In-Network Quantum Computing for Future 6G Networks

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In light of the imperative for expeditious data processing and enhanced global connectivity, the domain of communication technology is experiencing a rapid progression from the Fifth Generation (5G) to the forthcoming Sixth Generation (6G) within the research community. Furthermore, 6G promises to significantly augment the synergy between the human, digital, and physical realms, thereby necessitating the formulation of novel Key Performance Indicators (KPIs) as well as Key Values Indicators (KVIs), and the assimilation of commensurate technologies. Among these technologies, quantum computing is evolving rapidly due to its inherent advantages from quantum mechanics. Nevertheless, scant attention is directed toward a comprehensive exploration of the consequences attendant to its present-day application. The principal objective of this article resides in its endeavor to underscore, from a compensatory perspective, the convergence of 6G and quantum computing while concurrently considering the Sustainable Development Goals and its KVIs.

1. Introduction

The need for high data speed in mobile communications is increasingly insatiable. Due to changes in consumer behavior, business requirements, and technical improvements, there has been a considerable increase in the need for connectivity and data over time. Concerning this, a new technology in wireless cellular communication networks has been investigated and developed every ten years approximately.

With the 5G networks rapidly increasing across the globe, attention is growingly turning toward what lies beyond—a world defined by the promise of 6G. This forthcoming era of wireless communication heralds the potential for unprecedented speed and connectivity and introduces an array of transformative technologies and paradigms.

In the pursuit of 6G, researchers and industry stakeholders face multifaceted challenges and opportunities. Key Performance Indicators (KPIs) are pivotal, serving as compass points guiding the development of 6G networks. These KPIs will extend far beyond the established metrics of data rates and latency to encompass novel dimensions like inclusion, sustainability, and trustworthiness as Key Values Indicators (KVIs) that could be connected to the Sustainable Development Goals (SDGs) released by the United Nations. Furthermore, the architecture of 6G networks will poise for a paradigm shift–enabling a seamless convergence of terrestrial, satellite, aerial, and maritime networks, while accommodating diverse applications from augmented reality to ultra-reliable communications. Therefore, the utilization of Artificial Intelligence (AI), Machine Learning (ML), and the captivating realm of Quantum Computing (QC) holds imperative significance to face with such heterogeneous networks.

Despite the considerable anticipation and promises surrounding emerging quantum technologies, a comprehensive assessment of their practical potential necessitates a thorough consideration of their energy consumption. Presently, there is a notable absence of such evaluations, leading to substantial confusion and ambiguity regarding the claims made about the energetic footprint of these technologies. According to ref. [1], in the realm of fault-tolerant QC, there is a widely recognized acknowledgment that the overhead associated with the use of physical qubits for error correction will pose a significant challenge on the path toward achieving scalability.

The existing literature predominantly emphasizes the advantages of QC, often overlooking the sustainability costs associated with the development of quantum devices. Conversely, there is a need for an analysis that delves into the KVIs proposed for 6G development, aligning them with specific aspects of quantum computers. These aspects include the operating temperature requirements of qubits and the challenges posed by the

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DOI: 10.1002/qute.202300334

inherent noise in current quantum systems. In response to this, we present an overview of 6G and the integration of QC in the network through the potential correlation between the sustainability, scalability, and trustworthiness goals envisioned for 6G and the critical challenges, as perceived from our standpoint. This exploration aims to shed light on the intricate relationship between the intended advancements in 6G and the nuanced considerations that must be taken into account when advocating for the integration of quantum computers in the future.

The rest of the paper is organized as follows, Section 2 offers a concise overview of the literature, Section 3 provides a general, but completed overview of 6G concerning the SDGs, KPIs, KVIs, and architecture. Section 4 presents a general vision of QC, including the leading properties of quantum mechanics, types of qubits and quantum technologies that are in continuous development. In Section 5, we come up with the fundamental pillar of the paper, 6G-KVIs related to QC. Finally, Section 6 offers the main conclusion.

2. Literature Review

According to the literature, it is expected that QC has the potential to impact various aspects of 6G technology due to its unique computational capabilities, such as superposition and entanglement. In this regard, the convergence of QC with future mobile communication networks is increasingly prevalent in research community. A remarkably complete review is made in ref. [2], where the authors conduct a thorough examination of the current status of quantum communications, encompassing QC-assisted systems. They pinpoint certain unresolved research issues related to generalization, scalability, and algorithm parallelization within Quantum Machine Learning (QML)-based communication networks. Use cases are presented such as: Multi-Objective Optimization and Routing Optimization, Harmonization and Interoperability of Networks, Configurable Multi-Antenna, and many others. Also, in ref. [3], the author explores how quantum algorithms can tackle real-world challenges in telecommunication networks, encompassing issues such as network congestion management, scheduling, and resource allocation. Highlighted examples, where utilizing quantum algorithms has the potential to enhance the efficiency of network operations, like spectrum management, channel estimation, resource optimization, routing and network planning, fault diagnosis, and energy management. References can also include works that elaborate on particular use cases illustrating the application of QC in wireless communications:[4] handles the problem of power allocation channels in Multiple-Input Multiple-Output (MIMO) systems, which is computationally intractable for water filling algorithm with the increasing size of the channel. In ref. [5], the authors propose an application based on the quantum Euclidean distance for accurate positioning in 6G indoor scenarios. Recently,[6] suggests an innovative framework to facilitate ultra-fast and ultra-safe 6G networks capable of supporting intricate and demanding real-time applications. The proposal relies on four pivotal enabling technologies: performance prediction, AI-enabled task offloading, QML, and quantum-resistant communication. The authors reveal that in the advent of 6G applications emphasizing real-time quality of experience, task offloading empowered by AI takes advantage of edge computing. Furthermore, the utilization of quantum computers at the edge or in the cloud can decrease the execution time of intricate applications.

