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A Systematic Review of Challenges in Quantum Computing 2021 Error Mitigation, Quantum Networking, and Cross-Disciplinary Applications

Mohan Harish Maturi[1], Snehal Satish[1], Hari Gonaygunta[1], Karthik Meduri[1], Geeta Sandeep Nadella[1*]
[1]Department of Information Technology, University of the Cumberlands, Williamsburg, 40769, KY, USA

*Corresponding Author: gnadella3853@ucumberlands.edu

ABSTRACT

The laws of quantum physics were controlled by computer computing and provided previously unheard-of possibilities for solving challenging issues in nanomaterials science, artificial learning, and encryption. This paper delivers a systematic review of 200 research papers published between 2010 and 2021, concentrating on three critical areas: error mitigation, quantum networking, and cross-disciplinary applications. The depth of detailed analysis using tools like ASReview key challenges and solutions remained identified in managing quantum errors, developing scalable quantum communication networks, and addressing integration issues in various fields. The results reveal that while quantum error-corrections techniques, besides faults tolerant computation methods, are progressing, scalability and resources remain significant barriers. The advancements in quantum networking are promising for secure communication and research to address long-distance entanglement and practical deployment. The review also considers the right plus societal suggestions of Quantum computes on data confidentiality and employment. Future research directions are proposed, and the scalable error mitigation techniques in their progressions, cutting-edge quantum networking, and the growth of practically quantum with their algorithms for broader applications are emphasized.

Keywords: Systematic Review, Quantum Computing, Quantum Networking, ASReview.

I. INTRODUCTION

Quantum computing is the evolving field that binds the values of quantum mechanics to course info in ways that classical computers cannot. Traditional computers encode facts in the two bits (0s and 1s), and quantum computers use quantum bits or qubits, which can exist in many situations concurrently due to the sensation of superpositions [1]. This permits quantum computers to perform certain calculations exponentially sooner than their standard complements. The other important stuff of quantum systems is tangle, which enables tangled qubits to move rapidly in each other's state, even when divided into huge spaces. This interconnectedness is crucial for quantum computation and offers the potential to resolve difficult harms with extraordinary quickness and efficacy [2-3]. Quantum computing's potential impact is profound, with applications spanning various fields. In cryptography, quantum computers can break traditional encryption methods, which could revolutionize data security and the development of new cryptographic protocols [1-4].

In chemistry and supplies knowledge, quantum computers could pretend that difficult molecular structures are currently impossible for standard CPUs to speed up drug finding and the growth of fresh materials. Optimization logistics and quantum algorithms can provide more efficient solutions to problems that involve many variables, such as supply chain management, portfolio optimization, and route planning. Quantum machine learning is seen as the frontier for improving artificial intelligence and enabling faster processing of massive datasets [5]. The significance of quantum computing lies not just in its computational power but in its capacity to resolve complications that are presently inflexible and offer transformative advancements in science, industry, and technology. These challenges remain in building scalable and fault-tolerant quantum computers that can be practically deployed [6]. These challenges are error mitigation and quantum networking, which are crucial for recognizing the full latent of quantum computing.

1.1 Motivation for Review

The rapid advancements in quantum computing have highlighted both its immense potential and the important tests that are necessary to be overwhelmed for practical deployment. The promising breakthroughs and issues are error mitigation, scalability, and quantum networking, which remain critical hurdles that must be lectured to bind quantum computing's power completely. The interdisciplinary applications and spanning fields like cryptography, machine learning, and materials science present new opportunities and introduce complex integration challenges [5]. This review is motivated by the need to systematically examine the current research landscape, identify the key challenges, and highlight developing solutions in error mitigation, quantum networking, and cross-disciplinary applications. In doing so, this study aims to deliver an inclusive sympathy of the state of quantum computing in 2021 and offer upcoming instructions for study and development in this transformative field.

1.2 Scope and Objective of Review

This systematic review is on three critical aspects of quantum computing: error mitigation, quantum networking, and cross-disciplinary applications. The first area is **error mitigation,** which addresses the challenges related to noise, decoherence, and inaccuracies that occur during quantum computations and evaluates the current strategies and technologies being developed to minimize these issues. The second focus is **quantum networking**, and it explores the progress and challenges in establishing quantum communication networks that are essential for building the future quantum internet and the role of quantum key distribution and entanglement-based protocols in securing communications [10]. The third area and **interdisciplinary applications** investigating quantum computing are poised to transform cryptography, machine-learning learning, chemistry, and supplies science while examining the integration challenges of applying quantum technologies in these domains.

