

Quantum Communication for Video Transmission over Error-Prone Channels

Udara Jayasinghe, *Graduate Student Member, IEEE,* Prabhath Samarathunga, *Graduate Student Member, IEEE,* Nimesh Pollwaththage, *Graduate Student Member, IEEE,* Yasith Ganearachchi, *Graduate Student Member, IEEE,* Thanuj Fernando, *Student Member, IEEE,* and Anil Fernando, *Senior Member, IEEE*

***Abstract*—Quantum communication offers transformative potential for media transmission by addressing the limitations of classical communication systems. To realize this potential, the study proposes a quantum communication framework for transmitting compressed videos over error-prone channels, leveraging quantum superposition. Two channel coding schemes are analyzed: quantum error correction (three-qubit, five-qubit, and seven-qubit codes) and classical error correction (1/3 rate polar code), all operating within the same bandwidth constraints. The proposed systems are benchmarked against a classical communication system using 1/3 rate polar codes. Results show that the three-qubit error correction-based quantum communication system, while simple and efficient, achieves significant performance gains over both classical error correction-based quantum and classical communication systems, with up to 41.42 dB in peak signal-to-noise ratio (PSNR), 0.9639 in structural similarity index measure (SSIM), and 94.4042 in video multimethod assessment fusion (VMAF). However, the five-qubit and seven-qubit systems outperform the three-qubit system, with the seven-qubit system surpassing all others in high noise environments, demonstrating its robustness across various group of pictures (GOP) formats. These findings highlight the trade-offs between simplicity and complexity, as the three-qubit system is practical and efficient, while the five-qubit and seven-qubit channel codes offer higher fidelity and resilience at the cost of increased complexity.**

***Index Terms*—Quantum channel codes, quantum communication, quantum error correction, quantum superposition, video transmission.**

I. Introduction

VIDEO accounts for a significant portion of global Internet traffic, and its share is expected to increase to more than 80% by 2028 [1]. This growth is not merely a consequence of more content being produced but also reflects the rising demand for immersive high-quality video experiences across multiple platforms, driven largely by consumer electronics [2]. The proliferation of various video applications, such as virtual reality (VR) [3] and extended reality (XR) [4], along with their associated devices, such as head-mounted displays and smart glasses, will make video an integral feature in many future consumer technology applications.

This surge in video content presents a significant challenge for wireless communication systems, especially as more consumers rely on mobile devices to access video content [5]. Consequently, there is increasing pressure on wireless communication infrastructures to deliver seamless, real-time video experiences on a wide range of consumer electronics devices [6]. However, as wireless communication systems approach their fundamental capacity limits, any increase in capacity from successive mobile communication standards tends to come at the expense of coverage. Thus, the development of alternative approaches to address these challenges, particularly in video transmission, has become a critical and timely requirement.

Real-time video transmission over wireless channels poses a substantial challenge to any communications system, primarily due to errors created by noise channel conditions. These challenges are exacerbated by error propagation due to the correlation of the data, particularly in compressed formats, where even a single bit error can cause significant disruption to successfully decode video frames, severely degrading the received video quality. Classically, this challenge is overcome by using channel coding schemes at the expense of a large amount of redundancy to ensure error-free transmission, which is not always feasible when bandwidth is restricted. Moreover, the limited error correction capabilities of classical channel codes create the challenge of differentiating between bits of varying significance, which contributes to a loss of quality during transmission. These inherent challenges underscore the need for more advanced transmission techniques to improve the quality and reliability of video received over classical channels.

Quantum communication, an emerging field enabled by recent advances in quantum mechanics and quantum computing [7], shows potential as a viable alternative to meet this requirement, especially through quantum superposition. Therefore, we propose novel video transmission systems that utilize quantum communication principles, specifically direct quantum superposition, to outperform comparable classical communication systems in error-prone channels, positioning this as the pioneering work in the quantum domain for efficient and high-quality video transmission. The proposed methods utilize two distinct channel coding approaches: quantum error correction codes, such as the three-qubit, five-qubit, and seven-qubit codes originally developed for quantum computing but not previously used for communication, and a classical error correction code, specifically the rate 1/3 polar code, employed as an innovative method to analyze performance within the quantum communication domain. In quantum channel coding

Manuscript received 02 November 2024; revised 05 December 2024; accepted DD MMMM YYYY. Date of publication DD MMMM YYYY; date of current version DD MMMM YYYY. *(Corresponding author: Anil Fernando.)*

The authors are with the Department of Computer and Information Sciences, University of Strathclyde, Glasgow G1 1XQ, UK (email: anil.fernando@strath.ac.uk).

