Journal of Economy and Technology 2 (2024) 190–199

Contents lists available at ScienceDirect

Journal of Economy and Technology

journal homepage: www.keaipublishing.com/en/journals/journal-of-economy-and-technology/

Quantum cloud computing: Trends and challenges

Muhammed Golec[a,b,*,1], Emir Sahin Hatay[c], Mustafa Golec[d], Murat Uyar[e], Merve Golec[f], Sukhpal Singh Gill[a]

[a] *School of Electronic Engineering and Computer Science, Queen Mary University of London, United Kingdom*
[b] *School of Computer Engineering, Abdullah Gul University, Kayseri, Turkey*
[c] *School of Computer Science and Electronic Engineering, University of Essex, United Kingdom*
[d] *School of Computer Engineering, Kutahya Dumlupınar University, Kütahya, Turkey*
[e] *School of Electrical Electronics Engineering, Bursa Uludag University, Bursa, Turkey*
[f] *Faculty of Engineering and Natural Sciences, Bursa Technical University, Bursa, Turkey*

A R T I C L E I N F O

Keywords:
Quantum computing
Quantum cloud computing
Artificial Intelligence
Machine Learning
Cloud computing

A B S T R A C T

Quantum computing is a new paradigm that will revolutionize various areas of computing, especially cloud computing. Quantum computing, still in its infancy, is a costly technology that can operate in highly isolated environments because of its rapid response to environmental factors. This makes quantum computing a challenging technology for researchers to access. These problems can be solved by integrating quantum computing into an isolated remote server, such as a cloud, and making it available to users. Furthermore, experts predict that quantum computing, with its ability to swiftly resolve complex and computationally intensive operations, will offer significant benefits in systems that process large amounts of data, like cloud computing. This article presents the vision and challenges for the quantum cloud computing paradigm that will emerge with the integration of quantum and cloud computing. Next, we present the advantages of quantum computing over classical computing applications. We analyze the effects of quantum computing on cloud systems, such as cost, security, and scalability. Besides all of these advantages, we highlight research gaps in quantum cloud computing, such as qubit stability and efficient resource allocation. This article identifies the advantages and challenges of quantum cloud computing for future research, highlighting research gaps.

1. Introduction

The concept of quantum first entered the literature when it was discovered by atomic physicists in the early 1900s (Heim et al., 2020). The idea that a computer could be produced using quantum mechanics was first expressed by Richard Feynman in 1981 (Kandala et al., 2017). Since it was very difficult to maintain the stability of qubits operating based on quantum superposition and quantum entanglement, the first quantum computer prototypes began to emerge in the early 2000s only with the efforts of pioneering companies such as IBM (Singh and Bhangu, 2023). Quantum computers are still in the development phase, and it is predicted that

* Correspondence to: School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, United Kingdom.

E-mail address: m.golec@qmul.ac.uk (M. Golec).

1 ORCID(s): 0000-0003-0146-9735.

https://doi.org/10.1016/j.ject.2024.05.001
Received 1 May 2024; Received in revised form 29 May 2024; Accepted 29 May 2024
Available online 1 June 2024

they can perform a task in as little as 200 s, which would take 10,000 years for the world's best supercomputer (Sasaki et al., 2014). For this reason, complex and long-lasting processes such as the behavior of molecules can be carried out very quickly with quantum-based computers (von Lilienfeld et al., 2020). In addition, it is obvious that quantum computing will be one of the technologies that will shape the future as it begins to enter the military, civil, and commercial fields (Nahar et al., 2023).

In addition to the advantages they offer, quantum computers require a highly insulated environment because they are sensitive to external factors such as heat, temperature, and noise (Bernstein and Lange, 2017). For this reason, quantum computers are still an expensive and difficult-to-stabilize technology for end users. The idea of researchers being able to access quantum computer resources by integrating quantum computers with cloud computing was put forward as an extremely bright idea Ma et al. (2022). In this way, quantum computers can be placed in a highly isolated data center and provide service to the endpoints of the server. This model is called quantum cloud computing and a platform service can be offered for researchers where they can apply quantum applications and algorithms (Lou et al., 2024).

1.1. Motivation and contributions

With its superior computing capabilities compared to classical computers, quantum computing has already created great excitement in academia and the private sector. Recent academic studies show that quantum computing can be used to solve difficult problems in many fields such as health, chemistry, and physics (Gill et al., 2022a), (Aggarwal et al., 2023). However, it is still a great challenge to access quantum computers as they require high cost and high isolation technology to produce. Research shows (Gill et al., 2022a; Singh and Bhangu, 2023) that with the integration of quantum computers into cloud computing, the cost will decrease and the necessary isolation can be provided, so they can be offered to end users. Extensive research still needs to be conducted to identify trends and challenges that arise during the integration of these two paradigms.

To the best of our knowledge, this is one of the first research articles on quantum cloud computing, a field that emerged by integrating quantum computing with cloud computing. We can summarize the contributions of the article as follows:

- Explain the concept of quantum cloud computing and aim to lay the groundwork for future research by explaining it along with its basic concepts,
- Identify trends in quantum cloud computing and examine software tools, applications, and algorithms developed for it. In this way, we summarize the latest developments for the reader,
- Highlight the challenges in quantum cloud computing and identify those that may arise during the integration of quantum and cloud computing paradigms. This way, we aim to provide a future blueprint for researchers.

