Electronics Letters

LETTER OPEN ACCESS

Image Transmission Over Quantum Communication Systems With Three-Qubit Error Correction

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Received: 27 July 2024 | **Revised:** 31 December 2024 | **Accepted:** 3 March 2025

ABSTRACT

Quantum communication offers unparalleled reliability and efficiency, making it a promising solution for high-quality media transmission. To explore this potential, we propose a quantum communication system for image transmission, addressing the challenges of transmitting high-quality image data over error-prone channels. A crucial aspect of advancing this field is quantum channel coding, specific to quantum systems. Therefore, this research evaluates the performance of low-complex three-qubit quantum error correction code for image transmission over noisy channels. JPEG and HEIF images are encoded using three-qubit error correction method and compared to 1/3 rate polar codes with equivalent bandwidth. Results show that the three-qubit error correction code significantly outperforms advanced classical polar codes in both classical and quantum domains, achieving a maximum PSNR of 64.5 dB (SSIM = 0.9997) in HEIF and 58.3 dB (SSIM = 0.9994) in JPEG. These findings underscore its potential as a robust solution for quantum communication in media transmission.

1 | Introduction

Quantum communications represent a revolutionary advancement in the field of information and communication technology, leveraging principles of quantum mechanics to provide an alternative paradigm for reliable, efficient and secure data transmission. As classical communication technologies are reaching their saturation point, quantum communication is poised to become the primary communication process, overcoming the inherent limitations of classical systems. Therefore, researchers worldwide are dedicating their efforts to advancing various aspects of quantum communication, addressing challenges, and exploring the full potential of quantum technologies.

One critical area of application for quantum communication is media transmission, which is becoming increasingly essential in today's data-driven world. Within this context, image transmission, particularly in compressed formats, plays a vital role. Compressed image data is highly correlated, making it especially vulnerable to noise and errors. Even a single bit error can propagate throughout the data, leading to significant degradation in image quality. Classical error correction methods, while effective to some extent, require high levels of redundancy to ensure error-free transmission. This approach is often impractical in bandwidth-constrained scenarios.

The unique properties of quantum channel codes offer a promising alternative, leveraging quantum principles to address the challenges of noise and error propagation in image transmission. These methods ensure data fidelity while minimizing redundancy, aiming to achieve similar objectives to classical channel coding but tailored specifically for quantum channels. This is a critical concern because quantum communication systems are highly susceptible to errors caused by decoherence, noise, and other quantum-specific disturbances. Such errors can significantly degrade the fidelity of transmitted quantum information, making error correction an essential component for practical quantum communication systems. However, directly adapting classical error correction techniques for quantum communication is challenging due to the no-cloning theorem [1], which

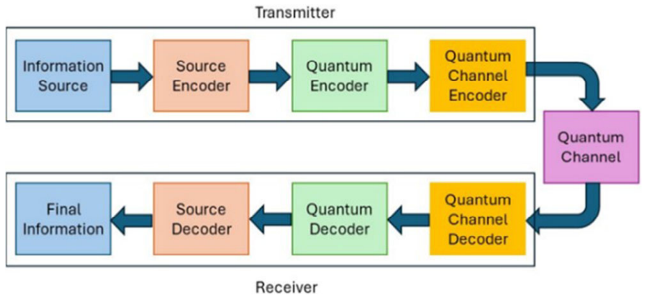

FIGURE 1 | End-to-end quantum communication system with three-qubit error correction method.

prohibits the duplication of quantum states in the same way classical bits can be copied.

Nevertheless, several quantum error correction codes have been proposed, reflecting significant progress in addressing errors in quantum computation. The initial breakthroughs in quantum error correction introduced the concept of using multiple qubits to protect a single qubit against various types of errors. For instance, the Shor code demonstrated that nine qubits could safeguard a single qubit [2], while the Steane code employed seven qubits for the same purpose [3]. Following these foundational works, many other error correction codes were developed, including the three-qubit error correction code [4], the five-qubit error correction code [5], the surface code [6], and stabilizer codes [7].

