



Limitations of quantum error correction in noisy intermediate-scale quantum (nisq) systems

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Received 1/10/2025, Received in revised form 3/11/2025, Accepted 9/11/2025, Published 15/1/2026

Study of the Issue Quantum error correction (QEC) is crucial yet incurs significant qubit overhead costs. The current QEC codes lack sufficient efficiency for near-term devices. The current generation of NISQ devices, which often rely on delicate nanostructured qubit architectures, is prone to noise, decoherence, and gate faults, which severely limit their computing capability and scalability. While traditional quantum error correction codes, such as the surface code, are theoretically resilient, they often require significant qubit overhead and complex management systems that exceed the hardware capabilities of NISQ-era devices. This raises the question of whether new, resource-efficient QEC strategies or hybrid error mitigation approaches can be tailored to the limits of nanostructured NISQ designs. This document examines the constraints of existing quantum error correction (QEC) codes, which are crucial for preserving the fidelity of quantum computations yet require substantial qubit resources. This study examines the shortcomings of current Quantum Error Correction (QEC) codes in relation to Noisy Intermediate-Scale Quantum (NISQ) devices and explores alternative strategies to create more efficient, low-overhead QEC frameworks appropriate for imminent quantum technologies.

Keywords: Quantum error correction; Noisy Intermediate-Scale Quantum; Qubit.

1. INTRODUCTION

Examination of the Matter Quantum error correction (QEC) is essential, but entails considerably qubit overhead expenses. The existing QEC codes exhibit inadequate efficiency for imminent devices.

Is it possible to create more efficient, low-overhead quantum error correction techniques for Noisy Intermediate-Scale Quantum (NISQ) devices? This article analyzes the limitations of current Quantum Error Correction (QEC) codes, which are essential for maintaining the fidelity of quantum calculations yet demand significant qubit resources. This study examines the deficiencies of existing QEC schemes concerning Noisy Intermediate-Scale Quantum (NISQ) devices and explores alternative approaches for developing more efficient, low-overhead QEC frameworks suitable for forthcoming quantum technologies.

The previous studies have significantly contributed to shaping the evolution of Quantum Error Correction (QEC) techniques and their practical realization. Quantum Error Correction (QEC) encompasses many techniques aim at alleviating errors resulting from the delicate characteristics of quantum states. The primary objective of QEC is to preserve the coherence of quantum information in the face of disruptive ambient noise, which may result in decoherence and operational mistakes. In the domain of Quantum Error Correction (QEC), various solutions exist, including stabilizer codes that leverage the characteristics of entangled states for efficient error detection and correction. Among these methodologies, surface codes are particularly distinguished for their remarkable fault tolerance, rendering them a preferred option in topological quantum computing applications. Moreover, novel high-performance codes like quantum low-density parity-check (qLDPC) codes have garnered attention for providing more straightforward decoding mechanisms while preserving robustness against diverse error types. Moreover, hybrid methodologies that integrate traditional error correction techniques with quantum methods are gaining popularity, mostly due to their substantial reduction in resource demands. The incorporation of machine learning into quantum error correction frameworks enhances decoding efficiency, facilitating adaptive responses to fluctuating error situations. As research advances, the multidisciplinary applications of QEC become increasingly evident across several domains spanning cryptography, where it guarantees secure quantum communications, to material science, where precise simulations facilitate the development of novel materials. Despite progress in code design and integration with advanced technologies like topological qubits and distributed systems, obstacles persist, including significant qubit overhead and intricate decoding requirements, which hinder scalability efforts [1,2].

Incorporating quantum error correction (QEC) into quantum computing poses considerable issues that must be resolved to improve system reliability. A significant issue is the considerable overhead linked to qubit resources; numerous physical qubits are frequently needed to accurately embody a single logical qubit, hindering practical applications as these systems expand. This desire stems from the necessity to effectively encode quantum information to withstand mistakes. Noise in quantum systems introduces an additional degree of complexity. Qubits are susceptible to environmental variations and decoherence, resulting in faults that Quantum Error Correction (QEC) seeks to rectify. Effective quantum error correction codes must conform to the distinct error characteristics of various hardware, rendering accurate noise modeling imperative. Formulating techniques for noise characterization and reduction is essential for enhancing QEC performance. Moreover, attaining real-time decoding capability presents a considerable barrier. Rapid reaction techniques are essential for preserving quantum information integrity, particularly as algorithms get increasingly intricate. As quantum computers improve, the demand for control mechanisms will escalate, requiring sophisticated hardware solutions that address both error correction and computing needs. These issues underscore the complexity of deploying practical quantum error correction systems in near-term noisy intermediate-scale quantum (NISQ) devices, necessitating joint endeavors that integrate theoretical progress with inventive engineering solutions [3-6]. Improving quantum error correction (QEC) for noisy intermediate-scale quantum (NISQ) devices requires strategies that minimize qubit usage while maintaining efficiency. Approaches such as approximate quantum error correction (AQEC) provide high fidelity without the heavy overhead of conventional codes, making them suitable for resource-constrained systems. Hybrid methods that

