communication architecture is generalized effectively across different compression levels and source encoding schemes. The consistent performance advantage across both QP = 25 and QP = 100 configurations validates the scalability and robustness of the COUS encoding-based three-qubit QEC framework, highlighting its potential for practical, high-fidelity quantum multimedia transmission. Furthermore, the proposed COUS-based three-qubit QEC framework improves error tolerance through redundancy and distance-based decoding, enabling reliable recovery in cases such as single-qubit errors. However, it does not guarantee correction of all error patterns (e.g., when two qubits are simultaneously corrupted), and therefore operates as a probabilistic error-resilient scheme rather than a deterministic error correction code.



(a)

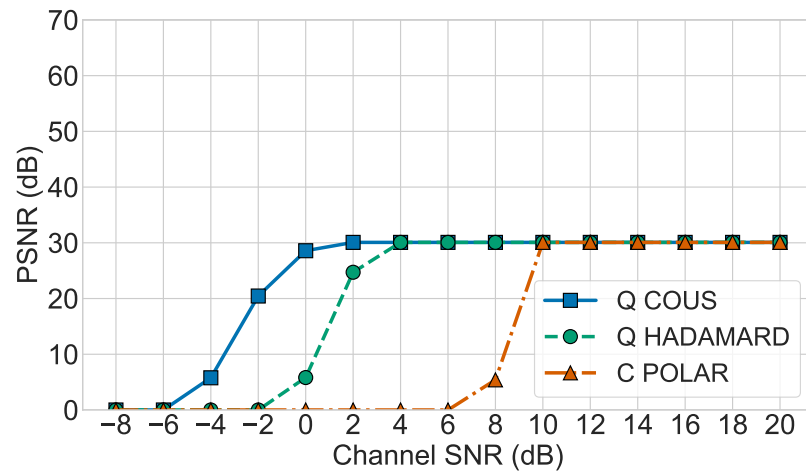


(b)

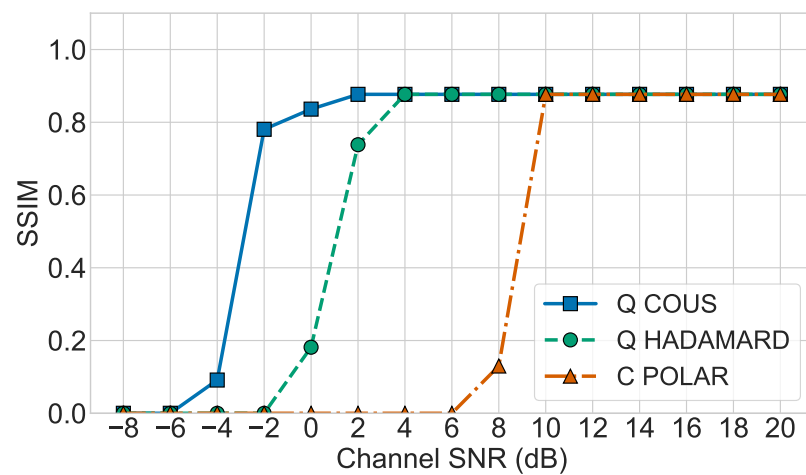


(c)

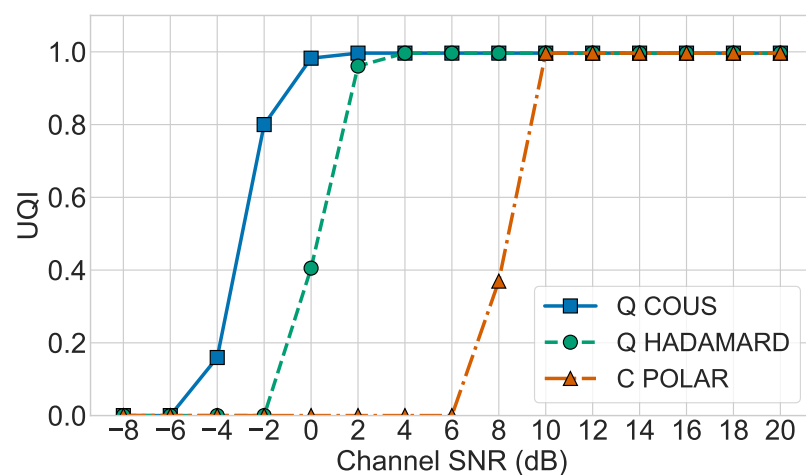
Figure 4. Performance of JPEG QP = 100 compressed image transmission evaluated using (a) PSNR, (b) SSIM, and (c) UQI, under the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).