On the other hand, concerns have arisen about the impact of using quantum computers. Some engaging articles related to the topic have been published. For example,[7] offers a valuable perspective, with the author emphasizing that: *"the lack of agreement on an energy use metric is, in part, because the field is so new"*. It contends that notable progress in QC has been achieved by researchers, arguably within the past decade. To date, numerous studies have concentrated on demonstrating the speedup quantum computers offer compared to classical computers, rather than delving into a comprehensive understanding of their energy consumption. In the vein of quantum energetic footprint,[1] discusses that the establishment and organization of a cross-disciplinary quantum energy initiative, interlinking quantum thermodynamics, quantum information science, quantum physics, and engineering, are deemed imperative for the prompt development of quantum technologies. This initiative represents the sole trajectory toward fostering energy-efficient and sustainable quantum technologies, with the potential to yield an energetic quantum advantage. Finally,[8] demonstrates that the critical threshold for achieving a green quantum advantage is significantly influenced by the quality of experimental quantum gates and the level of entanglement generated in the Quantum Processing Unit (QPU).

3. 6G Vision and Role of Computing in the Network

Even though the 5G is still in its development process, the research community is already focus on 6G of wireless communication. The advent of 5G technology has ushered in a new era of digitization in various industries. It has been focused on enabling machine control and connecting to multiple applications beyond industry, including agriculture, construction, and the energy sector, with smart grids and real-time Internet of Things (IoT) capabilities.[9] Consequently, 5G has been aiming to provide extensive support for a multitude of devices, improved video streaming, gaming, and augmented reality experiences, while maintaining minimal latency, reducing the delay between sending and receiving data, and higher data speed compared to its predecessors, reaching gigabit-per-second download speeds. In addition, the innovation of incorporating concepts like cloud computing, Software–Defined Networking (SDN), and Network Functions Virtualization (NFV), played a pivotal role in reshaping the concept of a communication network from its conventional understanding. However, a conservative and cautious thought is that *6G networks will be based on technologies that were not yet mature for being included in 5G systems*.[10] Following this idea, the evolutionary path is believed to continue into the next decade, leading to the widespread adoption of existing 5G applications. This adoption will come with substantially reduced deployment and operational expenses, enabling the development of new, inventive solutions driven by specific use cases, which will profoundly impact the economy and society.

3.1. What is 6G?

The future of connectivity lies in the development of digital twin worlds that faithfully mirror the physical and biological realms in both space and time, uniting our experiences across the physical, biological, and digital domains. Emerging themes are anticipated to influence the requirements and technologies of 6G, including: i) novel man-machine interfaces formed by the collaboration of multiple local devices working harmoniously, ii) pervasive universal computing distributed across various local devices and the cloud, iii) fusion of multi-sensory data to construct multiverse maps and innovative mixed-reality experiences, iv) precision sensing and actuation for controlling the physical world.[11] On the other hand, the future networks' design is anticipated to achieve equilibrium by balancing technological innovation, economic and environmental sustainability, and human-centric values. Therefore, 6G will focus on ensuring a more sustainable world, also defined in ref. [12] as *Sustainable 6G*. Hence, some of the primary research challenges include: integration of intelligence, network of networks, sustainability, global service coverage, extreme experience, and trustworthiness.

3.1.1. KPIs and KVIs of 6G

6G networks will demand exceptionally precise time and phase synchronization, aiming for near-perfect geographical coverage, sub-centimeter accuracy in geolocation, and millisecond updates in geolocation information to address various use cases, such as holographic communications and tactile applications. While 5G utilizes millimeter Wave (mmW) technology to deliver data rates in the Gbps range, 6G will require transmission data rates in the Tbps range to support applications like high-quality 3D video, Virtual Reality (VR), and combinations of VR and Augmented Reality (AR). As well as a user plane latency in the order of μs, and a speed of mobility of around 100 kmh^{-1} handling multiple moving platforms. To achieve these rates, terahertz (THz) and optical frequency bands are potential candidates.[13] The 6G vision encompasses four fundamental paradigm shifts. First, as 6G aims for global coverage, it extends beyond terrestrial networks, necessitating the integration of satellite and Unmanned Aerial Vehicle (UAV) communication networks, thus forming a comprehensive space-air-ground-sea communication network. Second, it will explore all available spectral bands, including sub-6 GHz, mmW, THz, and optical frequencies, to enhance data rates and connection density. Third, 6G networks will facilitate an array of intelligent applications, leveraging AI, Big Data technologies, and the emerging domains of QC. Lastly, the development of 6G networks will entail reinforced network security measures, and will introduce novel elements, including integrated sensing, AI, local compute-and-storage capabilities, and embedded devices.[14]

On the other hand, the existing set of KPIs will prove insufficient for framing the comprehensive research agenda of 6G, which necessitates an End-to-End (E2E) consideration. This expanded perspective must encompass additional facets, including but not limited to energy efficiency and service availability. To delineate the scope of 6G, the KVIs encompass the broader dimensions of impact, extending beyond deterministic performance metrics to encompass aspects such as sustainability, digital inclusion, and trustworthiness, being those the pillars of 6G vision and allowing the connection between the physical, digital, and human world.

3.1.2. 6G and the SDGs

In the development of standards for new generations of mobile communications, it is imperative to consider not only established requirements like spectrum efficiency, energy consumption, cost, and latency but also global challenges such as pandemics, climate changes, social inequalities, and skepticism in democracy. According to ref. [12], every facet impacting the current global economic, societal, and political agendas necessitates an extended and sustainable digitisation process across the global economy and society. Empowered by upcoming and transformative digital technologies, wireless networks are a pivotal facilitator for driving this profound transformation.

In 2015, it officially came into force the 17 SDGs released by the United Nations to achieve a better future for all, including important challenges as shown in **Figure 1**.

Due to the fact that 6G and SDGs are both targeted for 2030, the research community around the world is focused on covering as much as possible the SDGs including them in potential use cases for 6G. In accordance with ref. [15], when contemplating the advancement of 6G and mobile communication technology, it is crucial to bear in mind that the technology's development should prioritize sustainability and its subsequent usage should also align with sustainable practices.

A summary of the SDGs targets regarding 6G are categorized as follows:

- **Environmental Sustainability: SDGs 6,13,14, and 15 6G technologies must be capable enough to preserve and use natural resources like air, water, life, and land in a sustainable manner as well as preserving all natural life forms.** This demands managing issues like climate change, deforestation, water pollution, and loss of biodiversity.
- **Economic Sustainability: SDGs 8,9,10 and 12 Economic Sustainability through 6G refers to creating productive employment for the masses, leading to innovative industrialization and infrastructural development.** Moreover, it would promote higher resource consumption. An economically strong world would bring countries closer together.
- **Social Sustainability: SDGs 1,2,3,4,5,7,11, and 16 life for human beings**. This would involve achieving ample food, peace, prosperity, clean energy, quality education and a sustainable community for everyone.

