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A Review on Recent Advances in Quantum Error Correction: From Theory to Practical Applications

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Abstract. Quantum systems operate using quantum bits (qubits), which are highly sensitive to external noises and disturbances and they are easily prone to errors. In the Noisy Intermediate-Scale Quantum (NISQ) era, these errors make difficult to build reliable, fault tolerant quantum circuits for real world deployment. This work provides an overview of need for Quantum Error Correction (QEC) in NISQ devices, as qubits commonly get affected by bit-flip, phase-flip, and combined errors that degrades system performance and examines Quantum Error Correction Code (QECC) techniques usage in communication, computation, and quantum multimedia applications such as image and video transmission. In addition, a simple three-qubit repetition circuit is introduced to demonstrate an error-mitigation approach.
These findings, also show how QEC improves fidelity, reduces logical errors, and improves noise tolerance. The analysis also identifies challenges and outlines the future research direction aimed at achieving efficient and scalable fault tolerant quantum circuits.

1 Introduction

Classical technology has played a vital role, due its reliability and simplicity it has been widely adopted in applications such as wireless communication, digital electronics, multimedia processing, data storage, and sensing networks, but the demand for high-speed processing and securing of data has increased, classical technology begun to reach its limits [1, 2] such as increased latency, limited security, have motivated to find new technology to overcome these constraints that is quantum technology [1, 2].

Now, Quantum technology has developed as a best solution for solving these limitations of classical technology [1, 2]. It uses quantum mechanical principles named Superposition, entanglement, and interference, [3] these help quantum systems in performing operations in parallel, that is more number of possibilities at a time [4, 5], which enables to find applications in many areas including communication, computation, sensing, image processing, video transmission, and consumer electronics. Coming to the special principles, Superposition enables a qubit to encode multiple logical possibilities within a single state [4], entanglement creates strong relation between qubits, interference amplifies the correct state (constructive interference) and reduces the wrong state (destructive interference) which helps in choosing correct state or option. Because of these properties quantum has more advantage over classical in terms of speed, security and improved performance [5].

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Even with these advantages, quantum systems face some challenges because qubits are fragile, and they can be easily disturbed by external noises [5]. Decoherence, environmental noise, and imperfections in quantum hardware cause errors such as bit-flips, phase-flips, and mixed errors in qubits which collapses the superposition and breaks entanglement [6, 7].

In classical systems, we correct the errors by directly copying bits multiple times and measuring the transmitted bits, but in quantum we cannot use same techniques because of the two main challenges that is (i) measurement collapses the quantum state and (ii) no cloning theorem, we cannot create identical copies of qubits, these limitations make Quantum Error Correction (QEC) difficult [7, 8]. But in order to achieve fault tolerant quantum circuits [8] we need to apply QEC techniques which detects and correct the errors without measuring the actual data [8, 9]. A typical QEC process includes three main steps: (i) detection: which reveals the occurrence of errors, (ii) decoding: which identifies the affected qubit locations, and (iii) correction: which restores the qubit to its logical state [5, 8, 10]. Recent advancements shows the importance of QEC in various applications.

This paper provides a review based on practical application areas and discusses how QEC techniques are used in applications such as image and video transmissions.

2 Preliminaries

This section gives the basic insights about qubits, quantum gates, circuits, types of quantum errors, why classical techniques doesn't work for quantum and basics of quantum repetition codes.

2.1 Qubits

Quantum information is represented using qubits, which acts as a basic unit and it can be initialized in the state of $|0\rangle$, $|1\rangle$, or a superposition of both [4]. A qubit in its most general form, represented as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

The parameters α and β represents complex probability amplitudes whose magnitudes obeys normalization rule.

$$|\alpha|^2 + |\beta|^2 = 1$$

Upon measurement, a qubit yields a classical outcome corresponding to either 0 or 1.

2.2 Quantum Gates

Quantum Gates are unitary transformations applied to qubits to control their state evolution. Quantum gates are depicted in figure 1.

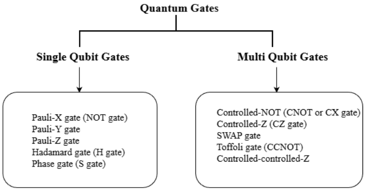

Figure 1. Classification of Quantum gates

Precise implementation of quantum gates are essential for reducing errors in quantum circuits.

2.3 Quantum Circuits

A quantum circuit is constructed by applying a sequence of quantum gates to qubits, followed by measurement to obtain the output. The circuits begins by initializing qubits, connecting quantum gates finally measuring the output of a circuit. They require precise control to prevent noise from affecting the results.