(a)

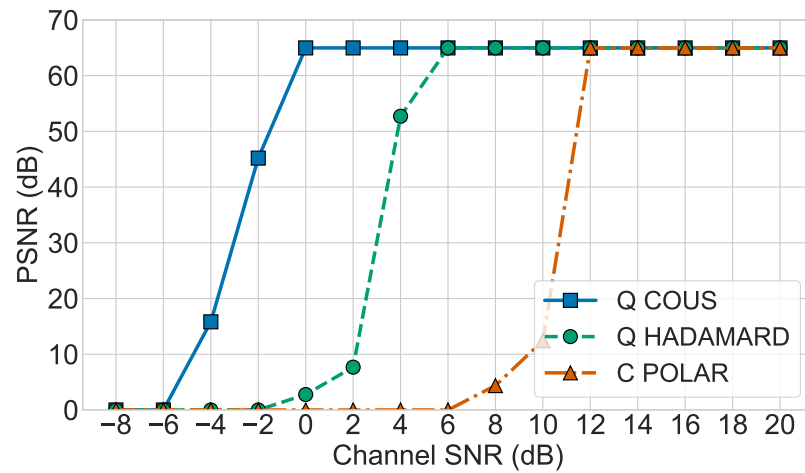


(b)

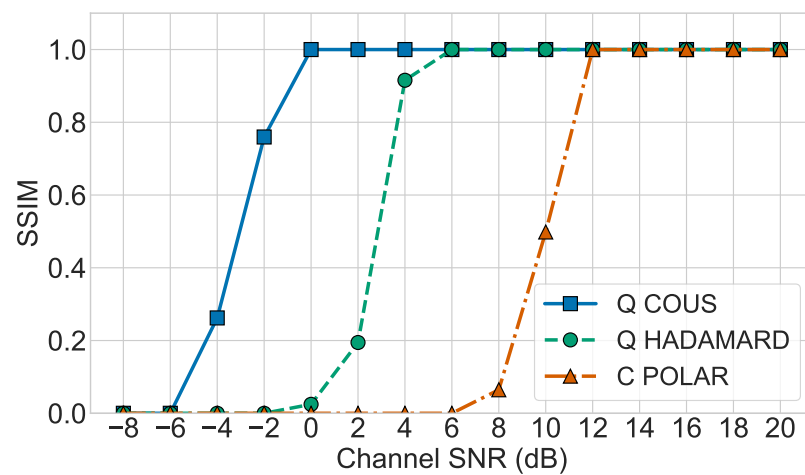


(c)

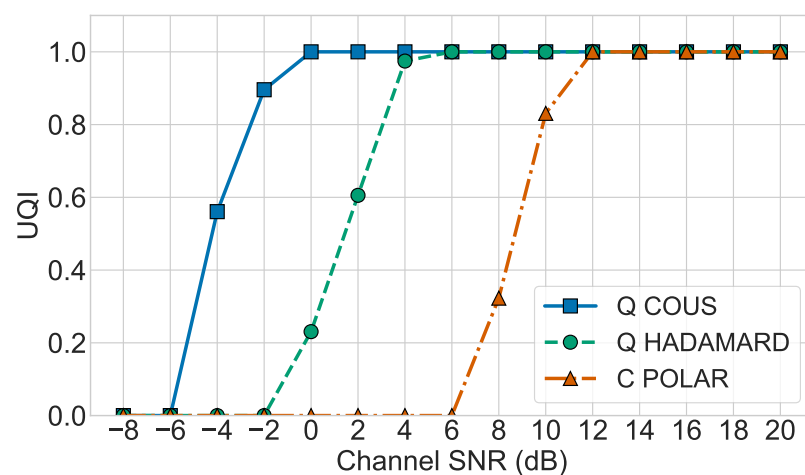
Figure 5. Performance of HEIF QP = 25 compressed image transmission evaluated using (a) PSNR, (b) SSIM, and (c) UQI, under the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).



(a)



(b)



(c)

Figure 6. Performance of HEIF QP = 100 compressed image transmission evaluated using (a) PSNR, (b) SSIM, and (c) UQI, under the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).

