Adaptive coding based quantum communication system for image transmission over error-prone channels

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Abstract

Adaptive coding in quantum communication offers a promising approach to enhance the efficiency and reliability of data transmission using quantum superposition, particularly in noisy and error-prone channels. This study investigates the effectiveness of quantum communication combined with adaptive coding for compressed image transmission using Joint Photographic Experts Group (JPEG) codec and High Efficiency Image Format (HEIF) with polar codes at varying rates. To maintain a similar bandwidth, the source coding rates are adjusted according to the channel coding rates. The results show that the adaptive coding based quantum communication system significantly outperforms equivalent classical systems, especially at low signal-to-noise ratios (SNR), achieving Peak Signal-to-Noise Ratio (PSNR) improvements up to 65 dB and Structural Similarity Index Measure (SSIM) values up to 0.9999 for HEIF images and PSNR values up to 58 dB with SSIM values up to 0.9994 for JPEG images. These findings demonstrate the superior robustness and higher image quality of adaptive coding based quantum communication in varying channel noise conditions and bandwidth restricted applications.

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Adaptive coding in quantum communication offers a promising approach to enhance the efficiency and reliability of data transmission using quantum superposition, particularly in noisy and error-prone channels. This study investigates the effectiveness of quantum communication combined with adaptive coding for compressed image transmission using Joint Photographic Experts Group (JPEG) codec and High Efficiency Image Format (HEIF) with polar codes at varying rates. To maintain a similar bandwidth, the source coding rates are adjusted according to the channel coding rates. The results show that the adaptive coding based quantum communication system significantly outperforms equivalent classical systems, especially at low signal-to-noise ratios (SNR), achieving Peak Signal-to-Noise Ratio (PSNR) improvements up to 65 dB and Structural Similarity Index Measure (SSIM) values up to 0.9999 for HEIF images and PSNR values up to 58 dB with SSIM values up to 0.9994 for JPEG images. These findings demonstrate the superior robustness and higher image quality of adaptive coding based quantum communication in varying channel noise conditions and bandwidth-restricted applications.

Introduction: Quantum communication is a groundbreaking technology that leverages quantum properties such as superposition [1] and entanglement [2] to overcome limitations of classical communication such as channel capacity and noise distortion, enabling more efficient and reliable data transmission. Image transmission is an increasingly important area where reliable transmission over capacity-limited and noisy channels has become a necessity, with many remote sensing applications which operate in such conditions requiring image capture and transmission. Classical communication systems typically experience drastic performance degradation under such noisy conditions, resulting in significant drops in received image quality. Due to the exploitation of pixel correlation in image compression schemes, such as the Joint Photographic Experts Group (JPEG) codec and the High Efficiency Image Format (HEIF), which are used for efficient image transmission, they are highly susceptible to errors caused by channel noise.

Channel coding schemes, which add redundancy to the compressed bitstream, are employed to overcome this challenge. These schemes enable detection and correction of bitstream errors up to an extent but come at the cost of adding complexity and increasing the required bandwidth. Common channel coding schemes include low density parity check (LDPC) codes, turbo codes, and polar codes. However, polar codes [3] are widely used in modern classical communication systems due to their efficiency in coding and superior error tolerance compared to other classical channel coding methods.

However, since most communication channels are time-variant, channel conditions change with time and thus create variance in the noise that affects signals transmitted through the channel. In such a situation, the use of a constant channel coding rate is neither efficient nor effective. Adaptive coding techniques [4] have emerged as effective solutions to optimise the system performance under such conditions. By dynamically adjusting the coding rate in response to real-time channel conditions, adaptive coding improves data transmission efficiency, ensuring optimal utilisation of available bandwidth. Multiple studies have explored adaptive coding in the realm of classical communication systems [5], [6], [7], but research on its application in quantum communication remains limited [8].

