

Review

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Review

A Comprehensive Review of Recent Progress in Quantum Error Correction: Codes, Decoders, and Fault-Tolerant Architectures

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Abstract

This review article provides a comprehensive overview of recent developments in the field of quantum error correction (QEC), which stands as one of the biggest challenges for quantum computing. The extreme sensitivity of quantum systems to environmental noise makes it difficult to build reliable and scalable quantum computers. Inspired by pioneering codes like those from Shor and Steane, this work discusses the most promising QEC approaches today, particularly topological codes such as surface codes and low-density parity-check (LDPC) codes. The paper delves into critical experimental successes from industry leaders like Google, IBM, and Quantinuum, including their "below-threshold" error correction demonstrations and roadmaps for fault-tolerant systems. It also presents a comparative analysis between classical algorithms like Minimum-Weight Perfect Matching (MWPM) and newer, machine learning-based decoder approaches. The discussion section addresses open problems that need to be solved in the future, such as correlated noise, cryogenic control, and the creation of fault-tolerant logical gate sets. This review aims to summarize the current state of the QEC field, serving as a guiding resource for both academics and industry professionals in shaping future research and development strategies.

Keywords: quantum error correction; codes; decoders; qubits; fault-tolerant architectures

1. Introduction and Motivation

Quantum computing holds the promise of surpassing the capabilities of classical computers, with potential applications like Shor's algorithm for integer factorization and Grover's search algorithm. However, the primary obstacle to realizing this revolutionary potential is the inherent fragility and high error rate of quantum systems. Quantum states are quickly corrupted by environmental noise and unwanted interactions (decoherence), leading to the loss of quantum information. This fundamental problem gave rise to the field of quantum error correction (QEC), a necessity for building a scalable and reliable quantum computer, also known as fault-tolerant quantum computing [1].

The roots of QEC are inspired by classical information theory but must adhere to the unique rules of quantum mechanics (especially the "no-cloning theorem"). A turning point in the field came in 1995 when Peter Shor published the first nine-qubit QEC code that could simultaneously correct both bit-flip and phase-flip errors [2]. Subsequently, in 1996, Andrew Steane developed a more efficient seven-qubit code [3], solidifying the theoretical foundations. These pioneering works demonstrated that quantum computers could be designed as systems resilient to physical errors, moving them from a purely theoretical concept toward a tangible reality.

The Calderbank-Shor-Steane (CSS) codes [4] and the stabilizer formalism developed during this period became the foundational building blocks of QEC theory [5]. Today, QEC is no longer a purely theoretical domain but a core engineering and scientific challenge for both academia and industry. The effective reduction of physical qubit errors is the key transition from the Noisy Intermediate-Scale Quantum (NISQ) era to truly functional and reliable quantum computers. This article systematically

analyzes the latest developments in quantum error correction over the past few years, focusing on the implementation of codes, hardware advances, next-generation decoder algorithms, and the roadmaps of industry leaders.

2. Theoretical Foundations of Quantum Error Correction

To understand QEC, it is essential to first grasp the nature of quantum errors. Unlike classical bits that can only be flipped from 0 to 1, a quantum bit (qubit) can experience more complex errors, including bit-flips, phase-flips, and combinations thereof. The fundamental principle of QEC is to encode a single logical qubit into a larger number of physical qubits. This redundancy allows for the detection and correction of errors without directly measuring the quantum state, which would destroy it. The general QEC cycle can be broken down into three main steps:

1. **Encoding:** The logical qubit is encoded into a protected state using multiple physical qubits.
2. **Syndrome Measurement:** Ancilla qubits are measured to extract information about the errors (the "syndrome") without revealing the state of the logical qubit.
3. **Decoding and Correction:** A classical computer uses the syndrome data to identify the most likely error and applies a corrective operation to the physical qubits.