combine classical and quantum error-correcting codes, including quantum low-density parity-check (qLDPC) codes, offer enhanced fault tolerance while conserving qubits. Additionally, advances like machine learning-based decoders and frameworks using ancilla-assisted operations further improve noise adaptation, error detection, and logical reliability, laying the groundwork for future fault-tolerant quantum systems [2,6,7].

The primary objective of this research is to identify and evaluate strategies that minimize qubit overhead while preserving error correction efficiency, thereby enhancing the practicality and scalability of QEC implementations in near-term quantum systems. Equally important is the design of low-overhead QEC frameworks tailored for NISQ environments. Key requirements include reducing the physical-to-logical qubit ratio, employing multi-dimensional codes for better scalability, and optimizing syndrome extraction and decoding to avoid excess time and energy consumption. Hybrid approaches that leverage classical machine learning for noise assessment have also emerged as promising solutions for adaptable QEC protocols. Ultimately, effective low-overhead designs depend on robust hardware implementations capable of rapid error correction cycles and parallel processing, ensuring both efficiency and practicality as quantum technologies advance toward fault tolerance [2,5,8].

2. MATERIALS AND METHODS

2.1 Qubit overhead considerations

Quantum error correction (QEC) is crucial for dependable quantum computing; nevertheless, the overhead associated with qubit utilization presents considerable hurdles. Conventional techniques, especially surface codes, typically necessitate thousands of physical qubits to construct a single logical qubit suitable for computations, complicating fault-tolerant quantum computing as the demand for qubits escalates. To resolve these challenges, novel families of error-correcting codes have been created, including Quantum Low-Density Parity Check (QLDPC) codes, which aim at minimizing the requisite number of physical qubits while maintaining efficient quantum operations. Recent improvements indicate that QLDPC codes can encode a single logical qubit using merely two physical qubits without sacrificing error correcting efficacy. Nevertheless, existing QEC approaches often constrain resource efficiency in near-term devices with a limited number of active qubits. As the quantity of qubits increases, the demands for maintenance and control escalate, complicating calibration and amplifying systemic faults. The pursuit of efficient quantum error correction (QEC) in Noisy Intermediate-Scale Quantum (NISQ) systems constitutes a significant domain for advancement, necessitating scalable solutions. To address the resource and functionality difficulties in NISQ nanostructure, novel designs such as compact three-dimensional structures seek to enhance error suppression, reduce physical resource requirements, and facilitate progress in practical quantum technology [5,7,9-12].

2.2 Efficiency gaps in near-term devices

Efficiency deficiencies in next-generation quantum devices mostly arise from the limitations of existing quantum error correction (QEC) methods. Traditional techniques, such as surface codes, may necessitate 1000 physical qubits to realize a single logical qubit, hence complicating scalability and hindering practical implementations. The noise and error rates of Noisy Intermediate-Scale Quantum (NISQ) devices are inconsistent, complicating fixed-distance quantum error correction (QEC) methods. Adaptive quantum error correction techniques have arisen to tackle these oscillations, potentially lowering the requisite number of physical qubits while preserving effective error mitigation.

The coherence timings of current qubit technologies present a significant issue, as numerous configurations have brief coherence durations that restrict the frequency and efficacy of error correction. Furthermore, restricted qubit connection hinders the implementation of effective quantum error correction codes in contemporary designs.

To address these efficient challenges, novel designs and programming approaches are being devised to reduce resource requirements while improving reliability. Recent developments in Quantum Low-Density Parity Check (QLDPC) codes exhibit superior performance in executing logical operations relative to conventional approaches, potentially hastening the timescale for realizing commercial-scale quantum computing [2,7,10-13].