Moreover, the smooth trends observed in Figures 3–6 are a result of averaging performed across both the dataset and multiple stochastic channel realizations. Specifically, PSNR, SSIM, and UQI values are computed as mean values over all test images (e.g., COCO and ImageNet datasets) and across 1000 Monte Carlo runs for each SNR level. This dual-level averaging reduces random fluctuations introduced by the probabilistic noise model and reveals the underlying performance behavior of the system. All simulations are conducted under controlled conditions using a fixed random seed, ensuring consistent channel realizations and reproducibility across experiments. As a result, the observed smoothness of the curves reflects the inherent stability of the proposed framework rather than a lack of statistical variability.

To further quantify this stability, Table 3 presents the mean and standard deviation of PSNR, SSIM, and UQI for a representative case of a COUS-based three-qubit QEC framework (JPEG, QP = 25) at selected SNR levels.

Table 3. Statistical variation of performance metrics for COUS-based three-qubit QEC framework (JPEG, QP = 25).

SNR (dB)	PSNR (Mean $\pm$ Std)	SSIM (Mean $\pm$ Std)	UQI (Mean $\pm$ Std)
20	29.60 $\pm$ 0.01	0.8762 $\pm$ 0.0005	0.9961 $\pm$ 0.0003
10	29.60 $\pm$ 0.02	0.8762 $\pm$ 0.0008	0.9961 $\pm$ 0.0005
−2	24.86 $\pm$ 0.15	0.7195 $\pm$ 0.008	0.8997 $\pm$ 0.010
−4	11.18 $\pm$ 0.30	0.4077 $\pm$ 0.015	0.6463 $\pm$ 0.020

The relatively small standard deviations compared to the mean values indicate that the proposed system maintains consistent performance across different images and channel realizations. This confirms that the reported trends are statistically reliable and not influenced by outliers or specific data samples. Overall, the results demonstrate that the proposed framework exhibits strong statistical stability, and the inclusion of standard deviation further enhances the interpretability and robustness of the experimental evaluation.

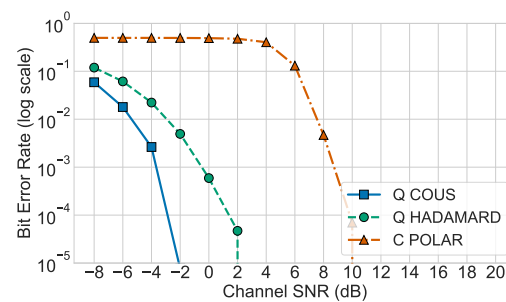
As shown in Figure 7a,b, the BER performance is further analyzed for both JPEG QP = 25 and JPEG QP = 100 compressed images transmitted over noisy quantum channels. Across all channel SNR values, the proposed Q COUS scheme achieves the lowest BER, demonstrating superior resilience to decoherence and transmission noise compared to both the Q HADAMARD and C POLAR systems, regardless of the image compression level. This highlights its enhanced ability to preserve quantum information integrity even when the input bitstream is highly compressed.

Moreover, the advantages of the COUS encoding-based three-qubit QEC system are observed across different spatial resolutions. As shown in Table 4, the relative SNR improvement of the COUS encoding-based three-qubit QEC system (Q COUS) and the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD) is reported relative to a classical baseline (C POLAR) for JPEG QP = 25 images with resolutions of 256×192 , 640×427 , and 450×450 . The results indicate that system performance is nearly consistent across resolutions, with channel SNR gains remaining stable. This demonstrates that the proposed framework provides robust error resilience regardless of image resolution.

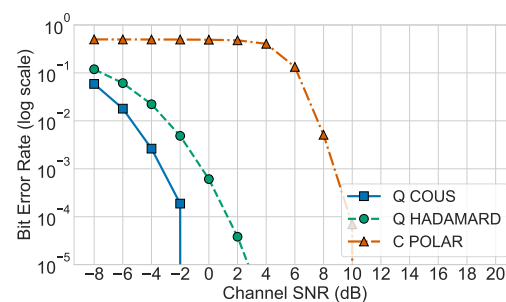
Table 4. Relative channel SNR gain of the COUS encoding-based three-qubit QEC system (Q COUS) and the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD) compared to the classical baseline system for JPEG QP = 25 across different spatial resolutions.