This process is repeated continuously to maintain the integrity of the logical qubit. The goal is to ensure that the error rate of the logical qubit is significantly lower than that of the physical qubits. This is known as reaching the "fault tolerance threshold" [6]. A key finding is that if the physical error rate is below a certain threshold, the logical error rate can be made arbitrarily low by increasing the code distance [7].

3. Deepening the Experimental Developments

After the theoretical foundations of QEC were laid, the main challenge became the successful implementation of these codes on physical hardware. In recent years, QEC experiments have yielded groundbreaking results, particularly in leading architectures such as superconducting qubits and trapped-ions.

3.1. Superconducting Qubits: A Focus on the Surface Code

Superconducting qubits, known for their fast gate operations, have been a primary platform for demonstrating QEC. A landmark achievement came in 2021 when a team from Google demonstrated "below-threshold" error correction using a surface code on their Sycamore processor [8]. The experiment used 49 physical qubits to encode and protect a single logical qubit. By repeatedly measuring the stabilizers—a set of operators that check for errors without disturbing the encoded logical state—they were able to detect and correct errors in real-time. The key result was that the error rate of the logical qubit (0.8%) was lower than the error rate of its constituent physical qubits (0.64%), a crucial proof-of-concept that QEC works in practice.

The surface code's effectiveness is directly tied to its code distance (d), which determines the number of physical qubits used to encode the logical one. Increasing the code distance exponentially suppresses the logical error rate, provided the physical error rate is below the fault-tolerance threshold. Recent work by teams at IBM and others has focused on building larger surface code instances with higher code distances ($d = 5$ and $d = 7$) to demonstrate this scaling behavior [9]. For instance, IBM's Eagle and Osprey processors, with over 100 qubits, have enabled demonstrations of complex logical operations, moving closer to a universal fault-tolerant system [10]. These large-scale experiments are also crucial for studying how noise propagates in a real-world quantum processor.

3.2. Trapped-Ion Systems: High Fidelity and All-to-All Connectivity

Trapped-ion quantum computers offer an alternative architecture with distinct advantages for QEC. Individual ions, held in place by electromagnetic fields, serve as qubits. Their primary strength lies in their exceptionally high gate fidelities, often exceeding 99.9% for two-qubit operations, and

long coherence times, which means they are less susceptible to decoherence than superconducting qubits. This high fidelity inherently reduces the initial physical error rate, making it easier to meet the fault-tolerance threshold [11].

The collaborative efforts of companies like Quantinuum and Microsoft have led to significant milestones in this field [12,13]. Their systems have successfully demonstrated logical qubits with error rates below the physical error rate, similar to the superconducting qubit demonstrations. A unique advantage of trapped-ion systems is their ability to physically shuttle and re-arrange ions within the trap. This all-to-all connectivity allows for the implementation of QEC codes that require non-local interactions, such as LDPC codes, which are difficult to realize on fixed-architecture platforms like superconducting qubits.

3.3. Alternative Architectures: Neutral Atoms and Photonics

Beyond superconducting and trapped-ion qubits, other platforms are also showing promise. **Neutral atom arrays** offer a path to massive scalability due to the ease of creating large arrays of individual atoms and their long coherence times. Researchers are exploring how to implement QEC in these systems, leveraging their high qubit connectivity and the ability to dynamically rearrange the atom positions, which could be beneficial for implementing complex logical gates [14].

Photonic quantum computing, which uses photons as qubits, is an active area of research for long-distance quantum communication and, in some cases, QEC. While generating and controlling single photons remains a challenge, a significant advantage is their immunity to thermal noise. Codes like the Gottesman-Kitaev-Preskill (GKP) code, which uses continuous variable states, are being explored as a method to achieve fault tolerance in photonic systems [15]. Finally, **bosonic qubits**, which encode quantum information in the multiple energy levels of a quantum harmonic oscillator, provide a different approach to redundancy and error suppression, as demonstrated by early experiments showing an extension of qubit lifetime beyond the bare physical limit [16].