2.3 Scalability issues

As quantum computing systems advance, scalability issues in quantum error correction (QEC) become more pronounced. The primary obstacle stems from the significant overhead resources necessary for efficient QEC coding. Conventional approaches frequently necessitate thousands of physical qubits to embody a single logical qubit. This imbalanced ratio constitutes a substantial obstacle to enhancing quantum computing capabilities, particularly in light of the constraints of existing hardware technologies. Furthermore, as quantum systems expand, attaining fault tolerance becomes increasingly intricate. Contemporary hardware systems sometimes encounter challenges, including insufficient qubit connections and restricted coherence times, hindering the effective execution of quantum error correction methods. The complexities of noise modeling introduce additional challenges; precise models that accurately represent individual hardware deficiencies are essential for guaranteeing the successful performance of QEC codes in real-world scenarios.

In response to these issues, researchers are investigating novel coding schemes designed to decrease the physical-to-logical qubit ratios while maintaining fault tolerance. Innovations such as multi-dimensional codes and energy-efficient structures demonstrate potential in reducing power requirements linked to syndrome extraction and decoding procedures, facilitating the development of more scalable systems. Integrating these advanced techniques into existing frameworks necessitates overcoming substantial practical obstacles that are associated with decoder design and system integration.

As we progress from noisy intermediate-scale quantum (NISQ) devices to more resilient systems that can facilitate large-scale quantum error correction (QEC) implementations, it is crucial to enhance the performance of individual components while ensuring their harmonious integration within intricate frameworks [2,14-16].

2.4 Definition and features of NISQ devices

The operation of NISQ devices that depend on their capacity to employ various quantum algorithms is designed for noisy conditions. For instance, approaches like the Quantum Approximate Optimization Algorithm (QAOA) have been refined to effectively harness the advantages of NISQ systems. Moreover, initiatives focus on error mitigation strategies such as dynamical decoupling and advanced quantum error correction (QEC) codes, including surface codes, which are crucial for reducing noise-related problems and enhancing computational accuracy.

Recent developments in programming platforms like Qiskit and Cirq have further propelled the growth and application of NISQ technologies, providing researchers with tools to manage qubits effectively and execute algorithms smoothly. Although these systems still face notable technical obstacles, particularly regarding coherence times and circuit complexity, NISQ devices are at the forefront of bridging current classical computing capabilities with future fault-tolerant quantum computing architectures [6,7,9,17].

2.5 Comparison with full-scale quantum computers

The shift from noisy intermediate-scale quantum (NISQ) devices to large-scale fault-tolerant quantum computers (FTQC) encounters considerable obstacles owing to their distinct operational frameworks. NISQ devices, constrain to tens or hundreds of qubits, encounter challenges with noise and decoherence, depending on variational algorithms that employ shallow circuits to sustain error rates. This limitation hinders their capacity to execute complex calculations. Conversely, FTQC systems pursue error correction via intricate codes, including surface codes, necessitating millions of physical qubits to attain high-fidelity logical qubits. NISQ devices can do particular jobs within noise limitations, whereas FTQC structures offer the potential for superior computational capabilities if effectively are realized. FTQC emphasizes high gate fidelity and coherence times that are required for performing complicated operations vital for applications in material simulation and advanced linear algebra, which currently exceed NISQ capabilities. Moreover, noise-resistant techniques from NISQ platforms do not adequately scale to fulfill FTQC needs. NISQ devices provide insights into practical quantum computing but have inherently constrained relative to the extensive capabilities expected from fault-tolerant quantum computers with future technological progress [6,7,9,18].

3. RESULTS AND DISCUSSION

3.1 Proposed solutions for QEC in NISQ devices

3.1.1 New code designs and algorithms

Recent advancements in quantum error correction (QEC) have resulted in novel code architectures and methods for noisy intermediate-scale quantum (NISQ) devices. A significant advancement is Approximate QEC (AQEC), which alleviates the stringent criteria of conventional QEC techniques, attaining high-fidelity outcomes under NISQ resource limitations. This adaptability is essential as accurate Quantum Error Correction becomes progressively unfeasible due to the scarcity of physical qubits.

Emerging coding frameworks, such as quantum low-density parity-check (qLDPC) codes, are becoming essential elements of scalable quantum error correction (QEC) systems, effectively utilizing fewer physical qubits while ensuring robust fault tolerance. Geometric and hybrid approaches augment error correction efficiency; many-hypercube codes utilize geometric characteristics to enhance correction capabilities across dimensions.

