

Quantum Computing based Channel and Signal Modeling for 6G Wireless System

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Abstract— Sixth-generation wireless technology (6G) introduces a paradigm shift and fundamental transformation of digital wireless connectivity by converging pillars of softwareization, virtualization, and wireless networks. Terahertz (THz) communication technologies are predicted to become more significant in 6G applications as the requirement for bandwidth grows and wireless cell sizes shrink. As a result, 6G will be able to deal with and manage numerous devices and services requiring enhanced spectral throughput and efficiently work with high interference levels. This convergence highlights the increased threat surface of 6G networks and the potentially severe impacts of sophisticated cyber incidents. Furthermore, the heterogeneity of connected devices and provided services will generate a huge amount of data to be processed and managed efficiently. Quantum computing (QC) can efficiently solve several 6G computationally hard problems with a quadratic speedup and provide adaptive techniques for controlling the current and future significant security threats of the 6G network. This article will discuss the role of various QC components on 6G and explore the opportunities and challenges to achieving such transformation.

I. INTRODUCTION

The 6G is expected to utilize the upper limits of the radio spectrum and support 1 Tbps speed and will bring down the communication latency to one microsecond, which is 1000 times faster than 5G latency. 6G will have the opportunity to extend wireless solutions into almost every facet of human-machine interaction and enable much of our critical infrastructures, emergency networks, industrial and automation networks, and support the ever-increasing mobile internet of things footprint [1]. The complexity of 6G architecture will experience major issues such as privacy, scalability, decision-making and performance. Solving 6G problems will require substantial computations and data analytics that are too expensive and require a high processing time to perform on classical computers. Furthermore, the security and privacy of 6G will be typically based on the assumption of computational security (prime integer factorization) or solving a complex satisfiability problem (discrete logarithm calculation) [2].

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Quantum computers are designed based on the laws of quantum mechanics, such as superposition and entanglement. The common model for realizing quantum algorithms is the gate model, where the algorithms are implemented as a series of unitary transformations which influences each component of the superposition concurrently. As a result, it produces considerable parallel data processing, reducing execution time and solving complex computational problems faster and more effectively than the classical system [3]. For example, quantum algorithms such as Grover can solve the unstructured search problem with a quadratic speedup. Shor's algorithm can factorize large integers exponentially faster than classical algorithms. In addition, quantum cryptographic algorithms (QCA) proved that an intruder couldn't obtain any information from transmitted qubits between communicating parties without disrupting their status [4]. A critical characteristics of THz communication for 6G is obtaining the highest levels of practical security over a long distance and with various types of attacks. Unfortunately, the development of quantum technology will allow the decryption of secured data by classical algorithms, which influence the 6G security infrastructure. Therefore, it is expected that QC will improve abilities and performances not yet achieved by classical methods for various 6G tasks. These improvements could include computing speed, ensured security, and minimum storage criteria [5].

This article overviews the opportunities and advantages for integrating four main quantum components: quantum machine learning, quantum algorithms, quantum blockchain, and quantum communication and cryptography. Furthermore, the transition timeline towards a fully 6G-Quantum network and the associated technological challenges are discussed.

II. QUANTUM MACHINE LEARNING (QML)

QC will play an important role in the performance and security of 6G, as shown in Fig.1. QML depends on quantum mechanics and machine learning laws, which provides a more powerful approach than classical machine learning [6]. Therefore, QML algorithms have a pivotal function for various applications towards next-generation networks communication and security, as illustrated in Fig.2.

A. Quantum Supervised learning (QSL)

QSL is used for solving nature problems based on quantum algorithms such as quantum support vector machines (QSVM). QSL can integrate with 6G and directly affect the

efficiency and performance of various 6G tasks, such as optimal Prediction of path loss in mm-wave schemes, Prediction of optimal function for network parameters and power allocation, allocation of bandwidth dynamically and improvement of latency performance. Additionally, it will be used for the Prediction of the requirements of users/devices in high-dynamic unmanned aerial vehicle (UAV) architectures, Prediction of transmit power and transmitter's beamforming schemes in multiple input single output channels, detection and classification of malware traffic and global positioning system spoofing signals and jamming and intrusion attacks in UAV systems. Furthermore, quantum sparse supervised learning can optimize the represented sparse features for 6G wireless and underwater acoustic communication [6].

