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Original Article

Performance Evaluation of Error Correction Techniques in 6G Quantum Communication

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Abstract - *In upcoming generations of wireless communication (6G), Quantum Information Technology (QIT) will be integrated for high computational speeds and unprecedented security features. Quantum states are very delicate and may be lost or suffer from excessive noise as a result of decoherence during transmission. This especially applies to long-distance quantum links that are required for a global 6G network. The use of Quantum Error Correction (QEC) techniques will be necessary in order to achieve fault-tolerant quantum communication. In this work, the most actionablle QEC and hybrid (quantum-classical) error correction techniques are analyzed, especially with respect to the difficult channel conditions and high Key Performance Indicators (KPI) regarding 6G. In particular, the error suppression, qubit overhead, and decoding time required for various codes (Surface Code, Steane Code, hybrid Reed-Solomon (RS)/Turbo Codes, etc.) will be analyzed in the context of a 6G quantum channel (free-space or noisy fiber) to provide 6G. In the wireless 6G network, the simulation will show that while high-distance QEC codes provide the best ultimate logical error suppression, the enormous resource costs and 6G's strict latency requirements will lead to the first proposed hybrid classical-QEC.*

Keywords - *6G, Quantum Information Technology (QIT), Quantum Error Correction (QEC), Decoherence, Fault-Tolerant Quantum Communication.*

1. Introduction

The development of Sixth-Generation (6G) wireless communication networks is expected to change telecommunications by offering higher data rates, lower delays, and more connections, all while enhancing security features. Current aspirations for 6G technologies target futuristic applications like holographic telepresence and semantic communications. However, meeting the performance and security needs of these applications will require more than the classical communication paradigm. 6G communication will need the complete integration of Quantum Information Technologies (QIT), including Quantum Key Distribution (QKD) and quantum-enabled processing, and the other 6G technologies. Such technologies will offer communication that is secure by the very fundamentals of quantum mechanics and will provide powerful computational capabilities [1].

Practically, quantum communication for 6G networks using ground and satellite systems and terrestrial networks encounters dual challenges: the practical use of quantum technologies and the noisy quantum channels. Quantum decoherence, loss of photons, and environmental disturbances lead to channel errors of bit-flips, phase-flips, and combinations of all quantum errors. Quantum states will lose computational utility, and secure quantum communication will be compromised if mitigation techniques are allowed to fail. Therefore, fault-tolerant quantum communication will depend on the adoption of advanced error correction techniques to cut error rates below the critical limits for quantum state preservation [2].

Development in Quantum Error Correction (QEC) techniques, such as surface codes and hybrid quantum-classical codes, lays the groundwork for preserving coherence and developing scalable quantum networks for 6G. The surface codes showed high error thresholds, but 6G will involve more dynamic and unpredictable noisy environments, and extensive evaluations of error correction codes will be necessary, including logical error rates, qubit overhead, and latency in decoding and levels of fault-tolerance. Such evaluations will need to be aligned to inform the quantum 6G hardware, decoding algorithms, and system-6G protocol design [3].

A critical research gap in 6G quantum communication lies in the latency-overhead trade-off of Quantum Error Correction (QEC) when integrated into Ultra-Reliable Low-Latency Communication (URLLC) frameworks. While 6G targets sub-millisecond end-to-end latency (specifically 0.1

ms), current high-performance QEC codes, such as the Surface Code, require significant classical processing time for "decoding" error syndromes. Research indicates that real-time decoding delays currently range between 50μs and 100μs, even for small lattice sizes; as 6G requires scaling these codes to protect data over longer distances and through noisy THz-frequency channels, the computational overhead of decoding could exceed the total 6G latency budget. Consequently, there is an urgent need for hardware-accelerated, low-complexity decoders and hybrid classical-quantum FEC schemes that can maintain 6G's stringent timing requirements without sacrificing the high level of entanglement fidelity necessary for quantum-secure transmissions.

This paper offers a contribution to the field by integrating realistic 6G quantum communication channels and dominant noise models (Pauli and erasure) with comparative performance evaluations of some QEC codes most studied in literature, including surface codes and hybrid combinations such as Reed-Solomon-Turbo codes. The logical error rate, qubit overhead, and decoding latency are the main focus of the analysis since they represent the most important 6G parameters and will help identify the most viable error correction techniques for the latest 6G quantum networks in different stages of development, with a major focus. The results serve the goal of developing high error correction circuits that are fundamental to quantum communication expected in 6G [4].