2.4 Types of Quantum Errors

A Quantum system uses qubits that are very fragile, easily affected by environmental noise, vibrations, cosmic rays, so these can give different kinds of imperfections in qubits which include bit flip, phase flip, and combined error effects. A bit flip error is referred as X error, and it flips the states $|0\rangle$ to $|1\rangle$ and $|1\rangle$ to $|0\rangle$. While coming to the Phase flip error also known as Z error which alters the sign of qubit phase, changing $|1\rangle$ to $-|1\rangle$ leaving $|0\rangle$ as unchanged. We can also observe another type of error where bit flip and phase flip effects occur together, resulting in a Y error.

In addition to the state errors, quantum systems also suffer from Gate errors, measurement errors, and crosstalk errors. Gate errors occur when quantum gate does not work as designed, measurement errors arise during the readout process, and crosstalk error occurs when one qubit affect neighboring qubit. These errors further complicate QEC in real hardware.

2.5 Why Classical Error Correction Cannot Be Used

Quantum states cannot be copied due to the no-cloning theorem, and any attempt to measure a qubit causes its state to collapse, which destroys special property of superposition and the information in it. In classical error correction, bits are replicated multiple times and compared to check the errors, which is impossible in quantum. As a result, quantum computing requires specialized error correction techniques that can detect and correct the errors while preserving the fundamental principles of quantum mechanics.

2.6 Basic Idea of QEC

The basic idea of QEC is illustrated through the process shown in figure 2.

Encoding: Encoding is a process of spreading logical qubit (data qubit) across multiple physical qubits using CNOT gates. These additional qubits used in this process are initially prepared in the $|0\rangle$ state.

Channel: Encoded qubits transmitted through the channel are susceptible to noise, that may alter their state.

Error Detection: Error Detection which is the core of the QECC, uses a special operation called syndrome measurement. This syndrome measurement checks the errors and identifies the location of error by using ancilla bits. This step need to be done carefully because measurement collapses the state of qubit.

Error Correction: After Detection process, appropriate correction gates are applied based on the syndrome output to mitigate the detected error. These operations restore the qubits to their intended logic states.

Decoding: After the errors are corrected, the decoding stage reconstructs the original logical qubit state.

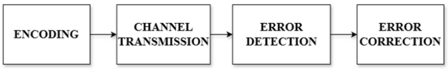

Figure 2. QEC Process

2.7 Three-Qubit Repetition Code for mitigating X and Z Errors

Three-qubit repetition code is a simple redundancy-based error correction scheme in which a single logic qubit is encoded across three physical qubits. If the data in a qubit is $|0\rangle$, it is encoded as $|000\rangle$, and if the data is $|1\rangle$, it becomes $|111\rangle$. This process is called encoding. This enables error detection and correction through appropriate stabilizer measurement technique. Even if one of the three copies get disturbed, the other two can reveal what exactly the correct logic value and it can be easily recovered.

A bit-flip error corresponds to a Pauli-X operation, which interchanges the qubit states from $|0\rangle$ to $|1\rangle$ or from $|1\rangle$ to $|0\rangle$. For example, if the encoded state is $|000\rangle$ and a bit-flip error affects the second qubit and the state becomes $|010\rangle$. The original value can be recovered by noting that two of the three qubits remain in same state, allowing erroneous qubit to be identified as $|000\rangle$. In this way the three-qubit repetition code is able to correct a single bit-flip error.

Quantum systems can also suffer from Phase-flip errors, which are represented by Pauli-Z operation. In phase-flip error the bit value is not changed, only the phase of the $|1\rangle$ component will changed and the state $|0\rangle$ remains unchanged, while $|1\rangle$ becomes $-|1\rangle$. Although this change is not measurable, but it affects the qubit's interference output, which is the important parameter to consider for correcting phase-flip error.

A similar repetition strategy can be used to address phase-flip errors by operating in an alternative basis. In this case, the qubits are encoded in hadamard basis, which places them in superposition states defined as $|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$ and $|-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$.

The encoded data forms as $|+ + +\rangle$ and $|- - -\rangle$. It behaves same like a bit-flip, allowing the usage of majority voting for correcting it. Consider an example, if one qubit in $|+ + +\rangle$ affected by a phase-flip then the state becomes $|+ - +\rangle$. In this the majority is $|+\rangle$, then the state is corrected to $|+ + +\rangle$.