B. Quantum Unsupervised learning (QUL)

The number of IoT and intelligent devices will be much more connected in a complex way in the 6G network, which will lead to various problems such as routing, security, and transmission. The main task of QUL is clustering, dimensionality reduction and data estimation. Moreover, QUL subroutines enhance the performance and maintain at least the exponential quantum speed up like QSL [6]. Therefore, QUL will provide cost-efficient 6G communication protocols by solving, for example, the problem of user selection and reaching the optimized required power, optimization of device-to-device (D2D) resource allocation and throughput, prediction and detection of root cause and fault of network components and optimization of radio resources and spectrum sensing for radio frequency (RF) and THz systems. Also, QUL will improve the security specifications of the 6G network by controlling traffic, detecting intrusion and anomaly attacks, fraud detection, improving the security of the physical layer, and source encoding/decoding operations.

C. Quantum Reinforcement learning (QRL)

The current classical RL algorithms have limitations for exploration strategy and slow learning speed with the exponential growth of parameters by raising dimensions. These limitations will affect the accuracy of decisions and required actions for various 6G applications providing routing, gaming, robotics operations and quality of service (QoS). QRL overcomes the previously mentioned limitations and efficiently increases the computation speed since it inherently employs quantum parallelism (function evaluates different values simultaneously at a certain point) and state superposition convention [6]. In the expectation of 6G communication techniques, QRL will provide methods for optimal spectrum assignment and improving the sum rate for D2D systems, power selection and energy harvesting to minimize the probability of network outage, Proactive caching for optimal resource allocation and hit rate in multi-access edge computing and wireless networks. From the perspective of 6G security, QRL will enable the 6G to resist various attacks, such as jamming and detecting malicious behaviours among the communicated devices, especially in dynamic, intelligent

reflecting surface environments. Furthermore, QRL will provide automation, prediction, and accurate decisions against future 6G attacks.

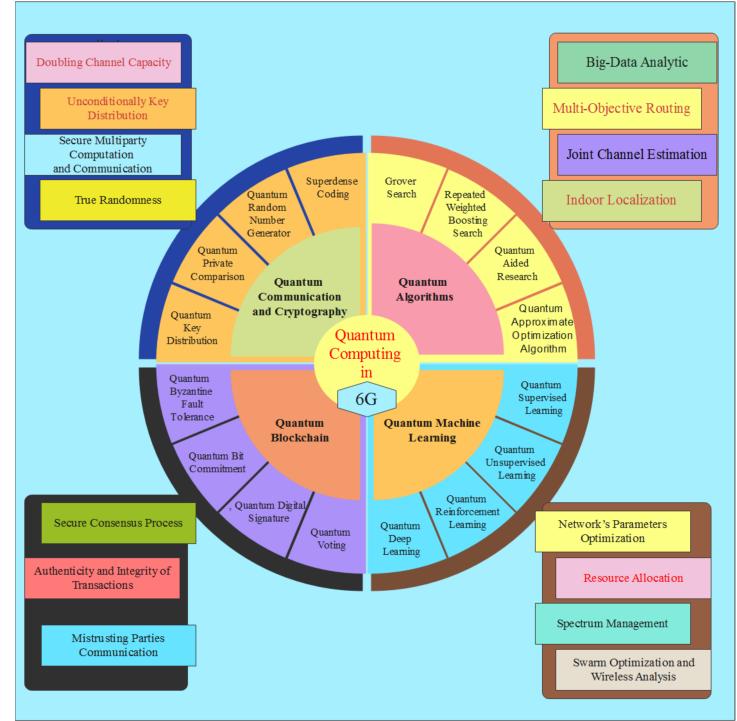


Fig. 1. A summarized QC component and their roles in 6G.