Lastly, SDG 17 would aim bring all goals together to achieve overall sustainability through 6G. Moreover, these SDGs are also related and play a crucial to impact each other. SDGs like quality education and good health would promote gender equality and help in building a society of peace and justice. Similarly, protecting and mindfully consuming natural resources would impact greater quality of life achieving goals of zero hunger and sustainable cities and societies. Altogether, investment in innovation and infrastructure would advance economic growth in a sustainable way.

3.1.3. Overview of 6G Architecture

Based on what 6G is expected to be, a new architecture is necessary. In essence, 6G represents a convergence of technological

Figure 1. United Nations' Sustainable Development Goals.[12]

advancements that will redefine how we interact with the world around us. It holds the potential to create a more interconnected, intelligent, and inclusive global society, where the boundaries between the human, physical, and digital dimensions blur, ushering in a new era of innovation and possibilities: immersive experiences, ubiquitous connectivity, human-machine interaction, digital twins, healthcare and well-being, security, and privacy, etc. **Figure 2** depicts the vision of 6G networks. Figure 3 encapsulates the evolving vision of 6G as constructed by collaborative efforts between the research community and prominent corporations.

From an architectural perspective, the authors in ref. [16] effectively summarize various design objectives, such as:

Specialization encompasses tailored features and functions, subnetworks, and advanced networking capabilities.

Programmability involves using micro-services, cloud-agnostic approaches, and programmable hardware to enhance system adaptability.

Flexibility pertains to function placement, scalability, and network topologies, which should be adaptable and versatile.

Simplification and Sustainability aim to minimize the number of protocols, simplify interfaces, and embrace automation to enhance system efficiency and longevity.

Cloud Platform encloses the choices between public, private, or hybrid cloud platforms and their deployment at various levels, including on-premises, at the edge, metro, or core, often with acceleration technologies.

Robustness and Security include ensuring full network coverage, establishing multiple connections, fostering trust, enhancing privacy, and fortifying network resiliency.

Furthermore, the architecture of this new network paradigm is expected to present the technical enablers in a layered structure composed of infrastructure and cloud layer, network service layer and application layer. **Figure 3** shows a general scheme by Hexa-X in its most recent deliverable.[12] The infrastructure and cloud layer encompasses a cluster of technological enablers collaborating harmoniously to underpin the ultra-high-speed, dependable, and fortified communication network. At its essence, this layer encloses a mesh of interlinked devices surrounding Internet of Things (IoT) and User Equipment (UE) devices, base stations, small and macro cells, access points, cloud infrastructure, and more. This intricate web of diverse entities forms the pivotal framework of the 6G network, responsible for facilitating the seamless data flow across the network. Moreover, this layer supplies the physical resources essential for accommodating network services, cloud applications, and application layer components.

The network service layer is responsible for delivering many services to end-users. Likewise, this layer encompasses network functions and their associated services utilized within the network but remain concealed from end-users. This layer assumes a key role in ensuring that users gain access to services that are not only high-quality but also reliable and secure. Beyond conventional services like communication, the 6G architectural framework demands a diverse array of novel services encompassing AI, computing, analysis, data collection, localization, and sensing. The 6G architecture can advance toward a more adaptable, intelligent, and efficient design by implementing all network functions, operations, and services as cloud-native micro services. Future network management and orchestration are moving toward full automation and closed-loop control, a trajectory supported by the simultaneous integration AI and ML advances. And more ambitiously, there is also QC. Finally, the top layer is the application layer, which interacts directly with end-user applications, facilitating the exchange of data and information.

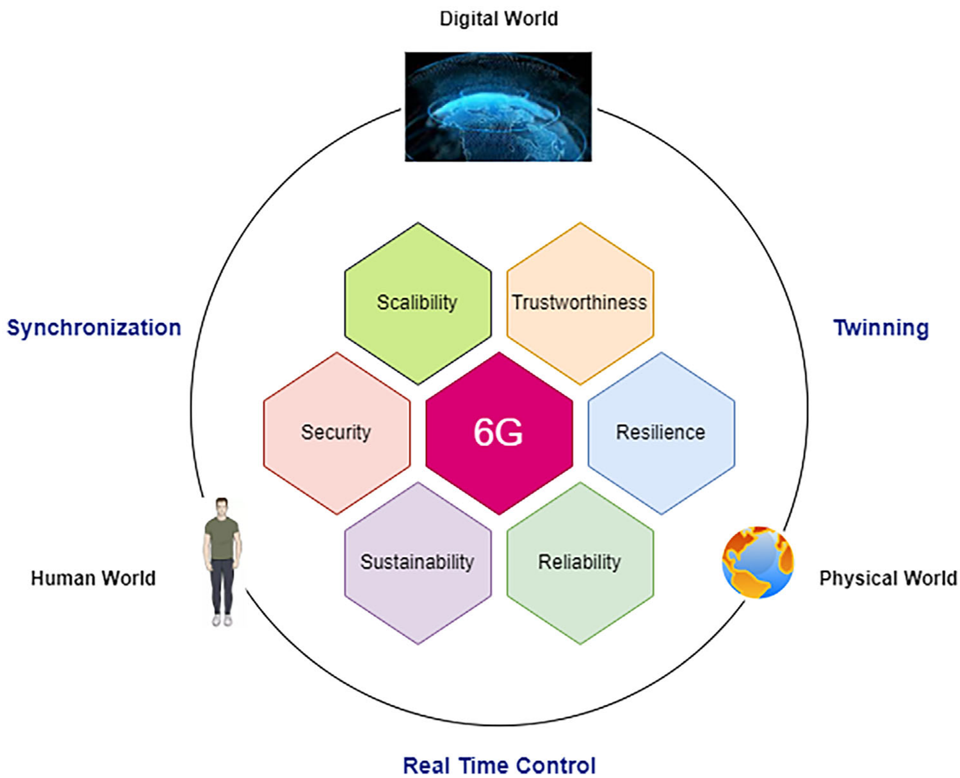

Figure 2. An overview of 6G KPIs and KVIs while bridging the gap between digital, human, and physical world.[12]