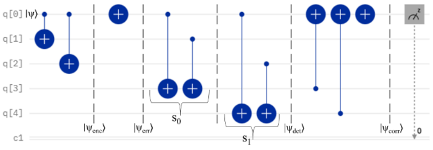

Figure 3. Quantum circuit for X error

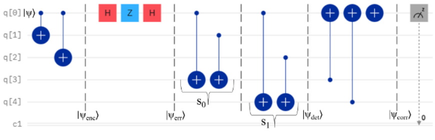

Figure 4. Quantum circuit for Z error

2.7.1 Illustrative Example on three qubit repetition code for X error mitigation

The X error occurs when qubit state changes from $|0\rangle$ to $|1\rangle$ and $|1\rangle$ to $|0\rangle$. Such a flip can alter the information. In order protect the qubit from X errors, the following steps are proposed. The mathematical representation of the circuit shown in Figure 3 is presented below. Initial State: The state of the data qubit is shown in equation **1**.

1. State Preparation

The system begins with the qubit in state of $|\psi\rangle$ and two encoding qubits $q[1]$ and $q[2]$ initialized to $|00\rangle$ and these combine to form a three-qubit state.

$$|\psi\rangle = \alpha|000\rangle + \beta|100\rangle \tag{2}$$

The ancilla qubits are initialized in the $|0\rangle$ state.

2. Encoding

After this the state $|\psi\rangle$ will be encoded as

$$|\psi_{\text{enc}}\rangle = \alpha|000\rangle + \beta|111\rangle \tag{3}$$

3. Introducing X Error

Here an X error was affecting first physical qubit which makes the state into

$$|\psi_{\text{err}}\rangle = \alpha|100\rangle + \beta|011\rangle \tag{4}$$

4. Error Detection (Syndrome Measurement)

Syndrome measurement provides the mathematical basis for detecting errors in a QEC. Stabilizer circuit reveals the location of the error where it has occurred without disturbing the encoded quantum information, allowing the quantum state to remain untouched throughout the process. By using two ancilla qubits $q[3]$ and $q[4]$, measure the stabilizers without interrupting the encoded information.

- Apply CX gate to $(q[0], q[3])$ and $(q[1], q[3])$, followed by measurement of $q[3]$.
- Apply CX gate to $(q[0], q[4])$ and $(q[2], q[4])$, followed by measurement of $q[4]$.

By measuring the ancilla it produces some binary outcomes, where 0 indicates no error and 1 indicates an error. Together, the pair (s_0, s_1) uniquely identifies the location of the X error. Interpret the two-bit syndrome (s_0, s_1). Table 1 shows the mapping between the syndrome and the error location.

Table 1. Binary Syndrome: Three-Qubit Repetition Code

(s_0)	(s_1)	Interpretation
0	0	No error
0	1	Error on $q[2]$
1	0	Error on $q[1]$
1	1	Error on $q[0]$

X Gate should be ignored on the $q[0]$ register line at the stage of correction for no error condition.

After syndrome extraction, state is

$$|\psi_{\text{det}}\rangle = \alpha|111\rangle + \beta|011\rangle \tag{5}$$

5. Error Correction

Based on syndrome measurement, determine the location of the error and the corresponding correction operation. The syndrome outcomes (1,1), (1,0), (0,1) indicates errors on qubits $q[0]$, $q[1]$, and $q[2]$ respectively, while (0,0) signifies error free state. The above circuits automatically corrects the corrupted qubit based on the syndrome measurement and brings it back to the original state.

$$|\psi_{\text{corr}}\rangle = \alpha|011\rangle + \beta|111\rangle \tag{6}$$

6. Decoding
To recover qubit $|\psi\rangle$, the inverse of the encoding step is applied. This retrieves original qubit state when needed, making it exactly looks like a initial state.

2.7.2 Illustrative Example on three qubit repetition code for Z error protection

A Z type error causes a phase disturbance in qubit state. Amplitudes of the qubits $|0\rangle$ and $|1\rangle$ are not changed but the sign of the $|1\rangle$ is changed. Thus, a state such as

$$\alpha|0\rangle + \beta|1\rangle \quad \Longrightarrow \quad \alpha|0\rangle - \beta|1\rangle.$$

This phase flip can corrupt the qubits. In order to protect the qubit from Z type errors, the following steps are proposed for the Figure 4.

