Potential Applications of Quantum Computing in 6G Networks

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Abstract: The advent of 6G technology ushers in a new era in digital connectivity, characterized by universal, continuous, and ultra-high-performance communications, as well as integration with artificial intelligence. In the face of increasing computational demands, quantum security, advanced cryptography, and energy efficiency requirements of these networks, quantum computing emerges as a promising solution to address such challenges. This study comprehensively investigates the potential roles and implications of quantum computing in the context of 6G networks. The research was conducted in two stages. In the first stage, a thorough literature review was carried out from 2018 to 2024 to identify the main applications of quantum computing in 6G technology. In the second stage, these applications were analyzed regarding their practical feasibility. The literature review reveals a growing consensus on the role of quantum computing in the advancement of 6G. As a result, 9 potential applications of quantum computing were identified, organized into three thematic areas: Quantum Technologies, Data and Network Management, Ultra-Precise Timing and Sensing. Moreover, the study systematizes the best practices extracted from the literature to guide future implementations, providing a solid foundation for researchers and professionals interested in incorporating quantum computing into 6G networks. Among the identified applications, Quantum Key Distribution and Ultra-Precise Timing stand out for their potential impact on 6G performance and security. The findings significantly contribute to the advancement of knowledge in the field, pointing to pathways for the efficient adoption of quantum computing and strengthening the understanding of its applications and implementation strategies in a rapidly evolving technological landscape.

Keywords: 6G networks. Quantum computing. Quantum Technologies. Emerging technologies.

1. Introduction

The 5G network marked a milestone in telecommunications, delivering ultra-high speed, low latency, and support for innovative applications such as smart cities, autonomous vehicles, augmented reality, and mobile healthcare systems. Despite these advances, 5G still presents significant limitations, including the need for proximity to antennas, restricted coverage in remote areas, and insufficient performance for certain critical operations.

In this context, 6G emerges with the goal of overcoming these barriers. This new generation is expected to offer speeds up to 50 times faster than 5G and latency as low as 1 millisecond, enabled by low Earth orbit satellites. It also promises global coverage through multiple interconnected access points, along with greater sustainability, as equipment will be manufactured from eco-friendly materials [1].

One of its key differentiators will be deep integration with Artificial Intelligence (AI), enabling reduced data loss, optimized energy consumption, automatic traffic adjustments according to demand, and lower operational costs. Such automation is expected to minimize the need for human intervention while increasing network efficiency and reliability.

Currently, 6G networks are in the development stage, with commercial deployment and initial use cases anticipated around 2030, starting in developed countries. However, this timeline is only indicative, as 5G implementation still faces considerable challenges. The adoption of 6G will depend on factors such as public policy, economic conditions, geographical constraints, and investment availability.

To facilitate comparison, Table 1 [2] presents the main characteristics of 5G and 6G networks, including access technology, maximum data rate, typical usage rate, and latency.

Table 1. Cellular generations and key applications.

Characteristics	5G	6G
Access technology	MIMO-OFDMA and mmWave beamforming	Terahertz technology
Peak data rate (downlink)	> 20 Gb/s	> 400 Gb/s
Typical user data rate (downlink)	> 200 Mb/s	> 1 Gb/s
Typical latency	< 1 ms	< 0.1 ms

One of the main drivers of the evolution toward 6G networks is the integration of quantum computing (QC) into wireless communication systems [2]. Quantum mechanics, once confined to the realm of theoretical physics, is now being applied to unlock new potential across various industries, including telecommunications [3].

The role of QC in 6G technology is multifaceted and offers a wide range of benefits [4]. For example, quantum key distribution, grounded in the principles of quantum mechanics, can enable theoretically unbreakable encryption, thereby strengthening the security of the extensive IoT networks envisioned for 6G [5, 6, 7]. In addition, quantum sensors have the potential to significantly improve device positioning and navigation accuracy—an essential requirement in the highly connected environments expected with 6G.