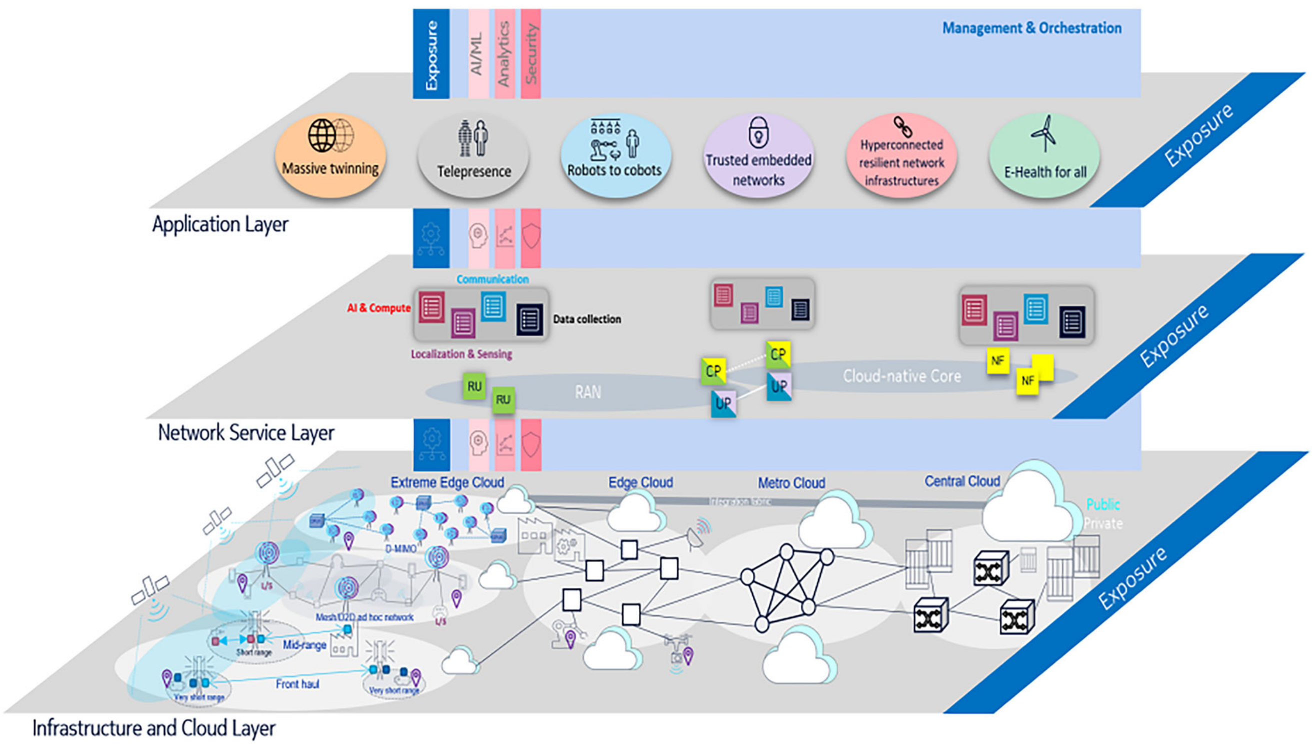

Figure 3. Hexa-x E2E architecture.[12]

4. Current Status of Quantum Computing

QC harnesses quantum mechanics to outperform traditional computational methods, particularly in simulating complex quantum systems. In contrast to conventional classical computers, which employ bits to represent data as 0 or 1, quantum computers utilize quantum bits, or qubits. Qubits can simultaneously exist in a superposition of both 0 and 1 states, constituting a linear combination of these fundamental states:[17]

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{1}$$

where α and β are complex numbers. The measurement of a qubit in a superposition state results in a collapse to one of its basis states ($|0\rangle$ or $|1\rangle$). The probability of obtaining $|0\rangle$ or $|1\rangle$ as the measurement outcome is determined by $|\alpha|^2$ and $|\beta|^2$, respectively.

The capacity of qubits to exist in multiple states simultaneously, termed superposition, empowers quantum computers to simultaneously explore numerous potential solutions to a problem. Quantum parallelism, a fundamental aspect of QC, facilitates the simultaneous exploration of extensive solution spaces, presenting the potential for more efficient solutions to complex problems compared to classical computers. Additionally, the phenomenon of entanglement interconnects the states of multiple qubits, creating correlations where changes in one qubit instantaneously influence others, regardless of their physical separation. This property is harnessed in quantum algorithms to efficiently execute complex calculations.

QC holds the potential to revolutionize diverse fields, generating global interest across disciplines such as cryptography, optimization, drug discovery, material science, and machine learning. The realm of wireless communications, particularly in the context of upcoming technologies like 6G and beyond, is also catching the attention of QC enthusiasts. However, the advancement of quantum computers demands formidable efforts to surmount a spectrum of technical, theoretical, and practical challenges. The susceptibility of qubits to external influences leading to the loss of quantum properties, known as decoherence, poses a significant obstacle. Developing error correction codes to counteract noise impact in quantum devices is a formidable task, and their implementation in quantum hardware further intensifies the challenge. Establishing and sustaining the physical infrastructure for QC, encompassing intricate cooling systems operating at extremely low temperatures, presents a substantial technical hurdle, accompanied by a notable environmental impact due to the energy required for temperature support.

4.1. Quantum Computing Technologies

The foundational bedrock of any quantum computer lies in its qubits. Beyond merely preserving quantum properties, these qubits must also be accessible for quantum manipulations.[18] The various types of qubits, shedding light on their intrinsic properties and practical implications, are presented bellow.

At the highest echelon of qubit classification, qubits bifurcate into two distinct categories:

- **Stationary Qubits**: As the nomenclature suggests, these qubits remain relatively static during operations. This category envelops diverse qubits, including trapped ions, cold atoms, electron spins, and superconducting loops.
- **Flying Qubits**: Typically embodied by photons, these qubits are dynamic, transmitting quantum information over varying distances.

4.1.1. Stationary Qubits:

Trapped Ions: Individual ions (atoms with a net charge) are confined using electromagnetic fields. Their quantum states are delicately manipulated using targeted laser beams.[19] Companies such as IonQ and Honeywell are pioneering advancements using trapped ion qubits, largely due to their prolonged coherence times.