The rest of this article is structured as follows. Section 2 introduces the reader to the background of quantum computing and then examines its application areas. Section 3 explains the advantages of combining quantum and cloud computing and discusses its applications, trends, and challenges, along with business aspects. Finally, Section 4 summarizes the article.

2. Quantum computing: buzzword or game changer

In computing systems, all operations such as data processing, communication, and storage are provided by bits consisting of 0 and 1 values (Gill et al., 2022b). Here, the one represented by 0 represents the low voltage in the electronic circuits, while the one represented by 1 represents the relatively high voltage in the electronic circuit (Walther et al., 2005). In today's computers, all operations are still performed with binary bit logic. Quantum Computing (QC), which has been frequently encountered in the academy and private sectors in recent years and is expected to shape the computing systems of the future, suggests that a bit can take values other than 0 and 1 (Brassard, 2003). Fig. 1 shows the working principle difference between QC and traditional computing. QC works based on three basic principles found in quantum physics (Schwaller et al., 2021) as shown in Fig. 2. The brief description of these principles is given below:

- *Wave-particle Duality*: In quantum mechanics, particles of light, photons, are considered both waves and matter (Niu and Yu, 2023). This makes it possible to find a particle everywhere rather than just in one place.
- *Uncertainty Principle*: This principle, also known as the Heisenberg Principle, states that it is impossible to measure a photon's position and momentum simultaneously (Xiao et al., 2023).
- *Superposition*: In quantum mechanics, it means that the photon can be in more than one different position at the same time and it is impossible to determine its position (Overstreet et al., 2023). In this way, for computing operations such as communication and storage, a bit can take values other than 0 and 1, unlike in classical computing.

Quantum computing brings some advantages over classical computing (Biamonte et al., 2017). The primary advantages are as shown in Fig. 3 and discussed below:

- *Speed*: QC has parallel processing capabilities, such as performing multiple operations simultaneously. This way, it works much faster than normal computers.
- *Security*: Since QC has the ability to break security algorithms such as RSA (Rivest-Shamir-Adleman) very quickly, it will lead to the development of the concept of quantum cryptography. This means much higher security.

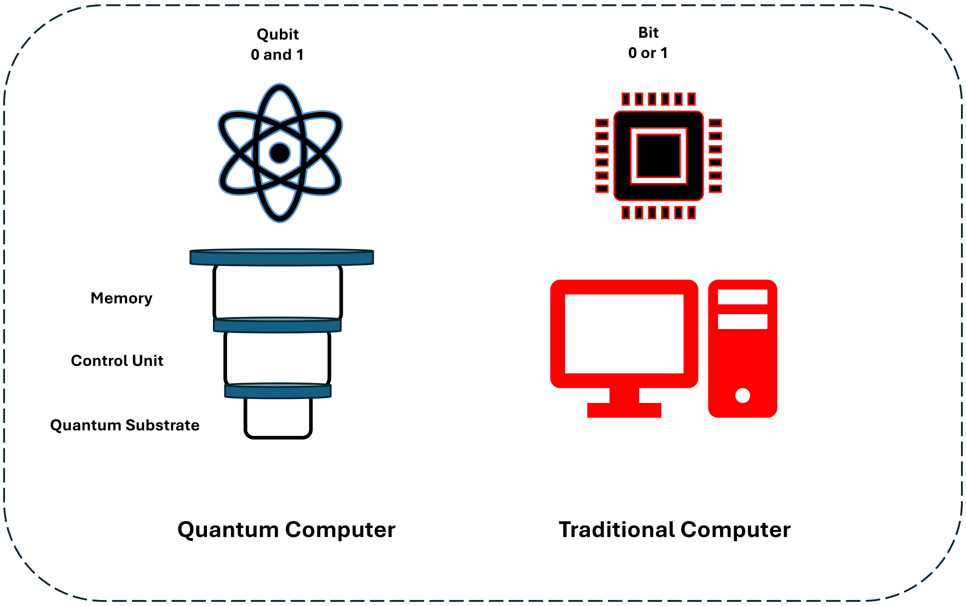

Fig. 1. Quantum Computing vs Traditional Computing.

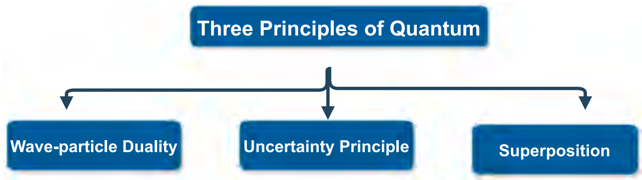

Fig. 2. Three Principles of Quantum Computing.