Moreover, machine learning methodologies, including adaptive decoders like AlphaQubit, address intricate noise patterns, optimize decoding operations and enhance performance. Hybrid classical-quantum methodologies enhance the applicability of quantum error correction.

Nanostructured $\text{AgZnFe}_2\text{O}_3$ has been found to inhibit the growth of antimicrobial-resistant Gram-negative pathogens, highlighting its potential as an effective antibacterial agent with broad biomedical and therapeutic applications. Likewise, Amazon's Ocelot chip utilizes cat qubit technology to address particular problems, improving quantum error correction implementation via its scalable nanostructure. Advancements in code designs are enhancing the resource efficiency of quantum error correcting schemes for NISQ devices [1,2,5,8,19-21].

3.1.2 Hybrid approaches combining classical methods with QEC

Hybrid solutions in quantum error correction (QEC) are progressively utilized to improve the reliability and efficacy of quantum systems. These methodologies integrate traditional error correction techniques with quantum strategies, proficiently mitigating noise in both realms. Classical systems are essential for

interpreting syndrome information from quantum states, which is critical for real-time error detection and correction, employing methods such as minimum-weight perfect matching (MWPM) and belief propagation.

Machine learning has significantly enhanced hybrid quantum error correction by facilitating adaptive decoding algorithms that react to intricate noise patterns in noisy intermediate-scale quantum (NISQ) devices. Quantum-assisted neural networks may evaluate high-dimensional data from quantum operations, enhancing error correction by utilizing conventional advantages in conjunction with quantum benefits. Furthermore, hybrid architectures optimize resource management across classical and quantum layers, enabling each to tackle distinct noise sources while augmenting overall system performance. This method enhances efficiency and enables quick reactions for modifications in the quantum environment. As these advances progress, hybrid QEC solutions present interesting avenues to address the shortcomings of current fault tolerance strategies and improve computational fidelity across diverse platforms. The incorporation of hardware accelerators such as FPGAs and GPUs is essential for attaining the low-latency decoding necessary for efficient error correction [2].

3.2 Simulation results and expected outcomes

Recent simulations of quantum error correction (QEC) techniques demonstrate significant progress in diminishing logical error rates in noisy intermediate-scale quantum (NISQ) systems. The implementation of surface codes has demonstrated a substantial enhancement in performance, attaining error levels that surpass those associated with physical qubits. For example, research employing a novel Willow architecture indicates that augmenting the code distance significantly reduces the logical error rate by half with each cycle, ultimately achieving an exceptional distance-7 logical lifespan that exceeds the longevity of the foundational physical qubits. The substantial decrease in logical mistakes is essential for the precise execution of intricate quantum computations [21].

Moreover, recent studies have investigated hybrid methodologies that integrate classical techniques with quantum error correction, demonstrating less overhead and enhanced fidelity in the context of superconducting qubits. The incorporation of quantum error mitigation (QEM) with quantum error correction (QEC) procedures has facilitated the attainment of optimal expectation values via efficient noise reduction methods. These simulations demonstrate that, despite constrained physical resources, effective quantum error correction may be realized by the utilization of resilient decoding systems that sustain performance over prolonged durations and several cycles.

Nonetheless, obstacles persist, especially in managing correlated error bursts and enhancing resource allocation for real-time decoding as code distances increase. Notwithstanding these challenges, forecasts indicate that reducing physical error rates may result in substantial improvements in logical performance, which is crucial for numerous algorithmic applications. The examination of these data offers significant insights for the creation of more effective quantum error correction systems specifically designed for NISQ devices [22-24].