II. METHODOLOGY

This chapter outlines the Figure 1 systematic approach used to comprehensively review the current challenges in quantum computing on error mitigation, quantum networking, and interdisciplinary applications. The rigorous search strategy was employed, drawing from major academic databases such as MDPI, Springer, IEEE, Elsevier, and Google Scholar and using targeted keywords to identify relevant studies [3]. Out of 200 extracted papers, the selection process based on inclusion and exclusion criteria was useful for the excellence and significance of the reviewed works. The chapter explains the process for extracting and synthesizing data to provide a thorough analysis of the advancements and obstacles within these critical areas of quantum computing.

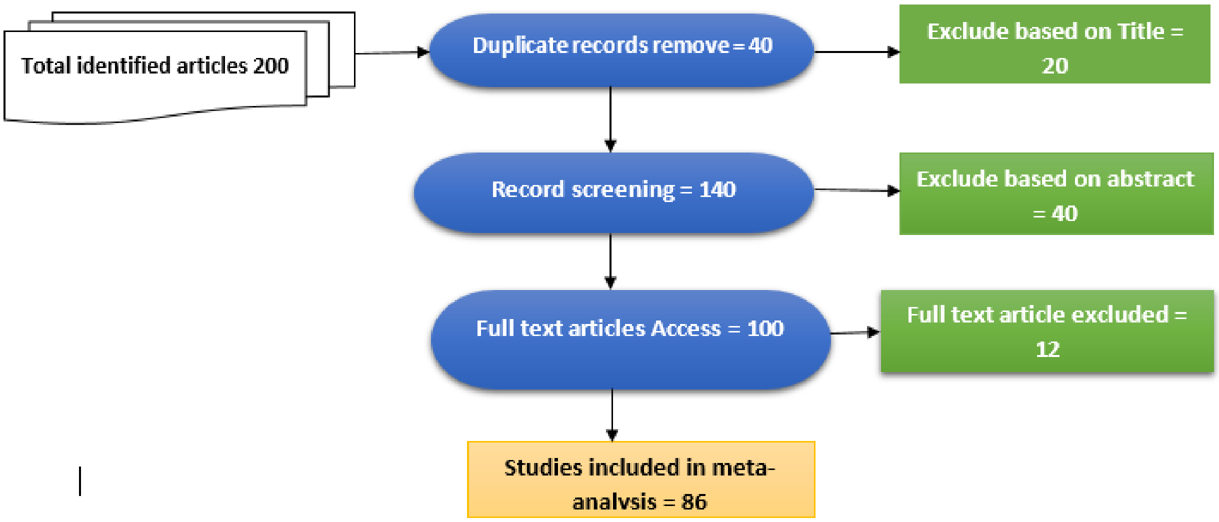

Figure 1: systematic approach

A. Review Strategy

To deliver a complete overview of quantum-computing challenges in 2021, a systematic search was conducted using several established research databases, including MDPI, Springer, IEEE Xplore, Elsevier, and Google Scholar. These sources were selected for their vast repository of peer-reviewed articles and relevant studies in quantum computing. The exploration was achieved using the mixture of keywords "quantum-computing," "error-mitigation," and "quantum-networking" plus "quantum-error-correction," "quantum-communication," "cross-disciplinary applications" and "quantum-computing in cryptography, machine-learning and chemistry." The search on papers printed between 2010 and

2021 to release the most recent advancements while incorporating foundational studies that have shaped the field [18].

B. Inclusion and Exclusion Criteria

The attachment measures for the evaluation were as follows: studies directly addressing key issues in quantum computing related to error mitigation, networking, and interdisciplinary applications; research papers offering new methodologies, technologies, and theoretical insights; and empirical studies that report experimental results relevant to quantum computing advancements. The review articles, conference proceedings, and case studies that contributed significantly to understanding the challenges in these areas were included. Studies were excluded if they focused solely on quantum computing theory without practical or experimental and lacked sufficient empirical evidence or were primarily speculative without a clear connection to solving specific challenges [5]. Papers outside the specified publication period or from non-peer-reviewed sources were also excluded to maintain the quality and relevance of the review.

C. Data Extraction and Synthesis

From the 200 papers initially extracted, relevant data were systematically organized and reviewed. Key information, including methodologies, findings, challenges, and proposed solutions, was extracted for each paper. This data was then categorized into three main focus areas: error mitigation, quantum networking, and interdisciplinary applications [6]. The findings were synthesized by analyzing patterns, identifying recurring challenges, and highlighting significant study advancements. Comparative analysis was employed to contrast different approaches to error correction, networking protocols, and cross-disciplinary quantum computing uses, ultimately providing the cohesive narrative of the current research landscape.