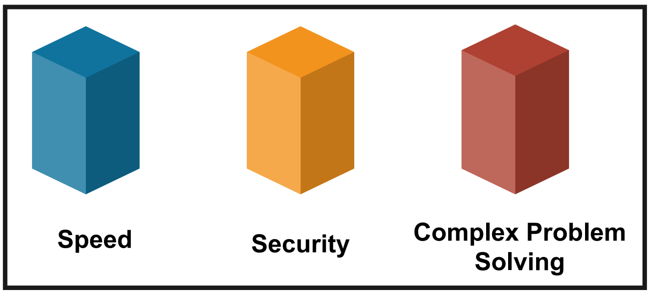

Fig. 3. Quantum computing advantages over classical computing.

- *Complex Problem Solving*: QC works more effectively in nonlinear and complex problems than classical computer systems, due to the features explained above and the nature of qubits (Jin et al., 2023).

2.1. Algorithms and software tools

In this subsection, we will examine algorithms and software tools developed for QC that have potential applications in quantum cloud computing.

2.1.1. Algorithms

Fig. 4 shows popular quantum computing algorithms. QC relies on the fundamental principles of quantum mechanics. The Deutsch-Jozsa algorithm is one of the first examples showing that a problem can be solved faster on quantum computers than on classical computers (Qiu and Zheng, 2020). It is a deterministic quantum algorithm discovered by David Deutsch and Richard Jozsa in 1992. It emphasizes the advantage of employing negative amplitudes, which classical computers are incapable of accomplishing, in the Deutsch-Jozsa algorithm, a precursor to the development of far more major quantum algorithms. The Bernstein-Vazirani quantum

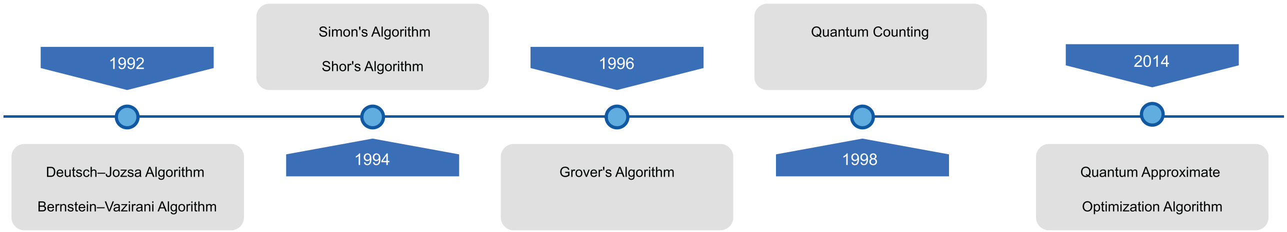

Fig. 4. The Timeline of Quantum Computing Algorithms.

algorithm, which is a limited version of the Deutsch-Jozsa algorithm developed by Ethan Bernstein and Umesh Vazirani in 1992, solves the hidden shift problem, which is important in error correction and cryptography (Nagata et al., 2017). Daniel Simon first published Simon's algorithm in 1994, which is superior to classical algorithms in terms of performance (Strubell, 2011). Simon's algorithm is employed to solve the black box function that fulfills a given collection of values and solves it at a much more exponential speed than any classical algorithm by using a quantum computer. Simon's algorithm served as the inspiration for Shor's algorithm, which is a quantum algorithm developed by Peter Shor in 1994 for the purpose of finding the prime factors of an integer. After these algorithms which were based on the Fourier transform, Grover's algorithm is a quantum algorithm that offers a better improvement than classical algorithms for unstructured search problems developed based on amplitude amplification, which enables quantum computers capable of quickly solving challenges that may be difficult to solve with classical computers and quantum counting based on it was developed respectively (Cerezo et al., 2021). Finally, quantum approximate optimization, a hybrid quantum-classical algorithm that focuses on solving graph theoretic problems and is predicted to obtain better solutions than classical algorithms, has recently been introduced (Zhou et al., 2020).

2.1.2. Software tools

Fig. 5 shows popular quantum software tools, which can be utilized for quantum cloud computing. Quantum software is an arising and less developed topic than quantum technology. The software that manages the quantum hardware is expected to be able to utilize complex quantum techniques and deliver high-level performance (Singh et al., 2024). In these days, there are different platforms for quantum computer programming depending on hardware solutions (Khan et al., 2023). One of these is Qiskit (Quantum Information Science Kit), a software development kit developed by IBM in 2017 for the operation of quantum computers at the algorithm and circuit level (Wille et al., 2019). Another is Cirq, an open-source framework developed by Google for quantum computers Hancock et al. (2023). PyQuil, which allows running programs on real quantum computers using the quantum cloud computing service, was developed by Rigetti Computing (Hibat-Allah et al., 2024). These frameworks are frequently made available by quantum developers under open-source and with API (Application Programming Interface) in Python.

2.2. Research gaps and new trends

In this subsection, we examine the research gaps and new trends related to QC. Fig. 6 highlights these research gaps regarding QC for researchers.

