Quantum Error Correction: Current State and the Promise of qLDPC Codes

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Abstract

Quantum error correction (QEC) is pivotal for realizing scalable and reliable quantum computing, addressing the inherent fragility of quantum states due to noise and decoherence. This paper reviews the current state of QEC, highlighting significant advancements in 2023 and 2024 across various platforms, including superconducting qubits, trapped ions, and reconfigurable atom arrays. Among the various QEC methodologies, quantum Low-Density Parity-Check (qLDPC) codes, particularly IBM's Gross code, emerge as the most promising due to their low qubit overhead, high error thresholds, and potential for scalability. We discuss the reasons for their prominence, propose improvements, and outline strategies for their implementation into quantum computing systems, positioning qLDPC codes as a cornerstone for future fault-tolerant quantum computers.

1 Introduction

Quantum computing promises to solve complex problems beyond the reach of classical computers, but its potential is hindered by the susceptibility of quantum bits (qubits) to errors from environmental noise, hardware imperfections, and decoherence. Quantum error correction (QEC) mitigates these issues by encoding logical qubits across multiple physical qubits, enabling error detection and correction without collapsing the quantum state. Recent years, particularly 2023 and 2024, have seen remarkable progress in QEC, shifting the focus from noisy intermediate-scale quantum (NISQ) devices to early error-corrected quantum computers. This paper surveys the current state of QEC, identifies quantum Low-Density Parity-Check (qLDPC) codes as the most promising methodology, and proposes strategies for their improvement and implementation.

2 Current State of Quantum Error Correction

QEC has evolved significantly, with breakthroughs across various quantum computing platforms. Below, we outline key advancements based on recent research.

2.1 Superconducting Qubits

Superconducting qubits have seen substantial progress in QEC, particularly with the surface code. In 2024, Google Quantum AI demonstrated below-threshold error correction using their Willow processors, implementing distance-5 and distance-7 surface codes with 72 and 101 qubits, respectively [1]. The logical error rate for the distance-7 code was $0.143\% \pm 0.003\%$ per cycle, with a suppression factor of $\Lambda = 2.14 \pm 0.02$ when increasing the code distance by 2. The logical qubit lifetime exceeded the best physical qubit by a factor of 2.4 ± 0.3, marking a significant milestone in achieving fault-tolerant quantum memory.

2.2 Trapped Ions

In April 2024, Microsoft and Quantinuum achieved a logical error rate 800 times lower than the physical error rate using a qubit virtualization system on Quantinuum's trapped-ion hardware [2]. This system created four logical qubits from 30 physical qubits, employing active syndrome extraction to diagnose and correct errors during computation without destroying the logical qubits. In June 2025, Quantinuum reported the first universal, fully fault-tolerant quantum gate set with repeatable error correction, validating techniques like code switching and compact error-detecting codes [3].

2.3 Reconfigurable Atom Arrays

Reconfigurable atom arrays have enabled fault-tolerant logic over hundreds of physical qubits. A 2023 study demonstrated a logical quantum processor based on atom arrays, achieving fault-tolerant entangling gates on the five-qubit code and the color code [4]. These advancements highlight the versatility of atom arrays for QEC experiments.

2.4 Qudits and Bosonic Codes

In January 2025, researchers at UNSW Sydney developed an error correction method using antimony-based materials and high-dimensional quantum states (qudits) with up to eight states, leveraging the nuclear spin of a phosphorus atom in silicon [5]. Additionally, a 2025 study demonstrated error correction of logical qutrits (d=3) and ququarts (d=4) using the Gottesman–Kitaev–Preskill (GKP) bosonic code, achieving lifetimes 1.82 ± 0.03 and 1.87 ± 0.03 times longer than the best physical qudits, respectively [6].

2.5 Other Notable Advances

- **Real-Time Decoding**: Google's real-time decoder for the surface code achieved a latency of 63 ± 17 μs for distance-5 codes, enabling practical error correction [1]. - **Machine Learning in QEC**: Google's AlphaQubit, an AI-powered decoder, reduced error rates by 6% compared to existing methods, demonstrating the potential of machine learning in QEC [9]. - **Theoretical Improvements**: Advances in hardware-efficient QEC and scalable decoders, such as FPGA-based implementations, have enhanced the practicality of QEC [10].

3 The Most Promising QEC Methodology: qLDPC Codes

Among the various QEC methodologies, quantum Low-Density Parity-Check (qLDPC) codes, particularly IBM's Gross code, stand out as the most promising due to their efficiency, scalability, and compatibility with near-term hardware.

Table 1: Recent Advancements in Quantum Error Correction (2023–2025)

Platform	Advance	Reference
Superconducting Qubits	Suppression of logical error with increasing code size (surface code, $\Lambda = 2.14 \pm 0.02$)	[1]
Trapped Ions	Logical error rate 800x lower than physical rate	[2]
Reconfigurable Atom Arrays	Fault-tolerant logic over hundreds of qubits	[4]
Qudits (GKP Code)	Error correction beyond break-even for qutrits and ququarts	[6]
General	Real-time fault-tolerant QEC and scalable decoders	[7, 8]

3.1 Description of qLDPC Codes

qLDPC codes are quantum analogs of classical low-density parity-check codes, characterized by sparse parity-check matrices where each qubit is involved in a limited number of checks, and each check involves a few qubits. The Gross code, a type of bivariate bicycle (BB) qLDPC code, has parameters [[144, 12, 12]], encoding 12 logical qubits into 144 data qubits with a distance of 12, using a total of 288 qubits [11]. Each qubit connects to six others, implementable in a two-layer planar architecture, making it suitable for superconducting qubit platforms like IBM's Eagle and Heron processors.