Digital Object Identifier 10.1109/TCE.XXXX.XXXXXXX

approaches, video bitstreams are encoded into qubit superposition states through a quantum encoder. Then quantum error correction codes are applied to protect the qubits from transmission errors. After traversing a noisy quantum channel, the qubits are decoded using quantum channel decoding to identify and correct errors, and a quantum decoder reconstructs the original video bitstream. In the classical channel coding approach, video bitstreams are first encoded using classical error correction techniques before being converted to qubit superposition states for transmission. In the receiver, quantum decoding is used to recover the classical bitstream, which is then processed through classical channel decoding to accurately reconstruct the original video bitstream. Ultimately, both methods highlight the promise of quantum communication in delivering reliable video transmission under challenging conditions, addressing the specific needs of consumer electronics [8], and offering significant advantages over classical systems.

The key novelties of the proposed system are the following.

- Derive the mathematical representation of the end-to-end quantum communication systems with quantum superposition and quantum error correction.
- Demonstrate the effectiveness of the proposed quantum communication systems for real-time video transmission over error-prone channels.
- Compare the performance of quantum error correction-based quantum communication systems with that of a classical error correction-based quantum communication system.
- Assess the performance of the proposed quantum communication systems in comparison to a bandwidth-equivalent classical communication system.

The remainder of the paper is organized to first present the work related to the proposed systems and then explain the methodology used to implement the systems in a simulation environment. The results of the tests are then presented along with a discussion of their implications, before concluding with a summary of the key findings and their relevance.

II. Related Work

Quantum communication, a rapidly evolving field rooted in quantum mechanics and information theory, is based on two key principles: entanglement [9] and superposition [10]. Entanglement establishes instantaneous correlations between quantum particles and underpins applications such as quantum key distribution (QKD) and quantum teleportation, both of which have been extensively explored by researchers. QKD enables secure encryption key sharing based on quantum entanglement [11], [12], while quantum teleportation transfers the quantum state of a particle without physical movement [13]. Researchers have also used entanglement for secure media transmission, particularly for image and video data [14], [15].

Superposition, the ability of quantum systems to exist in multiple states simultaneously, enhances the efficiency, reliability, and capacity of quantum communication systems [16]. This property allows qubits to represent multiple states simultaneously, increasing data throughput and improving robustness against errors in the communication process. Although the effects of superposition on communication complexity have been explored [17], no approach has yet fully integrated it into a complete, end-to-end quantum communication system that combines the principles of superposition with error correction techniques, specifically tailored for video transmission applications.

Quantum channel coding techniques [18] can be used to detect and correct errors during transmission, further improving the reliability and fidelity of quantum communication systems. These are essential for the reliable transmission and processing of quantum information, as quantum systems are inherently susceptible to various types of noise and errors. Early breakthroughs in quantum error correction demonstrated that multiple qubits could protect a single qubit from various types of errors, achieving this without violating the no-cloning theorem, which prohibits the exact copying of quantum states. For example, the Shor code [19] uses nine qubits to safeguard a single qubit, while the Steane code [20] requires seven qubits for single qubit protection. Based on these foundational codes, five-qubit [21] and three-qubit error correction codes [22] have also been developed.

Among these multi-qubit error correction methods, the three-qubit error correction code stands out as one of the simplest and most foundational technique. It is designed to detect and correct a single-qubit error, such as a bit-flip or phase-flip, by encoding a logical qubit into three physical qubits. The effectiveness of the three-qubit error correction code has been extensively studied in the context of quantum computing [23], [24].

Existing quantum error correction methods focus on quantum computation and remain largely unexplored for quantum communication, particularly in video transmission applications. To address this gap, this research aims to develop an end-to-end quantum communication system for video transmission, leveraging quantum superposition alongside low-complexity three-qubit quantum error correction and more advanced multi-qubit error correction codes, such as the five-qubit and seven-qubit methods. Furthermore, the study introduces a novel quantum communication system that incorporates classical error correction techniques, providing a comprehensive analysis of their performance and effectiveness in the quantum domain, an area that has not been explored in previous research. This analysis offers valuable insights into the efficiency and reliability of quantum communication systems and the trade-offs between performance and complexity, contributing to the development of robust and practical quantum communication systems. By evaluating the performance of existing theoretical methods, this research will lay the groundwork for demonstrating the potential of quantum communication for video transmission and for the development of novel quantum communication systems.

III. Methodology

The proposed quantum communication systems for video transmission are based on the principles of quantum superposition and use two distinct channel coding schemes: quantum channel coding and classical channel coding, to enable qubit

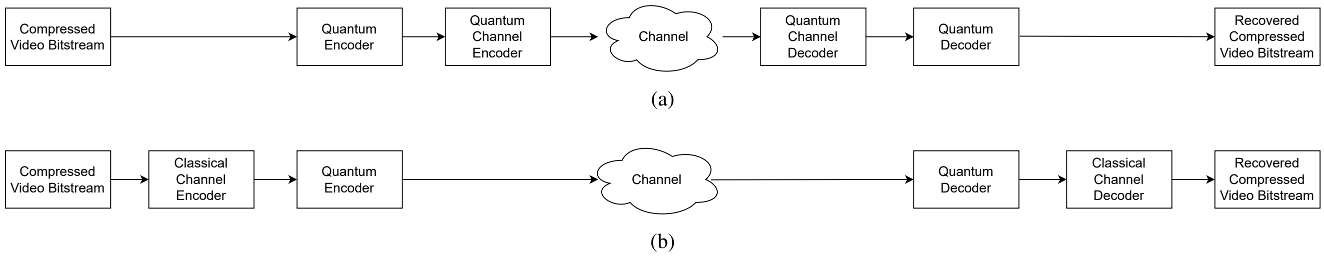


Fig. 1. Proposed frameworks of quantum communication systems for video transmission with: (a) quantum error correction, and (b) classical error correction