- **Quantum Mechanics-based Challenges**: Challenges arising from quantum mechanics have still not been overcome in quantum computers Imre (2014). We can broadly examine these difficulties under two subheadings (Magri et al., 2023): i) Qubits lose data due to the situation called decoherence in quantum mechanics. This causes the coherence time to be short and is undesirable in QC applications. ii) Quantum error correction poses a significant challenge. Compared to classical computers, error correction is a difficult task in quantum computers due to the more complex errors and the difficulty of copying the quantum state.
- **Quantum Artificial Intelligence (QAI)**: By combining Machine Learning (ML) & Deep Learning (DL) methods with quantum processing power, difficult and complex problems can be solved more effectively (Dunjko and Briegel, 2018). However, in

Fig. 5. Software Tools for Quantum Cloud Computing.

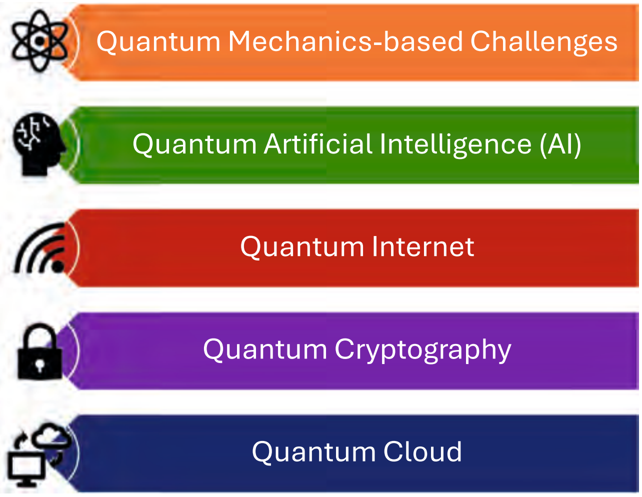

Fig. 6. Research Gaps and New Trends.

quantum computers that still contain a high number of qubits (millions), problems such as internal noise can reduce the performance of the models (Krenn et al., 2023).

- **Quantum Internet**: Unlike the traditional Internet, communication is achieved using quantum principles such as superposition and entanglement (Wehner et al., 2018). In this way, key distribution difficulties in cryptography are prevented and communication security is increased (Rozenman et al., 2023). In addition to this advantage, difficulties such as qubit fragility, transmission, and long-distance data transmission (entanglement dispersion) arising from quantum-based data need to be solved Azuma et al. (2023).
- **Quantum Cryptography**: It is thought that modern cryptography methods will be endangered with the proliferation of quantum computers with high processing capabilities (Kumar et al., 2022). For this reason, new measures based on quantum principles are needed to ensure secure key distribution and encryption (Subramani and Svn, 2023). Based on quantum principles, Quantum Cryptography can prevent a hacker from making a copy and monitoring the key in the encryption algorithm (Mehic et al., 2023). However, there is still a need for new Quantum Cryptography protocols that minimize the impact of qubits from environmental factors and prevent data loss due to decoherence during transmission.
- **Quantum Cloud**: Since quantum computers are expensive and require a high level of isolation due to qubit instability, it is a logical solution to make them available to users through a central server (Lou et al., 2024). However, intensive studies are required on this concept that combines QC and cloud computing (Gong et al., 2021). Providing quantum processing power to researchers through cloud platforms will provide great advantages for developing quantum algorithms, quantum simulations, and other quantum-based applications (Ravi et al., 2021). However, security, scalability (in line with increasing demand), infrastructure, and software studies still need to be carried out for quantum and cloud integration (Soeparno and Perbangsa, 2021).

3. Quantum cloud computing

This section examines the basic concepts, trends, applications, and challenges of Quantum Cloud Computing (QCC). The concept of QCC is a new computing paradigm that aims to facilitate end-user access to QC by using cloud computing platforms. Thanks to QCC, users will have easy access to quantum computers, which are costly and require high stabilization. Fig. 7 shows a general architecture of quantum cloud computing. The Quantum computer can be placed on a cloud-based platform and serve the end user via an Application Programming Interface (API) (Gong et al., 2021). Likewise, quantum processing power can be distributed to nodes such as edge and fog, which reduces latency and bandwidth traffic (Ravi et al., 2021). Cloud platforms provide the environment parameters (network infrastructure, storage, operating environment, etc.) required for the quantum computer and undertake the task of transmitting the calculation results on quantum computers to the farthest point of the network (Soeparno and Perbangsa, 2021). Edge and cloud technologies combine with quantum to play an important role in the business world by increasing efficiency and sustainability, in addition to all these advantages. The Network Layer shown in the Fig. 7 shows the computing technologies currently used in server-client communication. With the development of quantum internet technologies explained in Section 2.2, major improvements such as throughput and latency are expected to be achieved in data communication.