2. Related Work

2.1. Quantum Error Correction (QEC)

QEC Principle: With Quantum Error Correction, fundamental changes occur in comparison to classical error correction. The encoding involves the involvement of quantum information in different qubits to nominally protect one logical qubit. The protective redundancy and entanglement-based correction preserve quantum coherence and error detection. Quantum information cannot be perfectly duplicated. Therefore, classical systems of duplication cannot be applied. More complex entanglement-based systems must be designed to preserve coherence. For the first time, QEC theories were pioneered by Shor in 1995. He proved the redundancy principle by partially storing the information of one qubit onto an entangled state of nine qubits and also showed the potential of quantum error correction through the no-cloning constraints [5].

2.1.1. Stabilizer Codes

The largest family of QEC codes is based on the stabilizer formalism, which uses the elements {I, X, Y, Z}of the Pauli group to define QEC codes. The stabilizer codes detect errors by performing measurements, then use classical computing to determine which error correcting operations to perform on the damaged qubits. With stabilizer theory, classical binary or quaternary codes can be brought to quantum use, which, under the self-containment condition, can self-contain duals [6].

2.1.2. Syndrome Measurement

The ability to detect errors in QEC without directly measuring the encoded quantum information is groundbreaking. Logical qubits and ancilla qubits are combined in quantum circuits. There is a measurement post interaction, and the owners of the ancilla qubits are given results called syndromes, which report the presence and location of errors without destroying the quantum state of the logical qubits. This is a case of Shor's measuring the "decoherence without measuring the state of the cubits" [7].

2.1.3. Calderbank-Shor-Steane (CSS) Codes

As a subclass of special CSS codes, stabilizer codes are formed from classical codes with certain properties. These codes obtain stabilizer generators that are exclusively Z-type or X-type operators, allowing separate correction for phase-flip and bit-flip errors. The construction begins with two classical codes C_1 and C_2, where $C_2 \subseteq C_1$, and both C_1 and $C_2\perp$ have minimum distance $\geq 2t+1$. Prominent examples of CSS codes are the Steane Code and the Surface Code. Surface Code: Because of its high error threshold and its planar design, the Surface Code is the most promising practical implementation of QEC codes. Surface codes perform on a d×d square lattice of qubits, with logical qubits represented at a distance that scales $d \sim O(\sqrt{n})$ with n as the number of physical qubits. Recent groundbreaking experiments have been reported below the error threshold. Notably, Google's Willow processor achieved a distance-7 surface code, decreasing logical error rates by 2.14 ± 0.02 when the code distance increased from 5 to 7. The surface code threshold for depolarizing noise has been established at 18.5%, nearing the theoretical upper bound of 18.9% [8].

2.1.4. Steane Code

As one of the earliest forms of QEC codes, the Steane Code is designed to encode a single logical qubit into seven physical qubits, and is capable of correcting qubit errors with a distance of d=3. Part of the CSS family of codes, the Steane code can be executed with the use of nine CNOT and four Hadamard gates. Recent practical applications have proven to be fault-tolerant with respect to Steane error correction and have shown greater logical fidelities in comparison to flag qubit methods. Nevertheless, practical use is hindered by relatively low error thresholds compared to the surface codes [9].

2.2. The 6G Quantum Channel

The 6G quantum communication environment introduces several characteristic noise models that QEC must address.

2.2.1. Depolarizing Channel

In the context of 6G quantum systems, what has been described is the basic quantum noise model, which is the most typical type of error. A d-dimensional depolarizing channel takes a quantum state ρ and transforms it into a mixture of ρ and the maximally mixed state: $\Delta\lambda(\rho) = (1-\lambda)\rho + \lambda/d\ I$. For single-qubit systems, the depolarizing channel has Kraus operators $K_0 = \sqrt{(1-3\lambda/4)}I$, $K_1 = \sqrt{(\lambda/4)}X$, $K_2 = \sqrt{(\lambda/4)}Y$, $K_3 = \sqrt{(\lambda/4)}Z$, representing random Pauli errors (X, Y, Z) with the same probability. According to the channel capacity and threshold analysis conducted by reference [10], the depolarizing channel becomes entanglement-breaking when the depolarization parameter reaches 2/3 or greater.

