# Quantum Communications for Image Transmission over Error Prone Channels

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Introductions of quantum communications, enabled by advancements in quantum computing, is expected to play a significant role in the field of communications. Inherent properties of quantum objects, such as superposition and entanglement have the potential to provide novel solutions to overcome the challenges encountered by classical communication systems in bandwidth-intensive applications such as media transmission. This research explores the performance of a quantum communication system in image transmission using quantum superposition and investigates its performance using a simple quantum channel model. With increase of channel noise, there are significant gains in the rate distortion performance of images transmitted over the quantum channel, compared to an ideal classical channel. This novel attempt in constructing a quantum communication-based image transmission system indicates the potential of the approach to be applied to satisfy the ever-increasing demands of high-quality media transmission applications.

*Introduction:* Quantum technology has attracted significant attention in the recent past as an alternative way to transmit the information in ever increasing wireless communication applications. Advancement of quantum computing which utilise unique properties of quantum mechanics to improve efficiency and reliability of data transmission are ushering in a new era in the field of communication [1]. Superposition, which is the ability of a quantum particle to exist in multiple states simultaneously [2,3] and entanglement, where correlated quantum particles can exchange their properties with other particles without distance being a barrier [4], are the two main paradigms explored for implementation of quantum communication systems, as either of these can be used to encode information into quantum states. Several quantum communication systems have been developed based on entanglement, such as quantum key distribution (QKD) [5] and quantum teleportation [6]. However, quantum superposition has not yet been directly used to implement an end-to-end quantum communication system.

Information in quantum communication systems is carried by qubits, which are the quantum equivalent to bits in conventional communication systems, and they can exist in multiple states at the same time until a measurement or observation is made. Using this concept, we propose a novel superposition-based quantum communication system for transmitting images through error-prone channels. The approach aims not only to leverage the intrinsic efficiency of quantum communication [7], but also to address bandwidth constraints faced by conventional communication systems. To investigate the capabilities of the proposed quantum communication system, images are coded by the Joint Photographic Experts Group (JPEG) codec and the Higher Efficiency Image Format (HEIF) and channel coded using polar codes [8] before they are communicated through the proposed superposition-based quantum communication system.

*Related Work:* Quantum communication has grown with entanglement, but using superposition directly is still largely unexplored, holding great potential for new, advanced communication methods.

Quantum superposition plays a crucial role in communication tasks, as practically demonstrated in [9], highlighting the benefits of using superpositions in quantum communication protocols. This concept not only reveals the advantages, but also contributes to a more profound understanding of quantum communication systems.

Impact of quantum superposition on communication complexity is specifically examined by [10] introducing a communication task that illustrates how leveraging quantum superposition in communication direction enables a substantial reduction in communication requirements.

The research in [11] explores no-signalling channels that transform quantum systems within the local laboratories of Alice and Bob. These channels adhere to two distinct causal structures. Research demonstrates that initially indistinguishable no-signalling channels in standard quantum circuits can become perfectly distinguishable by employing the quantum superposition of circuits with varying causal structures. This finding underscores the unique capability of quantum superposition to enhance the distinguishability of channels that would otherwise be indistinguishable in the context of no-signalling communication.

However, none of the proposed systems have used superposition directly to create an end-to-end quantum communication system for information transmission. In response, this paper proposes a novel quantum communication system grounded in superposition to transmit images over error-prone channels with error correction codes.

*Proposed Framework:* Figure 1 illustrates the proposed framework for image transmission using an end-to-end quantum communication system.

A diagram of a channel decoder

Description automatically generated

Fig. 1 End-to-end information transmission system using quantum communications

The source of information represents the origin of the data or the message that initiates the communication process. In our experiment, we used test images sourced from the Microsoft Common Objects in Context (COCO) dataset as an information source [12].

The source encoder plays an important role in the communication process by taking information, often represented as a bitmap of pixels, and compressing it through the reduction of statistical redundancies. For our experiment, we used the Joint Photographic Experts Group (JPEG) codec and the High Efficiency Image Format (HEIF) as the chosen source encoding methods. The quantisation (Q) parameters applied during the encoding phase which determine the size of the encoded images. Lower Q values result in higher quantisation, leading to more information loss when image decoding. In our experiment, we explore a range of Q values (25, 50, 75, and 100) to represent various levels of image compression achieved through the classical source encoder. During the experimentation, polar codes are used as an error correction channel code [13], as they are very efficient and theoretically well-supported system in the realm of communications, and here has been extended to make it work for both classical and quantum communication processes. The polar code rate, measured by of the ratio between the number of information bits that are transmitted or encoded (K) and the total number of bits sent over the channel, including both information and redundancy bits (E) determine the level of protection provided by the channel coding scheme. In this research, we used E=256, K=128 for a coding rate of 1:2 (two encoded bits for each input bit) to analyse the performance of the quantum model.