3.1. New research paradigm

Work on quantum cloud computing, which is believed to be one of the most popular uses of QC in the future, continues at a great pace (Mehta et al., 2023). Leading cloud companies such as Amazon (Braket), Microsoft (Quantum Development Kit), and IBM (Quantum Experience) have now started to offer quantum services to the public, albeit with limited processing power (Singh et al.,

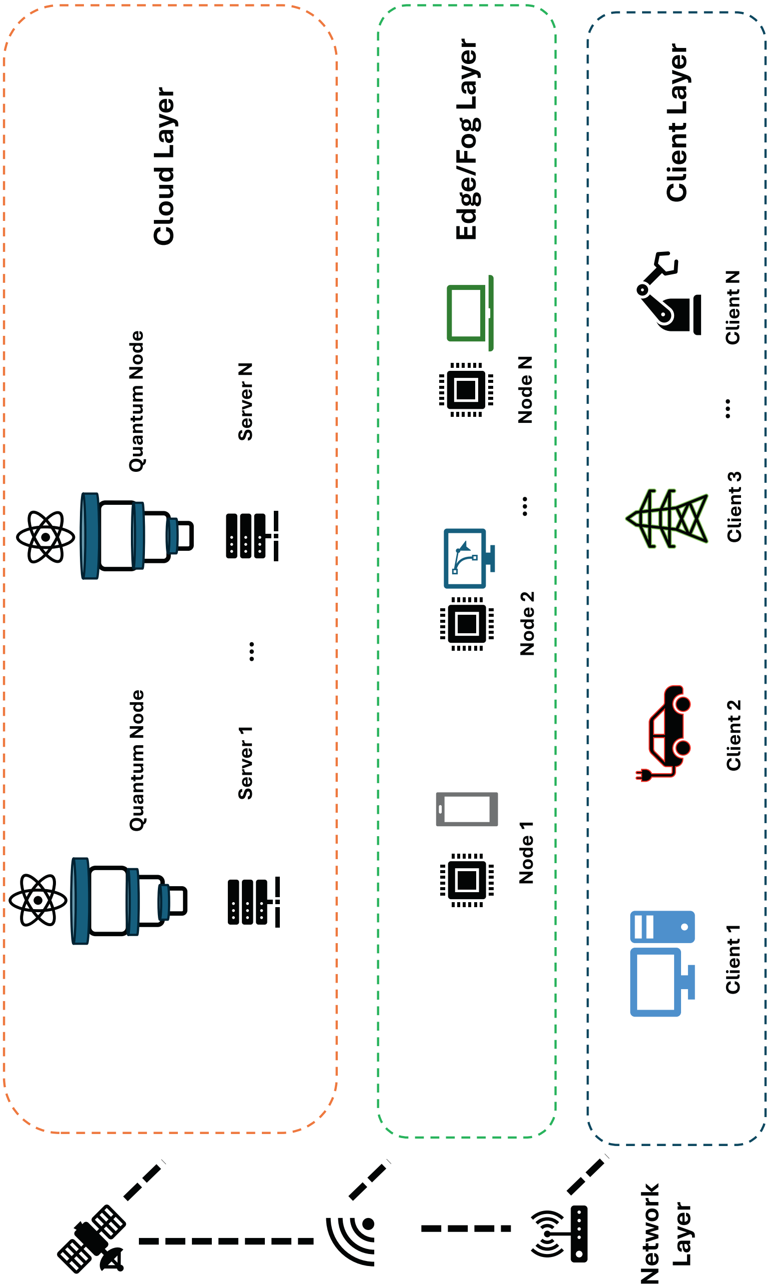

Fig. 7. General Architecture of Quantum Cloud Computing.

2022; Mehta et al., 2023). These initiatives, which are still in their infancy, provide clues that the accessibility of QCC will become even easier in the future (Furutanpey et al., 2023; Gill et al., 2024). The advantages of QCC can be listed as follows:

- Cloud-based QC platforms enable users to rapidly expand their computing capacity according to their needs. This feature enables the allocation of suitable resources for QC issues of varying magnitudes.
- Cloud-based QC training programs can be used to introduce quantum circuits and better understand the advantages of QC.
- Cloud-based QC can develop and test quantum algorithms before running them on actual quantum computers. This approach eliminates the need for specialized skills and expertize to access quantum computers, while also lowering cloud platform costs through cloud-based QC.
- It ensures that everyone has access to the same systems and makes it easier for individuals with Internet connections from all over the world to collaborate.
- QCC platforms can allow users to benefit from the quantum experts provided by the service platform. Thus, users or organizations new to QC can develop quantum calculations and run them on real quantum computers.
- It lessens the requirement for costly on-site physical security measures.

3.2. Applications, trends and open challenges

In this subsection, possible applications and future trends of QCC are examined. Fig. 8 shows the applications, trends, and challenges of QCC. By taking advantage of a quantum computer inside (Furutanpey et al., 2023; Singh et al., 2024), QCC can solve tasks where the processing power of traditional computers is insufficient or processes that take a long time with a traditional computer, in a very short time (Singh et al., 2022; Gill et al., 2024). Therefore, its future application areas are very wide.

3.2.1. Applications

An overview of some of these areas is as follows:

- *Data Analysis:* It can be used in applications containing large data sets,
- *Security:* It can be used to transmit and store data securely in the period when quantum computers become widespread,
- *Machine Learning:* It can shorten the training time of ML and DL models and significantly increase their accuracy rates,
- *Complex Problems:* It can be used to develop innovative solutions for challenging and complex technologies, such as drug design and gene technologies.