Among these, the three-qubit error correction code is the most fundamental and simplest method, capable of detecting and correcting a single qubit error. The effectiveness of the three-qubit error correction code has been extensively investigated in the context of quantum computing [8–10]. However, despite these advances, none of these methods have been analysed as channel coding techniques for their effectiveness in quantum communication processes involving image transmission, as they were originally developed for quantum computation. Also, current research predominantly focuses on secure quantum communication applications, such as quantum key distribution (QKD) [11] and quantum teleportation [12], and their applications in secure media transmission [13]. However, the development of quantum communication methods specifically designed for efficient and high-quality media transmission remains limited.

In this research, we focus on analysing the performance of the low-complex three-qubit quantum error correction code in the context of image transmission using quantum communication over error-prone channels. To investigate its capabilities, images are encoded using the joint photographic experts' group (JPEG) codec and the higher efficiency image format (HEIF). These images are then channel-coded using the three-qubit error correction method in the quantum communication process. We compare its performance in quantum channels against rate 1/3 polar codes [14] in both quantum and classical channels under equivalent bandwidth. Simulation results clearly show that three-qubit error correction code can significantly outperform rate 1/3 polar codes over both quantum and classical systems in terms of peak signal-to-noise ratio (PSNR), structural similarity index measure (SSIM) and universal quality index (UQI).

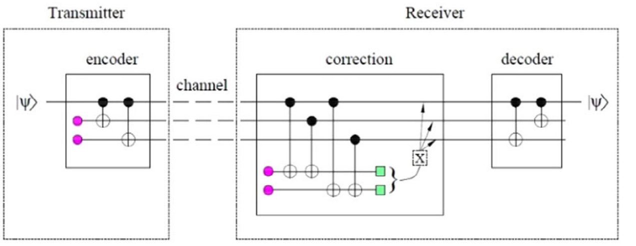

FIGURE 2 | Encoding and decoding process of the three-qubit error correction method.

Therefore, the key novel contributions of this paper are:

- Analyse the performance of the three-qubit error correction code in quantum communication for image transmission.
- Compare its performance against modern classical error correction methods in the quantum communication process.
- Propose a more robust quantum communication system for image transmission.

2 | Proposed Framework

The proposed quantum communication process with the three-qubit error correction code is illustrated in Figure 1.

In the proposed system, the information source comprises original images from the Microsoft COCO dataset [15], carefully selected to represent a diverse range of spatial information (SI) characteristics. These undergo initial processing using a source encoder (JPEG or HEIF), which compresses and formats the images into a stream of classical bits. These classical bits are then fed into a quantum encoder, which transforms them into qubits as we proposed in [16]. The uniqueness of this research lies in the quantum channel coding, where the three-qubit error correction method is used.

The encoding and decoding processes of the three-qubit code can be represented as shown in Figure 2. The initial quantum information is represented by $|\psi\rangle$, which is the general superposition state corresponding to $|0\rangle$ or $|1\rangle$. In the three-qubit quantum channel coding process, each qubit is encoded into three qubits. Therefore, the three-qubit general superposition state can be generated using two additional $|0\rangle$ qubits.

The state of the three qubits before the controlled not (CNOT) gates can be represented as shown in Equation (1).

$$\alpha\,|000\rangle + \beta\,|100\rangle \tag{1}$$

Here α and β are probability amplitudes [16]. Then the first CNOT gate is applied from the first qubit to the second qubit, and the second CNOT gate is applied from the first qubit to the third qubit. The final state after the CNOT gates is represented in Equation (2).

$$\alpha\,|000\rangle + \beta\,|100\rangle \rightarrow \alpha\,|000\rangle + \beta\,|110\rangle \rightarrow \alpha\,|000\rangle + \beta\,|111\rangle \tag{2}$$

TABLE 1 | Relationship between the received state, position of the error and ancilla state.