error detection and correction. As shown in Fig. 1, these two quantum setups are developed to analyze the performance of the quantum communication process. The first setup utilizes quantum error correction (three-qubit, five-qubit, and seven-qubit techniques) (Fig. 1a), while the second employs classical error correction with polar codes (Fig. 1b).

The first setup begins by converting a compressed video bitstream into qubit states using a superposition-based quantum encoder. These qubit states are then channel encoded using a multi-qubit quantum channel encoder, which includes the three-qubit, five-qubit, and seven-qubit error correction codes. In the five-qubit and seven-qubit error correction methods, the original video bitstream is further compressed to reduced quality to match the bitrate of the three-qubit channel encoded qubit stream. The second setup involves encoding the compressed video bitstream with a rate of 1/3 polar encoder (to align the bitrate with the three-qubit error correction). The resulting channel-encoded bitstream is then converted into qubit superposition states using a superposition-based quantum encoder.

In both setups, the resulting qubit superposition states are transmitted over a simulated quantum channel that introduces a range of random qubit errors, including bit-flip, phase-flip, depolarization, amplitude damping, and phase damping. In the first setup, the received qubit states are quantum channel decoded and then converted to a classical bitstream using a quantum decoder to recover the compressed video bitstream. In the second setup, the quantum decoder is first applied to extract the classical information, which is then channel decoded using the polar decoder to reconstruct the final bitstream. The performance of the proposed quantum communication systems is evaluated against a bandwidth-equivalent classical communication system with binary phase-shift keying (BPSK) modulation and a rate of 1/3 polar code for channel coding.

All proposed quantum systems operate on video bitstreams and can accommodate inputs from any video codec. For the purpose of simulations, the VVenC [25] implementation of Versatile Video Coding (VVC) [26] is considered to encode the video. Experiments are conducted with input videos in YUV420 format for a range of spatial resolutions (320×180, 1280×720, 1920×1080), frame rates (20, 30 and 50 frames per second) and different Group of Pictures (GOP) sizes (8, 16, 32), to assess their robustness. Simulations are performed using Python on a computing system with a 13^{th} Gen Intel(R) Core(TM) i5-1345U 1.60 GHz processor and 16.0 GB of RAM.

The following subsections provide detailed information on each functional block of the quantum communication frameworks shown in Fig. 1.

A. Classical Channel Encoder and Decoder

Polar codes with a rate of 1/3, utilized for classical channel coding in this research, align seamlessly with the three-qubit quantum channel coding scheme, ensuring bandwidth equivalence. Their superior error correction capability and low complexity [27] make them an ideal solution for both classical and quantum communication systems. Notably, polar codes excel in approaching the Shannon limit while maintaining a straightforward encoding and decoding process. In contrast, other classical channel coding techniques, such as LDPC and turbo codes, encounter significant obstacles in the quantum domain. LDPC codes rely on computationally intensive iterative decoding, which is impractical due to the constrained computational resources of quantum systems. Similarly, turbo codes, while effective for error correction, involve complex decoding algorithms that introduce high latency and computational overhead, rendering them unsuitable for real-time quantum communication. Therefore, the simplicity, efficiency, and adaptability of polar codes establish them as the optimal choice for advancing quantum communication research.

B. Quantum Encoder and Decoder

This study uses the low-complexity single-qubit encoding, where bit 0 is encoded as $|0\rangle$ and bit 1 as $|1\rangle$, with their corresponding matrix forms shown in (1) and (2). While multi-qubit encoding enhances error resilience, making it impractical for resource-limited applications due to its high complexity.

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

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

During quantum encoding, the Hadamard gate, shown in (3), is used to create superposition states that are highly compatible with existing quantum algorithms.

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

This transformation enables a qubit to exist in a combination of both $|0\rangle$ and $|1\rangle$ states simultaneously. The effect of the Hadamard gate on $|0\rangle$ and $|1\rangle$ is represented in vector form by (4) and (5).

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

$$H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |-\rangle \tag{5}$$

The quantum decoder utilizes projective measurement operators to extract classical information from received qubit superposition states. Following a measurement, the resulting quantum state is normalized to produce the post-measurement state $|\psi'\rangle$, as shown in (6).

