International Journal of Latest Research in Engineering and Technology (IJLRET)
ISSN: 2454-5031
www.ijlret.com || Volume 12 - Issue 05 || May 2026 || PP. 11-15

A Review Paper: Advances in Quantum Computing: Physical Principles and Experimental Challenges

Afrah Abass Abd Alkreem
Wasit Education Directory

Introduction

Quantum computing utilizes the basic principles of quantum mechanics, involving superposition and entanglement, for executing computational tasks that are intractable for classical computers [1]. The new paradigm uses the unique quantum properties of qubits for processing as well as storing data, providing exponential speedups of certain problems, such as prime factorization, database search, and simulation regarding complex quantum systems [2], [3].

A classical bit may only exist in 0 or 1 state but a quantum bit, or qubit, may exist in a superposition of 0 and 1 at the same time, which greatly enhances the computational capacity of quantum systems [4]. This intrinsic characteristic, along with the entanglement, in which qubits become correlated to the extent that the state of one cannot be specified without the rest, allows quantum computers to compute multiple computations in parallel [5], [6].

This property is the basis of quantum algorithm design, including the Shor’s algorithm of factoring and the Grover’s algorithm of unstructured search, which appear to have a major theoretical benefit over their classical counterparts [7]. This property of qubits to be in a superposition of states in addition to the entanglement phenomenon enables quantum computers to process very large volumes of information more effectively than the classical computers through quantum parallelism [4], [8]. This fundamental departure from classical computing is due to the wave-particle duality of the quantum mechanics that enables the exploration of multiple computational paths at the same time [9].

Moreover, the engineering of quantum circuits is the most accurate control of the enhancement of the performance and scalability of such algorithms especially in high-performance computing use [10]. But it is difficult to preserve these quantum states, because of the process of decoherence, where environmental interactions cause qubits to lose their quantum characteristics, and therefore coherence times are only milliseconds[11].

As a result, a reduction of decoherence and engineering fault tolerant quantum systems are some of the main issues in the creation of robust quantum computing systems [12]. This necessitates the development of more advanced error detection codes and novel hardware architecture to achieve the delicate quantum coherence, on which scalable and reliable quantum computation relies.

Literature Review

This paper gives a review of the recent developments in physical implementations of qubits and the experimental challenges with qubit scaling of quantum systems with quantum coherence. It also looks at the current development of quantum algorithms and the applications and performance standards through which they are assessed to be effective in the current quantum hardware [13]. It also explores the details of quantum gate operations that act on these qubit states, and the different quantum circuit architectures that implement more complicated quantum algorithms [8], [14].

Their application on a variety of quantum architectures, such as superconducting circuits, trapped ions, and others, is essential to the efficacy of these algorithms, and each has its own opportunities and challenges in relation to scalability and error rates [13]. The current endeavor to achieve fault tolerant quantum computing requires a rigorous examination regarding such architectural differences, especially in respect to the inherent resistance of their resilience to environmental noise and their ability to execute more complex quantum circuits [15].

Although there are major theoretical breakthroughs, practical implementation of large-scale, fault-tolerant quantum computers is limited by both hardware and software limitations, noise, lack of control, and decoherence are the most prominent challenges in many quantum computing systems [16]. Although it has already been demonstrated that superconducting systems can increase qubit count and quality, achieving practical fault tolerant quantum computing with standard quantum algorithms requires logical qubits of extraordinarily high quality (usually using error-correcting codes such as the surface code [17]).

This implies the need to investigate different physical systems to implement qubits with different benefits and drawbacks related to coherence, scalability, and error rates [18].

Methodology

The section outlines the systematic method used to survey and critically assess the current landscape in quantum computing in terms of interaction of physical principles and engineering issues. We were able to analyze the peer reviewed literature, preprints, and technical reports of experimental advances in qubit fabrication, quantum gate fidelity, and entanglement generation in the various modalities of quantum computing.

In particular, we have considered superconducting qubits, trapped ions, and topological qubits and evaluated their current development levels of coherence times and error reduction [4], [13]. Moreover, we have gone to the theoretical foundations of quantum error correction and fault-tolerant quantum computing and analyzed the architectures and their practicality in addressing environmental noise and operational imperfections [19]. We also discussed the measures to increase the stability and scalability of qubits, as they affect the future of developing practical and large-scale quantum processors [4].