Cold Atoms: These are atoms that are cooled down to near-absolute zero temperatures, enabling more controlled quantum operations due to reduced thermal noise.[20]

Electron Spins: By isolating and manipulating the intrinsic spin of electrons, quantum information can be encoded and processed.[21] The advantage here is the fine-grained control achievable at atomic levels.

Superconducting Loops: These qubits, based on Josephson junctions, exploit the quantum superposition of current flow in a loop of superconducting material.[22] Companies like IBM and Google are actively harnessing this technology for quantum computational purposes.

4.1.2. Flying Qubits

Photonic Qubits: At the heart of quantum communication lies the photon. As carriers of quantum information over vast distances, photonic qubits are central to endeavors like Quantum Key Distribution (QKD) and quantum teleportation.[23]

4.1.3. Classification of Quantum Computing Systems

Beyond the foundational qubit types, quantum computing expands into various modalities:

- **Analog Quantum Computers**: Here, continuous quantum variables drive computations rather than discrete states. They are particularly potent for specific tasks like quantum simulations.[24] Other key feature is quantum annealers, use continuous variables to explore solution spaces for optimization problems (D-Wave systems). Quantum annealing involves gradually transitioning the system to its ground state to find optimal solutions. Additionally, some implementations of analog quantum computers involve utilizing quantum harmonic oscillators, which exhibit continuous quantum states.
- **Digital Quantum Computers**: These are more general-purpose (IBM systems), leveraging gate-based quantum operations akin to the classical logic gates.[25] They are capable of executing all quantum algorithms.
- **Quantum-inspired Algorithms**: These are computational approaches that draw inspiration from principles found in QC,

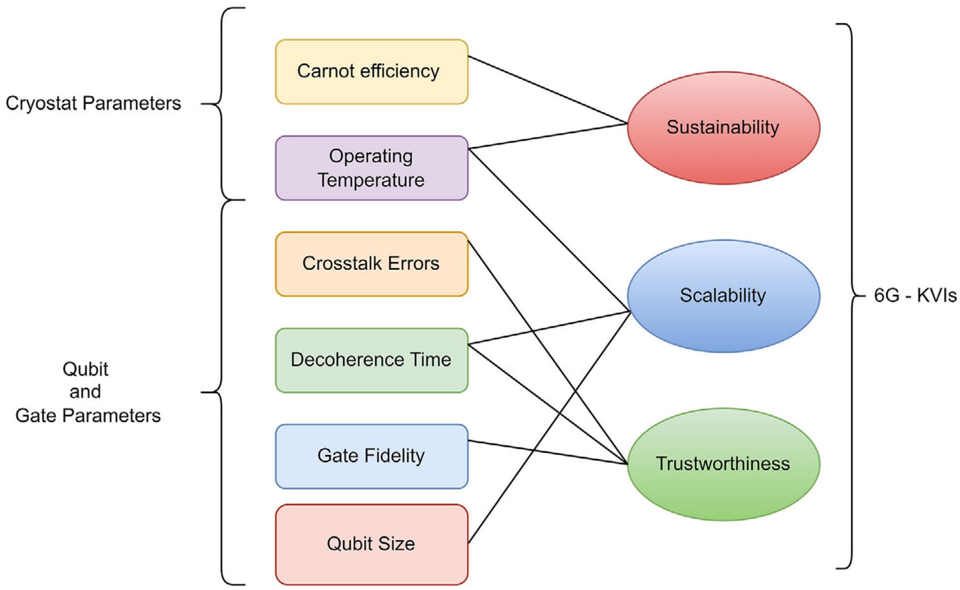

Figure 4. A diagrammatic representation of connection of 6G KVIs with specific parameters of quantum computing

even though they are executed on classical hardware. While these algorithms do not harness the full power of quantum parallelism or superposition, they leverage certain quantum-like concepts to potentially offer advantages over classical algorithms in specific problem domains, for example in ref. [26].

- **Quantum Emulators**: A bridge between classical and quantum realms, these tools emulate quantum algorithms on traditional computers, with scalability being a function of the emulated qubit count.[27]

5. Discussion on 6G KVIs Related to Quantum Computing

The integration of 6G and QC represents a transformative shift in communication technologies, promising enhanced security, optimized network operations, and the exploration of novel applications that leverage the unique capabilities of quantum computers. This convergence is poised to shape the future landscape of telecommunications and computing. The fundamental pillars at the heart of 6G's vision lie sustainability, trustworthiness that implies security, resilience, reliability, and scalability or digital inclusion. In this section, we delve into the interaction of QC with these pillars, assessing their alignment, potential synergies, and challenges in their confluence. **Figure 4** summarizes the relationship between the main 6G KVIs and essential characteristics of current quantum computers on the left.

Most of the qubits to maintain the properties of quantum physics, such as superposition, entanglement, and others, they must be isolated from the outside environment to preserve their coherence, as well as a very low temperature. Cryogenics, the branch of physics and engineering that deals with the production, behavior, and effects of materials at very low temperatures, typically below -150 degrees Celsius (-238 degrees Fahrenheit) or even colder, plays a critical role in achieving and maintaining these conditions. This technology finds widespread use in the majority of qubits, with the most exacting applications being for superconducting qubits, which require an operating temperature as low as 15 millikelvin (mK).[28] In contrast to photon qubits that require lightweight cryogenics operating at 4 to 10K for their photon sources and detectors. Specifically to work with quantum systems at cold temperatures, cryostats are used to control the cryogenic conditions for the storage and operation of trapped ions and superconducting qubits. The term 'cryostat' refers to a container that hosts devices or liquids at low temperatures. These temperatures are well below those found on Earth, typically lower than 120K. The performance of a cryostat is defined by its Carnot efficiency, which is referred to as the maximal thermal efficiency the cryostat can achieve, and it has a pivotal role in impacting sustainability and scalability on 6G. On the other hand, in terms of qubits and quantum gates, parameters to consider would be cross-talk errors, which refer to unwanted interactions or interference between qubits that can lead to errors in quantum computations. Decoherence time is the characteristic time scale over which a quantum system, particularly qubits in a quantum computer, retains its coherence before environmental interactions cause decoherence. Gate fidelity in quantum computing denotes the precision and dependability with which a quantum gate executes a particular quantum operation.