Notably, there is a significant gap in studies focusing on adaptive coding for end-to-end quantum communication, specifically aimed at image transmission. While a few studies have explored media transmission using quantum communication with quantum entanglement [9], [10], and quantum communication with quantum superposition, which has been shown to be highly effective for high-quality and reliable media transmission [11], none have utilised adaptive coding in this domain. This underscores the need for further exploration, as adaptive coding has the potential to significantly enhance the performance of quantum communication systems, especially in error-prone environments.

Therefore, this study investigates the performance of adaptive coding for image transmission in quantum communication with quantum superposition, specifically focusing on JPEG and HEIF image compression schemes. We use polar codes to implement an adaptive channel coding method, employing varying code rates to assess their impact on transmission quality. By examining the effects of channel noise on image transmission, we demonstrate the superior capabilities of the proposed quantum communication based model over the equivalent classical communication based model when combined with adaptive coding strategies. The findings highlight the potential of this innovative approach to meet the growing demand for bandwidth in media transmission while providing efficient, robust, and reliable solutions to the challenges posed by real-time channel noise in modern communication systems.

Proposed Framework: The proposed framework for implementing an end-to-end quantum communication system with adaptive coding is depicted in Figure 1.

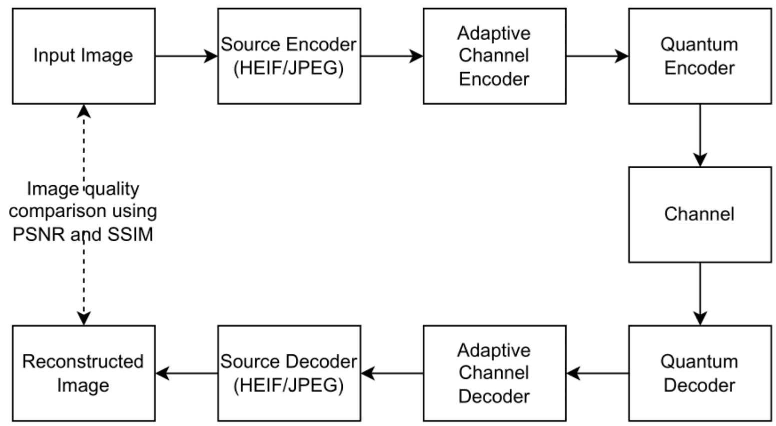


Fig. 1 Proposed end-to-end quantum communication system with adaptive coding for image transmission.

In this study, images with varying spatial information (SI) characteristics are used as an information source. These images are first compressed using either the JPEG or HEIF source encoding methods, converting them into classical bitstreams. For channel coding, polar codes with rates of 2/3, 1/2, 1/3 and 1/4 are considered and these channel coding rates are adaptively changed based on the channel conditions. To maintain a similar bandwidth, source coding rates (quality levels) are adjusted in the source coding process. By varying the quality level in response to different channel coding rates, the overall bitrate remains constant across the channel. Once the classical bitstreams are channel encoded, they are converted into qubit superposition states and these qubit states are then transmitted through the quantum communication channel. At the receiver, quantum measurement operators are applied to convert the received qubit states back into classical bits. After this, the appropriate channel decoding process is performed, corresponding to the applied polar coding rate. Finally, the recovered classical bitstream undergoes source decoding (JPEG or HEIF), reconstructing the final images. The following subtopics explain the details of each part of the proposed framework.

Information Source : In our experiment, a set of eleven images from the Microsoft Common Objects in Context (COCO) dataset [12] is used as the source of data, serving as foundational test images for the study. These images represent a range of spatial features that are considered essential for demonstrating the impact of the proposed framework.

Source Encoder : The selected images are compressed using two different source encoding methods: HEIF and JPEG. JPEG is widely used for lossy compression of digital images, while HEIF offers better compression efficiency and higher image quality. To evaluate the proposed system in a bandwidth-restricted environment, the HEIF and JPEG source coding rates are adjusted according to the channel coding rates, ensuring that the system's throughput remains nearly constant. After compression, the images are converted to classical bitstreams, sequences of binary data ready for further processing.