The focus was especially put on the knowledge of the constraints posed by the Noisy Intermediate-Scale Quantum era, especially on qubit coherence and gate error rates, which are currently limiting the complexity of the executable quantum algorithms [20]. This included scrutinizing physical-level metrics, including T1 and T2 times of qubit stability and fidelity of multi-qubit operations, which are important to measure the overall performance of the platform [21].

The benchmarks also covered entanglement resilience and basis-state uniformity to quantify a noise-induced deviation of theoretical gate specifications, specifically, in multi-qubit operations [22]. Other solutions that we explored to enhance qubit stability and reduce error rates were advanced materials engineering and design of topological protection schemes [11]. We also explored implication of device topology, native gate set and physical arrangement and connectivity of qubits on quantum circuit mapping together with execution efficiency regarding different quantum hardware platforms [23].

Results

The compiled results are used to explain the present state-of-the-art in each of these platforms not only in the improvements in qubit counts and in addition to the successes in improving the gate fidelities, but also in the ongoing challenges on how to achieve universal fault tolerant quantum computation [24]. As an example, although superconducting and trapped ion qubits dominate the landscape, neutral atom and silicon-spin qubits are rapidly advancing, each with its own set of trade-offs in the form of coherence, connectivity and scalability [25].

Although notable achievements have been made in the field of qubit coherence and gate fidelity on a variety of platforms, it is clear that there is a significant gap between predicted noise-free performance and measured hardware performance as demonstrated by the large degradation in fidelity in actual implementations [22]. This discrepancy highlights the urgent requirement of the robust benchmarking protocols that consider the variation in the performance in the state-dependent environment and the multifaceted interaction between quantum state preparation and gate implementation in noisy intermediate-scale quantum devices [22].

Benchmarking must include a thorough assessment at component, system and application level measures in order to describe in a comprehensive manner the performance of quantum computers [26]. These standards are not only made important to quantify the existing hardware capabilities; but also guide the further evolution of quantum architectures to seek the bottlenecks and the ways of improvement [27]. As an illustration, a crucial metric, including the gate fidelity, can vary significantly, based on the quantum platform, and the type of a gate that is being used, and needs a certain characterization technique [28].

These characterization techniques must also be used to measure the impact of environmental factors and control pulse engineering on gate performance particularly when the performance of multi-qubit operations is being considered, where crosstalk and coherent errors may critically impact overall fidelity [29]. The imperfections of gates, which are the characteristics regarding current Noisy Intermediate-Scale Quantum era, introduce the error into the program output, and the maximization of the algorithmic fidelity is an important performance measure of the current systems [25].

Discussion

This has stressed the need to develop thorough benchmarking approaches that extend beyond individual gate fidelities, to assess the overall system performance when subjected to realistic algorithmic workloads [28]. It is a multi-dimensional evaluation that uses metrics that include quantum volume, application based benchmarks and randomized benchmarking to give a more global picture as to the abilities and constraints of a given device [30], [31]. Randomized Benchmarking protocols are generally applied to quantify the average gate fidelity by using random Clifford gates and studying the depolarization channel due to errors [25].

These approaches tend to be simplified forms of error models, however, and more complex approaches are required to capture non-Markovian noise and coherent error processes in superconducting, trapped-ion and photonic quantum systems. Moreover, more detailed characterization regarding quantum operations via deterministic benchmarking methods, including quantum process tomography, provide the possibility for quantification regarding both coherent and incoherent error channels [32], [33].

However, quantum process tomography becomes computationally intractable with large numbers of qubits, and the number of measurements needed increases exponentially with the number of qubits, which has led to scalable alternatives such as gate set tomography [34].

Higher-efficiency characterization techniques are randomized benchmarking techniques that determine quantum gate error rates by random sequences of operations, such as randomized benchmarking [35], while direct randomized benchmarking which is suitable in non-Clifford operations [36]. The techniques of benchmarking play a critical role in estimating the performance that can be achieved with existing quantum hardware as well as offering useful metrics to assess improvements in the process of gate and circuit implementations [33].