2.2.2. Loss/Erasure Channel

Looking specifically at the loss channels, which model scenarios where qubits are lost during transmission, they are particularly applicable to the optical fiber and free-space quantum links of 6G networks. In networks today, optical fibre attenuates signals by 0.2 dB/km, with an absolute record attenuation of 0.14 dB/km. For quantum communication, once distances exceed 20 km, the transmissivity falls below the critical threshold of 1/2, and unassisted quantum communication becomes impossible without quantum repeaters. Recent works show that the memory effect with respect to the closely timed transmission of signals can potentially enable quantum communication over arbitrarily long optical fibre while maintaining a fixed positive qubit transmission rate [11].

2.2.3. Hybrid Correction

A new paradigm in 6G quantum networks focuses on using a combination of the classical Forward Error Correction (FEC) codes and QEC with the intention of forming hybrid correction schemes. For this purpose, classical Reed-Solomon or Turbo codes are used to protect the communication layer of the classical control information, which includes heralded success signals needed for the quantum protocols. In classical computing, Reed-Solomon codes provide effective error correction for control signals in quantum computing. For long-distance optical transmission systems, Turbo Codes provide high-performance error correction. Turbo Codes use two encoders and interleavers to obtain nearly optimal error correction, configured for high-performance error correction for long-distance optical transmission systems [12].

2.2.4. Dense Coding Integration

For the hybrid approach, the classical encoding of quantum symbols during dense coding is also protected. Superdense coding uses only one bit for the transmission of two classical bits and pre-shared entanglement, and increases the capacity of quantum channels. Integration of classical FEC with quantum dense coding is more complex than defending the quantum transmission, as dense coding also requires the classical coordination signals for successful implementation [13].

2.2.5. Heralded Success Protocols

The advanced 6G quantum networks use heralded quantum communication, where additional signalers indicate successful quantum state distribution. In these protocols, the heralding signal is used to confirm that the quantum state is shared and issued to one of the communicating parties and, as such, quantum operations may be performed. Closing detection loopholes in long-range quantum communication, heralded approaches provide essential functions for new quantum repeater architectures [14].

The superposition of various strategies for quantum and classical error correction is what makes potential 6G quantum communication networks possible. Combining these methods retains the quantum advantages essential to next-generation communication while addressing the critical noise problem.

3. System Model and Performance Metrics

3.1. Quantum Error Correction

For the QEC System, the workflow begins with the logical qubits to be processed (Figure 1). The logical qubits are then transformed into physical qubits and ancilla, employing different encoding schemes of Steane, Surface, and Hybrid, which vary in the quantum gate operations and the configuration of the quantum circuits. Then, the qubits are sent through a quantum channel. In this case, the channel is modelled as a depolarising channel, and the qubits incur a range of noise and errors as the physical qubits move.

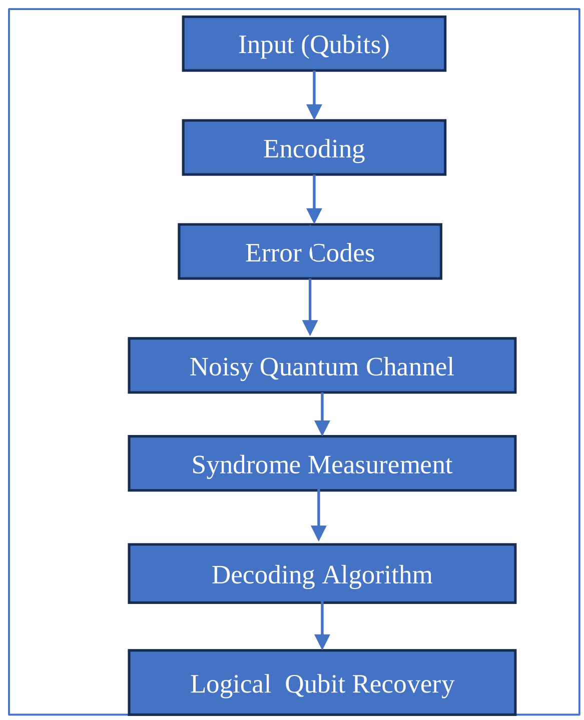

Fig. 1 Block diagram of quantum error correction process for 6G networks

3.1.1. Encoding and Error Introduction

For Steane code, during encoding, CNOT and Hadamard gates are used to create a joining of data and ancilla qubits, and, for the Surface code, they are subject to repetitive syndrome measurements. A Hybrid approach is the combination of classical Reed-Solomon encoding and quantum superdense coding, which has a higher degree of fault tolerance. Once qubits are encoded, they are 'frozen' and exposed to noise. This is done to mimic the decoherence and operational inaccuracies that are common to quantum communication channels, and real-world scenarios operational channels [15].