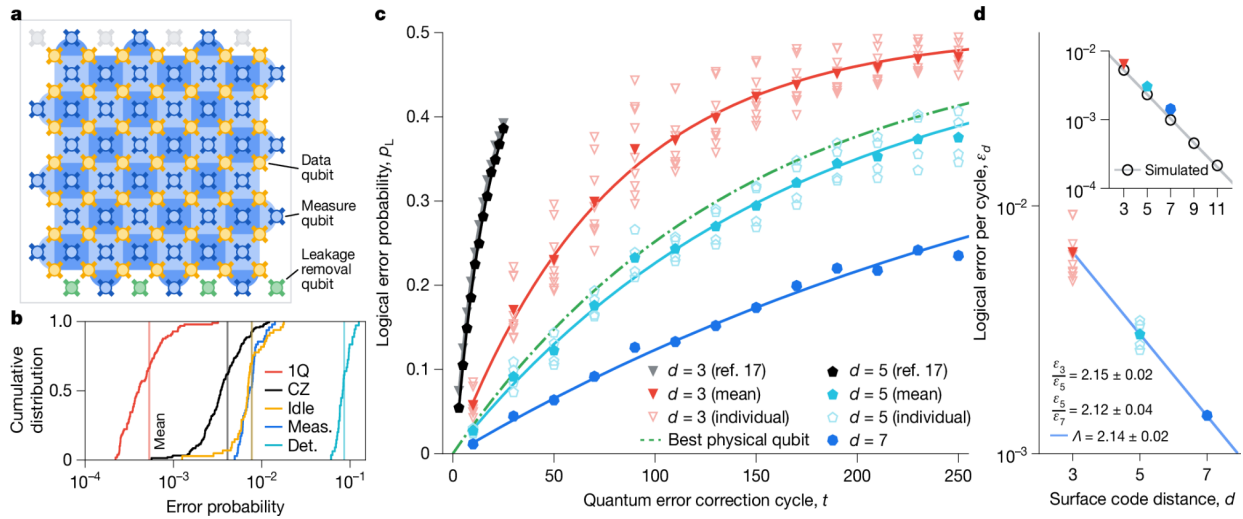


Figure 1 Performance of surface codes.

A schematic representation of a distance-7 ($d = 7$) surface code on a 105-qubit processor. Each measured qubit (blue) is linked to a stabilizer (blue tile). Data qubits (gold) constitute a $d \times d$ matrix. We eliminate leakage from each data qubit utilizing an adjacent qubit beneath it, supplemented by extra leakage removal qubits at the boundary (green). Cumulative distributions of error probability assessed on the 105-qubit processor. Red denotes Pauli errors for single-qubit gates; black indicates Pauli errors for CZ gates; gold represents Pauli errors for data qubits idling during measurement and reset; blue signifies identification errors for measurement; teal illustrates weight-4 detection probabilities (distance 7, averaged over 250 cycles). c, The likelihood of logical error p_L over various lengths of memory experiments. Each data point signifies 10^5 repetitions processed by the neural network and is averaged across the logical bases (X_L and Z_L). Black and grey, data from reference 17 for comparative analysis. Curves and exponential fittings subsequent to the averaging of p_L over code and base. To calculate ϵ_d values, we individually fit each code and basis, subsequently reporting their average (Supplementary Information). Logical error per cycle, ϵ_d , decreases with surface code distance d . The uncertainty for each position is below 7×10^{-5} . The symbols correspond to those in c. Means for $d = 3$ and $d = 5$ are computed from the separate ϵ_d fits for each code and basis. Line, fitted to equation (1), determining Λ . The inset shows simulations up to $d = 11$ alongside experimental points, both are decoded with ensemble matching synthesis for comparison. Line fits to simulation; $\Lambda_{sim} = 2.25 \pm 0.02$ [24].

3.3 Comparison with existing codes' performance metrics

Evaluating performance metrics for quantum error correction (QEC) codes is essential for their efficacy in rectifying faults in quantum systems. Essential measurements encompass logical error rates, fidelity, and qubit use efficiency. The logical error rate substantially affects the reliability of logical qubits obtained from physical qubits. For instance, Google improves surface codes by increasing code distance from five to seven, reducing logical error rates by a factor of 2.14. Fidelity quantifies the precision with which operations on logical qubits emulate ideal conditions; elevating fidelity signifies the successful maintenance of logical states in the face of physical qubit defects. Surface codes provide remarkable fidelity, rendering them appropriate for fault-tolerant quantum processing. Qubit usage efficiency evaluates the effectiveness of physical qubits in producing reliable logical qubits, gaining significance as quantum systems grow, as optimal resource utilization improves computational capability and cost-efficiency. Recent developments indicate varied efficacy among QEC techniques. Hybrid methods that integrate classical techniques with quantum encoding have demonstrated significant efficacy in

minimizing logical errors compared to conventional procedures. In summary, while current QEC codes exhibit varying success based on application contexts, ongoing research aims to push these boundaries toward achieving practical fault tolerance in quantum technologies [4,5,23,25].