Initial State: The state of the data qubit is shown in equation **1**.

$$|\psi\rangle \Longrightarrow \alpha|0\rangle + \beta|1\rangle \Longrightarrow \alpha|+\rangle + \beta|-\rangle \tag{7}$$

State Preparation: The system begins with the qubit in state of $|\psi\rangle$ and two encoding qubits initialized to $|00\rangle$ and the qubit state is

$$|\psi\rangle = \alpha|000\rangle + \beta|100\rangle \Longrightarrow \alpha|++\!+\rangle + \beta|-\!++\rangle \tag{8}$$

Encoding

$$|\psi_{\text{enc}}\rangle = \alpha|000\rangle + \beta|111\rangle \tag{9}$$

In terms of phase

$$|\psi\rangle \Longrightarrow \alpha|+++\rangle + \beta|---\rangle \tag{10}$$

Introducing a Z error in first qubit

$$|\psi\rangle = \alpha|-++\rangle + \beta|+--\rangle \tag{11}$$

In terms of bits the error looks like

$$|\psi_{\text{err}}\rangle = \alpha|100\rangle + \beta|011\rangle \tag{12}$$

Detecting the error

$$|\psi_{\text{det}}\rangle = \alpha|111\rangle + \beta|011\rangle \tag{13}$$

Correcting the error

$$|\psi_{\text{corr}}\rangle = \alpha|011\rangle + \beta|111\rangle \tag{14}$$

Decoding retrieves the original single-qubit state when needed, making it exactly looks like a initial state.

These Simple approaches show how both bit flip and phase flip errors can be handled, but complex quantum systems requires more advanced codes, such as the Shor, Steane, and surface codes.

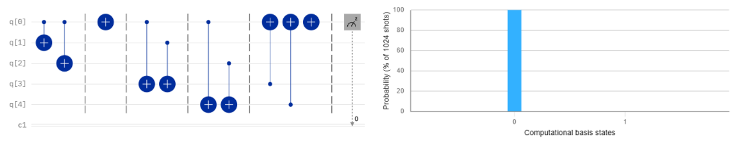

Figure 5. X error mitigation on a Qubit initialized to |0⟩: (a) Quantum Circuit for X error and (b) Corresponding probability distribution

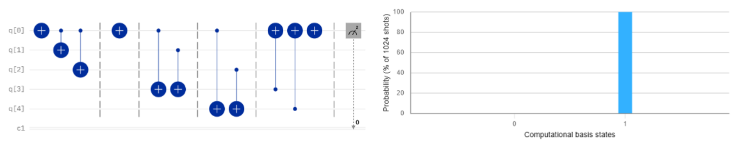

Figure 6. X error mitigation on a Qubit initialized to |1⟩: (a) Quantum Circuit for X error and (b) Corresponding probability distribution

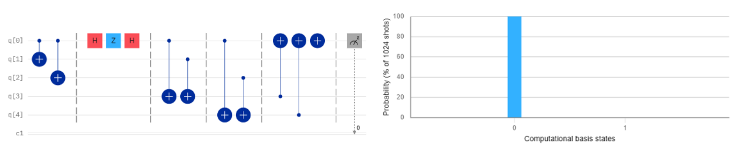

Figure 7. Z error mitigation on a Qubit initialized to |0⟩: (a) Quantum Circuit for Z error and (b) Corresponding probability distribution

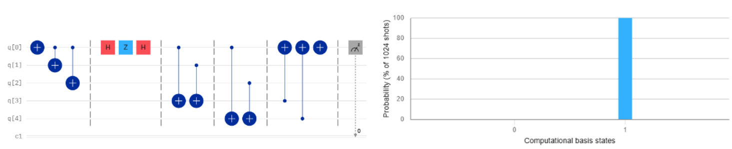

Figure 8. Z error mitigation on a Qubit initialized to |1⟩: (a) Quantum Circuit for Z error and (b) Corresponding probability distribution

The above diagrams shows the three-qubit repetition circuits used for correcting X and Z error separately. Figure 5 shows the correction process of a single X error on a qubit which was initialized in |0⟩. Figure 6 shows the correction process of a single X error on a qubit which was initialized in |1⟩. Figure 7 shows the correction process of a single Z error on a qubit which was initialized in |0⟩. Figure 8 shows the correction process of a single Z error on a qubit which was initialized in |1⟩.

In Figure 5 qubit is initialized to |0⟩ state and an X error is introduced on the first qubit and with the help of syndrome, error was detected and corrected. The result in the probability distribution shows that the recovered bit resemble exactly to the initialized state.