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

Here, M_m represents measurement operators, such as $M_0 = |0\rangle\langle 0|$ and $M_1 = |1\rangle\langle 1|$, which project qubit superposition states onto specific basis states. An example of this process with M_0 is detailed in (7) to (8).

$$|\psi'\rangle = \frac{|0\rangle\langle 0|\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)}{\sqrt{\left(\frac{1}{\sqrt{2}}\langle 0| + \frac{1}{\sqrt{2}}\langle 1|\right)(|0\rangle\langle 0|)\left(\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle\right)}} \tag{7}$$

$$= |0\rangle \tag{8}$$

While this section focuses on pure quantum states, section III *D* introduces density matrices representation to describe mixed states in noisy environments.

C. Quantum Channel Encoder and Decoder

After quantum encoding, the superposition states are processed by the quantum channel encoder using three-qubit, five-qubit, and seven-qubit channel coding techniques. The three-qubit process, shown in Fig. 2, forms the basis for extending to the five-qubit and seven-qubit codes.

The initial quantum state $|\psi\rangle$, a superposition of $|0\rangle$ and $|1\rangle$, is expanded into three-qubit states by adding two ancillary $|0\rangle$ qubits, forming a combined state as in (9) to improve error resilience.

$$\frac{1}{\sqrt{2}}|000\rangle \pm \frac{1}{\sqrt{2}}|100\rangle \tag{9}$$

Subsequently, the controlled NOT (CNOT) gates are applied sequentially. The first qubit acts as the control for a CNOT operation targeting the second qubit, and then another CNOT targets the third qubit. These operations transform the previous state in (9) into (10).

$$\frac{1}{\sqrt{2}}|000\rangle \pm \frac{1}{\sqrt{2}}|100\rangle \rightarrow \frac{1}{\sqrt{2}}|000\rangle \pm \frac{1}{\sqrt{2}}|111\rangle \tag{10}$$

This transformation establishes correlations among the qubits, preparing them for quantum error correction and enhancing noise resilience. Since the initial qubits are in superposition states, the Hadamard basis is used instead of the computational basis. By applying three additional Hadamard gates, as shown in Fig. 2, the qubit states are converted to the Hadamard basis, as in (11).

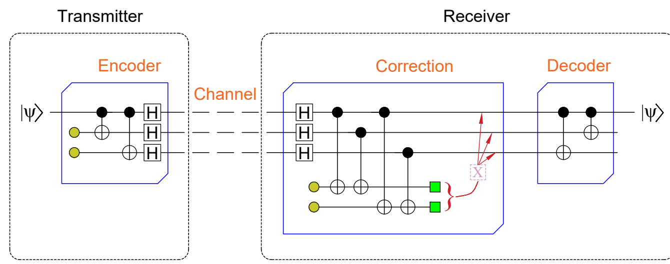


Fig. 2. Three-qubit encoder and decoder circuit.

TABLE I
RELATIONSHIP BETWEEN THE RECEIVED STATE, POSITION OF THE ERROR, AND ANCILLA STATE

State after Channel	Position of the Error	Ancilla State
$\frac{1}{\sqrt{2}}\lvert 000\rangle \pm \frac{1}{\sqrt{2}}\lvert 111\rangle$	No error	$\lvert 00\rangle$
$\frac{1}{\sqrt{2}}\lvert 100\rangle \pm \frac{1}{\sqrt{2}}\lvert 011\rangle$	Error in first qubit	$\lvert 11\rangle$
$\frac{1}{\sqrt{2}}\lvert 010\rangle \pm \frac{1}{\sqrt{2}}\lvert 101\rangle$	Error in second qubit	$\lvert 10\rangle$
$\frac{1}{\sqrt{2}}\lvert 001\rangle \pm \frac{1}{\sqrt{2}}\lvert 110\rangle$	Error in third qubit	$\lvert 01\rangle$
$\frac{1}{\sqrt{2}}\lvert 110\rangle \pm \frac{1}{\sqrt{2}}\lvert 001\rangle$	Error in first two qubits	$\lvert 01\rangle$
$\frac{1}{\sqrt{2}}\lvert 101\rangle \pm \frac{1}{\sqrt{2}}\lvert 010\rangle$	Error in first and third qubits	$\lvert 10\rangle$
$\frac{1}{\sqrt{2}}\lvert 011\rangle \pm \frac{1}{\sqrt{2}}\lvert 100\rangle$	Error in last two qubits	$\lvert 11\rangle$
$\frac{1}{\sqrt{2}}\lvert 111\rangle \pm \frac{1}{\sqrt{2}}\lvert 000\rangle$	Three qubits error	$\lvert 00\rangle$

$$\frac{1}{\sqrt{2}}|+++\rangle \pm \frac{1}{\sqrt{2}}|---\rangle \tag{11}$$

As these qubit states traverse a noisy channel, the introduction of noise can cause them to deviate from their original state. This means $|+\rangle$ can transform into $|-\rangle$, and vice versa. To analyze errors, the received states can be converted to the computational basis by applying Hadamard gates again, as shown in Fig. 2. This process results in the qubits collapsing into one of eight possible states, as represented in Table I.