The quantum encoder is the key element within the quantum communication system, which converts classical information (in bits) into quantum states suitable for transmission through the quantum channel. Through the utilisation of specific quantum states, classical bits, denoted 0 and 1, can be transformed into quantum bits, or qubits, within our proposed quantum communication framework. In practical terms, the quantum state |0⟩ corresponds to the classical bit 0, while the quantum state |1⟩ corresponds to the classical bit 1. The application of matrix formalism in quantum mechanics becomes instrumental in describing the quantum encoding process. The matrices outlined in (1) and (2) are employed to represent qubits in this context.

(1)

(2)

The Hadamard operator [14] is applied during the quantum encoding process. This transformation introduces the concept of quantum superposition, enabling the representation of information in a quantum superposition form. Consequently, qubits gain the ability to exist in states 0 and 1 simultaneously, thereby providing a quantum advantage in the representation and transfer of information. The matrix shown in (3) illustrates the Hadamard gate, which mathematically operates on a single qubit in this context.

H = (3)

When the Hadamard gate operates in the basis state |0⟩, it transforms into the superposition state , as shown in (4). Similarly, when applied to the basis state |1⟩, it becomes the superposition state , as indicated in (5).

(4)

(5)

While classical communication systems have been extensively researched and accurately modelled using empirical measurements to construct channel models, the exploration of quantum channels in quantum communication systems is still in its primitive stages. Currently, there is a lack of widely accepted models to simulate quantum channels effectively. As a result, we employ a simple channel model to simulate the quantum channel, introducing the impact of channel noise by incorporating random quantum noise across various noise variance levels.

To establish a baseline for comparison, we use an equivalent classical channel model, subjecting it to the same noise variance levels. Binary phase-shift keying (BPSK) modulation is employed as the encoding method to compare against the quantum encoding approach since it matches the symbol rate of the proposed quantum communication system.

The quantum decoder involves employing appropriate quantum measurement operators to perform measurements, revealing the classical information initially encoded by the quantum encoder. In quantum communication, this measurement process employs projective operators corresponding to observables, determining probabilistic outcomes, and revealing insights into the probabilistic nature of the quantum world.

The post-measurement state, denoted as |⟩, is determined by the measured outcome, as shown in (6), involving a normalization process.

(6)

In quantum measurement techniques, frequently used measurement operators are defined as outer products, as shown in (7) and (8).

*M0* = |0⟩⟨0| (7)

*M1* = |1⟩⟨1| (8)

Let’s take the *M0* measurement operator as an example. It effectively guides the projection of superposition states onto the |0⟩ state following the measurement process, as detailed in (9), (10), and (11).

(9)

(10)

(11)

The *M1* operator can also be employed to extract classical information from qubits, following a similar procedure as outlined above. In our research, both measurement operators were applied independently to superposition states. By examining the phase of the output value, we assign these states to classical 0 and 1. The equivalent classical decoding process involves utilising the respective decoders to reconstruct the images at the receiving end. The performance of image transmission is assessed using rate distortion metrics of the Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM) between the input image and the output images from either system.

*Results and Discussion:* We explored the practical use of the superposition principle in quantum communication, particularly its effect on the transmission of JPEG and HEIF images with polar codes over a noisy channel.Figure 2 represents the variation of PSNR and SSIM of the decoded image with different signal to noise ratio (SNR) of the channel for JPEG images with various quantization parameters (Q25, Q50, Q75, Q100). The quantum approach shows significantly better rate distortion performance in terms of both PSNR and SSIM, suggesting it is much more effective at preserving image quality at low SNR compared to the classical approach. Across all Q values, the quantum approach significantly outperforms the classical approach in terms of both PSNR and SSIM. This indicates that the quantum approach could potentially be a superior method for image transmission in error-prone channels, especially in scenarios where maintaining high image quality is critical.