Conclusions

Specifically, randomized benchmarking has been found to be robust in measuring the Markovian fidelity of individual operations, however its applicabilityto non-Markovian or context-dependent gate errors remains an understudied field [37]. Although the standard randomized benchmarking can be theoretically scalable, the practical implementation of it becomes difficult with systems of more than 5-6 qubits because of the depth of the Clifford circuits required, so variants that reduce the circuit depth with larger quantum processors are used [28].

Improved randomization benchmarking methods including cycle benchmarking and interleaved randomized benchmarking seek to address these shortcomings by offering more refined error estimates and allowing the characterization of particular gate operations in longer circuit sequences [33]. Furthermore, the ability of non-Markovian noise models to be integrated into randomized benchmarking frameworks is gaining more significance as quantum control methods push towards reduced timescales, at which the Markovian noise assumption fails [38].

This difficulty is especially relevant when it comes to the development of robust error correction codes where the accurate characterization of the noise channels including non-Markovian effects is essential in reaching fault tolerance. The future research efforts can therefore be aimed at developing benchmarking protocols that are capable of effectively characterizing the complex noise effects, such as cross-talk and state dependent errors which are usually not taken into account in simplified models [39].

This entails the advancement of methods of discerning as well as quantifying the delicate environmental interactions which balance imperfections that will cause coherent and incoherent errors [40]. The blind spots of the randomized benchmarking should also be researched further where there exists a temporal correlation, especially where worst-case metrics of error are considered as opposed to average gate errors [40].

References

[1]. S. K. Singh, Mr. S. Agarwal, and Mr. R. Gupta, “Quantum Computing: Fundamentals, Progress, and Implications,” *International Journal for Research in Applied Science and Engineering Technology*, vol. 11, no. 9, p. 1106, Sep. 2023, doi: 10.22214/ijraset.2023.55803.

[2]. V. Raseena, “Quantum computing: foundations, algorithms, and emerging applications,” *Frontiers in Quantum Science and Technology*, vol. 4, Dec. 2025, doi: 10.3389/frqst.2025.1723319.

[3]. G. Feng, D. Lu, J. Li, T. Xin, and B. Zeng, “Quantum Computing: Principles and Applications,” *SPIN*, vol. 13, no. 3, Jul. 2023, doi: 10.1142/s2010324723300013.

[4]. S. BAWA, “Exploring Quantum Computing: Principles and Applications,” *Journal of Quantum Science and Technology.*, vol. 1, no. 3, p. 57, Aug. 2024, doi: 10.36676/jqst.v1.i3.27.

[5]. E. O. Sodiya, U. J. Umoga, O. O. Amoo, and A. Atadoga, “Quantum computing and its potential impact on U.S. cybersecurity: A review: Scrutinizing the challenges and opportunities presented by quantum technologies in safeguarding digital assets,” *Global Journal of Engineering and Technology Advances*, vol. 18, no. 2, p. 49, Feb. 2024, doi: 10.30574/gjeta.2024.18.2.0026.

[6]. A. Vaezi, S. M. H. Kazemi, N. B. Noghrehy, S. M. Kazemi, M. Ghodsi, and A. Movaghar, “Quantum Complexity vs Classical Complexity: A Survey,” *arXiv (Cornell University)*, Dec. 2023, doi: 10.48550/arxiv.2312.14075.

[7]. W. Weon, “Understanding Basic Principles of Qubits in Quantum Computing,” *International Journal for Research in Applied Science and Engineering Technology*, vol. 13, no. 2, p. 1490, Feb. 2025, doi: 10.22214/ijraset.2025.67121.

[8]. S. Jin, "Efficiently Scaling Machine Learning Systems across Heterogeneous Resources," *Deep Blue (University of Michigan)*, Jan. 2025, doi: 10.7302/26908.

[9]. B. V. Padamwar and P. H. Rao, "Quantum Computing Mathematical Foundations and Practical Implications," *Türk bilgisayar ve matematik eğitimi dergisi,* vol. 11, no. 3, p. 2911, Dec. 2020, doi: 10.61841/turcomat.v11i3.14659.