Resolution	Channel SNR Gain (dB)	
	Q COUS	Q HADAMARD
256×192	10.5	6.0
640×427	10.6	6.1
450×450	10.6	6.1

Furthermore, a subjective evaluation of image quality is conducted to complement the objective performance metrics, as shown in Figure 8. The assessment follows a double-stimulus methodology in accordance with ITU-R BT.500 recommendations [56], involving 100 participants aged between 15 and 60 years with normal or corrected-to-normal vision. JPEG-compressed images at QP values of 25 and 100, representing both highly compressed and near-lossless conditions, are considered. These images are transmitted using the communication framework under all three evaluated systems: the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded transmission system (C POLAR), providing representative comparisons of quantum and classical approaches.



(a)



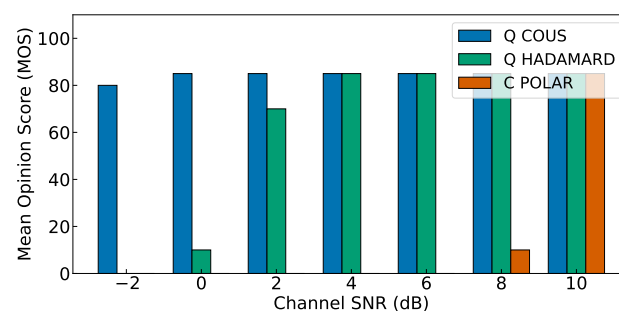
(b)

Figure 7. Bit error rate (BER) performance for (a) JPEG QP = 25 and (b) JPEG QP = 100 compressed image transmission under the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).

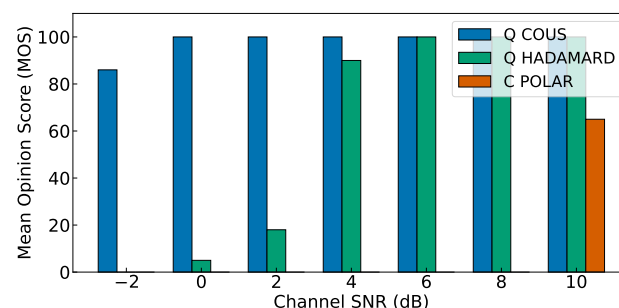
All visual stimuli are presented on calibrated display devices under controlled lighting conditions, with observers positioned at an approximate viewing distance of three times the screen height to ensure consistent perception. The sequence of displayed images

is randomized for each participant to avoid ordering bias, and evaluation sessions are designed with limited duration and scheduled breaks to minimize visual fatigue. For each SNR level, participants compare reconstructed images with their corresponding reference originals and assess visual quality based on criteria such as clarity, presence of artifacts, and overall perceptual fidelity. A continuous mean opinion score (MOS) scale ranging from 0 to 100 is employed, where scores are categorized as follows: 0–20 (bad), 21–40 (poor), 41–60 (fair), 61–80 (good), and 81–100 (excellent). The final MOS values are obtained by averaging individual ratings across all participants, ensuring statistically robust subjective evaluation. All participants provide informed consent prior to participation, and the study is conducted in compliance with institutional ethical standards, with approval granted by the ethics committee of the University of Strathclyde (protocol code 3048, approved on 9 December 2025). The subjective assessment results are consistent with objective performance metrics, including PSNR, SSIM, and UQI, indicating that improvements in measured quality correspond to enhanced perceptual experience.

In addition, representative decoded images at an SNR of 0 dB are shown in Figure 9, with the first column displaying images reconstructed using the proposed COUS encoding-based three-qubit QEC system (Q COUS) and the second column showing those reconstructed using the conventional Hadamard encoding-based three-qubit system (Q HADAMARD). It is evident that the COUS-encoded images preserve more structural details and exhibit fewer artifacts across both compression levels, demonstrating superior robustness to channel noise and better visual fidelity compared to the conventional method. The improvement is particularly noticeable for the highly compressed (QP = 25) images, highlighting the advantage of the COUS encoding-based three-qubit QEC system in maintaining image quality under challenging channel conditions.



(a)



(b)

Figure 8. Subjective visual quality assessment for (a) JPEG QP = 25 and (b) JPEG QP = 100 compressed image transmission using the proposed COUS encoding-based three-qubit QEC system (Q COUS), the conventional Hadamard encoding-based three-qubit QEC system (Q HADAMARD), and the classical polar-coded system (C POLAR).