III. CHALLENGES IN QUANTUM ERROR MITIGATION

3.1 Quantum Errors

Quantum computers are highly sensitive to their environments and various errors that can degrade their performance. The main challenges in quantum error mitigation stem from the fact that quantum states are delicate and can easily be disturbed by external issues such as noise, decoherence, and gate imperfections [6-7]. In detail, Figure 2 explores these types of quantum errors and their impact on quantum computation.

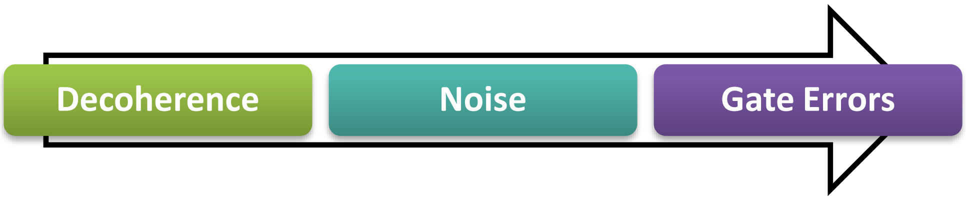

Figure 2: Quantum Error types

Types of Errors

1. **Decoherence** occurs when a quantum system loses its coherence, meaning it can no longer maintain a well-defined quantum state. This follows while the scheme interrelates with her exterior situation in an uncontrolled manner. In quantum computing, qubits are isolated to maintain superposition and entanglement, but complete isolation is impossible [7]. Even at very low levels, interaction with the environment can collapse the qubit's state from a superposition to a classical state. DE coherence destroys the capacity of important mainframes to complete designs that trust quantum superposition and entanglement. Once decoherence occurs, the quantum system can no longer maintain the information needed for computation, and mistakes in calculations or total loss of information [8].
2. Noise refers to any unintended alteration of a quantum state during computation, which can arise from environmental factors or imperfections in the quantum hardware [9].
    - **Types of Noise**: There are different forms of noise affecting quantum systems:
        - **Thermal noise**: This is caused by thermal fluctuations in the system's environment, which induce energy exchanges among the qubit and its surroundings.
        - **Shot noise:** Arises from discrete electron charges in quantum circuits and can cause fluctuations in signal measurements [10].
        - **Amplitude and phase damping**: These are types of noise that affect the amplitude or phase of the qubit and gradual decay or drift in its quantum state.

  - **Impact**: Noise affects the fidelity of quantum computations. Even slight deviations due to noise can accumulate over time and result in significant errors in the final output of a quantum algorithm. Classical computers and quantum computations cannot easily recover from noise owing to the probabilistic countryside of quantum states [10-11].

3. **Gate Errors**: Gate errors occur when quantum gates and the basic operations in quantum computation are implemented imperfectly, resulting in inaccuracies in the state transformation of qubits. Quantum gates, like classical logic gates, are prone to imperfections. In practice, quantum gates can be experienced [12]. Inaccurate gate operations can propagate errors in qubits in algorithms requiring many sequential gates (Shor's or Grover's algorithms). This cumulative error can significantly reduce the accuracy of the computation and render the result meaningless.
    - **Timing issues**: Incorrect application of gate pulses and incomplete or incorrect transformations of qubit states.
    - **Hardware imperfections**: Small variations in the control signals or qubit couplings and gate operations deviating from their intended function.
    - **Calibration drift**: Gate parameters may drift over time due to changes in the environment or quantum hardware, and the gate operations may be less reliable.

Quantum errors, whether from decoherence, noise, or gate imperfections, pose a significant challenge to reliable quantum computation [13]. Here are the main ways that affect quantum systems. Quantum computations rely on qubits remaining in coherent superposition states throughout the computation process. Decoherence and the collapse of these states erased the quantum advantage and turned the quantum system into a classical system. This is problematic in long-running algorithms or those that require multiple qubits to stay entangled over time. Errors from different sources can accumulate in quantum circuits as the system evolves. With every quantum gate operation, there is a risk of introducing noise or gate errors, and these errors can build up over time [7-14]. In highly complex quantum algorithms that require many steps, even small errors can escalate and drastically affect the final result.

Due to the sensitivity of qubits and fault tolerance, quantum computation requires that errors be detected and corrected before they propagate. The cost of achieving fault tolerance (e.g., through quantum error correcting codes like surface codes) is extremely high and requires a large amount of extra qubit toward implementing error corrections, which is a major practical challenge in current quantum computing architectures. The presence of errors diminishes this quantum advantage error, which can corrupt the delicate quantum states needed for these computations [15]. If errors are not mitigated, the quantum computation may provide no better results than a classical computer could achieve. These errors affect the stability of qubits, Q-gates' reliability, and the overall accuracy of Q-algorithms. Without effective error mitigation, it becomes difficult to harness quantum computers' potential fully. We aim to develop large-scale and fault-tolerant quantum systems in the future. Overcoming these challenges is a key focus of ongoing research in quantum computing [16].