3.2.2. Future trends

However, there is currently a lack of knowledge about QCC's application areas, which has resulted in significant research gaps for many researchers. Possible developments related to QCC include the following:

- Increasing the power of quantum computers for solving more complex problems and AI models involving large datasets,
- Expanding quantum cloud computing to broader areas such as health and education by reducing costs,
- Integrating quantum computing with the cloud raises questions about infrastructure development and security standards.

3.2.3. Open challenges

Despite being a promising paradigm, QCC still faces some challenges before adoption (Furutanpey et al., 2023; Singh et al., 2022; Gill et al., 2024). The most important of these challenges are as follows:

- **Transformative Applications**: For practical applications like robotics and quantum-safe cryptography, quantum computers are still in the development stage (Banafa, 2023).
- **Scalability**: In cloud computing, resources can be scaled to meet demand fluctuations (Singh et al., 2024). Quantum computers are difficult to manage on a large scale and may not meet the scalability expected in cloud services (Safi et al., 2023).
- **Production Cost**: Since producing quantum computers still requires high costs, QCC systems will also cause higher costs than traditional cloud services Wang and Wilde (2020).
- **Privacy**: With the widespread use of quantum computers with high processing power, cryptographic algorithms will become vulnerable (Li et al., 2024). For this reason, the data stored in QCC may cause privacy issues as it will be obtained by third parties. Additionally, since QCC is still in its infancy, the ways in which personal data is collected and protected need to be clarified.
- **Data Security**: ue to the ease of breaking traditional cryptographic methods, the widespread use of quantum computers will necessitate the development of new cryptographic techniques that are resistant to quantum processing power (Sharma and Ketti Ramachandran, 2021). Likewise, data transfer processes in quantum computers are different from classical methods, and new communication protocols may be needed to transmit data without distortion. These protocols are also vital to prevent unauthorized access (Azzaoui et al., 2022).
- **Technological Fairness**: Ease of access to quantum technologies will not be equally easy in developed and developing countries (Mutlu and Garibay, 2021). In addition, while QCC creates new areas of expertize and business, it may also negatively affect some business lines. All of this increases technological injustice.

(caption on next page)

Fig. 8. Applications, Future Trends and Challenges of Quantum Cloud Computing.

3.3. The business and economical aspects

In addition to its effects on technological developments, QCC also has significant impacts on new business models and economic opportunities (Prakash, 2023).

- **New Business Opportunities**: As QCC becomes widespread, new software and start-up companies are expected to emerge (Aljaafari, 2023). Furthermore, companies that use QCC have a competitive advantage in terms of performance and speed over those that do not use QCC.
- **Economical Aspect**: Companies need new infrastructure and qualified employees to use QCC. This will require significant investments in R&D costs (Liu and Ren, 2024). On the other hand, as quantum technologies become more widespread and cheaper, processing costs will decrease thanks to the higher speed they offer compared to classical computers.

4. Conclusions

Quantum computing is a new paradigm that is still in its infancy but has the potential to revolutionize many scientific and technological fields in the future. Due to quantum mechanics, quantum computers operate in well-insulated environments, making them susceptible to environmental factors like heat, temperature, and noise. As a result, it is still a difficult technology for quantum researchers to reach. By integrating quantum computing into cloud platforms, a well-isolated server can provide service to the network's edge, reducing costs. This brilliant idea may be possible with quantum cloud computing, which combines quantum computing and cloud computing. This article aims to provide guidance for researchers by highlighting the quantum cloud computing paradigm, future application areas, advantages, challenges, and research gaps.

CRediT authorship contribution statement

Muhammed Golec: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization, Writing – review & editing. **Emir Sahin Hatay:** Writing – original draft, Investigation, Methodology. **Mustafa Golec:** Conceptualization, Formal analysis, Writing – review & editing. **Murat Uyar:** Writing - review & editing, Conceptualization, Methodology. **Merve Golec:** Writing – review & editing, Conceptualization, Methodology. **Sukhpal Singh Gill:** Writing – original draft, Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Muhammed Golec would express his thanks to the Ministry of Education of the Turkish Republic, for their support and funding.