5.1. Sustainability and Energy Efficacy in 6G and Quantum Regimes

Sustainability, an imperative of the modern technological epoch, sits at the confluence of two game-changing frontiers: QC and the upcoming 6G wireless communication systems. While the Information and Communications Technology (ICT) sector, encompassing mobile infrastructure, radio access technology, data centres, and devices, have striven for decades to curtail energy usage per computational task and network data, the substantial demands of the digital economy necessitate even more significant computational resources, expanded connectivity, and increased bandwidth, resulting in heightened network traffic loads. Consequently, the overall energy consumption within the ICT sector continues to ascend. According to ref. [29], the evolution of 6G technology and beyond is, therefore, poised to be significantly impacted and propelled by distinct environmental sustainability paradigms, encompassing the decarbonization of energy generation and operational procedures, the adoption of circular economy principles, conscientious product design, utilization of sustainable materials, and the systematic recycling of equipment, among other facets. Thus, the transcendence of 6G hinges on its commitment to drastic energy conservation and intelligent resource optimization,[9] thereby ushering in a new era of ecological cognizance in communication architectures.

Certain propositions within the literature have already regarded the forthcoming iteration of mobile communications as a prospective avenue for augmenting and ameliorating the sustainability prospects of the world's future. Indeed, a conceptual framework for 6G communication has been proffered in ref. [30], with a specific emphasis on optimizing energy efficiency. Besides,[31] reflects that the undeniable strength of the interplay between mobile networks and Renewable Energy Sources (RES) stems from their mutually advantageous relationship, which fosters sustainability and technological progress.

However, a substantial body of research pertaining to the KPIs and attributes anticipated in 6G, mentioned in Section 3, predominantly centers on the attainment of superior connectivity, vastly accelerated data processing capabilities, and the integration of cutting-edge technologies such as AI, ML, and Neural Networks (NN). It is worth noting that all these advancements, encompassing computational augmentation within communication networks, are poised to engender heightened energy consumption. Aditionally, numerous compelling articles have explored the realm of QC, elucidating its multifaceted benefits that hold promise for future technologies. Evidently, within the domain of mobile communication networks, QC is hovered to assume a critical role in enhancing processing capabilities and accelerating information transfer speeds. MIMO and Non-Orthogonal Multiple Access (NOMA), which are key technologies from 5G and beyond have been raised in refs. [4] and [32] using QC to solve power allocation optimization and user pairing problems. Multi-objective routing optimization using Quantum Approximate Optimization Algorithm (QAOA) is presented in ref. [33], and many others.

Quantum computers promise computational capacities beyond the realms conceivable by classical paradigms.[17] For a perspective, a classical system tasked with factoring a large integer might toil for ages; a quantum system employing Shor's algorithm accomplishes the same feat in mere fractions of that time, leading to reductions in energy expenditures and bolstering operational efficiency.[34] Despite this computational advantages, QC will require substantial amount of resources in terms of energy consumption depending on the number and type of qubits used. To illustrate, establishing quantum data centers capable of handling resources on the order of 10^6 qubits, incorporating various gate implementations and measurement operations, addresses the requirements of 6G applications like smart cities or AI-assisted Vehicle-to-everything (V2X), will consume significantly more energy in contrast to the 53-qubit machine employed recently for sampling the output of a pseudorandom quantum circuit. To verify this straightforward example, in ref. [35], the authors define a relation between the total power load that scale as some power a of the number of physical qubits in a computer:

$$P_c \propto (n_p)^a \tag{2}$$

In this regard, while quantum computers have not yet achieved sustainability, evaluating particular parameters, as outlined in Figure 4, offers the potential for enhancing the energy efficiency of these systems. For example, some arguments are exposed in ref. [35]: The type of qubit chosen significantly influences the overall energy consumption. For instance, the Carnot efficiency of a system operating at the $4K$ temperature of trapped-ion qubits exceeds the Carnot efficiency of a system operating at the 10 mK temperature required by certain superconducting qubits by more than 400 times. Even slight increases in the operating temperatures for superconducting qubits are likely to result in significant improvements in energy efficiency. Although quantifying the impact of relocating electronics from the cryostat is challenging due to potential variations in electronics power consumption, cryostat size, and heat dissipation through interconnects, the substantial cost associated with cooling at low temperatures emphasizes the critical nature of this decision in minimizing energy consumption. Lastly, reducing the physical size of electronics, even if the power usage remains constant, will help minimize the cooling power necessary. Moreover, the other approach involves lowering the energy expenses associated with cooling quantum temperatures. In traditional data center operations, past instances demonstrate that meticulous engineering design and integration efforts aimed at decreasing non-computing energy costs can result in reducing Power Usage Effectiveness (PUE) from 1.60 to 1.02. This decrease equates to a thirty fold reduction in non-computational energy expenditures.

Additionally, in ref. [1], the author argues that the deployment of quantum technologies urgently calls for the creation and structuring of a quantum energy initiative through an important question: "Is there an energetic quantum advantage?" It emphasizes the importance of considering factors such as qubit type and operating temperatures in quantum computing systems to enhance energy efficiency. The article also highlights the significance of reducing cooling costs for quantum temperatures and draws parallels with energy-saving strategies employed in conventional data centers. Overall, the piece underscores the need for a comprehensive approach to address the energy implications of advancing quantum technologies. Thus, a brief summary of the worldwide resources required for constructing a quantum computer and explore how these needs might translate into an energy cost is provided.

From other perspective, the use of QC could contribute to sustainable 6G. For example, by leveraging quantum algorithms, 6G networks could optimize resource utilization and reduce energy consumption, contributing to a more sustainable and environmentally friendly communication infrastructure. Quantum algorithms could be also applied to optimize the design and configuration of communication networks, leading to more efficient use of resources and reduced environmental impact. QC's ability to simulate complex systems could be valuable in designing and testing advanced communication protocols and network architectures for 6G. This could streamline the development process, reducing the need for extensive physical testing and iterations. However, the practical implementations will depend on the development of mature quantum technologies.

We find ourselves at a juncture where the principles of QC have the potential not only to markedly enhance the processing capabilities of upcoming communication networks but also to play a pivotal role in establishing sustainable network infrastructures. Nonetheless, realizing these benefits requires awareness regarding the energy consumption of current devices, urging the development of more efficient and sustainable devices for the future. At this juncture, the impact of QC remains uncertain — it may usher in improvements or incur such high usage costs that prompt a reevaluation of its utility.