In quantum error correction, as shown in Fig. 2, two ancilla qubits initialized in the $|00\rangle$ state are introduced to detect and correct errors. By interacting with the data qubits through CNOT gates, they encode error information, enabling its correction. The CNOT gates establish correlations between the data qubits and ancilla qubits, making the ancilla qubits sensitive to specific transmission errors. The resulting ancilla states, shown in Table I, generate a two-bit syndrome upon measurement, which diagnoses errors in the original qubits as detailed in Table II.

TABLE II
CORRECTION ACTIONS BASED ON SYNDROME MEASUREMENTS

Syndrome Measurement	Correction Action
00	No adjustment required
01	Use Pauli X gate on the third qubit
10	Use Pauli X gate on the second qubit
11	Use Pauli X gate on the first qubit

As shown in Fig. 2, the decoding process applies CNOT gates between the first and third qubits, followed by the first and second qubits, restoring the original quantum state and removing any extra $|0\rangle$ states. To simulate this quantum operation accurately, matrix representations are used, with the tensor product constructing matrices for multi-qubit systems.

D. Quantum Channel

We simulate various quantum noise types [18], including bit-flip, phase-flip, depolarization, amplitude damping, and phase damping, to evaluate system performance under realistic conditions. Bit-flip noise (X noise) flips the state of a qubit from $|0\rangle$ to $|1\rangle$, or vice versa, with a probability p_X, as represented in (12).

$$\mathcal{E}_X(\rho) = p_X X \rho X^\dagger + (1 - p_X)\rho \tag{12}$$

Phase-flip noise (Z noise) alters the phase of a qubit state. The noisy qubit state, after passing through a quantum channel with phase-flip noise, operates with a probability p_Z, as represented in (13).

$$\mathcal{E}_Z(\rho) = p_Z Z \rho Z^\dagger + (1 - p_Z)\rho \tag{13}$$

Depolarization noise randomly mixes the state of a qubit with the maximally mixed state. The depolarization map is given by (14). Here p_D is the probability of depolarization.

$$\mathcal{E}_D(\rho) = (1 - p_D)\rho + \frac{p_D}{3}(X\rho X^\dagger + Y\rho Y^\dagger + Z\rho Z^\dagger) \tag{14}$$

The amplitude damping noise corresponds to the loss of energy in the system. The amplitude damping map is given by (15). Here p_A is the probability of amplitude damping.

$$\begin{aligned}\mathcal{E}_A(\rho) = &\begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p_A} \end{pmatrix} \rho \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p_A} \end{pmatrix}^\dagger \\ &+ \begin{pmatrix} 0 & \sqrt{p_A} \\ 0 & 0 \end{pmatrix} \rho \begin{pmatrix} 0 & \sqrt{p_A} \\ 0 & 0 \end{pmatrix}^\dagger \end{aligned} \tag{15}$$

Phase damping noise affects the coherence of a qubit without changing the population of the states. The phase damping map is given by (16), where p_P is the phase damping probability.

$$\begin{aligned}\mathcal{E}_P(\rho) = &\begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p_P} \end{pmatrix} \rho \begin{pmatrix} 1 & 0 \\ 0 & \sqrt{1-p_P} \end{pmatrix}^\dagger \\ &+ \begin{pmatrix} 0 & 0 \\ 0 & \sqrt{p_P} \end{pmatrix} \rho \begin{pmatrix} 0 & 0 \\ 0 & \sqrt{p_P} \end{pmatrix}^\dagger \end{aligned} \tag{16}$$

The overall quantum noise model can be expressed as (17).

$$\begin{aligned}\mathcal{E}(\rho) = &\, p_X \mathcal{E}_X(\rho) + p_Z \mathcal{E}_Z(\rho) + p_D \mathcal{E}_D(\rho) \\ &+ p_A \mathcal{E}_A(\rho) + p_P \mathcal{E}_P(\rho) \end{aligned} \tag{17}$$

In all equations, the density matrix ρ ($|\psi\rangle\langle\psi|$) describes both pure and mixed quantum states, which is essential in the context of quantum noise due to environmental interactions, extending the pure state formalism of Section III *B*. The symbol † denotes the conjugate transpose of the matrices, and $\mathcal{E}(\rho)$ represents the noisy qubit state after passing through the quantum channel. By varying the signal-to-noise ratio (SNR) in our simulations, which involves randomly adjusting the probability of each noise type, we obtain results to assess the performance of the system under various noise conditions.

IV. Results and Discussion

To analyze the effectiveness and reliability of superposition-based quantum communication systems for video transmission in noisy environments, we use three videos with varying levels of structural information (SI) and temporal information (TI) content. High-motion video [28] with rapid movements and frequent scene changes has high SI and TI, posing challenges for compression and transmission. Medium-motion video [29] features moderate movement with medium SI and TI, offering balanced complexity. Low-motion video [30] has medium SI and low TI, with minimal movement, making it easier to compress.