Received state	Position of the error	Ancilla state
$\alpha\|000\rangle + \beta\|111\rangle$	No error	$\|00\rangle$
$\alpha\|100\rangle + \beta\|011\rangle$	Error in first qubit	$\|11\rangle$
$\alpha\|010\rangle + \beta\|101\rangle$	Error in second qubit	$\|10\rangle$
$\alpha\|001\rangle + \beta\|110\rangle$	Error in third qubit	$\|01\rangle$
$\alpha\|110\rangle + \beta\|001\rangle$	Error in first two qubits	$\|01\rangle$
$\alpha\|101\rangle + \beta\|010\rangle$	Error in first and third qubits	$\|10\rangle$
$\alpha\|011\rangle + \beta\|100\rangle$	Error in last two qubits	$\|11\rangle$
$\alpha\|111\rangle + \beta\|000\rangle$	Three-qubit error	$\|00\rangle$

TABLE 2 | Action to correct errors.

Measured syndrome	Action to correct errors
00	No need to correct
01	Apply Pauli x gate to the third qubit
10	Apply Pauli x gate to the second qubit
11	Apply Pauli x gate to the first qubit

This three-qubit superposition state can be sent through a noisy quantum channel, which introduces noise into it. We use a simple quantum channel model to simulate the process, applying random quantum noise at different variance levels [17]. This leads to eight possible states to be received, as shown in Table 1.

In the error correction process, as in Figure 2, two additional qubits in the $|00\rangle$ state, called ancilla bits, can be employed to detect errors more efficiently and gather noise information. Using CNOT gates, the first and second qubits are connected with the first ancilla bit, and the first and third qubits with the second ancilla bit. This transforms the ancilla qubits into specific states, as represented in Table 1. The ancilla qubits are then measured, producing two classical bits based on Table 2, which are used to diagnose and correct any errors in the qubits.

In the three-qubit channel decoder, a CNOT gate is applied from the first qubit to the third qubit, and another from the first qubit to the second qubit to retrieve the original qubit's superposition state, as depicted in Figure 2.

This theoretical process is simulated using matrix representations. The tensor product is used to calculate matrices for multi-qubit systems, with $|0\rangle$ and $|1\rangle$ matrices, which are shown in Equations (3) and (4).

$$|0\rangle = (1\ 0)^T \tag{3}$$

$$|1\rangle = (0\ 1)^T \tag{4}$$

TABLE 3 | Received states and corresponding matrices.

Received vectors	Corresponding matrices
$\frac{1}{\sqrt{2}}(\|000\rangle +/- \|111\rangle)$	$(1\quad 0\quad 0\ 0\quad 0\quad 0\ 0 +/-1)^{\mathrm{T}}$
$\frac{1}{\sqrt{2}}(\|001\rangle +/- \|110\rangle)$	$(0\quad 1\quad 0\ 0\quad 0\quad 0 +/-1\ 0)^{\mathrm{T}}$
$\frac{1}{\sqrt{2}}(\|010\rangle +/- \|101\rangle)$	$(0\quad 0\quad 1\ 0\quad 0 +/-1\ 0\ 0)^{\mathrm{T}}$
$\frac{1}{\sqrt{2}}(\|100\rangle +/- \|011\rangle)$	$(0\quad 0\quad 0 +/-1\quad 1\quad 0\ 0\ 0)^{\mathrm{T}}$

Also, three-qubit multiple systems can be generated as in Equations (5) and (6).

$$|000\rangle = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{pmatrix}^{\mathrm{T}} \tag{5}$$

$$|111\rangle = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0 & 0 & 0 & 0 & 0 & 0 & 0 & 1\end{pmatrix}^{\mathrm{T}} \tag{6}$$

Then, the three-qubit superposition state $\alpha|000\rangle + \beta|111\rangle$ is mapped to a matrix S as shown in Equation (7).

$$S = \alpha\,(10000000)^{\mathrm{T}} + \beta\,(00000001)^{\mathrm{T}} \tag{7}$$

At the receiver, the received matrix is compared with eight possible received state matrices. By analysing the signs of the values, the results are mapped to eight possible state matrices corresponding to binary values 0 and 1, as illustrated in Table 3.