Channel Encoder : For channel coding, polar codes are employed with specific rates: 2/3, 1/2, 1/3, and 1/4. Polar codes are a type of error correction code that is known for its capacity-achieving properties and can efficiently handle noise in communication channels. The different rates indicate varying levels of redundancy and error-correcting capabilities, which influence the robustness of the encoded data.

Quantum Encoder : The Hadamard gate is a fundamental quantum operation that creates superposition states, where classical bits are transformed into qubits superposition. This transformation allows the classical information to be transmitted through a quantum communication channel. This process is similar to the method that we proposed in our previous work [11].

Channel : The qubits superposition states are then sent through the quantum communication channel.

Unlike classical channels, quantum channels are characterized by the properties of quantum mechanics. But in this process, we use a simple channel model to simulate the quantum channel with varying signal-to-noise ratios (SNR), based on the concept that the behaviour of quantum channels under different SNR conditions can be evaluated using a classical channel with equivalent SNR conditions up to a certain level of noise [13].

Quantum Decoder : At the receiver's end, quantum measurement operators are applied to the received qubit states as described in [11]. These operators collapse the qubit superposition states back into classical bits. Measurement in quantum mechanics is the process by which quantum information is retrieved from qubits and converted into a format that can be processed by classical systems.

Channel Decoder : The classical bits recovered from quantum measurement are then subjected to channel decoding processes that correspond to the polar coding rates used during encoding. This step involves applying the appropriate decoding algorithm to correct any errors and reconstruct the bitstream accurately.

Source Decoder : Finally, the recovered classical bitstream undergoes source decoding using the same method employed during the source encoding phase (JPEG or HEIF). This step reconstructs the final images from the bitstreams, effectively reversing the compression and encoding processes to retrieve the images as they were before transmission.

To demonstrate the proposed quantum communication system for image transmission, we analyse the average performance of the input images across different SNR conditions and coding rates. By dynamically varying the channel noise, we select the optimal channel coding rate for a given channel SNR of the adaptive coding system.

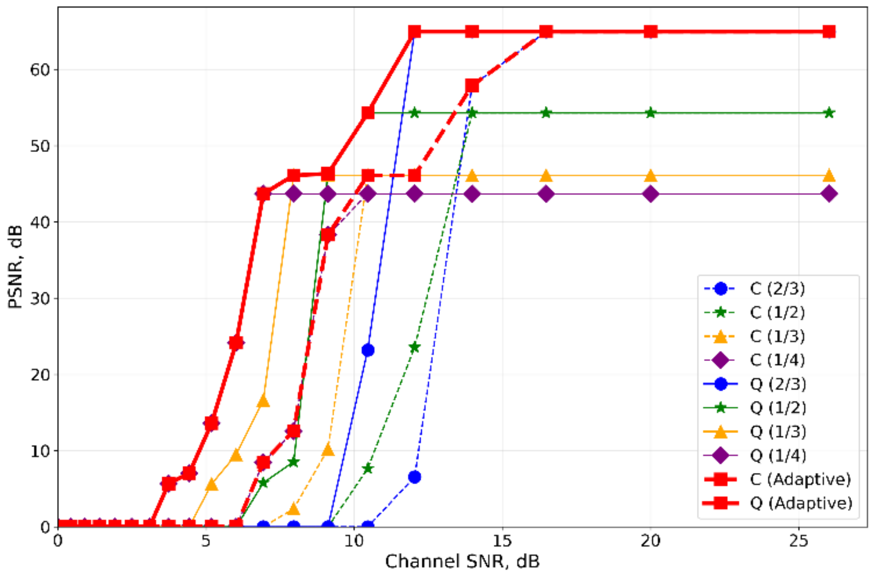
To ensure a fair comparison with the proposed adaptive coding based quantum communication system, an equivalent classical communication system is employed using the same channel coding rates and binary phase-shift keying (BPSK) modulation. This approach helps maintain consistent bandwidth across both methods. The Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index Measure (SSIM) values are computed for images reconstructed using both adaptive coding based quantum and the classical communication systems. These metrics provide quantitative measures of image quality, allowing for a direct comparison of performance between the two systems. By analysing the PSNR and SSIM results, the study assesses the effectiveness of the proposed adaptive coding based quantum communication system relative to the equivalent classical system, identifying advantages in terms of image quality and overall performance.