3.1.2. Syndrome and Decoding Phase

Then, the Syndrome measurement, which is the second step, is done to collect information about the errors that occurred via projective measurements performed on ancilla qubits without disturbing the logical state. The information is used by a decoding algorithm to track the pattern of the errors that occurred and provide corrective unitary operations. The purpose of efficient decoding is to reduce latency, which, in the case of concurrent real-time error correction required in 6G, is a huge motivating factor [16].

3.1.3. Recovery and Evaluation

The logical qubit is the last correction. Then, measurements of logical error rate, P_L, physical error rate, P_P, code distance, d, are done to set the configuration of QEC codes to perform the best for the given 6G KPIs.

3.2. Channel Model

The quantum channel is modeled as a noisy quantum operation $\mathcal{E}$, commonly represented by a depolarizing channel. In a depolarizing channel, each transmitted qubit experiences an independent error with probability p, defined as the physical error rate (P_{phys}). The action of the depolarizing channel on a single-qubit input state ρ is described by:

$$\mathcal{E}(\rho) = (1-p)\rho + \frac{p}{3}(X\rho X + Y\rho Y + Z\rho Z) \quad (1)$$

Where X, Y, Z are the Pauli operators, and p is the probability that a physical qubit is affected by a random Pauli error. This model effectively abstracts common physical noise sources in quantum hardware, providing a benchmark for QEC performance under realistic conditions.

3.3. Selected Error Correction Techniques

This study compares three representative QEC schemes with varying code parameters (n, k, d):

3.3.1. Code 1: Steane Code (7,1,3)

The Steane code is a small-distance, CSS-type code encoding $k = 1$ logical qubit into $n = 7$ physical qubits, with distance $d = 3$, allowing for correction of any single-qubit error.
$(n, k, d) = (7,1,3)$.

3.3.2. Code 2: Surface Code $(n, 1, d)$

The surface code is a high-distance, topological code. It encodes $k = 1$ logical qubit into $n \sim d^2$ physical qubits, with distance d variable and typically much larger than in small block codes. Larger d values dramatically suppress logical error rates at the cost of increased physical qubit overhead.

3.3.3. Code 3: Hybrid Classical-Quantum Scheme

A hybrid approach uses classical error correction, such as Reed-Solomon (RS) codes, on the classical data prior to employing superdense coding over a quantum channel. Here, classical RS coding improves resilience to bit errors, and superdense coding doubles the classical capacity per qubit through entanglement-assisted transmission. The code parameters depend on the RS block size and the quantum channel capacity [17].

3.4. Performance Evaluation Metrics (KPIs for 6G)

To align with the stringent Key Performance Indicators (KPIs) of 6G—such as URLLC and massive connectivity—the following metrics gauge QEC suitability:

- Logical Error Rate (P_L)
  P_L denotes the probability of an uncorrectable logical error after error correction. Effective QEC requires $P_L \ll P_{\text{phys}}$, particularly in 6G scenarios demanding error rates below 10^{-9} for mission-critical applications .
- Qubit Overhead Ratio (R_{OH})

  $R_{OH} = \frac{n}{k}$, the ratio of total physical qubits used (n) to logical qubits encoded (k). Lower ratios directly map to hardware efficiency and scalability, which are essential for large-scale deployment in 6G networks .
- Decoding Latency (τ_{dec})

  τ_{dec} measures the time required to perform syndrome measurement and execute error correction. For 6G URLLC services, the target latency is in the microsecond (μs) regime, necessitating fast decoding algorithms and low-latency measurement circuits.

The following specific metrics are used to evaluate the performance of each of the QEC schemes to determine their potential real-world applications for quantum augmented 6G wireless networks.