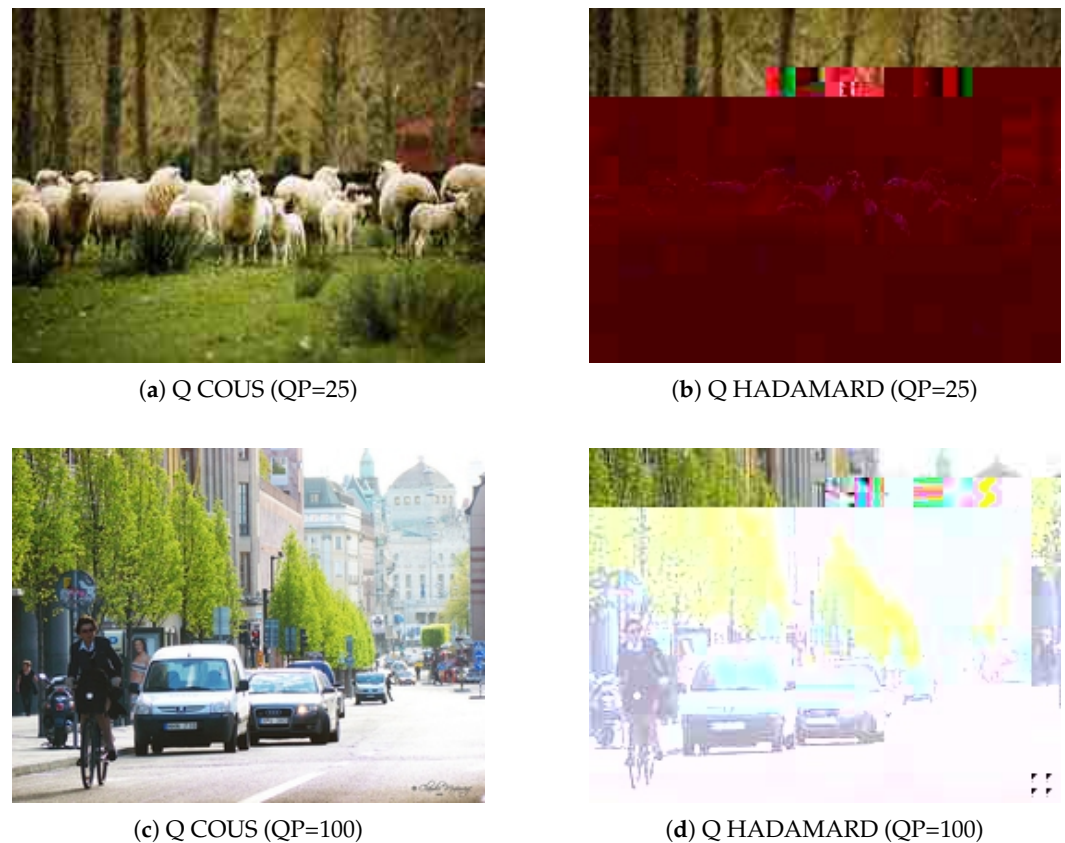


Figure 9. Decoded JPEG images at channel SNR = 0 dB.

4.1. Theoretical Analysis and Performance Advantages of COUS Encoding

The proposed COUS encoding framework introduces a fundamentally different representation of quantum information compared to conventional quantum encoding methods. While traditional approaches such as Hadamard encoding operate within a real-valued amplitude space, COUS extends the representation into a joint amplitude–phase domain, thereby increasing the expressive capability of quantum states.

Under ideal (noise-free) conditions, both Hadamard and COUS encoding schemes preserve orthogonality between encoded states due to the unitary nature of the transformations. For two normalized quantum states $|\psi_1\rangle$ and $|\psi_2\rangle$, the squared Euclidean distance (d) is given by Equation (32).

$$d^2 = \|\psi_1 - \psi_2\|^2 = 2 - 2 \operatorname{Re}\{\langle\psi_1|\psi_2\rangle\}. \quad (32)$$

Since $\langle\psi_1|\psi_2\rangle = 0$ for orthogonal states, both encoding schemes achieve the same minimum distance $d = \sqrt{2}$, as shown in (32). Therefore, COUS does not increase the classical minimum distance but instead provides advantages under realistic channel conditions.

