Quantum communications for image transmission over error-prone channels

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The introduction 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 an increase in 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 at 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 information in ever-increasing wireless communication applications. The advancement of quantum computing, which utilises unique properties of quantum mechanics to improve efficiency and reliability of data transmission, is ushering in a new era in the field of communication. Superposition, which is the ability of a quantum particle to exist in multiple states simultaneously [1, 2] and entanglement, where correlated quantum particles can exchange their properties with other particles without distance being a barrier [3], are the two main paradigms explored for the 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) [4] and quantum teleportation [5]. 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 [6], 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 [7] before they are communicated through the proposed superposition-based quantum communication system.

Related work: Quantum communication has advanced with entanglement, but using superposition directly is still largely unexplored, holding great potential for new, advanced communication methods. However, the effectiveness of quantum superposition in communication tasks has been mainly investigated previously [8]. Specifically, they introduced a task that demonstrates the advantages of employing superposition, contributing to a deeper understanding of quantum communication protocols. Additionally, the impact of quantum superposition on communication complexity has been examined in previous works [9, 10], which introduced a communication task illustrating how leveraging quantum superposition in the direction of communication enables a substantial reduction in communication requirements.

Several works related to entanglement have advanced quantum communication for various purposes, such as QKD. It is a secure method for exchanging information or encryption keys exclusively known to shared and trusted parties. This technique implements a cryptographic protocol incorporating quantum mechanics components [11]. Additionally, an entanglement-based novel method for securely transmitting images has been developed in reference [12], ensuring that any eavesdropper is detected, similar to the principles of QKD.

However, none of the limited 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.

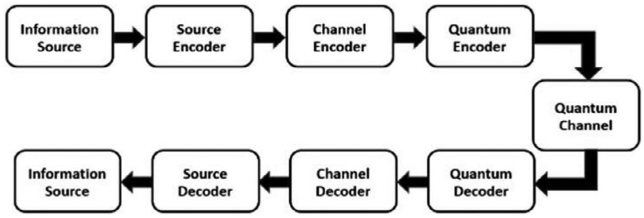

Fig. 1 *End-to-end information transmission system using quantum communications*

Proposed framework: The proposed framework for image transmission using an end-to-end quantum communication system is illustrated in Figure 1. The source of information represents the origin of the data or the message that initiates the communication process. In our experiment, test images sourced from the Microsoft Common Objects in Context (COCO) dataset are used as an information source [13].

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, JPEG and HEIF codecs are used as the chosen source encoding methods. The quantisation (Q) parameters are applied during the encoding phase, which determines 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 with a code rate of 0.5 are used as an error correction channel code, as they are a 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 quantum encoder is the key element within the quantum communication system, which converts classical 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 $|0\rangle$ corresponds to the classical bit 0, while the quantum state $|1\rangle$ 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.

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{1}$$

$$|1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{2}$$

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 quantum superposition form. Consequently, qubits gain the ability to exist in states 0 and 1 simultaneously, thereby providing a quantum advantage

Table 1. Modulating schemes for classical and quantum communication

Scheme	Bits	Symbols
Classical (e.g. BPSK)	0	1
	1	−1
Quantum (e.g. Hadamard gate)	0	$1/\sqrt{2}\,(\lvert 0\rangle + \lvert 1\rangle)$
	1	$1/\sqrt{2}\,(\lvert 0\rangle - \lvert 1\rangle)$

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.

$$\mathrm{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{3}$$

When the Hadamard gate operates in the basis state $|0\rangle$, it transforms into the superposition state $\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)$ as shown in (4). Similarly, when applied to the basis state $|1\rangle$, it becomes the superposition state $\frac{1}{\sqrt{2}}(|0\rangle-|1\rangle)$ as indicated in (5).

$$\mathrm{H}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \tag{4}$$

$$\mathrm{H}\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix} \tag{5}$$

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. It has been demonstrated that any noisy quantum channel can be simulated by a corresponding classical channel with the same level of noise [15]. This is a significant finding, as it bridges the gap between classical and quantum communication theory. As shown in Table 1, to establish a baseline for comparison, we use an equivalent classical channel model subjected to the same noise variance levels. Binary phase-shift keying (BPSK) modulation is employed as the baseband transmission method for encoding. This allows for a comparison against the quantum encoding approach since BPSK matches the symbol rate of the proposed quantum communication system. In the quantum approach, symbols are modulated into a superposition state using the Hadamard operator.

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 $|\psi'\rangle$, is determined by the measured outcome, as shown in (6), involving a normalization process.

$$|\psi'\rangle = \frac{M_m\,|\psi\rangle}{\sqrt{\left\langle \psi \left| M_m^{\dagger} M_m \right| \psi \right\rangle}} \tag{6}$$

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

$$M_0 = |0\rangle\langle 0| \tag{7}$$

$$M_1 = |1\rangle\langle 1| \tag{8}$$

Let us take the M_0 measurement operator as an example. It effectively guides the projection of superposition states onto the $|0\rangle$ state following the measurement process, as detailed in (9).