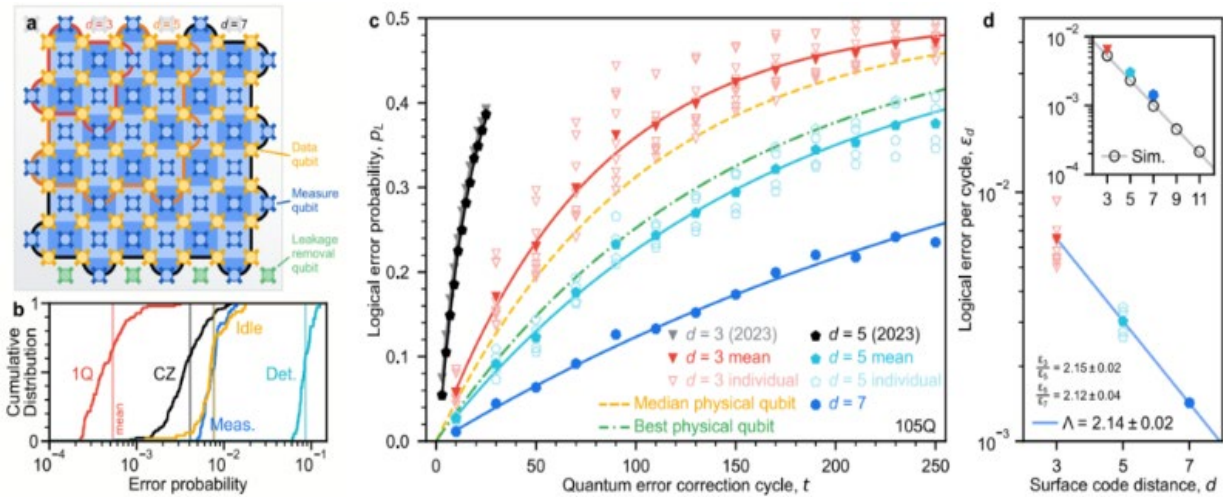


Figure 2 Logical Qubit Error Rates vs. Code Distance.

The diagram depicts the shift to sub-threshold performance and the "beyond break-even" behavior attained using distance-7 codes [4].

Logical error per cycle vs. code distance

- This panel shows logical error rate per cycle (ϵ_d) as a function of code distance d on a logarithmic scale.
- The inset compares experimental data with simulations.
- The near-linear relationship in the log-log plot indicates an exponential suppression of logical error:

$$\epsilon_d \approx \Lambda^{-d} \tag{1}$$
 where Λ is the *error suppression factor*.
- The slope corresponds to $\Lambda = 2.14 \pm 0.02$, meaning that each increment in code distance roughly doubles the suppression of logical error.

Key Equations

1. Logical Error Rate Scaling:

$$\epsilon_L(d) = A (p/p_{th})^{(d+1)/2} \tag{2}$$

- $\epsilon_L(d)$: logical error rate
- p : physical qubit error rate
- p_{th} : threshold error rate
- A : constant factor related to decoder efficiency
- d : code distance
- Indicates exponential decay of logical errors when $p < p_{th}$.

2. Exponential Decay Relation (as seen in panel d):

$$\epsilon_d = \epsilon_0 e^{-\alpha d} \tag{3}$$

or equivalently,

$$\log_{10}(\epsilon_d) = -\alpha d + \log_{10}(\epsilon_0) \tag{4}$$

where α represents the error suppression coefficient per code distance unit.

3. Logical Error Probability Over Time (panel c):

$$P_L(t) = 1 - (1 - \epsilon_d)^t \approx t \epsilon_d \quad (5)$$

Valid for small ϵ_d , showing a linear increase of logical error probability with cycle count.

4. Threshold Condition:

$$p < p_{th} \implies \text{fault-tolerant regime} \quad (6)$$

Once the physical error rate p drops below the threshold p_{th} (typically $\sim 1\%$), increasing d yields exponential improvement.

3.4 Practical applications of efficient QEC schemes

3.4.1 Use cases in quantum computing applications

Quantum error correction (QEC) greatly enhances the scope of quantum computing applications across various domains, facilitating diverse use cases. Quantum chemistry is a significant domain where QEC facilitates precise simulations of molecular interactions. This capacity is particularly crucial for drug development and materials science, as it enables researchers to simulate intricate systems that traditional computers find challenging due to their fundamental constraints. The integration of QEC-enhanced quantum simulations significantly enhances the accuracy of forecasting molecular behaviors and interactions, which is essential for the advancement of novel medications. In cryptography, Quantum Error Correction (QEC) fortifies communication channels against interception and potential quantum attack threats. Quantum error correction (QEC) strengthens the security of sensitive information exchanges, including financial transactions and national security affairs, by decreasing errors in quantum key distribution protocols. Compelling use emerges in artificial intelligence (AI). The integration of Quantum Error Correction with machine learning algorithms accelerates operations and improves data analysis capabilities. Industries like finance can utilize these developments to enhance predictive models and optimize investment strategies, all underpinned by high-precision quantum calculations.