In practical quantum communication systems, transmitted pure states are transformed into mixed states due to channel noise, which can be modeled by a quantum channel $\mathcal{N}(\cdot)$. In this context, system performance is determined by the distinguishability between the resulting noisy states, which is commonly quantified using the trace distance. As defined in Equation (33), the trace distance $D(\rho'_1, \rho'_2)$ measures the separation between two quantum states ρ'_1 and ρ'_2 , where $\|\cdot\|_1$ denotes the trace norm (i.e., the sum of the singular values of a matrix) and ρ'_1 and ρ'_2 represent the noisy density matrices corresponding to different transmitted states.

$$D(\rho'_1, \rho'_2) = \frac{1}{2} \|\rho'_1 - \rho'_2\|_1 \quad (33)$$

The proposed COUS encoding enhances state distinguishability by embedding information across both amplitude and phase components of the quantum state. Unlike conventional real-valued encoding schemes, COUS utilizes the complex Hilbert space, enabling partial preservation of information even when noise affects one component. As a result, the degradation in trace distance after transmission is reduced, leading to improved state separability and more reliable decoding under realistic noise conditions. Consequently, the decoding process relies on maximizing the distinguishability defined in (33) after the channel transformation.

The key distinction between COUS and conventional Hadamard encoding lies in the structure of the encoded quantum states. Hadamard encoding produces real-valued superposition states, as shown in Equations (3) and (4), thereby confining information to a single (real) dimension of the Hilbert space. In contrast, COUS encoding generates complex-valued states, as shown in Equations (13) and (14), distributing information across both amplitude and phase components.

This dual-domain representation provides enhanced robustness under realistic noise conditions. In practical quantum channels, noise processes such as amplitude damping, phase damping, and depolarizing effects simultaneously perturb both magnitude and phase. Since COUS encoding distributes information across these components, degradation in one domain does not completely eliminate the encoded information, thereby preserving distinguishability between quantum states. Consequently, the effective trace distance in (33) remains higher compared to conventional quantum encoding approaches.

This advantage can be interpreted as a form of amplitude–phase diversity, analogous to classical communication systems where the use of in-phase and quadrature components improves noise resilience. From a geometric perspective, this behavior can be visualized on the Bloch sphere, where COUS-encoded states occupy orthogonal axes due to their phase components, whereas Hadamard-encoded states remain confined to a single plane and are therefore more susceptible to noise-induced perturbations. When extended to a three-qubit encoding framework, these benefits become more pronounced. Although both COUS and Hadamard encoding utilize the same number of qubits, COUS produces complex-valued entangled states that maintain greater separation under noisy conditions, resulting in improved decoding reliability without increasing system complexity. These theoretical advantages are reflected in the experimental results. The COUS-based system consistently achieves higher PSNR, SSIM, and UQI values across all SNR levels, demonstrating improved preservation of structural details and perceptual quality. In particular, under low SNR conditions, the proposed method significantly reduces reconstruction artifacts, highlighting its enhanced robustness to channel impairments.

4.2. Hardware Implementation, Complexity, and Latency Analysis

The proposed COUS gate for a single qubit is defined as $G_{\text{COUS}} = S \cdot H \cdot S$. In the three-qubit QEC system, this transformation is applied independently to each qubit, allowing fully parallel execution. Each qubit requires three single-qubit operations, resulting in a total of $3 \times 3 = 9$ gates, while the circuit depth remains constant, $D = O(1)$, due to parallelism. This shallow depth minimizes decoherence and cumulative errors, and the encoding simultaneously exploits both amplitude and phase information, enabling robust image transmission over noisy quantum channels. In contrast, conventional Hadamard-based encoding applies a single Hadamard gate per qubit, requiring a total of 3 gates and a depth of $D = O(1)$ when applied in parallel. Simpler, Hadamard encoding only modulates amplitude, resulting in lower noise resilience and reduced fidelity. Overall, although COUS uses three times more gates per qubit than the Hadamard scheme, its fully parallelizable structure ensures low latency, with execution time approximately $T_{\text{latency}} \approx t_{\text{gate}} \cdot D$, where

t_{gate} is the duration of a single-qubit gate. The fixed gate count and constant depth make COUS highly practical for three-qubit quantum error correction, achieving superior fidelity and robustness without significant hardware overhead.