Despite its potential, the integration of QC into 6G remains in its early stages and requires substantial research and development efforts [7, 8]. While recent studies provide valuable contributions, they often address specific aspects of this integration without offering a comprehensive analysis of the topic. This gap highlights the need for a broader understanding of QC's roles in the 6G context and for the identification of effective practices for its implementation.

Accordingly, this research aims to deepen the analysis of potential QC applications in 6G by examining 9 key use cases reported in the existing literature. Each application was assessed in terms of its practical feasibility and the current limitations that must still be addressed.

2. Methodology

The central problem of this research is: What are the main application areas of quantum computing (QC) in 6G technology? To address this question, a comprehensive literature review was conducted. The investigation included the analysis of peer-reviewed articles published in journals and conference proceedings between 2018 and 2024.

The search was carried out in Google Scholar and other academic search engines, using specific keywords to identify relevant studies. Works that directly discussed the applications of quantum computing in the context of 6G were considered, as well as studies that, although not exclusively focused on these applications, provided relevant insights and case reports.

The data processing and organization followed the qualitative coding steps proposed by Braun and Clarke [9], structured into three levels: "code," "theme," and "higher-level theme." Based on this procedure, the identified concepts were reformulated and organized, resulting in a final list of key applications. These applications were then mapped to their corresponding main areas, with continuous revisions throughout the process to minimize bias and ensure consistency in the classifications.

3. Results

In this section, the results and discussions are presented. Section 3.1 details the findings from the literature review, while Section 3.2 maps these areas, organizing them into four major thematic categories. The mapping aims to synthesize the main application domains of Quantum Computing (QC) in the context of 6G.

3.1. Results of the Literature Review

The literature review identified nine key application areas (Applications of Quantum Computing, AQC) with significant potential to drive the advancement and success of 6G through quantum computing. These areas are presented and described below.

(i) AQC-01 – Advanced data processing

Quantum computing, by processing large volumes of data simultaneously, can improve processing in 6G networks, increasing speed, reliability, and efficiency [10]. To overcome the main challenge of applying quantum technology to 6G, best practices such as skills development, early adoption, robust governance, and strategic partnerships are essential [11].

(ii) AQC-02 – Quantum Key Distribution (QKD)

Security is crucial in communication systems. QKD uses quantum principles to encrypt data and distribute keys with theoretically unbreakable security [12]. In 6G, QKD can protect extensive IoT networks [13]. To enable this application, best practices such as training, adequate infrastructure, and multi-layered security are essential.

(iii) AQC-03 – Quantum Machine Learning
Machine learning algorithms will be key to managing and optimizing 6G networks. Quantum computing can enhance the efficiency and accuracy of these algorithms, improving network performance [10]. Quantum machine learning enables features like predictive maintenance and automated optimization [14].
Hybrid classical-quantum practices, including data quality assurance and testing, are essential for this application.

(iv) AQC-04 – Quantum sensors
Quantum sensors can enhance the accuracy and resolution of positioning and navigation systems, which are fundamental for high-frequency, high-density 6G networks [15]. This application relies on best practices such as rigorous calibration and maintenance, integration with legacy systems, and ensuring data security and privacy.

(v) AQC-05 – Ultra-precise time
Quantum clocks, due to their high precision, can improve synchronization in 6G networks, which is essential for autonomous vehicles and industrial automation [16-17]. This application requires practices such as rigorous calibration, maintenance, efficient integration with existing systems, and appropriate security measures. These practices ensure continuous adjustment of quantum components, minimizing drift and inaccuracies that could compromise the network's timing performance.

(vi) AQC-06 – Resource and Interference Management
Quantum computing can optimize resource allocation in 6G networks, addressing the diversity of services and devices [2]. Quantum algorithms offer greater efficiency in tackling these challenges, including interference management, which is critical due to high density and the use of high-frequency bands [18-19]. To mitigate interference in 6G, practices such as a hybrid quantum-classical approach, continuous experimentation, governance, and integration with network systems are essential.