3.2 Error Correction Techniques

In quantum computing, errors introduced by decoherence, noise, and imperfect gate operations must be managed for reliable computation. Different traditional computing OF bits also have 0 or 1 qubits in superposition states, and quantum error correction is more complex. Various techniques have been developed to notice and correct errors minus disturbing the quantum information [17-18]. Two primary strategies are Quantum's Errors-Correcting Codes (QECC) and Faults-Tolerates-Quantum-Computations.

1. Quantum Error-Correcting Codes (QECC)

These codes stay protocols that enable the uncovering and improvement of errors in Quantum's levels of states without unswervingly determining the qubit's value, which would collapse its superposition. QECCs use several bodily to encode the state of a logical qubit in errors canister be branded plus corrected [19].

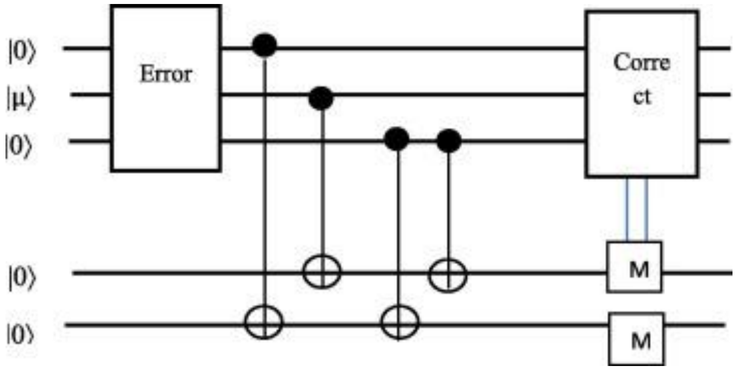

Figure 3: Quantum Error-Correcting Codes (QECC)

Figure 3 shows the decoding process is the reverse of the encoding procedure, where the qubits return to their original states, and any entanglement is removed. If no errors occur during the computation, the quantum state will be returned to its initial form, s0|000⟩+s1|111⟩ rangles, which represents the superposition of two distinct states. This final state is achieved by applying two operations to the error state. After decoding, the three qubits are disentangled, meaning they no longer share quantum correlations [19-20]. One potential issue can arise: the first qubit becomes flipped (reversed), as seen in the second line of the output. This inconsistency can be fixed using a Toffoli gate.

- **Redundancy**: Quantum error correction relies on encoding a single logical qubit in several somatic qubits'. In issuing their quantum info, individual physical qubit container errors can be identified without disturbing the encoded state [21].
- **Syndrome Measurement**: Error syndromes are measured to detect errors. These syndromes reveal the type and location of an error without collapsing the quantum state itself and allowing for correction [22].

Types of Quantum Error-Correcting Codes:

- **Shor Code**:
  - Uniquely, the primary quantum errors are corrected codes, and the Shor-code protects against both bit flips plus phase flips of errors by encoding a solitary rational q-bit into a system of 9-physical qubits. The code applies a combination of classical repetition and phase error detection techniques to preserve the integrity of quantum information [23].
  - **Example**: If some bit-flip errors occur, one of the physical qubits and the other qubits can be used to identify and correct this error without disturbing the overall quantum state.
- **Steane Code**:
  - A 7 qubit quantum error corrects codes being detected, and precise lonely qubit errors protecting against together bits are towards flip besides phase-flip errors. The given code embeds quantum information into a larger Hilbert space using additional qubits [24].
  - The Steane code protects quantum gates and operations from errors in building more complex quantum-Algo.
- **Surface Code**:
  - The surface code is among the most promising QECCs due to its scalability and relatively low overhead. It encodes a logical qubit into a 2D type of frame of carnal qubits anywhere error correction is based on the geometry of the qubit arrangement [25].
  - It is effective at correcting and can be implemented on hardware using local interactions among neighboring qubits. It is also highly practical for large-scale quantum systems [26].

One of the main drawbacks of QECC is the significant overhead required to encode a single logical qubit. Depending on the code, many physical qubits may be needed to represent just one logical qubit, which increases the resource demands for quantum computations. While QECC can detect and correct errors, decoding these errors (i.e., identifying what kind of error occurred and where) can be computationally complex [27]. Efficient decoding algorithms are needed to make error correction feasible in real time.

2. Fault-Tolerant Quantum Computation

The design and execution of quantum computations that they container tolerate a sure equal of error besides still producing correct results. This requires error-correcting codes and special techniques to ensure that quantum operations do not introduce errors [28].