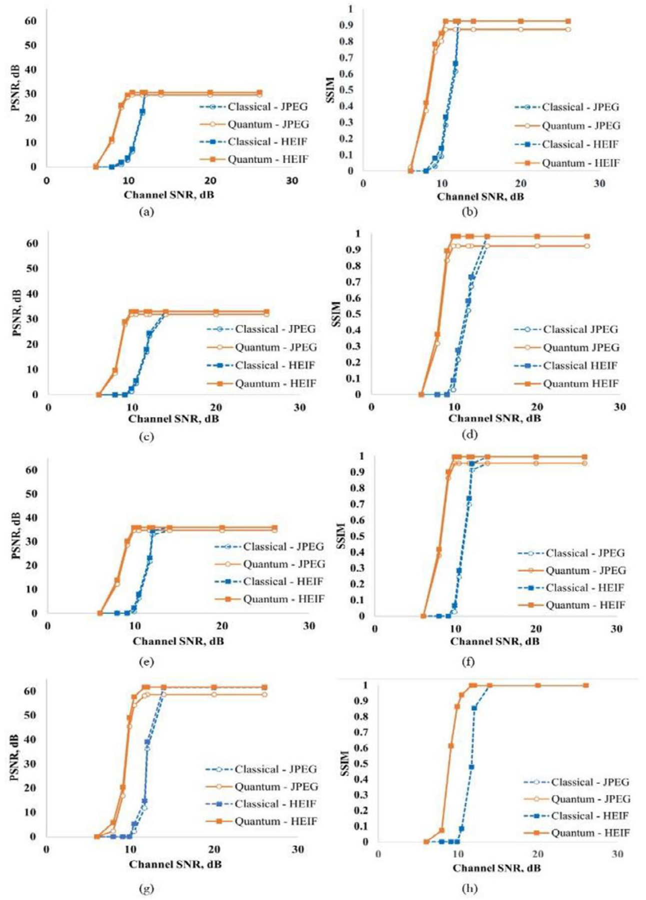

Fig. 2 *Rate distortion performance measured by the averaged peak signal-to-noise ratio (PSNR) and averaged structural similarity index (SSIM) of the test images over classical and quantum channels for different* Q *values (*Q *= 25, 50, 75, and 100) and Joint Photographic Experts Group and Higher Efficiency Image Format image formats: (a) Q25 – PSNR, (b) Q25 – SSIM, (c) Q50 – PSNR, (d) Q50 – SSIM, (e) Q75 – PSNR, (f) Q75 – SSIM, (g) Q100 – PSNR, (h) Q100 – SSIM*

$$|\psi'\rangle = \frac{|0\rangle\langle 0|\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)}{\sqrt{\left(\frac{1}{\sqrt{2}}\langle 0| + \frac{1}{\sqrt{2}}\langle 1|\right)(|0\rangle\langle 0|)\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)}} \tag{9}$$

$$|\psi'\rangle = \frac{\frac{1}{\sqrt{2}}|0\rangle}{\sqrt{\frac{1}{2}}} \tag{10}$$

$$|\psi'\rangle = |0\rangle \tag{11}$$

The M_1 operator can also be employed to extract classical information from qubits, following a similar procedure as outlined above. In our research, both measurement operators are 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 explore 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 images with different signal-to-noise ratios (SNR) of the channel for JPEG and HEIF images across various Q parameters (Q25, Q50, Q75, and 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

Fig. 3 *Sample of a decoded images (Joint Photographic Experts Group) from the experiment for* Q = *100 and SNR 10.45 dB: (a) classical and (b) quantum*

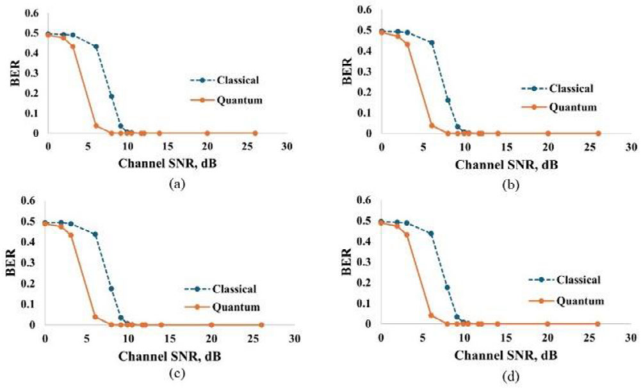

Fig. 4 *Bit error rate versus signal-to-noise ratio variations of Joint Photographic Experts Group format images for quantum and classical channels: (a) Q25, (b) Q50, (c) Q75, and (d) Q100*

to the classical approach. Across all Q values, the quantum approach significantly outperforms the classical approach in terms of both PSNR and SSIM. Additionally, HEIF images have similar performance compared to the JPEG ones, supporting the conclusion that the quantum system's advantage over the classical system is consistent across different image source coding formats.

A sample of decoded images (JPEG) from the experiment for $Q = 100$ and SNR 10.45 dB using classical and quantum communication is represented in Figure 3. Additionally, the variations of bit error rate (BER) with SNR for various Q values ($Q = 25$, 50, 75, and 100) for the JPEG format are presented in Figure 4.

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 employ 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 interest and has the potential to overcome the limitations of conventional communication systems. This study 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 in 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 highlights that further investigations of quantum modulation schemes and the properties of the quantum channel are needed to fully harness its potential.

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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 [13].

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