In climate science, QEC is essential for facilitating accurate simulations that enhance predictions of environmental changes. This capability is increasingly vital for simulating complex climate dynamics and formulating strategies that facilitate the incorporation of renewable energy. The application of good QEC methodology uncovers new potential across various technological fields, enabling us to leverage the benefits of quantum computing while mitigating its weaknesses [5,26].

3.4.2 Impact on future quantum technologies

The importance of robust quantum error correction (QEC) techniques in the development of emerging quantum technologies is remarkable, affecting various fields and leading to new advancements. Quantum error correction (QEC) techniques enhance the dependability of quantum computations, which are essential for practical applications in quantum cryptography. This enhancement fortifies secure communication systems, protecting sensitive information from potential intrusions in vital areas such as finance and healthcare. Moreover, QEC is essential in climate modeling and environmental studies. Enhancing the stability of quantum simulations facilitates more accurate climate predictions and the examination of complex environmental interactions. These innovations can guide policy-making efforts to address climate change and promote sustainable habits. The integration of Quantum Error Correction with artificial intelligence presents avenues for advancement. It fosters more reliable decision-making processes in societal contexts such as medical diagnostics or judicial systems. This capability will allow for seamless interoperability among various quantum platforms, laying the groundwork for future advancements within computing networks.

In summary, effective QEC methodologies are not just improvements to existing technologies but are fundamental elements that will drive the progress of many fields beyond traditional computing paradigms [2].

4. CONCLUSIONS

Quantum error correction (QEC) remains a cornerstone for achieving reliable quantum computation, particularly within the constraints of Noisy Intermediate-Scale Quantum (NISQ) devices that suffer from noise, decoherence and operational faults. Despite the robustness of traditional codes such as the surface code, their high qubit overhead and complexity exceed the capabilities of current hardware, highlighting the urgent need for more efficient, resource-aware approaches. Recent advances suggest that hybrid strategies integrating classical error correction, machine learning and adaptive algorithms can enhance error mitigation while maintaining practical scalability. Future research should prioritize the design of low-overhead QEC frameworks tailored to NISQ architectures, supported by interdisciplinary collaboration and simulation-based validation. Such developments will not only advance quantum hardware performance but also expand the applicability of quantum computing across domains like chemistry, optimization, and cryptography, ensuring equitable and sustainable technological progress.