- **Fault Tolerance Threshold**: On behalf of the quantum system towards faults and the error rates per qubit operation must be below a certain threshold (known as the fault-tolerance threshold). If this threshold is exceeded, errors will accumulate faster than they can be corrected.
- **Logical Operations**: Fault-tolerant Quantum computationally requires that logical operations (quantum gates) be designed to not propagate errors beyond what can be corrected. Fault-tolerant quantum gates and this error does not spread to multiple qubits [29].
- **Transversal Gates**: A transversal gate is a quantum gate that operates independently on each qubit in an error-correcting code. Transversal gates are crucial in fault-tolerant quantum computation because they limit error propagation among the qubits [30]. In the transversal CNOT gate, errors are prevented after spreading between different logical qubits.
- **Error Correction on the Fly**: Fault-tolerant computation performs error correction continuously during the computation process rather than waiting until the end. This real-time error detection and correction and errors do not accumulate and become unmanageable [31].

Fault-tolerant quantum computation and cylinder can be accomplished reliably, even in errors. This is achieved using QECC during computation and designing quantum operations that prevent error propagation. Fault tolerance relies on maintaining the error rate below a certain threshold, known as the fault tolerance threshold. Techniques like transversal gates limit error spreading between qubits and real-time error corrections [15-30]. These methods are essential for achieving scalable and reliable quantum computing systems.

3.3 Current Challenges Error Mitigation

The main obstacle to the creation of useful quantum tech is abatement. The fragility of little bits and dynamic systems extremely prone to mistakes from faulty gate activities seriously impair the dependability of mathematical computations [31]. Quant Error Correction Coding (QECC) and failure-tolerant computation approaches have been created to tackle these problems with error repair solutions. These developments and the mistakes correcting techniques used today are subject to several restrictions on complexity, flexibility, and resource waste [12-32]. A significant obstacle to realizing scalable, resilient quantum IT is balancing error reduction alongside the development and practical application of quantum systems [33]. These advancements in atomic correction have been made, and existing techniques are hampered in their use in practice by many issues:

- **Resource Overhead**: One of the major drawbacks of Q codes (QECC) is the substantial overhead required to encode a single rational qubit. Many physical qubits are needed to represent just one common-sense qubit and suggestively make the computational possessions mandatory. The superficial cypher, one of the most promising QECCs, requires hundreds of physical qubits for each logical qubit [34].
- **Decoding Complexity**: While QECCs can detect and correct errors, decoding these errors is computationally intensive. Efficient decoding algorithms are needed to identify and correct errors in real time, but this adds complexity to the computation as the number of qubits and error rates increase [35].
- **The fragility of Qubits**: Qubits are inherently more fragile than classical bits, and existing error correction techniques can struggle to maintain coherence over extended periods and during long computations. Quantum schemes are also subtle to various types of noise, introducing errors that are difficult to detect and correct effectively [36].
- **Fault-Tolerant Gates**: the fault-tolerant quantum gates are designed to prevent error propagation, and constructing these gates is challenging and requires intricate designs that are not yet fully realized in practical quantum hardware. These operations remain fault-tolerant while maintaining computational efficiency, an ongoing research area.
- **Scalability vs. Resource Requirements**: As the scope of a quantum computer grows, the amount of qubits needed for error correction increases exponentially. This poses a major challenge for scaling quantum systems, as the physical qubits required for large-scale error correction grow much faster than the number of logical qubits [37]. To form great quantum computers skilled in running composite algorithms, researchers must find ways to minimize the resource overhead of error correction without compromising performance.

- **Computation Speed vs. Error Correction**: Implementing error correction codes and fault-tolerant operations slows down quantum computation. Correcting errors in real-time requires additional operations, increasing the computational cost and time needed to perform even basic quantum algorithms. This tradeoff between maintaining the fidelity of quantum states and achieving fast and large-scale computations is one of the key tests in the growth of quantum processors [38].

The quantum-errors adjustment methods are essential for enabling large-scale quantum computation but come with significant resource demands and scalability tradeoffs. These challenges are critical for realizing practical and fault-tolerant quantum computers that are skillful in resolving difficult complications outside the range of conventional systems [39].

IV. QUANTUM NETWORKING AND CROSS-DISCIPLINARY APPLICATIONS

4.1 Fundamental Quantum Networking

Quantum networking is developing the field that leverages the values of quantum systems to create more secure and efficient communication systems [40]. Traditional networks rely on moments as the important unit of info, and quantum networks use quantum bits, or qubits, to encode and transmit information. Quantum networks utilize the two key phenomena, quantum mechanics, entanglement, and superposition, to have fundamentally different capabilities compared to classical communication systems. Embarrassment is the singularity where two units become related; in this way, the state of one element is directly related to the state of the other, no matter the distance between them. When qubits are tangled, their properties are connected in a way that cannot be explained in standard physics. This property of entanglement is useful in quantum communication because it allows for the instant transmission of associated information among two distant qubits, and facilitating protocols are quantum teleportation and Quantum-Key-Distribution (QKD). Entanglement enables the concept of quantum cryptography, where the safety of the communications is the laws of quantum mechanics [41]. If a listener tries to measure or interrupt the quantum communication, it will disturb the system and reveal the observer's existence and the safety of the transmitted data.