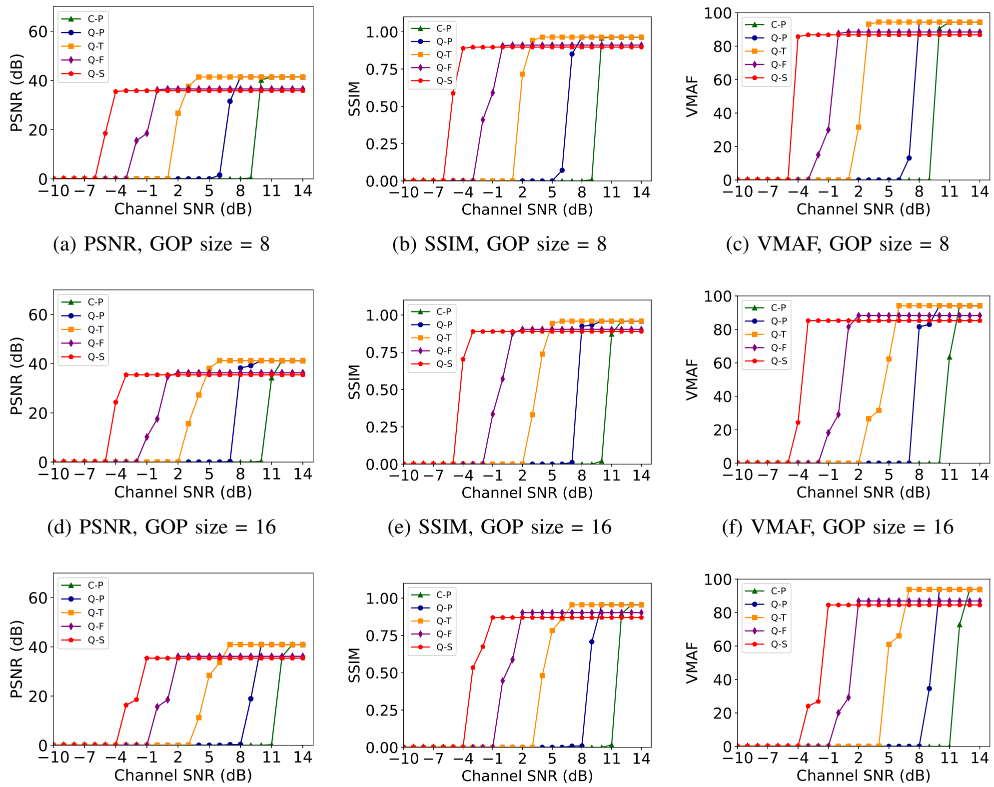
In addition, this research uses the peak signal-to-noise ratio (PSNR), the structural similarity index measure (SSIM), and the video multimethod assessment fusion (VMAF) to evaluate the performance of quantum systems in error-prone environments. These metrics are chosen for their effectiveness in assessing video quality and resilience to channel noise. The analysis shows that all proposed quantum systems consistently outperform the classical system in mitigating channel noise across various SNRs. Furthermore, the findings demonstrate that the proposed quantum systems effectively manage transmission errors, maintaining high video quality even under challenging conditions, as illustrated in Fig. 3.

Additionally, the evaluation of the quantum communication system with classical error correction demonstrates a performance comparable to that of the classical communication method using the same polar codes. However, this hybrid system, combining classical error correction with quantum communication, benefits from quantum communication's inherent error-correcting properties, particularly under low SNR conditions. As a result, this approach surpasses classical communication systems in video quality, highlighting its potential for robust and reliable video transmission.

As shown in Fig. 3, the quantum communication system with quantum error correction consistently outperforms both the classical communication system and the quantum communication system with classical error correction. This superiority is evident across spatial correlation metrics (PSNR and SSIM) and spatial-temporal coherence (VMAF), regardless of the GOP size (8, 16, or 32). Performance improvement remains robust even under low SNR conditions, demonstrating the reliability and effectiveness of the proposed system in various scenarios. In particular, the five-qubit and seven-qubit systems outperform the three-qubit system, with the seven-qubit system achieving the best performance under low SNR conditions.

As the GOP size increases, the number of inter-coded frames also increases. These inter-coded frames are successively predicted based on intra and inter frames of the GOP. Consequently, any errors that occur in the middle of the GOP can significantly affect the quality of the subsequent inter-frames. This effect is evident in Fig. 3, where all systems exhibit reduced performance as GOP size increases. To mitigate this effect, we can use adaptive error correction based on GOP structure and error-resilient encoding techniques.