4. Comparison of Code Families

Quantum error correction has evolved from a theoretical concept into a field with a diverse toolkit of codes, each with unique advantages and disadvantages tailored to specific hardware. These codes are fundamentally about encoding logical quantum information into a larger, redundant system of physical qubits.

4.1. Topological Codes: The Path to Scalability

Topological codes are currently the most favored class of QEC codes for physical implementation due to their resilience to local noise. Their structure is based on a 2D or 3D lattice, and they are defined by a set of local stabilizer measurements. The logical information is encoded in a way that makes it dependent on the global properties of the lattice, meaning that a localized error cannot corrupt the information.

- **Surface Code:** The surface code is a prime example of a topological code that has gained immense traction [17,18]. It is defined on a 2D grid of data qubits and ancilla qubits. Errors are detected by measuring stabilizers on small, local groups of qubits (plaquettes). These measurements generate a "syndrome" that indicates the location and type of an error. The local nature of these interactions makes it a perfect fit for planar architectures like superconducting qubits. The surface code has a relatively high error threshold (around 1%), making it compatible with today's noisy hardware [19]. However, its main drawback is its high resource overhead: a single logical qubit may require thousands of physical qubits to achieve a low logical error rate, which is a significant engineering challenge.
- **Color Codes:** Color codes are a generalization of the surface code. They operate on a 2D lattice but with a more complex geometric structure, often a trivalent lattice with faces of three colors [20,21]. This structure provides a key advantage: all logical Clifford gates (like Hadamard and

CNOT) can be implemented in a fault-tolerant manner using only local operations, a property known as "transversality" [22]. This is a major improvement over the surface code, where some logical gates require complex and resource-intensive techniques like "magic state distillation."

4.2. Other Code Families: Beyond the Topological Paradigm

While topological codes are the current frontrunners, other code families offer different trade-offs and are actively being researched.

- **LDPC (Low-Density Parity-Check) Codes:** Inspired by classical coding theory, quantum LDPC codes are defined by a sparse set of parity-check equations, meaning each qubit is involved in only a few checks. This leads to a higher code rate, meaning they can encode more logical qubits with fewer physical ones, in principle [23,24]. They can also offer higher error thresholds than surface codes. The main challenge with LDPC codes is that their check operations often require non-local interactions, which can be difficult to implement on current hardware architectures with limited connectivity. However, as technologies like neutral atoms with all-to-all connectivity mature, LDPC codes could become a more viable and efficient option.
- **Shor and Steane Codes:** These historical codes were crucial in establishing the theoretical feasibility of QEC. The Shor code [2] can correct any single-qubit error (both bit-flip and phase-flip) using nine physical qubits. The Steane code [3], a type of CSS code, achieves the same with only seven qubits. While they are resource-intensive and not practical for large-scale computation, their importance cannot be overstated. They were the first to show how to simultaneously correct for different types of quantum errors and laid the groundwork for the more complex stabilizer formalism and topological codes used today.

5. Software and Decoders: The Brains of QEC

The best QEC codes are useless without efficient and fast decoders. The decoder's job is to take the syndrome data—the result of the stabilizer measurements—and, in real-time, determine the most likely error pattern that caused it. This process is a classical computation, but for a large-scale quantum computer, it must be performed with incredibly low latency.

5.1. Classical Decoder Algorithms: The Workhorse of QEC

- **Minimum-Weight Perfect Matching (MWPM):** For surface codes, the MWPM algorithm has become the standard classical decoder [25]. The syndrome data from the stabilizer measurements is mapped onto a graph. The nodes of this graph represent the locations of the syndrome measurements that showed an error, and the edges represent paths between these locations. The weight of each edge corresponds to the probability of an error occurring on that path. The MWPM algorithm then finds a perfect matching with the minimum total weight, which corresponds to the most likely error chain. The algorithm's output is then used to apply a corrective operation to the data qubits. While MWPM is highly effective and reliable for the surface code, its computational complexity can become a bottleneck as the size of the quantum computer scales. For a large number of qubits, the MWPM problem can be too slow for real-time decoding, which is a critical requirement for continuous QEC [26].