In Figure 6 qubit is initialized to $|1\rangle$ state and an X error is introduced on the first qubit and with the help of syndrome, error was detected and corrected. The result in the probability distribution shows that the recovered bit resemble exactly to the initialized state.

In Figure 7 qubit is initialized to $|0\rangle$ state and an Z error is introduced on the first qubit and with the help of syndrome, error was detected and corrected. The result in the probability distribution shows that the recovered bit resemble exactly to the initialized state.

In Figure 8 qubit is initialized to $|1\rangle$ state and an Z error is introduced on the first qubit and with the help of syndrome, error was detected and corrected. The result in the probability distribution shows that the recovered bit resemble exactly to the initialized state.

3 Literature Survey

This section gives the Literature review on different Quantum Error Correction codes (QECC) and applications of QEC across domains.

3.1 Literature Survey on QECC

These QEC mechanisms help to protect qubits from environmental noise, hardware imperfections, decoherence. Several important QECC were discussed here.

3.1.1 Shor Code

The first QECC was proposed by peter shor in 1995 and is regarded as a foundational QECC. It encodes a single logical qubit into nine physical qubits. It mitigates arbitrary single qubit errors including X, Z and Y [5, 8, 11].

3.1.2 Steane Code

Steane code is also a foundational QECC proposed by Andrew Steane in 1996, which encodes single logical qubit into seven physical qubits, build based on the classical [7,4] hamming code. It is the one of the example of Calderbank–Shor–Steane (CSS) code which corrects both bit and phase flip errors [5, 8, 11].

3.1.3 Topological Codes

In contrast to traditional error correction techniques which rely on encoding qubits information in physical qubits, topological codes uses spatial arrangement and connectivity of qubits. In this codes quantum information is stored in non-local properties, this makes the qubits information safe from local errors [5, 8].

3.1.4 Surface Code

Surface codes are one of the earliest known topological codes. These are designed in two-dimensional lattice of qubits which forms a grid like structure. This 2D grid helps in efficient fault tolerance by allowing multiple errors correction simultaneously [5, 8]. It supports the detection of both bit flip and phase flip errors.

3.1.5 Bacon–Shor Code

Modified and improved QECC of original shor code. It helps in reducing the overhead bits, but still gives good protection against errors which are caused by decoherence and environmental noise [8].

3.1.6 3D Color Code

This is an extension to the topological error correction codes into three dimensions. Geometric structure of the lattice is used here in order identify and correct the errors [8].

3.2 Literature survey on applications of QEC

Quantum Error Correction (QEC) plays an important role in making fault-tolerant practical circuits. In previous section of the Literature Survey on QECC, different QECC were discussed.

However, those correction codes requires more physical qubits for encoding which in turn increases the number of quantum gates as well decoding complexity. This also increases hardware need and make it difficult for practical circuits. Some recent studies shows that QEC techniques can be applied to several applications.

In image transmission, multi-qubit encoding methods were used for making images more resistant towards channel noise. In this approach larger quantum states are encoded using 4-qubit or 8-qubit states, for better protection and good visual quality, and it also uses adaptive techniques to change number of qubits according to the channel conditions. This helps in maintaining image quality while saving quantum resources when channel is less noisy [1].

The research of QEC was extended on video communication by applying different QEC codes like 3-qubit, 5-qubit and 7-qubit. Results showed that a clear improvement in video quality standard evaluation metrics even when the channel noise is high. Stronger QEC codes offer better protection, but also require more overhead qubits which creates complex circuits [2].

In consumer technology QEC plays an important role which supports future consumer devices such as quantum sensors, IOT systems, and many small scale processors. It provides a clear explanation of QEC techniques from encoding to detection and correction. It shows how fidelity can be improved after QEC technique. It also highlights QEC techniques requires many physical qubits, which causes more power consumption and complexity, which causes challenge in integrating QEC into compact and energy efficient consumer electronics [8].

The next important research direction is focused on the energy usage of QEC. The above QEC codes like Shor, Steane, and topological consumes high amount of energy because of stabilizer measurements, continuous error checks and some of the decoding operations, and most of the QECC contains overhead bits. To reduce this overhead and to make energy efficient QEC approaches like when a lot of noise is present it uses stronger error correction and when noise is less, it uses lighter method are suggested. This work uses adaptive error correction techniques and designing decoders which works closely with quantum system to save energy. So the system does not waste too much energy while fixing errors [12].

On considering the above works [1, 2, 8, 12], it is clear that QEC is an important technique for reliable and fault tolerant quantum circuit across all the applications. Along with the advantage QEC also has major challenges which are related to high resource usage, hardware complexities and increased energy consumption. These factors must be carefully considered when designing QEC for real world quantum applications.