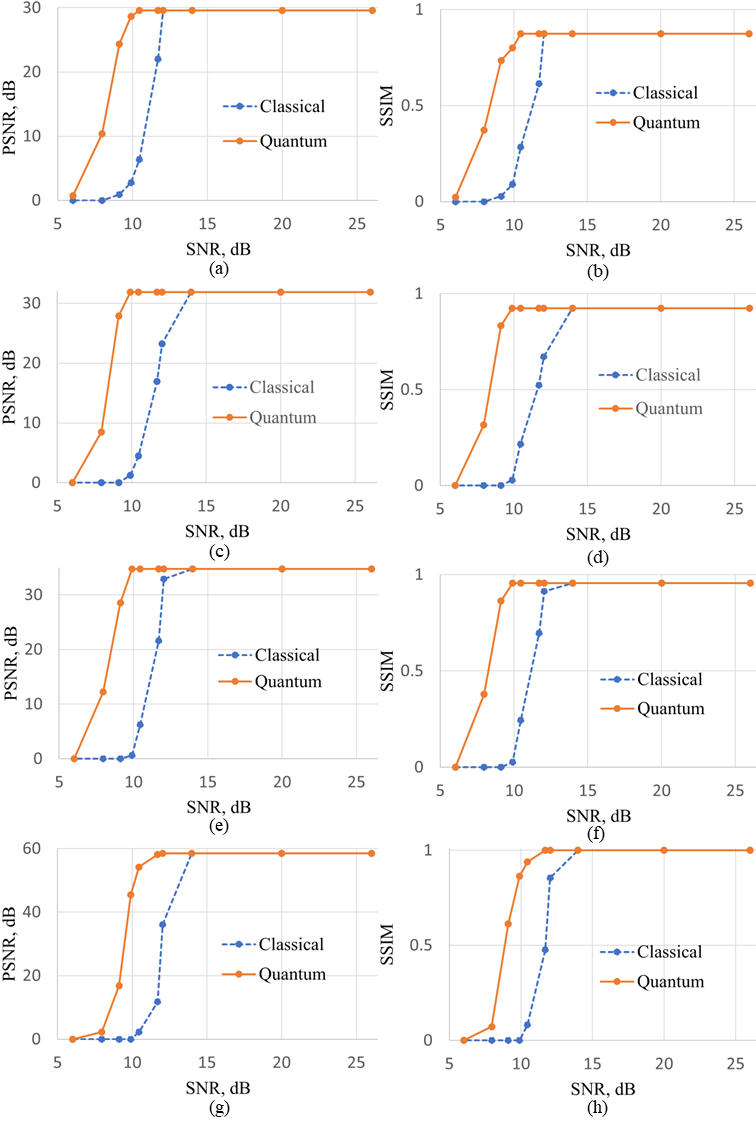


Fig. 2 Rate distortion performance measured by averaged PSNR and averaged SSIM of the test images over classical and quantum channels for different quality levels (Q = 25,50,75,100) and JPEG image compression format with polar code rate 0.5(a) Q25-PSNR (b) Q25- SSIM (c) Q50- PSNR (d) Q50- SSIM (e) Q75-PSNR (f) Q75- SSIM (g) Q100- PSNR (h) Q100- SSIM

 Sample of decoded images (JPEG) from the experiment for Q = 100 and SNR 10.45 dB using classical and quantum communication are represented in Figure 3.

Fig. 3 Sample of a decoded images (JPEG) from the experiment for Q = 100 and SNR 10.45 dB (a) JPEG over classical modulation, (b) JPEG over quantum modulation

Figure 4 compares the performance of classical and quantum systems in terms of PSNR and SSIM for HEIF encoded images under different quantisation parameters (Q25, Q50, Q75, Q100). It has similar performance compared to the previous JPEG ones, supporting the conclusion that the quantum system's advantage over the classical system is consistent across different image source coding formats.

A graph of different types of data

Description automatically generated with medium confidence

Fig. 4 The rate distortion performance was measured by averaged PSNR and averaged SSIM of the test images over classical and quantum channels for different quality levels (Q = 25,50,75,100) and the HEIF image compression format with polar code rate 0.5 (a) Q25-PSNR (b) Q25-SSIM (c) Q50-PSNR (d) Q50-SSIM (e) Q75-PSNR (f) Q75- SSIM (g) Q100- PSNR (h) Q100- SSIM

Our investigation is to explore a practical use of the superposition principle in quantum communications, and it reveals a significant potential for future exploration. Although we employed a basic quantum communication system in this study, it is a foundation to build more complex quantum systems which can be compared with more elaborate classical systems as well as to develop more comprehensive models for quantum channels and accurately simulate quantum noise. Such advances will pave the way for applying this concept in real-world scenarios alongside the application of quantum computing in mainstream technology.

Despite showing superior performance compared to traditional channels the quantum channel, remains prone to errors from environmental noise and decoherence. These issues can lead to a reduction in signal quality and a loss of important information. Implementing quantum error correction codes, optimised for quantum modulation techniques and channels, similar to classical channel codes, could mitigate these errors and improve the transmission fidelity of quantum information. Thus, the development of quantum channel coding emerges as a crucial area for future research to enable the use of quantum communication systems for media transmission, as shown with image transmission in our study.

In terms of computational complexity, quantum signal encoding shares similarities with existing classical modulation techniques, such as quadrature amplitude modulation (QAM). Nonetheless, further studies are necessary to assess and benchmark its performance against classical methods. Optimising quantum communication schemes will also require a deeper understanding of the nature of the quantum channel.

*Conclusion*: Quantum communications, enabled by developments in quantum computing, is an exciting new field that is gaining wide interests having the potential to overcome limitations of conventional communication systems. This study to investigates the application of quantum superposition and a quantum communication channel for image transmission over a noisy channel. In simple channel-state simulations, it is observed that the quantum system is better at reducing rate distortion, compared with its classical analogies, especially for small SNR values (which correspond to larger noise variances) and associated channel errors at the presence of a channel coding system. The performance improvement can mainly be attributed to the added resilience to noise that the symbols inherit from the properties of quantum superposition. This underscores the potential of quantum communications to overcome the limitations of classical communication frameworks, but also highlight that further investigations of quantum modulation schemes and properties of the quantum channel are needed to fully harness its potential.

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