By analysing the received 8×1 matrices and matching it with the corresponding matrix, we map the result to either $|0\rangle$ or $|1\rangle$. After this single-qubit extraction, the qubits are converted to classical bits and used to reconstruct the image. To evaluate the performance of the three-qubit error correction method, we compare it with a classical channel model that uses binary phase-shift keying (BPSK) modulation and rate 1/3 polar codes. These code rates and modulation scheme are chosen in order to maintain a similar bandwidth utilisation in both systems. This comparison helps assess how the quantum error correction method performs relative to a classical channel coding system under similar conditions. Additionally, the results of the three-qubit error correction method are compared with the 1/3 code rate polar codes within a quantum communication setup to analyse the performance of classical error correction methods in the quantum domain compared to quantum error correction.

The performance of image transmission in this three-qubit channel-coded quantum communication system is analysed using average PSNR, SSIM and UQI, which are widely accepted quality matrices in analysing the quality of reconstructed images in image coding and transmission.

3 | Results and Discussion

This study analyses the performance of the three-qubit error correction method in quantum communication and compares it

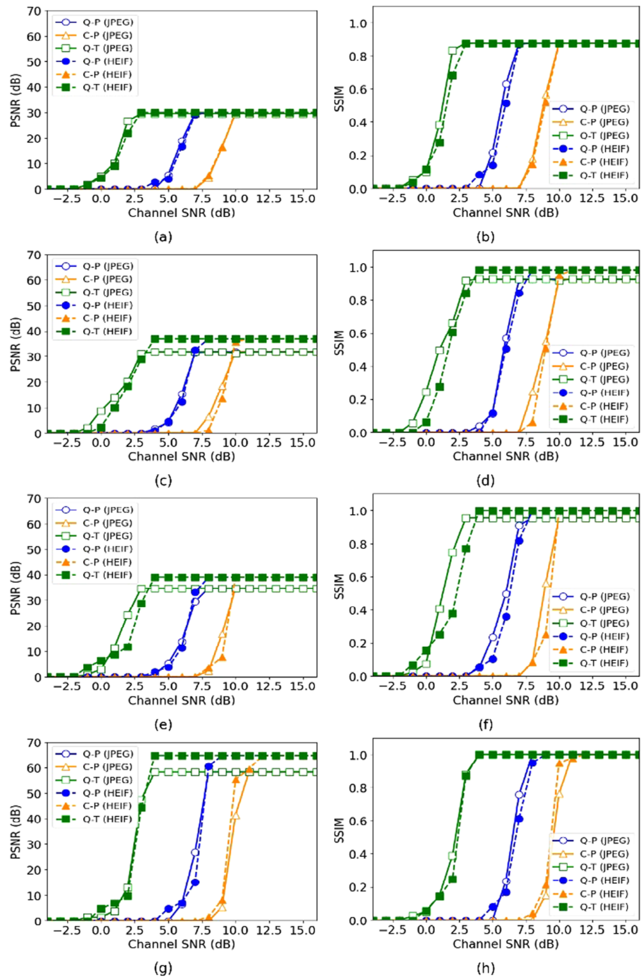

FIGURE 3 | Average PSNR and SSIM variation of the test images for different Q values ($Q = 25, 50, 75,$ and 100) for quantum communication with three-qubit codes (*Q*-T), quantum communication with polar codes (*Q*-P), and classical communication with polar codes (C-P) for JPEG and HEIF image formats: (a) *Q*25 - PSNR, (b) *Q*25 - SSIM, (c) *Q*50 - PSNR, (d) *Q*50 - SSIM, (e) *Q*75 - PSNR, (f) *Q*75 - SSIM, (g) *Q*100 - PSNR, and (h) *Q*100 - SSIM.

with 1/3 code rate polar codes in both classical and quantum domains. Figure 3 illustrates the variation in PSNR and SSIM of decoded images at different channel signal-to-noise ratios (SNR) for JPEG and HEIF images across various quantisation (Q) parameters (*Q*25, *Q*50, *Q*75, and *Q*100), ranging from low quality to very high quality. The three-qubit quantum approach's superior performance is evident across all Q values, indicating its robustness in preserving image quality under high noisy conditions. Additionally, the UQI variation with channel SNR, as shown in Figure 4 for all Q values, further validates the proposed method's superiority compared to classical error correction-based quantum communication systems and classical communication systems. Moreover, the performance consistency between HEIF and JPEG images suggests that the three-qubit error correction method's advantages are applicable across different image source coding formats, reinforcing its potential as a versatile solution for high-fidelity image transmission using quantum communications.