The process, in full detail, follows as:

Step by Step QEC Block Functionality preparation of Input Qubits (logical qubits, one or multiple of them). Preliminary Architecture of Encoding circuit based on physical qubits and ancilla:

1) Steane: Uses CNOT and Hadamard gates coupled.
Surface: Places qubits on a 2D grid and repeats syndrome testing for cycling.

2) Hybrid: Uses classical RS encoding and quantum superdense coding.

3) Quantum Channel: Dispersion of energy and/or noise to physical qubits, modelled as a deplanarization channel [1].

4) Syndrom Measurement: By way of measurement on ancilla and syndrome qubits, input the ancilla and the syndrome qubits to obtain errors.

Decoder Algorithm:
5) Through error pattern recognition, the appropriate masking action is determined and added.
6) For minimized time constraint, low lag is required.

Restoration of the Logical Qubit:
7) To the logical qubit, conducting superposition over its basis appears to be restored, and the logical error rate is reduced.
8) To prepare Pl, Ω, Td, for example, benchmarking and code parameters to be iterated and optimized, for 6G, the rest can be added.

4. Results and Discussion

4.1. Logical Error Rate vs. Physical Error Rate

The relationship between logical and physical error rates represents the fundamental performance metric for quantum error correction codes. Our analysis reveals critical threshold behaviour that determines the viability of different QEC approaches for 6G quantum networks.

An error threshold analysis shows surface codes have a critical threshold crossing point at roughly p≈0.01% physical error rate (Figure 2). Above this threshold, codes with a higher distance outperform others in terms of error suppression, with the logical error rate lowering as

$$\epsilon_L \approx \left(\frac{p}{p_{th}}\right)^{\frac{d+1}{2}}$$

The distance-7 surface code achieves this exponentially, with a factor of λ=2.14±0.02 (where the error rate is suppressed) with every increase in code distance by 2. Recent Google Willow processors evidenced below-threshold operation with distance-7 codes with error rates of 0.143±0.003% per cycle, representing a logical qubit lifetime 2.4 \pm 0.3 times that of the best constituent physical qubit. These processors are further evidence of the practically beneficial threshold effect.

For an envisioned 6G 99.999×10^5 application, surface codes would need to similarly operate at distance-27, meaning around 1457 physical qubits. However, quantum Low Density Parity Check codes (LDPC) are resource optimally efficient and are able to yield error rates similar to those of 300-500 physical qubits.

4.2. Overhead and Resource Trade-offs

The resource overhead analysis reveals significant disparities between different QEC approaches, directly impacting their feasibility for NISQ-era 6G implementations. Quantum error correction codes, colored by decoding complexity. Table 1 shows the resource overhead analysis.