Superposition is the aptitude of a quantum system like a qubit to be in manifold states at once. Unlike classical bits, which are either 0 or 1, a qubit can exist in a superposition of both 0 and 1 simultaneously. This superposition property can be used in quantum communication to send multiple messages or encode info in ways standard systems cannot [42]. Superposition enables quantum parallelism, where quantum computers or networks can process multiple computations or data streams simultaneously, resulting in faster processing and potentially more efficient communication protocols.

Table 1 shows the differences between Quantum and classical networking. While both Quantum and classical networking are designed for communication purposes, they operate under fundamentally different principles and have distinct advantages and challenges. Classical networks use bits and follow traditional information transmission principles based on electrical signals, while quantum networks utilize qubits and bind the exclusive belongings of quantum mechanics to predicament and superposition.

Table 1: Differences Between Quantum and Classical Networking

Aspect	**Classical Networking**	**Quantum Networking**
Information Unit	Classical networks use **bits** (0 or 1) [41].	Quantum nets use **qubits**, which can be in superposition (both 0 and 1 concurrently).
Transmission Medium	Classical networks use physical signals like electrical pulses [21].	Quantum networks rely on **quantum states** transmitted via entangled particles (photons or atoms)
Superposition	In classical systems, each bit is either in state 0 or 1 at any given time [20].	Qubits in quantum networks exist continuously.

Entanglement	No concept of entanglement. Each bit is independent and not correlated [22].	Quantum networking uses **entanglement**, where two qubits can be correlated over long distances
Security	Classical networks rely on cryptographic protocols (e.g., RSA, AES) for security,	Quantum networks offer **quantum key distribution (QKD)**, providing theoretically unbreakable security.
Error Detection/Correction	Classical systems have well-established methods for error detection [24].	Quantum networks face challenges with **quantum error correction**, as directly observing qubits disrupts their quantum states.

4.2 Application of Quantum Computing

The rising field binds the values of quantum mechanisms to complete divisions previously deemed impossible or highly impractical with classical computers. Traditional computing, which trusts binary binary-bits and quantum computers, uses qubits that can exist in many states simultaneously due to superposition and embarrassment [43]. This ability lets quantum computers resolve complex complex-problems at speeds exponentially quicker than their standard counterparts. Quantum computing continues to change; its requests are expanding in many fields, including cryptography, machine learning, chemistry, physics, and resources science. From breaking classical encryption algorithms to revolutionizing drug discovery and understanding the fundamental laws of nature, quantum computing promises to transform industries and scientific research [44].

A. Quantum Computing in Cryptography

Quantum computing poses an important danger to classical encryption approaches such as RSA and ECC (Elliptic Curve Cryptography) due to its ability to resolve computationally infeasible difficulties [9-45]. These Shor's and quantum procedures can factor great integers, undermining the safety of public key encryption systems based on prime factorization. Classical encryption relies on the computational difficulty of glitches like factoring or computing separate logarithms. However, with their ability to handle superposition and parallelism, quantum computers can answer these problems exponentially sooner, and these encryption methods are susceptible to future quantum attacks. To counter the potential fears posed by quantum computing, Post-Quantum-Cryptography (PQC) is being developed. PQC systems are intended to be unaffected by quantum-based attacks while remaining secure against classical computational methods [45]. These algorithms rely on exact glitches that quantum computers cannot resolve professionally, such as frame-founded cryptography and hash-grounded autographs with multivariate-quadratic calculations.

B. Quantum Computing in Machine Learning

Quantum-computing proposals are promising advancements in machine learning (ML) in quantum bits (qubits) that can be in many states. This permits quantum algorithms to course and analyze large datasets much quicker than standard procedures and enables pattern recognition, classification, and clustering breakthroughs. Quantum machine-learning systems are quantum support-vector-machines (QSVM), and quantum neural networks (QNN) can deliver exponential speedups in learning chores in scenarios where large amounts of complex data must be processed in big data analysis, optimization problems, and drug discovery [46]. Quantum quantum computing deals with revolutionary possibilities; important progress in both hardware and software is required before it can be seamlessly combined into current machine-learning frameworks.