3.2 Why qLDPC Codes Are Promising

qLDPC codes offer several advantages over other QEC methodologies, particularly the surface code, which is currently the most widely pursued:

1. **Low Qubit Overhead**: The Gross code protects 12 logical qubits with 288 physical qubits, compared to approximately 3,000 qubits required by the surface code for similar performance [11]. This 10-fold reduction in qubit overhead enhances scalability, a critical factor for large-scale quantum computing. 2. **High Error Threshold**: qLDPC codes have an error threshold of approximately 0.7%–1%, allowing them to tolerate higher physical error rates than surface codes, which is advantageous for noisy quantum hardware [11, 13]. 3. **Scalability**: The reduced overhead and sparse connectivity make qLDPC codes more feasible for scaling to thousands or millions of qubits, enabling quantum circuits with billions of gates [11]. 4. **Hardware Compatibility**: qLDPC codes are designed to be implementable on existing superconducting qubit architectures with manageable connectivity requirements, as demonstrated by IBM's roadmap for their Starling quantum computer by 2028 [12]. 5. **Recent Advancements**: Theoretical work by Panteleev and Kalachev in 2022, followed by IBM's Gross code and Photonic Inc.'s SHYPS codes, validated through simulations, indicate practical viability [11, 14]. Photonic's SHYPS codes require up to 20 times fewer qubits than surface codes, further highlighting the potential of qLDPC codes [14].

Table 2: Comparison of Quantum Error Correction Codes

Code	Advantages	Limitations	Status
Surface Code	High threshold (1%), experimentally demonstrated, compatible with 2D architectures	High qubit overhead (3,000 qubits for 12 logical qubits)	Mature, below-threshold demos [1]
qLDPC (Gross Code)	Low overhead (288 qubits for 12 logical qubits), high threshold (0.7%–1%)	Limited experimental demos, complex decoding	Theoretical, simulations [11]
GKP (Qudits)	Encodes more information per system, beyond break-even	Limited to bosonic systems, complex implementation	Experimental for qutrits/ququarts [6]
Color Code	Simpler logical gates, high threshold	Higher overhead than qLDPC, less studied	Experimental demos [4]

3.3 Comparison with Other QEC Codes

- **Surface Code**: The surface code is the most mature, with experimental demonstrations achieving below-threshold error correction and logical qubit lifetimes exceeding physical qubits by a factor of 2.4 [1]. However, its high qubit overhead limits scalability. - **GKP Code for Qudits**: The GKP code has shown promise for qutrits and ququarts, achieving QEC gains of 1.82–1.87, but its application is limited to bosonic systems, and scalability remains challenging [6]. - **Color Code**: The color code supports simpler logical gate implementations and has been demonstrated experimentally, but it requires more qubits than qLDPC codes and is less studied [4].

qLDPC codes outperform others in efficiency and scalability, making them the most promising for future quantum computing, despite their current lack of experimental demonstrations.

4 Improvements for qLDPC Codes

To realize the full potential of qLDPC codes, several areas require improvement:

1. **Optimized Code Parameters**: Research should focus on identifying qLDPC codes with higher encoding rates and distances to further reduce overhead and improve error correction capabilities [11]. 2. **Efficient Decoding Algorithms**: qLDPC codes require complex decoding due to their sparse structure. Developing faster, hardware-efficient decoders, possibly leveraging machine learning as in Google's AlphaQubit, is crucial [9]. 3. **Hardware-Specific Adaptations**: Tailoring qLDPC codes to specific hardware platforms, such as optimizing connectivity for superconducting qubits or neutral atoms, will enhance practical implementation [13]. 4. **Experimental Validation**: Small-scale experimental demonstrations are needed to confirm theoretical predictions and address practical challenges, such as managing long-range connectivity [14].

5 Implementation into Quantum Computing Systems

Implementing qLDPC codes into quantum computing systems involves several steps:

1. **Hardware Design**: Quantum processors must support the connectivity required for qLDPC codes, such as

2. **Control Systems**: Robust control systems are needed to perform syndrome measurements and corrections efficiently, ensuring low-latency operations compatible with qLDPC code requirements [1]. 3. **Software Integration**: qLDPC codes must be integrated into quantum computing software stacks, including compilers and error correction modules, to enable seamless operation [11]. 4. **Algorithm Compatibility**: Demonstrating that qLDPC-encoded logical qubits can execute useful quantum algorithms with high reliability is essential for practical applications [13]. 5. **Scalability**: Ensuring that qLDPC implementations can scale to larger systems while maintaining low error rates is critical for achieving fault-tolerant quantum computing [12].

6 Conclusion

Quantum error correction is at a pivotal stage, with significant advancements in 2023 and 2024 paving the way for fault-tolerant quantum computing. While surface codes have led the field with experimental successes, qLDPC codes, exemplified by IBM's Gross code, offer superior efficiency and scalability, positioning them as the most promising methodology for future quantum computers. By addressing challenges in decoding, hardware design, and experimental validation, qLDPC codes can enable scalable, error-corrected quantum systems, bringing us closer to practical quantum computing.

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