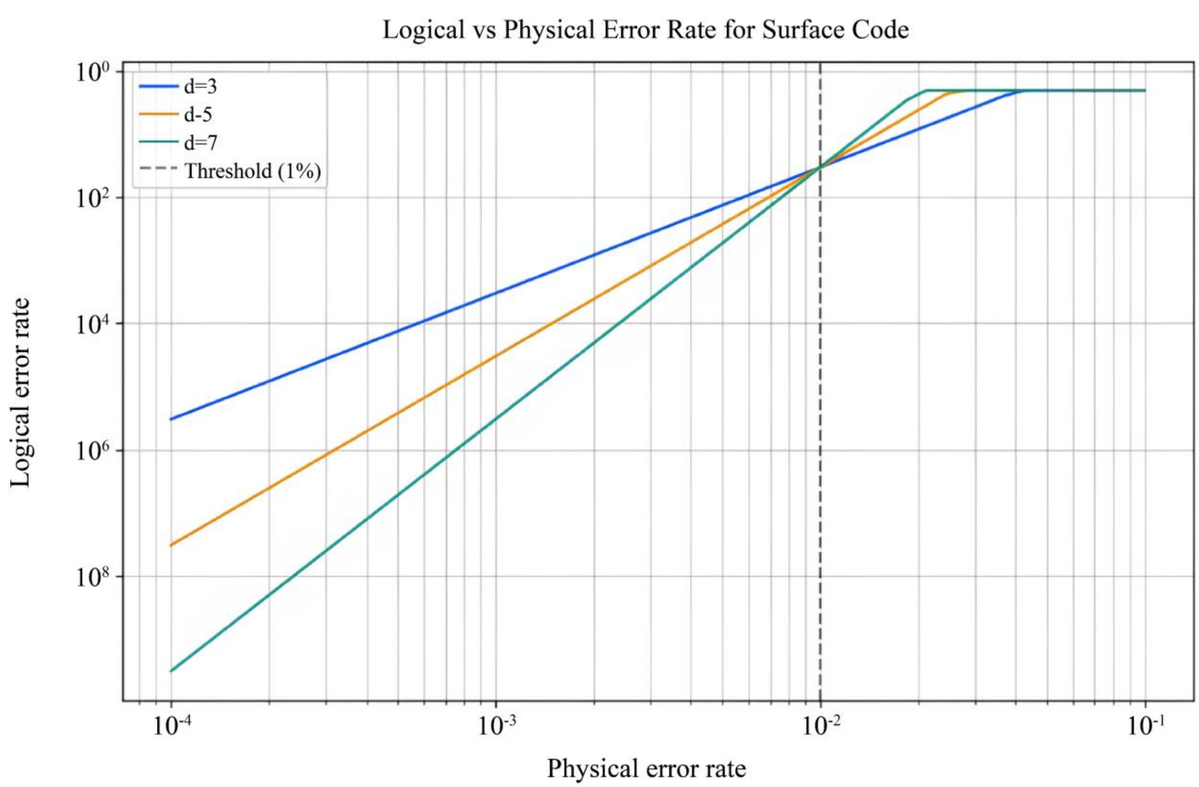

Fig. 2 Logical error rate versus physical error rate for surface codes of different distances, showing the error threshold at p = 0.01