III. QUANTUM ALGORITHMS

Quantum algorithms can efficiently solve several 6G computationally hard problems with a quadratic speedup [9]. This will be sufficient to significantly improve provided 6G services such as indoor localization, as discussed below.

A. Indoor Localization

The problem for indoor localization depends on various complex parameters such as received/transmitted signal strength, time/angle of arrival, or difference or arrival time. The estimation and tracking the device's/user's location or movement accurately will enable the 6G to achieve the desired throughput. Therefore, the problem can be formulated as a search optimization problem on the database of these parameters. Unfortunately, the classical search algorithms will achieve the required optimal solution with high computational time complexity. Therefore, employing the quantum Grover search algorithm and its successors will have similar performance or higher with a quadratic speedup even when increasing the search database and the presence of noise. So, the quantum search can be integrated with 6G to solve the localization problem for various systems such as Visible Light Communication (VLC) and mm-Wave based with higher accuracy and less time. This will directly affect 6G applications, such as estimating the optimal location of UAV and increasing the data rate in a multiple-input/multiple-output environment.

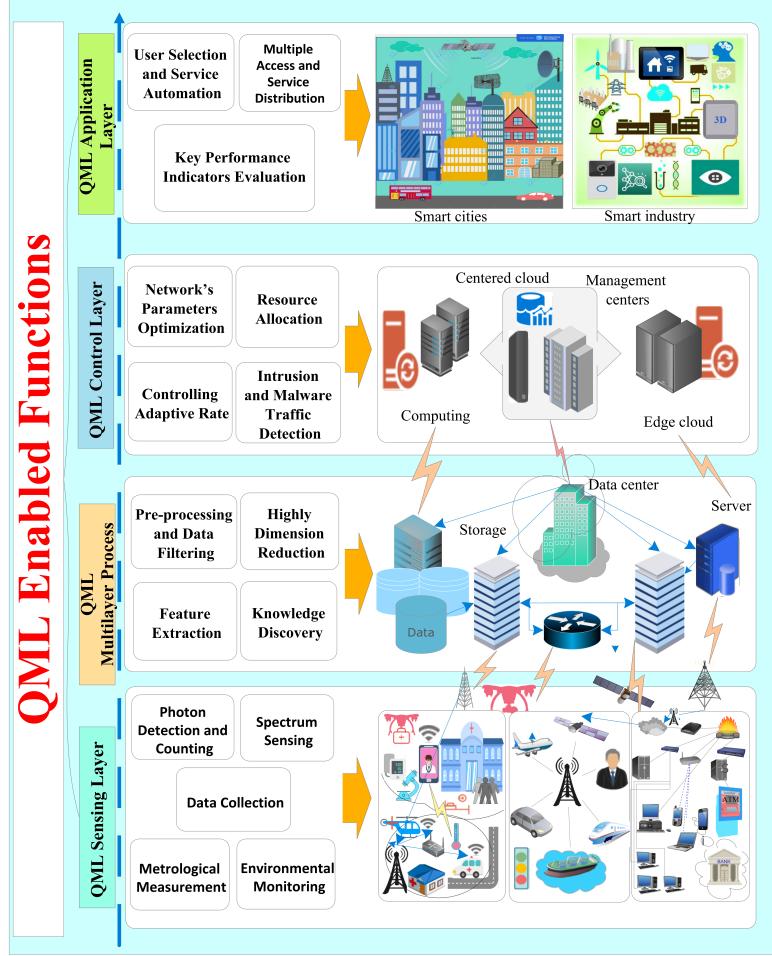


Fig. 2. QML enabled functions in 6G.

B. Joint Channel Estimation

The Joint Channel Estimation problem will be appeared in the uplink of multi-user 6G systems (with multi-antennas, Non-orthogonal multiple access (NOMA) or with multi-carrier, Orthogonal frequency-division multiplexing (OFDM)) since the joint channel has to be estimated accurately to prevent the influence of the channel when the signal reaches the base station. Therefore, various classical heuristic and evolutionary search algorithms have been proposed for searching the optimized parameters to estimate the joint channel. Unfortunately, the performance of these algorithms is low and with high computational complexity, which affect the operations of a multi-user network in 6G. So, integration of quantum heuristic or quantum repeated weighted boosting search algorithms with 6G will reduce the computational complexity and outperform its corresponding classical evolutionary algorithms for estimating the joint channel without decreasing the system's performance.