4.3. Scalability

The COUS encoding-based three-qubit QEC framework can be naturally extended to larger, multi-qubit QEC systems. For a logical block of m qubits, where $m \in \{5, 7, 9\}$, each qubit undergoes three single-qubit operations, resulting in a total gate count of $N_{\text{gates}}^{(m)} = 3 \cdot m$. Because the COUS gates are applied independently to each qubit, the circuit depth remains constant, $D^{(m)} = O(1)$, ensuring that cumulative errors remain low and fidelity is preserved even as block size increases. In comparison, Hadamard-based multi-qubit encoding requires only one gate per qubit, $N_{\text{gates,HAD}}^{(m)} = m$ with a circuit depth of $D_{\text{HAD}}^{(m)} = O(1)$, but it does not exploit phase information, which limits noise resilience. The benefits of COUS encoding grow with block size. With 5, 7, or 9 qubits, information is distributed across multiple orthogonal components, improving distinguishability and robustness to noise without increasing circuit depth. The resulting latency remains low, approximately $T_{\text{latency}}^{(m)} \approx t_{\text{gate}} \cdot D^{(m)} \approx t_{\text{gate}} \cdot O(1)$, where t_{gate} denotes the duration of a single-qubit gate. This indicates that the COUS encoding scales efficiently for high-dimensional multi-qubit QEC schemes, maintaining low computational complexity and minimal processing delay. Consequently, the proposed framework achieves robust, low-latency, and high-fidelity quantum image transmission, making it well-suited for future large-scale quantum communication systems.

4.4. Practical Feasibility of COUS Encoding

The proposed COUS encoding scheme is designed with practical implementation considerations in mind, particularly for near-future quantum communication systems. Unlike complex quantum encoding strategies that require deep circuits or multi-qubit entanglement, COUS relies solely on standard single-qubit operations. Specifically, the transformation $G_{\text{COUS}} = S \cdot H \cdot S$ is composed of fundamental gates that are natively supported in superconducting, trapped-ion, and photonic quantum platforms. From a circuit perspective, COUS requires only three single-qubit gates per qubit, applied in parallel, resulting in a constant circuit depth $O(1)$. This property is critical for noisy, intermediate-scale quantum (NISQ) devices, where decoherence and gate errors increase with circuit depth. Compared to Hadamard-based encoding, COUS introduces only a modest increase in gate count while providing significantly improved robustness through joint amplitude-phase encoding. The framework is further integrated with a three-qubit QEC structure, which is among the simplest and most experimentally feasible error mitigation techniques. Unlike large-scale QEC codes that require substantial qubit overhead and deep circuits, the three-qubit scheme maintains low complexity and has been demonstrated in multiple experimental platforms. In addition, COUS encoding has a natural physical interpretation in photonic systems. The resulting complex-valued superposition states correspond to circular polarization modes, which are widely used in optical quantum communication. This allows direct mapping of the proposed encoding onto existing hardware without requiring new physical encoding mechanisms.

4.5. Simulation Framework and Validation

The proposed system is implemented within a numerical simulation framework developed in Python 3.13, utilizing NumPy for efficient linear algebra operations. All experiments are conducted on a computing system equipped with an Intel Core i5-1345U processor (1.60 GHz) and 16 GB of RAM, ensuring sufficient computational resources

for simulation execution and performance evaluation. Rather than relying on external quantum software development kits such as Qiskit or Cirq, the proposed framework models quantum operations directly using their mathematical representations. Specifically, quantum gates (e.g., Hadamard, phase, Pauli operators, and the COUS gate) are implemented as unitary matrices, while quantum states are represented as complex-valued vectors, enabling precise and flexible simulation of the quantum system. The simulation primarily follows a state-vector-based approach for unitary evolution, while quantum noise is modeled using a density matrix formulation via Kraus operators for bit-flip, phase-flip, depolarizing, amplitude damping, and phase damping channels. The overall pipeline includes classical bitstream generation from compressed images, mapping to quantum basis states, application of encoding operations, noise injection, quantum decoding with error correction, and reconstruction of the classical bitstream. To ensure reproducibility and fairness, all stochastic components are controlled using a fixed random seed (seed = 42), which guarantees deterministic and repeatable generation of noise weights, channel realizations, and Monte Carlo trials. This ensures that identical channel conditions are applied across all encoding schemes, enabling a fair comparison. This hybrid state-vector and density-matrix simulation approach is computationally efficient for small-scale systems such as three-qubit QEC while maintaining physical accuracy. The adopted methodology is consistent with standard practices in early-stage quantum communication research, where mathematical simulations are used prior to hardware implementation.