Furthermore, we extend our analysis to compare the performance of the proposed systems across different frame rates and



(a) PSNR, GOP size = 8 (b) SSIM, GOP size = 8 (c) VMAF, GOP size = 8

(d) PSNR, GOP size = 16 (e) SSIM, GOP size = 16 (f) VMAF, GOP size = 16

(g) PSNR, GOP size = 32 (h) SSIM, GOP size = 32 (i) VMAF, GOP size = 32

Fig. 3. PSNR, SSIM, and VMAF variation for VVC videos with different GOP values over quantum communication system with quantum error correction (Q-S (seven-qubit), Q-F (five-qubit), Q-T (three-qubit)), quantum communication system with classical error correction (Q-P), and classical communication system with classical error correction (C-P): (a) PSNR (GOP8), (b) SSIM (GOP8), (c) VMAF (GOP8), (d) PSNR (GOP16), (e) SSIM (GOP16), (f) VMAF (GOP16), (g) PSNR (GOP32), (h) SSIM (GOP32), (i) VMAF (GOP32).

TABLE III
MAXIMUM SNR GAIN FOR EACH QUANTUM COMMUNICATION SYSTEM COMPARED TO CLASSICAL COMMUNICATION SYSTEM ACROSS DIFFERENT RESOLUTIONS AND FRAME RATES

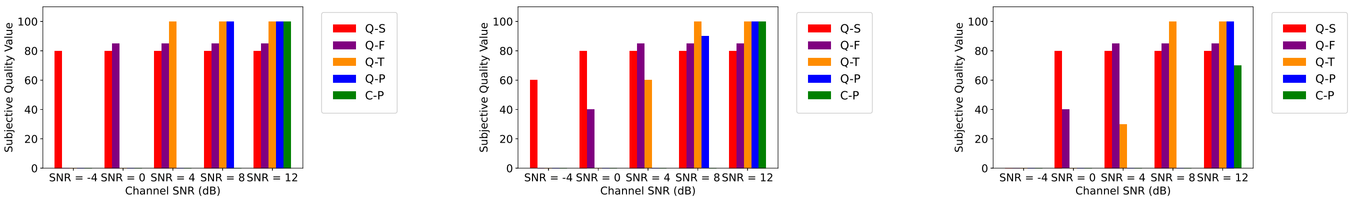
Frame Rate (fps)	320x180				1280x720				1920x1080			
	Q-S	Q-F	Q-T	Q-P	Q-S	Q-F	Q-T	Q-P	Q-S	Q-F	Q-T	Q-P
20	15.0 dB	13.0 dB	8.0 dB	4.0 dB	15.2 dB	13.3 dB	8.2 dB	4.3 dB	15.1 dB	13.2 dB	8.4 dB	4.1 dB
30	15.1 dB	13.2 dB	7.9 dB	4.1 dB	15.3 dB	13.4 dB	8.1 dB	4.1 dB	15.3 dB	13.3 dB	8.3 dB	4.1 dB
50	14.9 dB	13.1 dB	7.9 dB	4.1 dB	15.1 dB	13.2 dB	8.3 dB	4.2 dB	15.3 dB	13.4 dB	8.3 dB	4.4 dB

resolutions for the example case of GOP8. According to the results, the maximum SNR gains are nearly similar, indicating that frame rate and resolution have no significant effect on the maximum SNR gains of the proposed systems compared to the classical system. This is because both frame rate and resolution influence quantum and classical communication systems in a similar way. These findings are summarized in Table III.

In summary, multi-qubit error correction codes address single-qubit bit-flip (X) and phase-flip (Z) errors by leveraging quantum superposition [31]. While the multi-qubit codes struggle with noise types like depolarization, amplitude damping, and phase damping, which create mixed quantum states, simulations model their impact, highlighting the need for advanced techniques such as concatenated or surface codes for effective correction.

Although polar codes are known for their relatively low complexity in classical channel coding, the proposed three-qubit quantum approach achieves even lower complexity for video transmission systems by encoding a classical bit into three-qubit superposition states without increasing bandwidth due to the properties of quantum superposition. In contrast, the five-qubit and seven-qubit codes require more qubits for encoding and error correction, leading to increased complexity as the number of qubits rises. The three-qubit system, though less robust than the five-qubit and seven-qubit systems, offers lower complexity and minimal resource requirements, making it ideal for resource-constrained quantum devices, low-power systems, short-distance communication, and low-fidelity applications.

Notably, the three-qubit system achieves approximately a 30% reduction in encoding, transmission, and decoding time compared to the five-qubit system, and about a 50% reduction compared to the seven-qubit system. Although quantum communication with polar codes requires more time than the three-qubit system, classical systems match the performance time of the three-qubit system. Future advancements in quantum



(a) GOP size = 8 (b) GOP size = 16 (c) GOP size = 32

Fig. 4. Subjective experiment results for VVC videos with different GOP values over quantum communication systems with quantum error correction using seven-qubit (Q-S), five-qubit (Q-F), three-qubit (Q-T), quantum communication system with classical error correction (Q-P), and classical communication system with classical error correction (C-P): (a) GOP8, (b) GOP16, (c) GOP32.

hardware and error correction are expected to enhance error resilience and reduce latency, solidifying quantum systems for practical applications.