Results and Discussion: This research focuses on comparing the performance of adaptive coding based quantum communication systems with adaptive coding based classical communication systems. The results reveal significant insights into how each system adapts to varying SNR levels, particularly in terms of image quality and error resilience. Furthermore, both HEIF and JPEG image formats are analysed to understand their performance in these communication systems.

The analysis of PSNR for the HEIF image format, as shown in Figure 2, reveals that adaptive coding offers substantial benefits in preserving signal quality across varying SNR levels. Both quantum (Q) and classical (C) systems exhibit notable improvements when adaptive coding is employed, outperforming their non-adaptive counterparts. Notably, the adaptive coding based quantum system exhibits significantly higher PSNR values compared to the adaptive coding based classical system, particularly in the lower SNR range (below 16 dB). This trend is particularly evident, as the proposed quantum communication system achieves a rapid increase in PSNR starting around 4 dB SNR, indicating its robust performance under noisy conditions.

The results also show that the highest PSNR values achieved with high polar coding rates are lower than those obtained with low polar coding rates due to the bandwidth-restrictive conditions imposed during implementation. However, adaptive coding implementations in both quantum and classical communications can mitigate this issue by switching to higher quality values when the channel SNR improves, as the required optimum polar coding rate decreases.

Therefore, as the SNR increases beyond 16 dB, both systems achieve high PSNR values, reaching up to 65 dB. Notably, the earlier rise in PSNR for the proposed quantum system at low SNR (4-12 dB) demonstrates its capability to maintain high-quality transmission under less-than-ideal conditions.