C. Applications in Chemistry, Physics, and Materials Science

Quantum computing can transform chemistry and medication findings by permitting accurate molecular simulations that are computationally classy for classical computers. Quantum computers model the behavior of electrons in molecules and help scientists better understand chemical reactions, binding properties, and the creation of new materials or drugs [47]. This level of precision is valuable in pharmaceutical research; the quantum imitations assist in the detection of novel drugs, in predicting molecular connections and in optimizing drug efficacy before clinical trials. These advancements could drastically reduce the time and costs of developing new medications [48].

V. REVIEW ANALYSIS

This chapter focuses on the systematic review of the literature surrounding Quantum Computing in 2021, a crucial step in synthesizing and analyzing the body of knowledge on this subject. 200 research papers have been extracted for analysis, and the ASReview tool has been employed to conduct a competent course and review a huge amount of information [10]. The machine-learning-based tool utilizes active learning algorithms to streamline the systematic review process in prioritizing relevant papers, permitting the more precise and well-organized identification of key findings, trends, and gaps in the literature. This method not only improves the excellence of the review but also meaningfully decreases the time and resources required for manual screening.

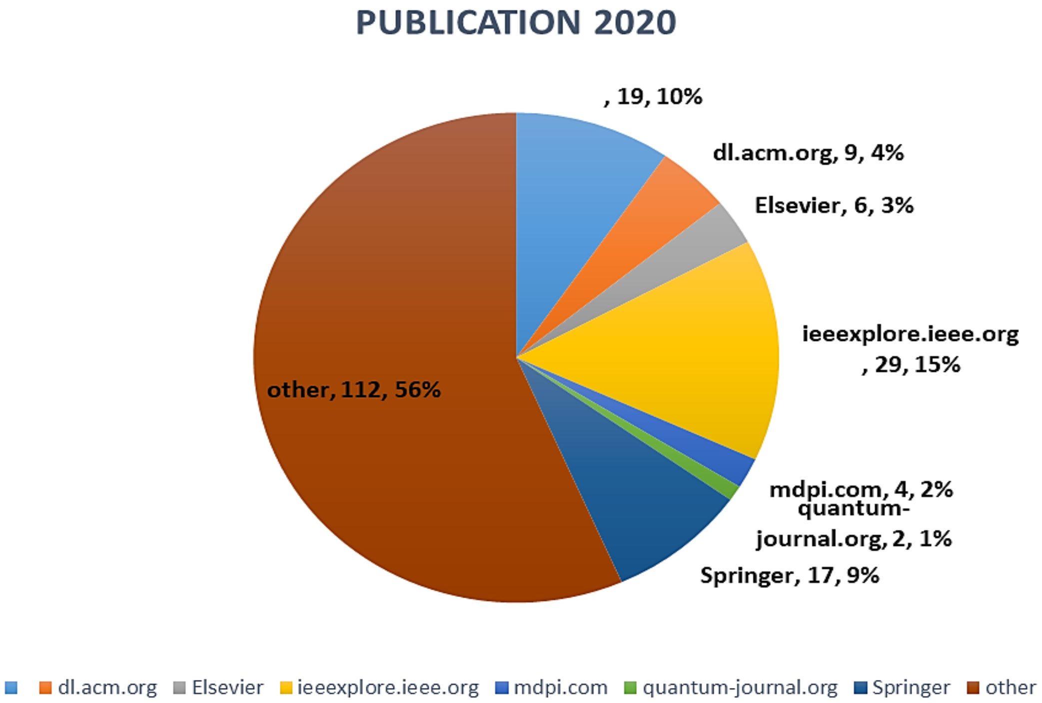

Figure 4: Publication in 2021

As shown in Figure 4, quantum computing research saw significant contributions from various academic and scientific platforms. The largest share of publications came from general sources (112) followed by prominent databases like IEEE Xplore (29) and Springer (17), arXiv (19), ACM Digital Library (9) and Elsevier (6), MDPI (4), and Quantum Journal (2). These studies largely focused on error mitigation techniques crucial for enhancing the reliability of quantum computations and cross-disciplinary applications that expand the use of quantum technologies in different fields, such as cryptography, material science, and artificial intelligence [34].