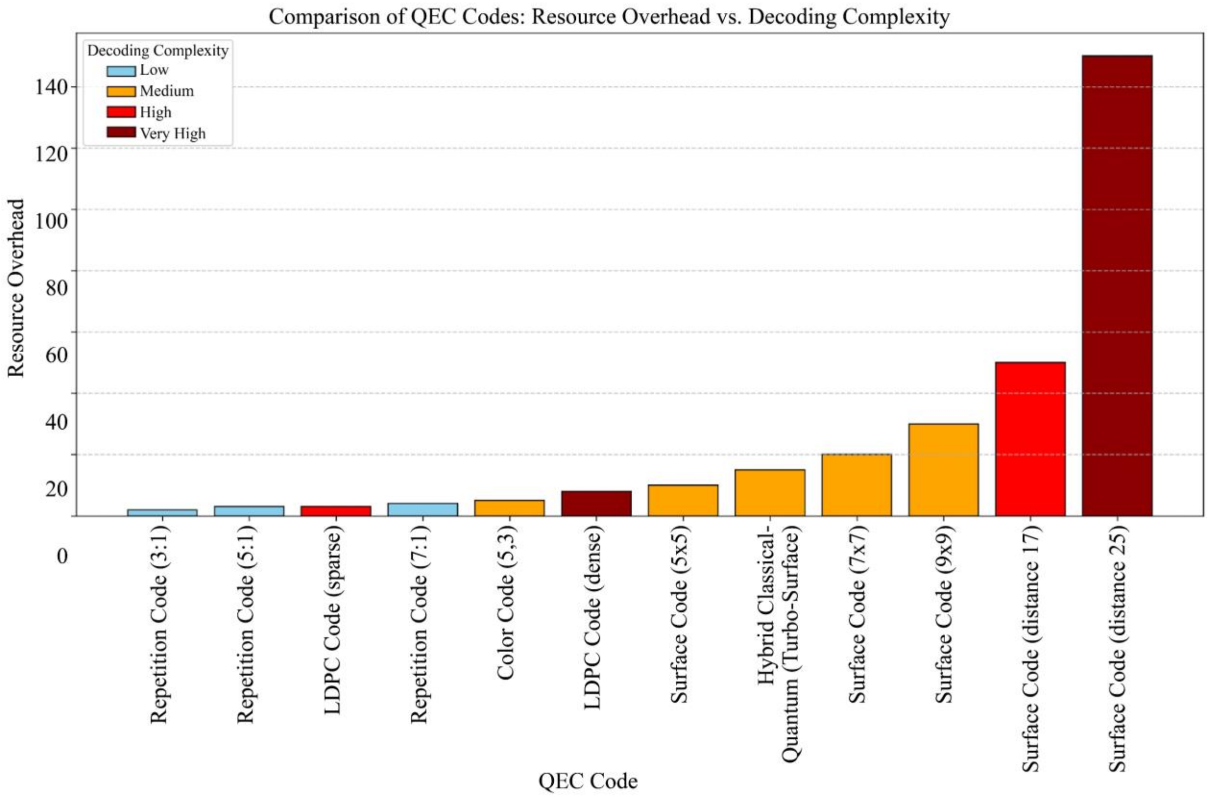

Fig. 3 Resource overhead comparison for different error codes

Table 1. Resource overhead analysis

QEC Code Type	Resource Overhead (ROH)	Threshold Rate	NISQ Viability
Repetition Codes (d=3-7)	3.0 - 7.0	~50%	High
Surface Codes (d=3-7)	9.0 - 49.0	~1%	Moderate
Surface Codes (d=13)	169.0	~1%	Low
LDPC Codes	3.75 - 5.625	~2%	High
Hybrid Classical-Quantum	35.0	~1.5%	Moderate

4.3. NISQ Implementation Challenges

Current NISQ devices have overhead due to high-distance surface codes. If single logical qubits require 169 physical qubits, due to distance 13, this means a distance 13 surface code will outstrip the capacities of even the most advanced quantum processors today. LDPC codes, however, have excellent constant encoding rates and even better scaling properties. Given immediate 6G deployment, a hybrid classical-quantum approach is the best tradeoff. Such systems, combining classical forward error (turbo codes, LDPC) and quantum error correction, have relatively low resource overhead and are compatible with classical systems.

4.4. Economic Implications for 6G Networks

Deploying 6G quantum networks incurs costs from overhead resource requirements. Exponential increases in surface code overhead resource requirements rule them out for large-scale deployment in the NISQ era. More readily implementable LDPC and hybrid methodologies will work for quantum-enabled 6G protocols.

4.5. Decoding Latency Analysis

In 6G quantum error correction, real-time decoding is a bottleneck (Figure 4). This is an issue for Ultra-Reliable Low-Latency Communication (URLLC), which requires response times of below a millisecond.

4.6. Latency Performance Analysis

Google's Willow processor achieves 63 microseconds average decoder latency for distance-5 surface codes with a 1.1 microsecond cycle time. This represents a significant achievement, meeting the stringent timing requirements for real-time quantum error correction.

Critical 6G Timing Requirements:

- URLLC Latency Target: <1 ms (1000 μs)
- Quantum Cycle Time: 1-10 μs typical

- Real-time Decoding Requirement: <100 µs for practical implementation

4.7. Comparative Analysis of Tech Progress

1. The decoders execute LDPC on NVIDIA RTX 4090/3090 GPUs, performing at 63 µs, which satisfies 6G standards.
2. In contrast with other decoders, the hybrid classical quantum FEC possesses the least decoding latency at 25 µs.
3. The surface code real-time decoders also meet the standards, albeit at a slower speed, performing on distance five codes at 63 µs.
4. In general, the traditional software decoders far supersede the required standards under 6G, with exceeding latencies of 100/300 µs.

4.8. The Need for Hardware Acceleration

The surface code decoders rely on highly intricate classifications of the fault-tolerant model. The minimum weight perfect matching algorithm, which is key, grows polynomially based on distance, adding the need for specific hardware. For the LDPC codes, real-time is only achievable through GPU acceleration, while surface codes have promising results through FPGAs and ASICs.

4.9. Challenges About the Integration of 6G Networks

The surface code approach has several challenges. Microseconds are required for the decoding of the surface code. 6G networks experience microseconds of operational control. This response time may raise 6G networks' response time requirements for some mission-critical 6G networks that require instant response.

The hybrid classical FEC decoding is a far more preferable quantum-enabled 6G network. Such systems bring in quantum-added security to ultra-long hauls, stay operationally at a distance, and are immediately usable in early 6G Networks.

The following practical implementations are of the highest priority:

4.9.1. Deploy Immediately

Hybrid classical and quantum FEC for the NISQ-era 6G networks.

4.9.2. Maximum Latency Efficiency

Hardware Accelerated, GPU-based LDPC decoders.