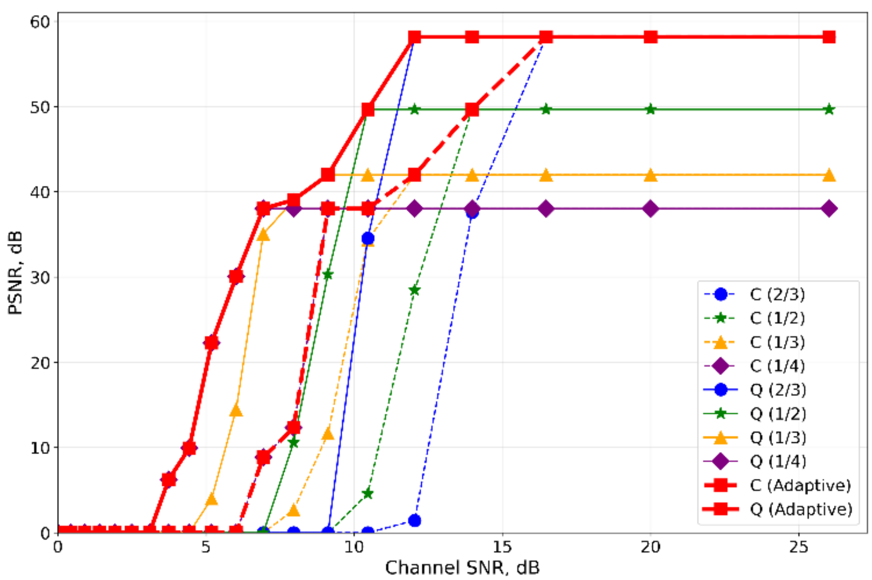


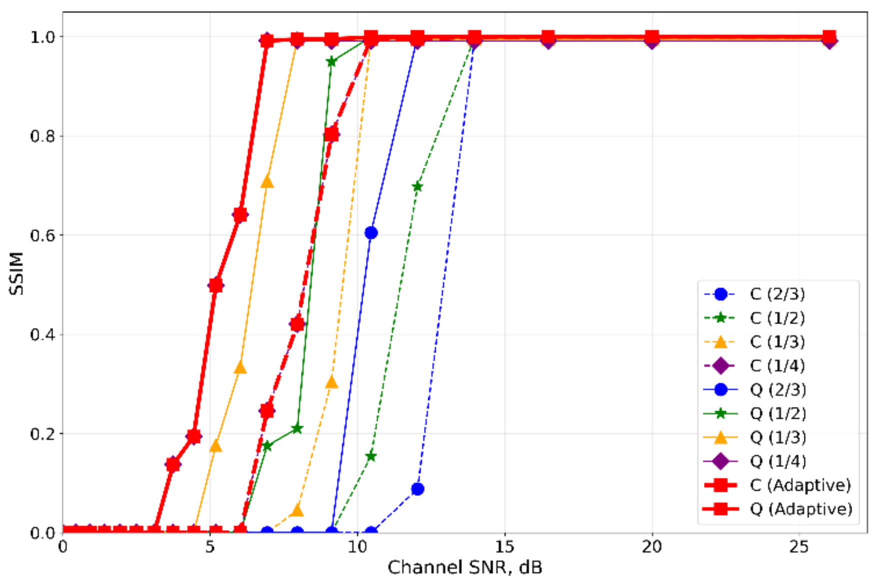
*Fig.***2** *Variation in average PSNR for HEIF encoded images across different polar coding rates for classical (C) and quantum (Q) systems*

Fig. **3** *Variation in average PSNR for JPEG encoded images across different polar coding rates for classical (C) and quantum (Q) systems*

In contrast, as shown in Figure 3, the PSNR values for JPEG images exhibit results similar to HEIF, indicating that the adaptive coding based quantum communication system outperforms the adaptive coding based classical communication system, achieving a PSNR value up to 58 dB. This suggests that JPEG generally achieves lower PSNR scores than HEIF across all SNR levels, highlighting that HEIF maintains superior image quality during transmission,

particularly in noisy environments. This further reinforces HEIF's efficiency in compression and resilience to transmission errors. Importantly, the use of this adaptive coding method allows us to achieve higher PSNR values and better error resilience compared to fixed-rate channel coding systems.

As shown in Figure 4, the SSIM analysis for HEIF image format further supports the findings of the PSNR evaluation. For HEIF images, the adaptive coding based quantum communication system reaches SSIM values nearing 0.9999 more quickly than the adaptive coding based classical system, demonstrating its superior ability to preserve structural details and overall image quality during transmission. This trend is especially pronounced in low SNR conditions (below 16 dB), where the proposed quantum system significantly outperforms the equivalent classical system. Similarly, as shown in Figure 5, for JPEG images, the proposed adaptive coding based quantum system reaches the maximum SSIM value of 0.9994 at an SNR of 12 dB, whereas the adaptive coding based classical system requires an SNR of 16 dB to achieve the same SSIM. This demonstrates the proposed quantum system's superior efficiency in preserving image quality, especially under challenging transmission conditions, further underscoring its ability to outperform the equivalent classical system across various formats.