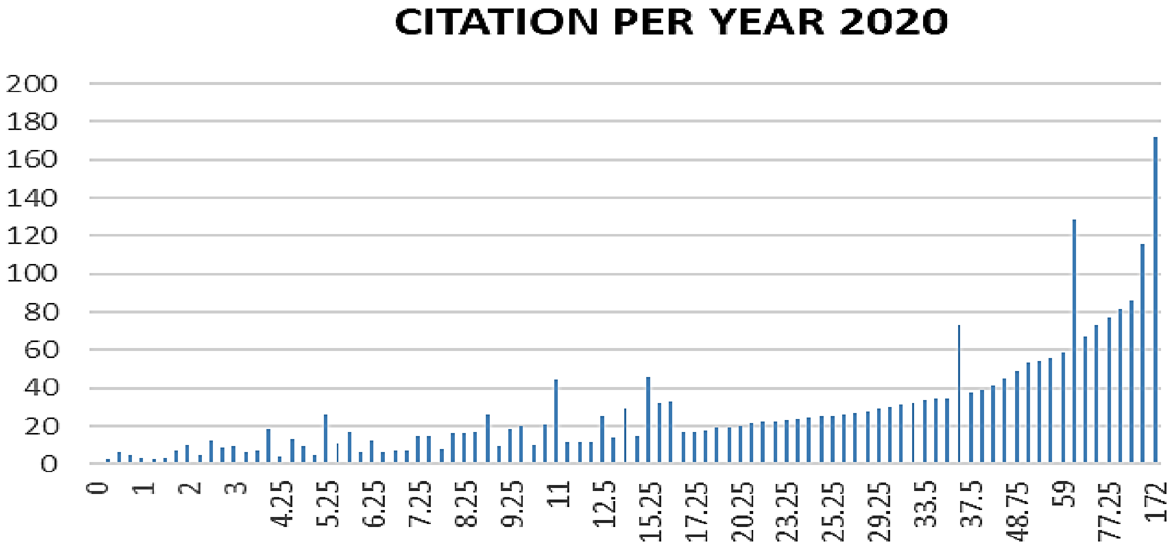

Figure 5: Citation per Year 2021

The citation data for quantum computing research in 2021 from Figure 5 reveals a steady increase in academic recognition over the year, with citation counts starting modestly and progressively rising. Early in the year, citations were relatively low, but they began to pick up after midyear with several peaks, such as 26.25, 44, and 73.5 citations. The trend continues upward with notable spikes in the latter part of the year, reaching values as high as 128.5 and 172, ultimately peaking at 2604.5. This suggests growing interest and acknowledgment of the field in later months, and more research on quantum computing gained visibility and traction.

The citation data per author in quantum computing research for 2021 indicates a significant range of citations and reflects varying levels of influence among contributors. The citations are relatively low, starting from 0 and increasing gradually. Midrange values are 54, 70, and 115 citations, suggesting moderate recognition for several authors. There are notable peaks, including 147, 179, and 229 citations, with a dramatic surge toward the end and culminating in 3553 citations. This highlights the substantial impact of key researchers in the later stages of the year and signifies their major contributions to the field.

VI. CONCLUSION AND FUTURE DIRECTION

6.1 Summary of Key Findings

In this review of quantum computing as of 2021, we have explored the primary challenges and developed the solutions in three critical areas: error mitigation, quantum networking, and cross-disciplinary applications.

- **Error Mitigation**: Quantum systems are characteristically fragile and disposed to errors due to decoherence, noise, and gate imperfections. Key solutions are Quantum Error Correcting Codes (QECC) and fault-tolerant quantum computation, which were highlighted, but they still face challenges in scalability, resource overhead, and complexity.
- **Quantum Networking**: Networking in quantum systems introduces novel possibilities through quantum entanglement and superposition. While quantum networking holds promise for secure communication via quantum key distribution (QKD), the technology is still in its infancy, with practical implementations needing substantial improvements in error correction and long-distance entanglement maintenance.
- **Cross-Disciplinary Applications**: Quantum computing shows potential in many fields, including cryptography, chemistry, machine learning, and the science of resources. While quantum procedures are Shor's algorithm for cryptography and quantum simulations in chemistry are revolutionary, integrating quantum computing into these domains still presents significant challenges in hardware and software development.

6.2 Ethical and Societal Considerations

The improvements in quantum computing have profound inferences for ethics and society:

- **Data Privacy and Security**: in breaking classical encryptions, Quantum computers could compromise data security on a massive scale. While this poses a significant risk, it also drives the development of quantum-resistant cryptographic methods to protect sensitive information.
- **Employment**: Quantum quantum computing continues to develop its influence on the job market, which must be considered. It may shift labor demands in industries reliant on encryption, software development, and scientific research [49-50]. The need for new skill sets related to quantum technology could result in job displacement, creating opportunities in quantum research and its practical applications.

Future Work

Upcoming exploration should Raise the more resource-efficient error correction procedures critical to realizing fault-tolerant quantum computers. This could involve optimizing quantum codes or reducing the physical qubit overhead. To achieve functional quantum communication, systems and researchers must address long-distance entanglement and integrate quantum networks with classical infrastructure for real-world applications. The practical quantum algorithms need to be developed, and their integration into current technologies should be explored to expand the cross-disciplinary use of quantum computing in fields like AI, medicine detection, and optimization.

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