It is important to note that the hardware required for implementing large-scale, COUS-encoding-based, three-qubit QEC communication systems is still in the early stages of development. By performing simulations first, we can validate system design, explore scalability, and optimize encoding strategies without the constraints of nascent quantum hardware. This approach provides a practical, low-cost, and safe methodology to predict performance and guide future experimental implementation. Overall, the simulation-based study serves as a valid and necessary precursor to hardware realization, offering insights into robustness, error resilience, and scalability of the COUS-encoding-based, three-qubit QEC framework in realistic channel conditions.

4.6. Potential Applications and Implications

The proposed COUS-encoding-based, three-qubit QEC framework offers significant potential across a range of applications where high-fidelity and efficient data transfer is critical. By encoding information simultaneously in amplitude and phase while employing three-qubit QEC schemes, the system provides robust performance even under low SNR and noisy channel conditions.

Potential applications include:

- **Quantum-secured multimedia transmission:** High-quality images and video can be transmitted over quantum networks with enhanced error resilience, making the framework suitable for confidential communications in governmental, medical, and defense sectors.
- **High-fidelity remote sensing and imaging:** The robustness of the proposed method to channel noise ensures reliable delivery of satellite, aerial, and scientific imaging data, even under adverse transmission conditions.
- **Future quantum networks:** As large-scale quantum internet infrastructure develops, proposed method provides a scalable approach for transmitting classical information over quantum channels, bridging the gap between classical and quantum communication technologies.
- **Efficient, error-resilient cloud computing:** Quantum image processing applications can benefit from low-latency, high-fidelity transmission between distributed quantum nodes.

Beyond specific applications, the implications of this work extend to the broader design of practical quantum communication systems. The demonstrated scalability, low-latency execution, and robust performance highlight a pathway toward experimentally realizable quantum networks capable of handling high-dimensional data. Moreover, insights gained from simulation-guided design can inform the development of future hardware, error correction techniques, and adaptive encoding strategies, accelerating progress in the emerging field of quantum information technologies.

5. Conclusions and Future Work

In this study, we presented a novel quantum image transmission framework that integrates COUS encoding with a three-qubit QEC scheme. By preserving both amplitude and phase information, the COUS encoding enhances reconstruction fidelity while maintaining low complexity and practical scalability. The proposed system effectively protects compressed images, using either JPEG or HEIF standards, against quantum channel noise and decoherence. Extensive simulations demonstrate that the COUS-encoding-based three-qubit QEC framework consistently outperforms conventional Hadamard-encoding-based three-qubit QEC schemes and classical polar-coded systems under equivalent bandwidth conditions. Performance gains are observed across multiple metrics, including PSNR, SSIM, and UQI, with maximum channel SNR improvements of up to 6 dB compared to conventional Hadamard-encoding-based, three-qubit QEC schemes and 12 dB over classical polar-coded communication. The results collectively validate the robustness, low-latency execution, and scalability of the proposed approach, highlighting its potential as a practical solution for high-fidelity quantum image communication. Overall, the proposed COUS-encoding-based, three-qubit QEC framework for image transmission provides a robust, scalable, and low-complexity foundation for future high-fidelity quantum communication systems.

For future work, several directions can be explored to further enhance the proposed framework. The current approach can be extended to higher-qubit QEC schemes, enabling improved error resilience under more challenging channel conditions. In addition, adaptive multi-qubit encoding strategies can be developed to dynamically adjust the encoding process based on channel state information, thereby improving both transmission efficiency and robustness. Further improvements can be achieved by integrating advanced error mitigation techniques, including hybrid classical–quantum coding approaches, which have the potential to reduce error rates and enhance overall reconstruction quality. Another promising direction is the extension of the proposed framework to high-dimensional video transmission and multi-user quantum communication networks. Although video transmission introduces additional challenges, such as real-time processing and temporal consistency, these can be addressed by applying the proposed pipeline on a frame-by-frame basis with parallel and low-latency processing. By incorporating efficient video coding and adaptive transmission mechanisms, the framework can be made scalable and suitable for future large-scale quantum multimedia communication systems.

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Abbreviations

COUS	Complex-Valued Orthogonal Unitary Superposition
HEIF	High-Efficiency Image Format
JPEG	Joint Photographic Experts Group
LDPC	Low-Density Parity Check
MIMO	Multi-Input Multi-Output
PSNR	Peak Signal-to-Noise Ratio
QEC	Quantum Error Correction
QFT	Quantum Fourier Transform
QKD	Quantum Key Distribution
QP	Quantization Parameter
SNR	Signal-to-Noise Ratio
SSIM	Structural Similarity Index Measure
UQI	Universal Quality Index

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