5.2. Scalability: Quantum Computing for Intelligent Orchestration

Scalability plays a crucial role in 6G as it is intricately connected to digital inclusion, a key aspect of future wireless communication networks. Digital inclusion refers to ensuring that all individuals and communities, including those in remote or underserved areas, have access to and benefit from digital technologies and services. Scalability denotes the system's capacity to effectively manage expansion and heightened requirements arising from the growing numbers of users, devices, and applications. Both are integral to creating a 6G ecosystem that is not only technologically advanced but also inclusive and capable of serving diverse user needs. Balancing these aspects is essential for successfully deploying and adopting 6G networks worldwide. Within [12] the concept of key-value inclusion pertains to an individual or group's ability to utilize a service, encompassing the ease of access to that service. This concept incorporates technical considerations like network coverage (both spatial and temporal availability) as well as user-centric factors such as the availability and accessibility of the service for specific groups. This may involve innovative Human Machine Interfaces (HMIs) or interaction with robots. Consequently, "inclusion" is employed interchangeably with "digital inclusion."

6G's architectural blueprint foresees an intricate mesh of intelligent network orchestration bolstered by real-time data streams and adaptive management protocols. The potency of QC, with its inherent capability to process complex computations at unprecedented speeds, can be the linchpin in this elaborate setup.

In this sense, there are 6G use cases such as telepresence (remote work), earth monitor, and E-Health for all. Each of them stands to gain from the benefits of QC, provided there are sufficient qubits and less noisy systems, along with a low decoherence time to enable greater precision. However, the challenge is more significant when increasing the number of qubits in a quantum system, which also increases energy consumption due to the operating temperature they require, as mentioned above. On the other hand, the type of qubit or technology implemented also represents an essential factor. For example, trapped ions excel in qubit fidelity and connectivity, but presently, scaling beyond a hundred ions proves challenging, and the process is notably slow. In the case of superconducting qubits, its production of is relatively straightforward, leveraging semiconductor circuit fabrication techniques, even though certain materials, such as niobium and aluminum, differ from traditional semiconductor components. Despite this, this qubits operate at 15mK, a very low temperature and have many challenges dealing with scalability. The microwave RF generators are typically positioned outside the cryogenic enclosure of the quantum processor, resulting in a substantial amount of wiring, averaging about three to four cables per qubit. The control frequencies of qubits must be distinct and adjusted for adjacent qubits. The fidelity of these qubits is not considered best-in-class and appears to diminish as the number of qubits increases.[28] One more example is quantum dots electron spin that are developed with scalability in sight. The majority of them employ a configuration with two trapped electrons in a quantum well – one serving as the qubit and the other utilized for measurement purposes. These qubits are commonly produced using silicon-based complementary metal-oxide-semiconductor (CMOS) circuits. Facilitating easy miniaturization to below 100 nm, these qubits operate effectively at temperatures ranging from 100 mK to 1K, surpassing the temperature range of superconducting qubits. This extended temperature range permits the incorporation of more electronics around the chipset, enabling the generation of microwaves and other necessary electric signals for creating qubit gates and managing qubit readout. However, it is not one of the most used technologies, as with IBM's superconducting qubits. Finally, Photons represent the most prevalent form of flying qubits, and numerous implementation varieties exist. One particular type is grounded in a horizontal/vertical polarization observable. While the majority of these qubits operate at room temperature, it's noteworthy that the photon sources and their detectors typically require cooling to temperatures ranging between 4 and 10K. Although this is a cooling requirement, it is significantly less demanding than the extremely low temperatures of 15 mK for superconducting qubits.

Recent advancements in quantum research have brought potential solutions to the scalability challenge to light. However, achieving scalability in quantum computers is contingent upon several crucial parameters. Across various qubit technologies mentioned earlier, the size of a single qubit varies, ranging from 1 to 100 μm. Considering the number of operational qubits and the diversity of available technologies, scalability can span from hundreds to 10,000 qubits.[28]

Maintaining the decoherence time and managing the impact of noise becomes crucial as quantum systems scale. Such challenges pose a risk to measurement accuracy, a factor that should not be compromised in the pursuit of scalability. To uphold the performance of Quantum Computing (QC) algorithms in large-scale systems, establishing deeper qubit connectivity and enabling parallel operations is paramount.

5.3. Trustworthiness in Quantum-6G Convergence: A Theoretical Exploration

Trustworthiness in 6G refers to the reliability, security, and overall integrity of the new generation of wireless communication technology. Ensuring trustworthiness in 6G involves addressing various challenges related to privacy, data security, network resilience, and the prevention of cyber threats. This may include the development and implementation of robust encryption methods, secure authentication protocols, and measures to protect against emerging cybersecurity risks. The concept underscores the importance of establishing a trustworthy and secure foundation for the advanced communication technologies that will define the 6G era.

This prompts the consideration that QC is poised to play a crucial role in 6G communication networks, particularly in enhancing security through QKD. Converging future mobile communications with QC involves reconciling the strengths and weaknesses inherent in each technology. For 6G to benefit from the security and reliability advantages that QC offers, it is imperative to address potential conflicts that may arise, particularly in terms of sustainability and scalability. If the necessary scalability is not achieved to meet the multifaceted requirements of 6G, the path forward becomes less straightforward. In discussions about security, reliability, and resilience, it becomes essential to factor in the errors, operating temperature, and decoherence time associated with current quantum devices as it is shown in Figure 4. Establishing a balanced relationship among these elements is pivotal, considering key aspects to foster the advancement of quantum computers in a manner that aligns with the evolving demands of 6G technology.

5.3.1. Quantum Key Distribution (QKD): Beyond Classical Cryptography

Encryption techniques are at the heart of secure communication over open networks and are continuously evolving. Nevertheless, the prevailing encryption and digital signature algorithms currently in use rely on the idea that classical computers cannot efficiently solve prime factorization or discrete logarithm problems within a reasonable time frame. This assumption, however, is now being questioned due to the growing capabilities of quantum computers, which are anticipated to possess the required computational power in the coming decades. The ethereal realm of quantum mechanics unfurls a tantalizing tool for ultra-secure communications: QKD. Rooted in the principles of superposition and entanglement, QKD transcends classical cryptographic confines.