4 Comparative Analysis

This section compares different Quantum Error Correction Codes (QECC's) and explains how they protect quantum information from errors and reviews well-known codes of QECC.

This section also discusses code performance, the resources required, and how suitable they are to the applications, different uses—such as consumer devices, high-quality media transmission, and in energy-efficient quantum networks.

The Comparative analysis of QECC's and its applications are discussed in the **Table 2** and **3** respectively.

Table 2. Comparison of different QECC's

Code	**Description**	**Advantages**	**Disadvantages**
Three-bit repetition code [5, 8]	Simple code capable of correcting a single bit or phase flip errors	Easy to implement and useful for understanding fundamental QEC concepts	Cannot correct arbitrary errors and requires multiple qubits for limited protection
Shor's 9-qubit code [5, 13]	Basic, first QECC which can correct arbitrary single qubit errors.	Basic and easy one to learn and understand the QEC codes.	It needs 9 qubits for encoding single logical qubit, inefficient one.
Steane's 7-qubit code [5, 14]	Basic QECC, based on the Classical Hamming code, corrects a single qubit error and is an example of CSS code	Easy one to learn and understand the QEC codes.	It needs 7 qubits for encoding single logical qubit, inefficient one.
Toric Code [5]	It is a 2D grid code, works on Spatial arrangement and connectivity of qubits	Good error tolerance, robust and fault - tolerant.	2D lattice is needed and it has complexity in decoding.
Surface code [5, 15]	Widely used and works on 2D grid and very stable with high error threshold.	Error threshold is very high and many efficient decoders available.	Needs more physical qubits (large overhead).
Bacon–Shor Code [5]	Subsystem code that splits error correction into smaller parts	Simple design; supports some transversal gates	Lower error threshold compared to topological codes
3D Color Code [5]	3D version of color/surface codes. Gives better error correction	Higher error threshold; supports transversal gates	Hard to build because it needs a 3D structure

Table 3. Comparison of QECC's in Applications

Methods	**Findings**	**Application**	**Limitations**	**Performance Metrics**
Uses JPEG/ HEIF compression + polar coding (1–8 qubits) and Adaptive encoder that switches qubit count based on noise [1]	Adaptive system helps in reducing resources when channel is less noisy and more qubits improve image reconstruction quality	Transmits images using multi-qubit encoding	Adaptive system needs correct channel information for efficient working and more qubits cause higher computation complexity	SNR = 15 dB (JPEG), 17 dB (HEIF).
Applies 3-, 5-, and 7-qubit codes on compressed video and transmitted video using superposition, compared results with classical polar code [2]	3-qubit QEC has improvement in video quality standard evaluation metrics. 5-qubit and 7-qubit codes even perform better when noise is high	Applies QEC to video streams	More qubits increase cost and complexity	PSNR = 41.42 dB SSIM = 0.9639 VMAF = 94.4042 for three-qubit QEC.
Reviews some of the basic QEC codes with simple error models [8]	It is found that QEC improves fidelity and reliability in consumer technology.	It introduces basic idea of QEC in consumer technology	QEC needs many overhead bits	Fidelity(F) = $\|\langle\psi \mid \phi\rangle\|^2$ = 0 indicates states are different, 1 indicates states are same ($0 \leq F \leq 1$).
Analyzes surface codes, code distance vs. fidelity and power usage [12]	Surface codes greatly helps in reducing logical errors as the code distance increases, supports energy-efficient quantum networks	Energy impact of using QEC	Energy usage increases with the number of qubits.	Error Threshold $\approx 1\%$, logical Qubit Fidelity $\approx 99\%$ (Surface Code).

5 Conclusion

Although Quantum Error Correction Codes (QECC) are improving, there are still some disadvantages in the currently adopted coding techniques. All the works reviewed above are based on the simulation only, not tested in any of the real hardware, it may behave differently because of hardware noises and imperfect gates. There are multiple techniques in QECC's, yet no single framework to support all requirements across various applications like consumer devices, images, and videos. All the QECC techniques are still in the developing stage, need developed work to implement in real world applications to obtain a quantum system that can tolerate errors.

There is also a necessity for better adaptive methods, hardware-aware decoding and energy-efficient QEC designs. As quantum technology continues to grow, the need for simple, scalable and application specific QEC methods that can operate under practical hardware constraints is required to make quantum technology closer to practical real world use.

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