References

- [1] Asaad T. Al-Douri, Alaa A. Khaleel, Luay Mannaa Ibrahim, Abeer Talib Abdulqader, Ammr Khalid Shihab, Mustafa Khaleel Ibrahim, Maksood Adil Mahmoud Al-Doori, Exp. Theo. NANOTECHNOLOGY 9 (2025) 563 <https://doi.org/10.56053/9.4.563>
- [2] Mehmet Keçeci, Open Science Articles 1 (2025) 36 <https://doi.org/10.5281/zenodo.17328737>
- [3] Bisma Bilal, Suhaib Ahmed, Vipin Kakkar, Exp. Theo. NANOTECHNOLOGY 3 (2019) 33 <https://doi.org/10.56053/3.1.33>
- [4] Muhammad AbuGhanem, quant-ph 3 (2024) 1 <https://doi.org/10.48550/arXiv.2410.00917>
- [5] Mehmet. Keçeci, Open Science Articles 1 (2025) 1 <https://doi.org/10.5281/zenodo.15515113>
- [6] Yutaro Akahoshi, Kazunori Maruyama, Hirotaka Oshima, Shintaro Sato, Keisuke Fujii, PRX quantum 5 (2024) 010337 <https://doi.org/10.1103/PRXQuantum.5.010337>
- [7] Riki Toshio, Yutaro Akahoshi, Jun Fujisaki, Hirotaka Oshima, Shintaro Sato, Keisuke Fujii, Physical Review X 15 (2025) 021057 <https://doi.org/10.1103/PhysRevX.15.021057>
- [8] Carmen G Almudéver, Leonid Pryadko, Valentin Savin, Bane Vasic, Dagstuhl Reports, 14 (2024) 173 <https://doi.org/10.4230/DagRep.14.5.173>
- [9] Bin Cheng, Xiu-Hao Deng, Xiu Gu, Yu He, Guangchong Hu, Peihao Huang, Jun Li, Ben-Chuan Lin, Dawei Lu, Yao Lu, Chudan Qiu, Hui Wang, Tao Xin, Shi Yu, Man-Hong Yung, Junkai Zeng, Song Zhang, Youpeng Zhong, Xinhua Peng, Franco Nori, Dapeng Yu, Frontiers of Physics 18 (2023) 21308 <https://doi.org/10.1007/s11467-022-1249-z>
- [10] David Layden, Mo Chen, Paola Cappellaro, Physical review letters 124 (2020) 020504 <https://doi.org/10.1103/PhysRevLett.124.020504>
- [11] Valentine Nyirahafashimana, Nurisya Mohd Shah, Umair Abdul Halim, Mohamed Othman, Quantum Information Processing 24 (2025) 292 <https://doi.org/10.1007/s11128-025-04904-5>
- [12] Connor T Hann, Kyungjoo Noh, Harald Putterman, Matthew H Matheny, Joseph K Iverson, Michael T Fang, Christopher Chamberland, Oskar Painter, Fernando GSL Brandão, PRX Quantum 6 (2025) 030305 <https://doi.org/10.1103/75x7-5ysv>
- [13] Subrata Das, Swaroop Ghosh, Quantum Physics 3 (2025) 1 <https://doi.org/10.48550/arXiv.2505.06165>
- [14] A. M. Ahmed Alwaise, Raqeeb H. Rajab, Adel A. Mahmood, Mohammed A. Alreshedi, Exp. Theo. NANOTECHNOLOGY 8 (2024) 67 <https://doi.org/10.56053/8.3.67>
- [15] Qurban A Memon, Mahmoud Al Ahmad, Michael Pecht, Quantum Reports, 6 (2024) 627 <https://doi.org/10.3390/quantum6040039>
- [16] Francesc Rodríguez-Díaz, David Gutiérrez-Avilés, Alicia Troncoso, Francisco Martínez-Álvarez, ACM Computing Surveys 58 (2025) 1 <https://doi.org/10.1145/3764582>
- [17] Keyi Yin, Xiang Fang, Zhuo Chen, Ang Li, David Hayes, Eneet Kaur, Reza Nejabati, Hartmut

Exp. Theo. NANOTECHNOLOGY 10 (2026) 1-11

- Haeffner, Wes Campbell, Eric Hudson, *Quantum Physics* 5 (2025) 1
<https://doi.org/10.48550/arXiv.2504.16303>
- [18] Maria S. da Dunla, *Exp. Theo. NANOTECHNOLOGY* 8 (2024) 23
<https://doi.org/10.56053/8.2.23>
- [19] Dominic J. Williamson, Nouédyn Baspin, *Nature Communications* 15 (2024) 9528
<https://doi.org/10.1038/s41467-024-53881-3>
- [20] Muhammad AbuGhanem, *EPJ Quantum Technology* 12 (2025) 102
<https://doi.org/10.1140/epjqt/s40507-025-00405-7>
- [21] Yusuke Hama, Hirofumi Nishi, *Scientific Reports* 14 (2024) 6077
<https://doi.org/10.1038/s41598-024-52485-7>
- [22] Yasunari Suzuki, Suguru Endo, Keisuke Fujii, Yuuki Tokunaga, *PRX Quantum* 3 (2022) 010345
<https://doi.org/10.1103/PRXQuantum.3.010345>
- [23] I Trond, Markus Ansmann, Frank Arute, Kunal Arya, Abraham Asfaw, Nikita Astrakhantsev, Juan Atalaya, Ryan Babbush, Dave Bacon, Brian Ballard, *Nature* 638 (2025) 27
<https://doi.org/10.1038/s41586-024-08449-y>
- [24] Guo Zheng, Wenhao He, Gideon Lee, Liang Jiang, *Physical Review Letters* 132 (2024) 250602
<https://doi.org/10.1103/PhysRevLett.132.250602>
- [25] J. S. Kith N. M. Slaber, *Exp. Theo. NANOTECHNOLOGY* 9 (2025) 9
<https://doi.org/10.56053/9.1.9>
- [26] Nick S. Blunt, Laura Caune, Róbert Izsák, Earl T. Campbell, Nicole Holzmann, *PRX Quantum* 4 (2023) 040341
<https://link.aps.org/doi/10.1103/PRXQuantum.4.040341>