(vii) AQC-07 – Quantum Error Correction
Quantum error correction codes improve transmission reliability in 6G networks, especially in challenging environments [20–22]. This area requires practices such as integration with existing systems, continuous monitoring, adjustments, and ongoing performance evaluation to optimize error correction.

(viii) AQC-08 – Signal Processing
Quantum computing can make signal processing more efficient, enhancing service quality in 6G

networks by increasing data rates and reducing latency [23–24].

This area relies on a hybrid quantum-classical approach, iterative testing, and security practices to optimize processing and handle signal complexity.

(ix) AQC-09 – Quantum Cryptography
Beyond Quantum Key Distribution (QKD), techniques like quantum digital signatures can protect data transmissions in 6G networks [12]. This area requires best practices such as a hybrid quantum-classical approach, continuous monitoring, and integration with existing security infrastructure, combining the strengths of both technologies to enhance 6G security [25].

3.2. Thematic Mapping of QC Applications in 6G

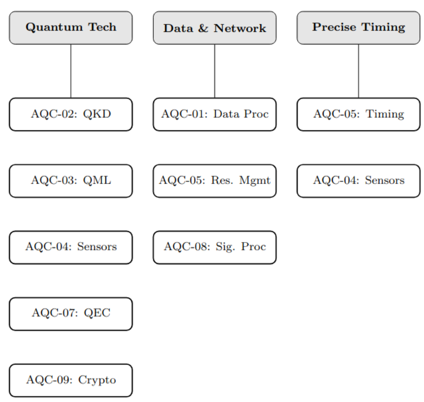
This section presents a mapping of quantum computing applications in the context of 6G, organized into thematic areas that indicate the greatest need for tools, methods, and training. Finally, a figure summarizes all the elements (Figure 1).

(i) Quantum Technologies
Includes AQC-02 (Quantum Key Distribution - QKD), AQC-03 (Quantum Machine Learning), AQC-04 (Quantum Sensors), AQC-07 (Quantum Error Correction), and AQC-09 (Quantum Cryptography). These areas leverage quantum principles such as superposition and entanglement to extend capabilities beyond classical limits, enabling ultra-secure communication, advanced learning, enhanced sensor precision, robust error correction, and strengthened cryptography.

(ii) Data and Network Management
Covers AQC-01 (Advanced Data Processing), AQC-05 (Resource and Interference Management), and AQC-08 (Signal Processing). Quantum computing can improve efficiency in processing large data volumes, optimize resource allocation and interference management, and accelerate and enhance signal processing in 6G networks.

(iii) Ultra-Precise Timing and Sensing
Focuses on AQC-05 (Ultra-Precise Timing) and AQC-04 (Quantum Sensors). Quantum technology can significantly improve timing accuracy and sensor sensitivity, enhancing synchronization and coordination in 6G networks and enabling detection with accuracy levels beyond traditional systems.

Figure 1. Mapping of Applications by Thematic Area in Quantum Computing



4. Conclusion

This study demonstrates the fundamental role of quantum computing in shaping the evolution of 6G networks. Based on an extensive literature review and feasibility analysis, nine key applications were identified and grouped into three thematic areas: Quantum Technologies, Data and Network Management, and Ultra-Precise Timing and Sensing. Notably, Quantum Key Distribution (QKD) and advanced modulation schemes emerged as highly promising for improving security and performance.

By consolidating best practices for their implementation, the research offers a strategic framework for accelerating the integration of quantum computing into 6G. This research not only reinforces the transformative potential of quantum computing but also provides concrete guidelines for researchers and industry stakeholders, paving the way for innovation in next-generation networks.

Future research should address the scalability challenges of quantum computing in large-scale 6G deployments and assess real-world performance metrics.

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