[10]. S. Kommidi, "Quantum Integration in HPC: Current Paradigms, Industrial Applications, and Research Frontiers," *International Journal for Research in Applied Science and Engineering Technology*, vol. 12, no. 9, p. 145, Sep. 2024, doi: 10.22214/ijraset.2024.64143.

[11]. M. S. Osmanca, M. Güllü, D. Karhan, and S. Çimen, "Quantum Computing in 6G Networks: Opportunities and Challenges," *DergiPark (Istanbul University)*, Apr. 2025, Accessed: Oct. 2025. [Online]. Available: https://dergipark.org.tr/en/pub/gmbd/issue/94345/1673183

[12]. S. Dasgupta, "Stability of Quantum Computers," *arXiv (Cornell University),* Apr. 2024, doi: 10.48550/arxiv.2404.19082.

[13]. A. Tamrakar and R. Sharma, "Quantum Computing: A Comprehensive Review," *Türk bilgisayar ve matematik eğitimi dergisi,* vol. 10, no. 3. Karadeniz Technical University, p. 1634, Dec. 13, 2019. doi: 10.61841/turcomat.v10i3.14623.

[14]. P. Escofet, S. B. Rached, S. Rodrigo, C. G. Almudéver, E. Alarcón, and S. Abadal, "Interconnect Fabrics for Multi-Core Quantum Processors," p. 34, Oct. 2023, doi: 10.1145/3610396.3623267.

[15]. T. Felefly, "Apprentissage automatique quantique et classique pour l'analyse d'images des tumeurs cérébrales," Ludwig-Maximilians-Universität München, 2024. Accessed: Oct. 2025. [Online]. Available: http://www.theses.fr/2024STRAJ064/document

[16]. S. Kan *et al.,* "Benchmarking Optimizers for Qumode State Preparation with Variational Quantum Algorithms," *arXiv (Cornell University),* May 2024, doi: 10.48550/arxiv.2405.04499.

[17]. H. Li *et al.*, "Utilizing Quantum Processor for the Analysis of Strongly Correlated Materials," *Physica Scripta*, vol. 99, no. 10, p. 105117, Sep. 2024, doi: 10.1088/1402-4896/ad770b.

[18]. B. Cheng *et al.,* "Noisy intermediate-scale quantum computers," *Frontiers of Physics,* vol. 18, no. 2, Mar. 2023, doi: 10.1007/s11467-022-1249-z.

[19]. Y. Zhang *et al.,* "Fault-tolerant quantum algorithms for quantum molecular systems: A survey," *arXiv (Cornell University),* Feb. 2025, doi: 10.48550/arxiv.2502.02139.

[20]. S. Tomar, R. K. Tripathi, and S. Kumar, "Comprehensive Survey of QML: From Data Analysis to Algorithmic Advancements," *arXiv (Cornell University),* Jan. 2025, doi: 10.48550/arxiv.2501.09528.

[21]. F.-M. L. Régent, "Awesome Quantum Computing Experiments: Benchmarking Experimental Progress towards Fault-Tolerant Quantum Computation," *arXiv (Cornell University),* Jul. 2025, Accessed: Oct. 2025. [Online]. Available: http://arxiv.org/abs/2507.03678

[22]. M. AbuGhanem, "Practical Fidelity Limits of Toffoli Gates in Superconducting Quantum Processors," *arXiv (Cornell University),* Sep. 2025, doi: 10.48550/arxiv.2509.05395.

[23]. H. Safi, M. Bandić, C. Niedermeier, C. G. Almudéver, S. Feld, and W. Mauerer, "Stacking the Odds: Full-Stack Quantum System Design Space Exploration," *arXiv (Cornell University),* Jun. 2025, doi: 10.48550/arxiv.2506.02782.

[24]. K. R. Brown *et al.,* "5 Year Update to the Next Steps in Quantum Computing," *arXiv (Cornell University),* Jan. 2024, doi: 10.48550/arxiv.2403.08780.