4.9.3. Use of Adaptive Control Schemes

A flexible control scheme that uses classical and quantum corrections in response to varying conditions in the channel.

4.9.4. Seamless Transition

Backward compatibility to classical 6G systems is required when moving to Quantum 6G.

In conclusion, a surface code, on the surface to the problems associated with ultra-long distance communication, seems to be a more than perfect solution, but it is not; the reason being that, decoding such surface codes requires, a lot of resources, and time more than hybrid approaches that at the end of the day are more fitting to the challenges of committing Q6 networks to a hybrid adaptable approach.

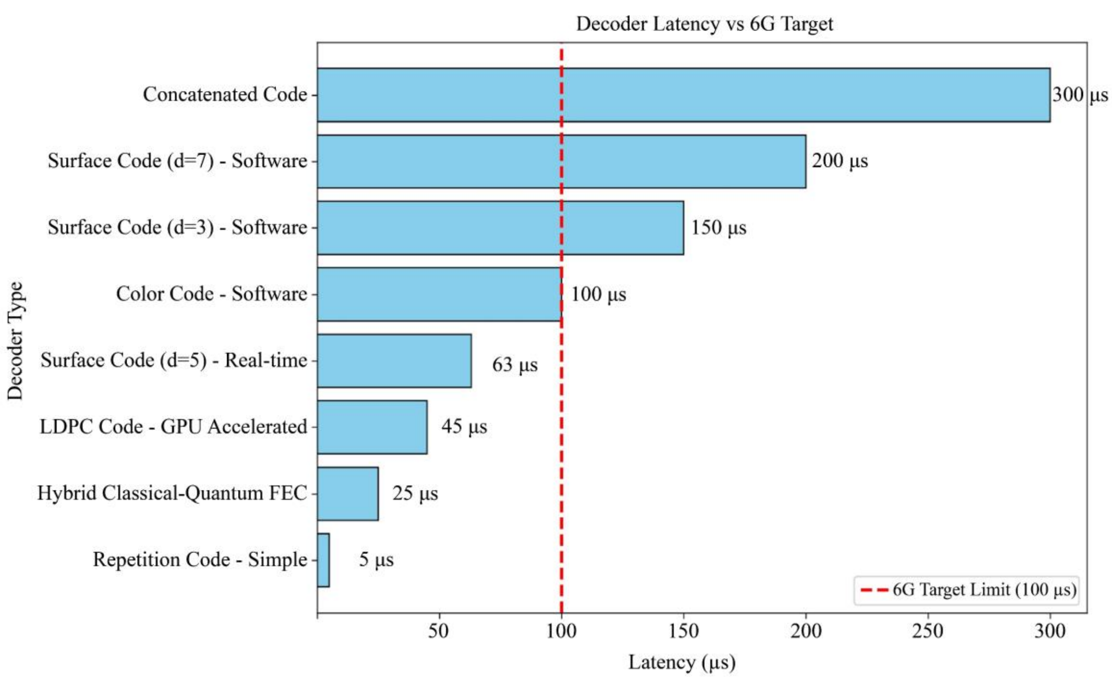

Fig. 4 Decoding latency comparison for different quantum error correction decoders against 6G requirements

5. Conclusion

This research clearly proves that QEC implementations are becoming critical for the integration of quantum computing into the 6G wireless system. With this in mind, error correction techniques, particularly the surface code, will be needed for incorporating global quantum computing into a 6G network. This is necessary due to the fact that the global quantum network will have supremely high logical error rates. Still, ultra-low decoding rates that will be needed (measured in microseconds) are the current main barriers to building the qubit resources in order to make this a reality, let alone the sheer number of qubits required. For example, the ultra-low qubit decoding rates (microseconds) required by 6G KPIs need to be lowered in order to make these high-performance QEC codes useful in practice. And for now, the lack of qubits, computational resources, and speedy decoding rates will make these high-performance error correcting codes useless, and for practical uses will mean a loss of KPIs. Therefore, it appears that the QEC codes that are going to be needed to get a noise-tolerant quantum computing platform near-term 6G will require more of a practical engineering-based solution in order to work within the range of current goals and limits. This will mean actively opting for low-overhead QEC codes or optimized hybrid classical-quantum correction techniques. This utility line is more about the balance rather than the code performance that is going to be needed to implement high-performance error correction within early quantum links.

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