In classical cryptography, security often relies on computational hardness (e.g., difficulty factoring large numbers). But QKD, especially the BB84 protocol,[36] shifts this paradigm. Rather than relying on mathematical complexity, it harnesses the quantum behavior of particles. The Heisenberg Uncertainty Principle ensures that measuring a quantum system invariably disturbs it. This feature is the bedrock of QKD: an eavesdropper trying to intercept quantum keys would inevitably introduce detectable errors.

Thus, QKD offers ‘information-theoretic security’, a gold standard where security is not based on unproven computational assumptions but fundamental laws of physics.[37] For 6G, which envisions a globally connected, data-intensive ecosystem, incorporating QKD could set unprecedented benchmarks in communication security.

In the context of mobile networks, it was shown in ref. [38] that QKD can provide sufficiently high key generation rates. In an indoor environment, QKD was implemented assuming a mobile photon source. Power spectral density of photons and field of view of QKD receiver were shown to be significantly impacting the key generation between the parties.

However, for widespread adoption of QKD, several crucial challenges must be addressed, including secret key rate, distance, size, cost, and practical security. According to ref. [39], cooling is unnecessary for QKD as the authors present the analysis based on photon qubits implementations, and it is much less demanding. Nevertheless, the algorithm exposed in ref. [40] that uses Qiskit presents the main issues of superconducting qubits. The main problems of gate-based quantum computers, such as gate fidelity, decoherence time, and crosstalk errors, are worth highlighting.

5.3.2. Quantum Error Correction (QEC) and Reliability in 6G

Quantum systems, although poised to revolutionize computations, are inherently noisy. Their surroundings can easily perturb their states, leading to errors derailing quantum calculations. Enter Quantum Error Correction (QEC) – a theoretical framework to identify and rectify quantum errors without directly measuring (and hence destroying) the quantum information.[41] The crux of QEC is to encode a logical qubit into multiple physical qubits. The surface code, a leading error-correcting code, employs a 2D lattice of qubits where quantum states traverse, enabling the detection of errors by observing their trajectories without collapsing the quantum state.

As 6G targets reliability, embedding QEC becomes paramount. Imagine a 6G network leveraging quantum algorithms for optimization tasks. Quantum devices without robust QEC, noisy quantum results could cascade into network inefficiencies, making QEC desirable and essential for reliable quantum-6G operations.

Yet again, we find ourselves in a dilemma concerning the energy consumption of quantum computers. Increasing the number of qubits necessitates a greater amount of resources to sustain their coherence. Moreover, qubits and gates have a limited time period during which they maintain purity and desired performance. The decoherence time for qubits is much greater compared to gate operation time. Hence, while designing circuits for QEC the estimated gate count should not be very large. Otherwise, the qubits may dephase by the time the measurement occurs for the system.

5.3.3. Quantum System Resilience: From Fragility to Fortitude

While quantum systems offer unmatched computational might, they are intrinsically delicate. They require isolation from external influences, and any minor perturbation can lead to decoherence, erasing the stored quantum information. Resilience in quantum systems, therefore, becomes a multifaceted challenge. At the hardware level, it involves creating designs like superconducting qubits or ion traps that can maintain coherence over more extended periods. Concurrently, it demands rapid error identification and mitigation strategies at the software and algorithmic level. The entire ecosystem must be orchestrated to recover swiftly from disruptions, hardware failures like cryostat malfunctions or external radioactive interference.[42]

Various concerns surrounding QC can impact the resilience of 6G networks. The need for significant energy and cost in deploying quantum hardware raises the prospect of cloud-based QC services as a viable means to provide widespread access. However, relying on cloud services introduces security challenges, with the potential for malicious entities to exploit vulnerabilities by assigning substandard hardware or reporting inaccurate error rates. The use of third-party compilers becomes essential for optimizing quantum circuits by enhancing depth and reducing gate count. However, if these third parties are not trustworthy, there is a risk of circuit cloning or extracting critical elements, posing potential security, and resilience issues. These concerns may manifest in resilience issues related to crosstalk errors within circuits, highlighting the importance of addressing security and trustworthiness at multiple levels when integrating QC into 6G networks.

6. Conclusion

The intersection of QC and 6G is a vibrant fusion of possibilities and challenges. While the hurdles, especially in aligning QC with 6G's KPIs, are substantial, they are not insurmountable. With rigorous research, collaboration, and innovation, combining quantum mechanics and 6G can redefine wireless communication's future, transforming how we connect, compute, and communicate.

From this perspective, this work has aimed to encompass the envisaged landscape of upcoming 6G technology as outlined in the existing literature. We have explored its role in advancing SDGs, dissected its architectural facets, and contemplated the integration of QC into the future of mobile communications. Throughout this exploration, we have highlighted the benefits while acknowledging potential limitations stemming from current QC technology demands and its impact on 6G KVIs.

While quantum mechanics offers a compelling vista of possibilities, realizing them necessitates overcoming significant challenges. Qubits are susceptible to external disturbances, leading to decoherence. Maintaining most of quantum states requires cryogenic temperatures, an energy-intensive process that seems counter intuitive to 6G's sustainability goals.[43] Moreover, QEC, vital for reliable quantum computations, is still developing and demands extensive research.[44]

Taking this into account, most of the time, only the benefits are talked about, and little is said about the main problems of quantum systems. The need to consider them and investigate possible solutions is increasing. That has been the main objective of this work.

Acknowledgements

6G-life: The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the programme of "Souverän. Digital. Vernetzt.". Joint project 6G-life, project identification number: 16KISK001K. **CeTI**: Funded by the German Research Foundation (DFG, Deutsche Forschungsgemeinschaft) as part of Germany's Excellence Strategy – EXC 2050/1 – Project ID 390696704 – Cluster of Excellence "Centre for Tactile Internet with Human-in-the-Loop" (CeTI) of Technische Universität Dresden. **UPV**: The research was founded by the Research and Development Grants Program (PAID-01-20) of the Universitat Politècnica de València. The research stay of the author at Technische Universität Dresden (Germany) was founded by the Program of Grants for student mobility of doctoral students at the Universitat Politècnica de València in 2022 from Spain, and by Erasmus+ Student Mobility for Traineeship 2023.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Keywords

6G, quantum computing, sustainable development goals, wireless communication

Received: September 29, 2023
Revised: January 29, 2024
Published online: March 10, 2024

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