References

Aggarwal, L., Sachdeva, S., Goswami, P., 2023. Quantum healthcare computing using precision based granular approach. Appl. Soft Comput. 144, 110458.
Aljaafari, M., 2023. Quantum computing for social business optimization: a practitioner's perspective. Soft Comput. 1–23.
Azuma, K., Economou, S.E., Elkouss, D., Hilaire, P., Jiang, L., Lo, H.K., Tzitrin, I., 2023. Quantum repeaters: From quantum networks to the quantum internet. Rev. Mod. Phys. 95, 045006.
Azzaoui, A.E., Sharma, P.K., Park, J.H., 2022. Blockchain-based delegated quantum cloud architecture for medical big data security. J. Netw. Comput. Appl. 198, 103304.
Banafa, A., 2023. Quantum Computing and Other Transformative Technologies. River Publishers.
Bernstein, D.J., Lange, T., 2017. Post-quantum cryptography. Nature 549, 188–194.
Biamonte, J., Wittek, P., Pancotti, N., Rebentrost, P., Wiebe, N., Lloyd, S., 2017. Quantum machine learning. Nature 549, 195–202.
Brassard, G., 2003. Quantum communication complexity. Found. Phys. 33, 1593–1616.
Cerezo, M., Arrasmith, A., Babbush, R., Benjamin, S.C., Endo, S., Fujii, K., McClean, J.R., Mitarai, K., Yuan, X., Cincio, L., et al., 2021. Variational quantum algorithms. Nat. Rev. Phys. 3, 625–644.
Dunjko, V., Briegel, H.J., 2018. Machine learning & artificial intelligence in the quantum domain: a review of recent progress. Rep. Prog. Phys. 81, 074001.
Furutanpey, A., Barzen, J., Bechtold, M., Dustdar, S., Leymann, F., Raith, P., Truger, F., 2023. Architectural vision for quantum computing in the edge-cloud continuum. Quantum Phys. 88–103.
Gill, S.S., Kumar, A., Singh, H., Singh, M., Kaur, K., Usman, M., Buyya, R., 2022a. Quantum computing: A taxonomy, systematic review and future directions. Softw.: Pract. Exp. 52, 66–114.
Gill, S.S., Wu, H., Patros, P., et al., 2024. Modern computing: Vision and challenges. Telemat. Inform. Rep. 13, 100116.
Gill, S.S., Xu, M., Ottaviani, C., Patros, P., Bahsoon, R., Shaghaghi, A., Golec, M., Stankovski, V., Wu, H., Abraham, A., et al., 2022b. Ai for next generation computing: emerging trends and future directions. Internet Things 19, 100514.
Gong, C., Dong, Z., Gani, A., Qi, H., 2021. Quantum k-means algorithm based on trusted server in quantum cloud computing. Quantum Inf. Process. 20, 1–22.
Hancock, A., Garcia, A., Shedenhelm, J., Cowen, J., Carey, C., 2023.Cirq: A python framework for creating, editing, and invoking quantum circuits.
Heim, B., Soeken, M., Marshall, S., Granade, C., Roetteler, M., Geller, A., Troyer, M., Svore, K., 2020. Quantum programming languages. Nat. Rev. Phys. 2, 709–722.