5.2. Machine Learning-Based Decoders: A Promising New Frontier

To overcome the limitations of classical decoders, a new area of research has emerged, focusing on the use of machine learning for decoding.

- ****Neural Networks**:** Researchers are training deep neural networks to act as quantum decoders. These networks can learn the complex, non-linear relationships between syndrome data and error patterns [27]. Unlike MWPM, which relies on a specific model of independent errors, a neural network can be trained on a dataset that includes more complex error patterns, such as correlated noise, which is a major challenge in real physical systems. The trained network can then provide

a decoding solution much faster than traditional algorithms, which is crucial for high-speed QEC cycles.

- ****Reinforcement Learning****: Reinforcement learning (RL) is also being explored. In this approach, an RL agent learns to decode by interacting with a simulated quantum system. The agent receives a reward for successful corrections and a penalty for failed ones, teaching it to develop an optimal decoding policy for a given noise model. This approach is particularly promising for adapting to changing or unknown noise conditions in real-time. The main challenge for machine learning decoders is the need for large, high-quality training datasets and the computational cost of the initial training phase. However, once trained, these decoders can offer significant speed advantages.

6. Open Problems and Future Perspectives

Despite the significant progress made in quantum error correction, the obstacles to building fault-tolerant quantum computers have not been completely overcome. This section will discuss the biggest "open problems" in the field and future projections.

6.1. Quantum Hardware and Engineering Challenges

- **Cryogenic Control**: Superconducting qubit systems must be operated at extremely low temperatures (milli-Kelvin range) to minimize thermal noise. The engineering challenge of integrating a large number of control and measurement lines into these cryogenic environments without introducing additional noise is a major hurdle for scalability.
- **Correlated Noise**: Most current QEC models assume that qubits err independently. However, in physical systems, an error in one qubit can affect neighboring qubits, creating correlated noise. This phenomenon, often caused by shared control lines or thermal effects, can seriously reduce the performance of existing decoders, and new codes and decoding algorithms are needed to handle such errors [28].
- **Qubit Uniformity**: Manufacturing large numbers of qubits with nearly identical properties (e.g., resonance frequencies, coherence times) is a significant challenge. Variations can lead to different error rates across the chip, making uniform QEC difficult to implement effectively.

6.2. Fault-Tolerant Logical Gate Sets

The purpose of QEC is not only to protect information but also to perform error-free operations on this encoded information. This requires the development of new protocols that can implement basic operations like single-qubit gates and two-qubit CNOT gates on logical qubits in a fault-tolerant manner. This is a non-trivial task, as any operation can introduce new errors. In particular, complex techniques such as "magic state distillation" are essential to make certain gates (like the T-gate) fault-tolerant by generating high-fidelity magic states from noisy ones [29].

6.3. The Path to Scalability

The ultimate goal is to build quantum computers with a large number of logical qubits, enabling them to solve problems that are intractable for classical computers. This will require a fully integrated quantum stack, from hardware to software. The development of quantum compilers that can translate high-level algorithms into fault-tolerant circuits is a crucial step [21]. Furthermore, the development of new communication protocols for distributed quantum computing could enable the construction of modular quantum computers, which may be more scalable than a single monolithic chip [30].

7. Conclusions

Quantum error correction remains the cornerstone of the quantum computing field, enabling the transition from noisy, small-scale prototypes to reliable, fault-tolerant systems. The pioneering theoretical work of Shor and Steane paved the way for modern topological codes, and recent experimental breakthroughs have shown that QEC is not just a theoretical concept but a viable engineering

reality. As the field progresses, the focus is shifting towards solving complex hardware challenges like correlated noise and developing a complete fault-tolerant stack from the physical layer to the application layer. While significant obstacles remain, the rapid pace of innovation from both academia and industry suggests that a practical, large-scale quantum computer is on the horizon. This review has summarized these crucial developments, serving as a guide to the current state of QEC and highlighting the areas where future research is most needed.

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