In addition, a subjective user experiment is conducted using a double stimulus quality assessment technique [32] to evaluate video quality, involving 50 participants aged 18 to 55 years. The results, shown in Fig. 4, align with the objective metrics, strengthening the relevance of the study to consumer applications. This simulated experiment lays the foundation for demonstrating feasibility before real-world implementation, offering theoretical validation for the proposed quantum communication system. As quantum technologies evolve, these findings will guide practical implementations, including prototype development, testing, and emulation, leading eventually to full-scale deployment. Furthermore, analysis of the advantages of quantum communication paves the way for applications in telemedicine, remote healthcare, consumer electronics (including VR/AR), and other emerging technologies.

Future work will focus on enhancing quantum communication systems by exploring advanced error correction methods, such as surface and concatenated codes, to mitigate quantum noise. By analyzing the performance of existing error correction methods, the research will lay the foundation for developing novel error correction techniques. Additionally, quantum encoding methods like multi-qubit, angle, and phase encoding will be combined with error correction codes to optimize efficiency and expand system capacity. Quantum-native compression algorithms will also be examined to improve video transmission, alongside evaluations of computational complexity. These efforts aim to create robust and efficient quantum communication protocols for practical, real-world applications.

V. Conclusion

This study explores the potential of quantum communication systems for video transmission using quantum superposition, incorporating both quantum and classical error correction methods, and compares their performance to classical communication systems. The results consistently show that the proposed quantum communication systems outperform the classical communication system across various video GOP sizes. These findings highlight the ability of quantum communication systems to maintain high video quality, structural integrity, and improved viewer satisfaction in noisy environments. In particular, the three-qubit quantum error correction system achieves significant performance gains, with up to 41.42 dB in PSNR, 0.9639 in SSIM, and 94.4042 in VMAF, particularly under low SNR conditions, demonstrating the effectiveness of quantum error correction for high-quality video transmission with low complexity. While higher complexity five-qubit and seven-qubit systems offer better fidelity and resilience, a trade-off between simplicity and performance becomes clear. Among these, the seven-qubit system consistently outperforms all others, showing the greatest improvements in fidelity and resilience in low SNR conditions.

These results highlight the potential of quantum error correction in addressing challenges in complex video communication scenarios and in advancing next-generation quantum technologies. While the quantum communication system with classical error correction surpasses classical communication systems, it lags behind quantum error correction-based systems. Future research should explore advanced and novel error correction methods to improve the reliability and efficiency of quantum communication.

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Udara Jayasinghe (Graduate Student Member, IEEE) received her B.Sc. (Second-Class Upper Hons.) in Physics from the University of Sri Jayewardenepura, Sri Lanka, in 2020. Currently, she is pursuing her Ph.D. in quantum communication for media transmission at the Department of Computer and Information Sciences, University of Strathclyde, UK. Her research interests include quantum communication, quantum machine learning, and semantic communication.

Prabhath Samarathunga (Graduate Student Member, IEEE) received his B.Sc. (First-Class Hons.) in Software Engineering from the University of Plymouth, UK, in 2021. Currently, he is pursuing his Ph.D. in semantic communication-based video streaming for M2M communication at the Department of Computer and Information Sciences, University of Strathclyde, UK.

Nimesh Pollwaththage (Graduate Student Member, IEEE) received his B.Sc. (Second-Class Upper Hons.) in Electrical and Electronic Engineering from the University of Peradeniya, Sri Lanka. Currently, he is pursuing a Ph.D. in Computer and Information Sciences at the University of Strathclyde, UK. His research interests include quantum communication, semantic communications, and machine learning.

Yasith Ganearachchi (Graduate Student Member, IEEE) received his B.Sc. (First-Class Hons.) degree in Electrical and Electronic Engineering from the University of Peradeniya, Sri Lanka, in 2008, an MBA (Merit) from the University of Sri Jayewardenepura, Sri Lanka, in 2019, and a PMBADT (Merit) from the Asian Institute of Technology, Thailand, in 2022. Currently, he is pursuing a Ph.D. in Computer and Information Sciences at the University of Strathclyde, UK.

Thanuj Fernando (Student Member, IEEE) is in his second year of B.Sc. in Computer Science at the Department of Computer and Information Sciences, University of Strathclyde, UK. His research interests include machine learning, vision processing, and communication.

Anil Fernando (Senior Member, IEEE) received the B.Sc. degree (Hons.) in Electronics and Telecommunication Engineering from the University of Moratuwa, Sri Lanka, in 1995, the M.Sc. degree (Hons.) in Communications from the Asian Institute of Technology, Bangkok, Thailand, in 1997, and the Ph.D. degree in Computer Science (Video Coding and Communications) from the University of Bristol, UK, in 2001. He is currently a Professor of Video Coding and Communications with the Department of Computer and Information Sciences, University of Strathclyde, UK, where he leads the Video Coding and Communication Research Team. He has graduated more than 110 Ph.D. students and is currently supervising 20 Ph.D. students. He has published more than 450 papers in international journals and conference proceedings and a book on 3D video broadcasting. His main research interests include video coding and communications, machine learning, artificial intelligence, semantic communications, media broadcasting, and quantum communications.