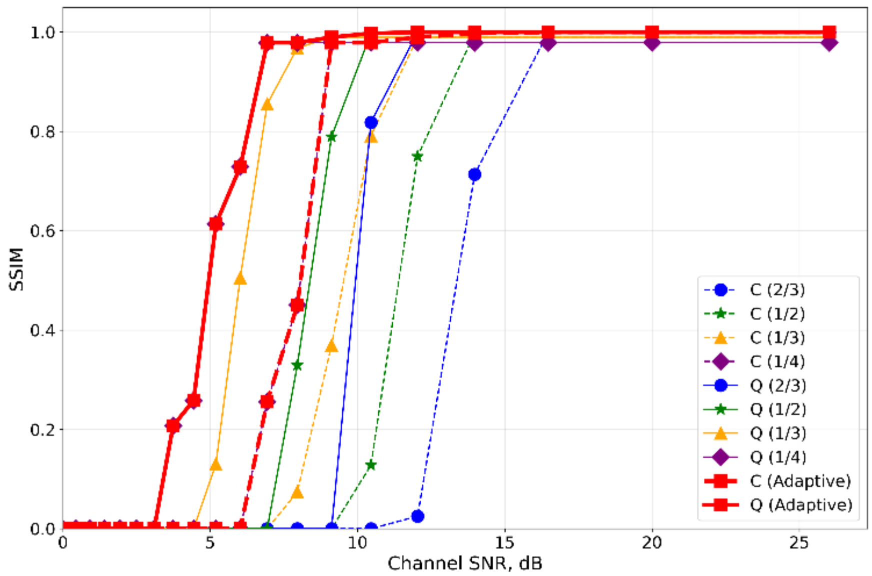


*Fig.***4** *Variation in average SSIM for HEIF encoded images across different polar coding rates for classical (C) and quantum (Q) systems*

Fig. **5** *Variation in average SSIM for JPEG encoded images across different polar coding rates for classical (C) and quantum (Q) systems*

Also, the benefits of the proposed adaptive coding based quantum communication system are particularly evident in scenarios where bandwidth is constrained, reinforcing the findings from the PSNR and SSIM analysis. Additionally, the inherent error correction mechanisms in superposition-based quantum communication systems [11] provide a significant advantage in enhancing resilience to channel noise and transmission errors. Although the adaptive coding based classical communication system also benefits from adaptive coding, it struggles more with performance degradation in low SNR environments compared to its quantum counterpart. This trend further supports the superior performance of the proposed quantum system, which effectively addresses many of the challenges faced by equivalent classical communication systems. Therefore, the proposed adaptive coding based quantum communication system is particularly well-suited for real-world applications where unpredictable channel noise can severely affect transmission quality.

Future research should focus on developing adaptive coding strategies with quantum channel codes to further optimise performance in various transmission scenarios. Investigating how adaptive coding can be further refined in conjunction with advanced quantum channel coding techniques could lead to significant improvements in error resilience and overall data integrity. Additionally, exploring the integration of these adaptive coding methods with emerging quantum communication protocols will be essential to move towards practical applications of quantum communication systems. Moreover, it is crucial to analyse the performance of these systems for video transmission, as this would provide valuable insights into their efficiency and robustness in handling high-bandwidth media, especially since a significant portion of media traffic transmitted over communication systems consists of videos.

Conclusion: This study highlights the superior performance of adaptive coding based quantum communication systems compared to equivalent classical communication systems, particularly under challenging low SNR conditions. The proposed quantum system demonstrates exceptional noise resistance, achieving PSNR improvements up to 65 dB and SSIM values up to 0.9999 for HEIF images, and PSNR values up to 58 dB with

SSIM values up to 0.9994 for JPEG images, while outperforming the equivalent classical system, especially at low SNR levels. This shows that quantum communication not only retains image quality more effectively but also outperforms classical methods in maintaining signal integrity, even when transmission conditions are less than ideal. The efficient utilisation of bandwidth and the effective error correction mechanisms inherent in the quantum communication system further enhance its performance, making it particularly suitable for applications that require high signal integrity. Overall, this study highlights the significant potential of quantum communication techniques to improve image transmission quality in challenging environments, demonstrating their potential for real-world implementations where media transmission systems must operate in bandwidth-restricted environments.

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