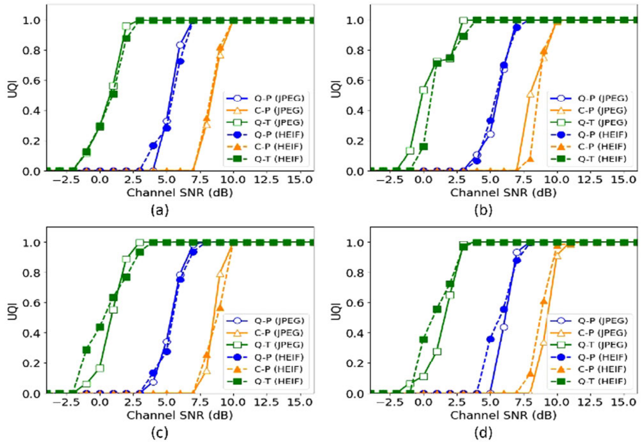

FIGURE 4 | Average UQI variation of the test images for different Q values ($Q = 25, 50, 75,$ and 100) for quantum communication with three-qubit codes (*Q*-T), quantum communication with polar codes (*Q*-P), and classical communication with polar codes (C-P) for JPEG and HEIF image formats: (a) *Q*25, (b) *Q*50, (c) *Q*75, and (d) *Q*100.

Our findings demonstrate that the three-qubit error correction code, when combined with the unique properties of quantum superposition, surpasses classical error correction methods in the quantum domain. This highlights its significant potential to preserve pixel values and spatial corelation, ensuring accurate image reconstruction. Unlike polar codes, which are widely recognized for their low-complexity in classical channel coding, the three-qubit quantum approach achieves even lower complexity for image transmission by representing classical bits as three-qubit superposition states without increasing bandwidth requirements.

While this study employs a basic quantum communication system, it serves as an essential starting point for investigating more advanced systems. Simulations indicate the importance of incorporating advanced channel coding techniques, including concatenated, stabilizer, and surface codes, to further enhance error correction. Also, future efforts will focus on designing more robust new quantum channel coding techniques to improve the reliability and fidelity of quantum communication systems, particularly for transmitting images and videos over realistic quantum channels. Additionally, video transmission using three-qubit error correction will be analysed in future studies. Such advancements are expected to accelerate the adoption of quantum communication technologies for practical applications in media transmission and beyond.

4 | Conclusion

A key obstacle for the widespread acceptance of quantum communication systems as a viable alternative for classical communication systems is the unavailability of effective error correction methods for quantum channel coding. This challenge is particularly evident in media transmission. As a solution for this problem, we propose the use of three-qubit error correction codes to improve the quality and the fidelity of the images transmitted over noisy channels. We demonstrate that the three-qubit error correction code significantly outperforms rate 1/3 polar codes in both quantum and classical domains by offering better PSNR (64.5 dB-HEIF and 58.3 dB-JPEG), SSIM (0.9997-HEIF and 0.9994-JPEG) and UQI (HEIF-0.9999, JPEG-0.9998) across various image quality levels and formats. Its robustness in maintaining image quality under very low channel SNR conditions underscores its effectiveness. While this research utilizes a basic quantum communication system with a simple quantum channel coding method, it provides a foundation for exploring advanced quantum error correction techniques for media transmission. Future research should focus on exploring more advanced quantum channel coding methods to enhance quantum communication technologies for practical, real-world applications.

Author Contributions

Udara Jayasinghe: conceptualization, methodology, programming, writing – original draft. **Prabhath Samarathunga**: programming. **Thanuj Fernando**: visualization, review. **Yasith Ganearachchi**: review and editing. **Anil Fernando**: supervision, formal analysis, investigation, review.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the 'Coco Data Set' at [COCO—Common Objects in Context (cocodataset.org)] (http://cocodataset.org), reference number 15.

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