Hibat-Allah, M., Mauri, M., Carrasquilla, J., Perdomo-Ortiz, A., 2024. A framework for demonstrating practical quantum advantage: comparing quantum against classical generative models. Commun. Phys. 7, 68.
Imre, S., 2014. Quantum computing and communications–introduction and challenges. Comput. Electr. Eng. 40, 134–141.
Jin, S., Liu, N., Yu, Y., 2023. Time complexity analysis of quantum algorithms via linear representations for nonlinear ordinary and partial differential equations. J. Comput. Phys. 487, 112149.
Kandala, A., Mezzacapo, A., Temme, K., Takita, M., Brink, M., Chow, J.M., Gambetta, J.M., 2017. Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets. nature 549, 242–246.
Khan, A.A., Ahmad, A., Waseem, M., Liang, P., Fahmideh, M., Mikkonen, T., Abrahamsson, P., 2023. Software architecture for quantum computing systems—a systematic review. J. Syst. Softw. 201, 111682.
Krenn, M., Landgraf, J., Foesel, T., Marquardt, F., 2023. Artificial intelligence and machine learning for quantum technologies. Phys. Rev. A 107, 010101.
Kumar, A., Ottaviani, C., Gill, S.S., Buyya, R., 2022. Securing the future internet of things with post-quantum cryptography. Secur. Priv. 5, e200.
Li, C., Kumar, N., Song, Z., Chakrabarti, S., Pistoia, M., 2024. Privacy-preserving quantum federated learning via gradient hiding. Quantum Sci. Technol. 9, 035028.
vonLilienfeld, O.A., Müller, K.R., Tkatchenko, A., 2020. Exploring chemical compound space with quantum-based machine learning. Nat. Rev. Chem. 4, 347–358.
Liu, J., Ren, T., 2024. Economic impact of quantum sports technologies on healthcare artificial intelligence based study. Opt. Quantum Electron. 56, 168.
Lou, X., Zan, H., Xu, X., 2024. Quantum circuit-based proxy blind signatures: A novel approach and experimental evaluation on the ibm quantum cloud platform. Chin. Phys. B.
Ma, Y., Kashefi, E., Arapinis, M., Chakraborty, K., Kaplan, M., 2022. Qenclave-a practical solution for secure quantum cloud computing. npj Quantum Inf. 8, 128.
Magri, L., Schmid, P.J., Moeck, J.P., 2023. Linear flow analysis inspired by mathematical methods from quantum mechanics. Annu. Rev. Fluid Mech. 55, 541–574.
Mehic, M., Michalek, L., Dervisevic, E., Burdiak, P., Plakalovic, M., Rozhon, J., Mahovac, N., Richter, F., Kaljic, E., Lauterbach, F., et al., 2023. Quantum cryptography in 5g networks: A comprehensive overview. IEEE Commun. Surv. Tutor.
Mehta, D., Ranadive, A., Prajapati, J.B., Pandey, R., 2023. Survey of open-source tools/industry tools to develop quantum software. Quantum Computing: A Shift from Bits to Qubits. Springer, pp. 311–332.
Mutlu, E., Garibay, O.O., 2021.A quantum leap for fairness: quantum bayesian approach for fair decision making, In: HCI International 2021-Late Breaking Papers: Multimodality, eXtended Reality, and Artificial Intelligence: 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings 23, Springer.489-499.
Nagata, K., Resconi, G., Nakamura, T., Batle, J., Abdalla, S., Farouk, A., 2017. A generalization of the bernstein-vazirani algorithm. MOJ Ecol. Environ. Sci. 2, 00010.
Nahar, S., Pithawa, D., Bhardwaj, V., Rawat, R., Rawat, A., Pachlasiya, K., 2023. Quantum technology for military applications. Quantum Comput. Cybersecur. 313–334.
Niu, C., Yu, S., 2023. Wave-particle duality via quantum fisher information. Chin. Phys. Lett. 40, 110301.
Overstreet, C., Curti, J., Kim, M., Asenbaum, P., Kasevich, M.A., Giacomini, F., 2023. Inference of gravitational field superposition from quantum measurements. Phys. Rev. D. 108, 084038.
Prakash, P.M., 2023. Enhancing business performance through quantum electronic analysis of optical data. Opt. Quantum Electron. 55, 1056.
Qiu, D., Zheng, S., 2020. Revisiting deutsch-jozsa algorithm. Inf. Comput. 275, 104605.
Ravi, G.S., Smith, K.N., Gokhale, P., Chong, F.T., 2021.Quantum computing in the cloud: Analyzing job and machine characteristics, In: 2021 IEEE International Symposium on Workload Characterization (IISWC), IEEE.39-50.
Rozenman, G.G., Kundu, N.K., Liu, R., Zhang, L., Maslennikov, A., Reches, Y., Youm, H.Y., 2023. The quantum internet: a synergy of quantum information technologies and 6g networks. IET Quantum Commun. 4, 147–166.
Safi, H., Wintersperger, K., Mauerer, W., 2023.Influence of hw-sw-co-design on quantum computing scalability, In: 2023 IEEE International Conference on Quantum Software (QSW), IEEE.104-115.
Sasaki, T., Yamamoto, Y., Koashi, M., 2014. Practical quantum key distribution protocol without monitoring signal disturbance. Nature 509, 475–478.
Schwaller, N., Dupertuis, M.A., Javerzac-Galy, C., 2021. Evidence of the entanglement constraint on wave-particle duality using the ibm q quantum computer. Phys. Rev. A 103, 022409.
Sharma, N., Ketti Ramachandran, R., 2021. The emerging trends of quantum computing towards data security and key management. Arch. Comput. Methods Eng. 28, 5021–5034.
Singh, J., Bhangu, K.S., 2023. Contemporary quantum computing use cases: taxonomy, review and challenges. Arch. Comput. Methods Eng. 30, 615–638.
Singh, M., Dhara, C., Kumar, A., Gill, S.S., Uhlig, S., 2022. Quantum artificial intelligence for the science of climate change. Artificial Intelligence, Machine Learning and Blockchain in Quantum Satellite, Drone and Network. CRC Press, pp. 199–207.
Singh, P., Dasgupta, R., Singh, A., Pandey, H., Hassija, V., Chamola, V., Sikdar, B., 2024. A survey on available tools and technologies enabling quantum computing. IEEE Access.
Soeparno, H., Perbangsa, A.S., 2021. Cloud quantum computing concept and development: a systematic literature review. Procedia Comput. Sci. 179, 944–954.
Strubell, E., 2011. An introduction to quantum algorithms. COS498 Chawathe Spring 13, 19.
Subramani, S., Svn, S.K., 2023. Review of security methods based on classical cryptography and quantum cryptography. Cybern. Syst. 1–19.
Walther, P., Resch, K.J., Rudolph, T., Schenck, E., Weinfurter, H., Vedral, V., Aspelmeyer, M., Zeilinger, A., 2005. Experimental one-way quantum computing. Nature 434, 169–176.
Wang, X., Wilde, M.M., 2020. Cost of quantum entanglement simplified. Phys. Rev. Lett. 125, 040502.
Wehner, S., Elkouss, D., Hanson, R., 2018. Quantum internet: a vision for the road ahead. Science 362, eaam9288.
Wille, R., Van Meter, R., Naveh, Y., 2019.Ibm's qiskit tool chain: Working with and developing for real quantum computers, In: 2019 Design, Automation & Test in Europe Conference & Exhibition (DATE), IEEE.1234-1240.
Xiao, Y., Yang, Y., Wang, X., Liu, Q., Gu, M., 2023. Quantum uncertainty principles for measurements with interventions. Phys. Rev. Lett. 130, 240201.
Zhou, L., Wang, S.T., Choi, S., Pichler, H., Lukin, M.D., 2020. Quantum approximate optimization algorithm: performance, mechanism, and implementation on near-term devices. Phys. Rev. X 10, 021067.