[25]. J. Kalloor, M. Weiden, E. Younis, J. Kubiatowicz, W. A. de Jong, and C. Iancu, "Quantum Hardware Roofline: Evaluating the Impact of Gate Expressivity on Quantum Processor Design," *arXiv (Cornell University),* Feb. 2024, doi: 10.48550/arxiv.2403.00132.

[26]. J. Lorenz *et al.,* "Systematic benchmarking of quantum computers: status and recommendations," *arXiv (Cornell University),* Mar. 2025, doi: 10.48550/arxiv.2503.04905.

[27]. F.-M. L. Régent, "Awesome Quantum Computing Experiments: Benchmarking Experimental Progress towards Fault-Tolerant Quantum Computation," *arXiv (Cornell University),* Jul. 2025, doi: 10.48550/arxiv.2507.03678.

[28]. A. Acuaviva, D. Aguirre, R. Peña, and M. Sanz, "Benchmarking Quantum Computers: Towards a Standard Performance Evaluation Approach," *arXiv (Cornell University),* Jul. 2024, doi: 10.48550/arxiv.2407.10941.

[29]. K. V. Chawale, "Probing Quantum Entanglement in Superconducting Circuits at Ultra-Low Temperatures," *International Journal for Research in Applied Science and Engineering Technology,* vol. 13, no. 6, p. 3781, Jun. 2025, doi: 10.22214/ijraset.2025.72914.

[30]. J. P. Zwolak *et al.,* "Data needs and challenges for quantum dot devices automation," *arXiv (Cornell University),* Dec. 2023, doi: 10.48550/arxiv.2312.14322.

[31]. J. Frank, E. Kashefi, D. Leichtle, and M. de Oliveira, “Heuristic-free Verification-inspired Quantum Benchmarking,” *Quantum Science and Technology*, Mar. 2025, doi: 10.1088/2058-9565/adc298.

[32]. S. B. Rached *et al.*, “Characterizing the Inter-Core Qubit Traffic in Large-Scale Quantum Modular Architectures,” *arXiv (Cornell University)*, Oct. 2023, doi: 10.48550/arxiv.2310.01921.

[33]. V. K. Tripathi, D. Kowsari, S. Kumar, H. Zhang, E. Levenson-Falk, and D. A. Lidar, “Deterministic Benchmarking of Quantum Gates,” *arXiv (Cornell University)*, Jul. 2024, doi: 10.48550/arxiv.2407.09942.

[34]. M. AbuGhanem and H. Eleuch, “Full quantum tomography study of Google’s Sycamore gate on IBM’s quantum computers,” *EPJ Quantum Technology*, vol. 11, no. 1, May 2024, doi: 10.1140/epjqt/s40507-024-00248-8.

[35]. P. Lewandowska and M. Beseda, “Benchmarking gate-based quantum devices via certification of qubit von Neumann measurements,” *arXiv (Cornell University)*, Jun. 2025, doi: 10.48550/arxiv.2506.03514.

[36]. R. Au-Yeung, B. Camino, O. Rathore, and V. Kendon, “Quantum algorithms for scientific computing,” *arXiv (Cornell University)*, Dec. 2023, doi: 10.48550/arxiv.2312.14904.

[37]. G. A. L. White, C. D. Hill, and L. C. L. Hollenberg, “Performance Optimization for Drift-Robust Fidelity Improvement of Two-Qubit Gates,” *Physical Review Applied*, vol. 15, no. 1, Jan. 2021, doi: 10.1103/physrevapplied.15.014023.

[38]. P. Taranto, S. Milz, M. Murao, M. T. Quintino, and K. Modi, “Higher-Order Quantum Operations,” *arXiv (Cornell University)*, Mar. 2025, doi: 10.48550/arxiv.2503.09693.

[39]. D. Volya and P. Mishra, “Quantum Benchmarking via Random Dynamical Quantum Maps,” *arXiv (Cornell University)*, Apr. 2024, doi: 10.48550/arxiv.2404.18846.

[40]. V. Srivastava, A. K. Roy, S. Mahanti, J. Kaur, S. Karuvade, and A. Gilchrist, “Blind-spots of Randomized Benchmarking Under Temporal Correlations,” *arXiv (Cornell University)*, Oct. 2025, doi: 10.48550/arxiv.2510.13051.