C. Multi-Objective Routing

The transmission of information among the communicated nodes in the 6G network will depend on various multi-hops

devices (used for routing purposes) such as antennas and base stations. Finding the optimal route with the desired QoS specifications and lowest cost is a major challenge for developing 6G since it requires precise optimization for several sensitive parameters such as bandwidth, location, and power. Unfortunately, the performance of classical multi-objective optimization algorithms degraded since they failed to converge to local optima. So, quantum aided search algorithms can solve the routing problem with reduced complexity, high performance, and less time. The best complexity to find the set of optimal routes for L routes is $O(L)$ since the quantum algorithms can work concurrently on several partitioned spaces.

D. Big-Data Analytic

6G will be a hybrid large-scale network that integrates various advanced devices and components. Therefore, a large amount of varied data must be analyzed efficiently to maximize the 6G performance and throughput. For example, quantum image processing algorithms can extract both strong and weak images with more feasible and efficient accuracy than classical algorithms. Furthermore, they can provide su-

perior segmentation with multiple levels that offer the highest correlation between the original and the segmented image. The problem for searching unstructured high-volume data and analyzing it can be solved by quantum search and QML algorithms with a higher speedup. Therefore, integrating quantum algorithms with 6G will improve the automation and decision-making sensitive applications such as intelligent transportation systems (Vehicle-to-vehicle (V2V), Vehicle-to-everything (V2X)) and smart healthcare.

IV. QUANTUM BLOCKCHAIN

The complexity of 6G architecture will experience major issues such as scalability, rolling out new services and private provision. Decentralization is one of the major advantages of the blockchain. By removing single points of failure, the blockchain can dramatically increase the resiliency of a 6G infrastructure. In addition, blockchain technology has several built-in features for 6G technology, providing important services such as access control, infrastructure scalability, and security [7]. These features will enhance the performance of 6G services, such as network slicing, spectrum and resource management, data sharing, and network virtualization. Furthermore, blockchain will provide various security advantages, from decentralization and transparency to secrecy and traceability without requiring any intermediaries, which will improve the security of 6G networks and the potential to develop the transformation of upcoming mobile service industries [11].

However, the key security algorithms of the blockchain (hashing and public-key digital signatures) rely on complicated mathematical computations, which have been proven theoretically and practically in their inability to provide complete security of information against internal, external and penetration attacks. Unfortunately, the security of the 6G Blockchain will be influenced by the progress of various quantum algorithms [8]. For example, the Grover search algorithm can solve the hash difficulty problem with a quadratic speedup, using the same idea for enhancing NP-complete problems by treating the hash function as a search oracle. This will possibly facilitate the few enabled quantum nodes to control the transmitted transactions and manage the appendage of blocks to the blockchain ledger. Furthermore, Shor's algorithm can break the security of public-key digital signatures for blockchain, implying that an adversary could fraudulently sign off on illegitimate transactions, thereby committing falsified contracts to the blockchain. Therefore, quantum blockchain is a mandatory component to enhance the security and provide services for 6G since the quantum protocols will prevent the key security threats for classical blockchain 6G services (see Table 1).

V. QUANTUM COMMUNICATION AND CRYPTOGRAPHY

The deployment of 6G will adapt the transmission of significant amounts of data in real-time with the expectation of increasing the capability of underlying physical infrastructure. Quantum communication can transfer large amounts of

data by utilizing the principle of superdense coding, thus reducing the traffic on 6G communication networks and doubling the 6G channel capacity [14]. Furthermore, it is prominent that quantum networking protocols can deal with the diverse network topologies that are likely to present themselves in the future real-world quantum internet. Unfortunately, the security of 6G will be compromised by current quantum algorithms and future quantum attacks. For example, a brute-force attack to retrieve the private key by a quantum computer can achieve a quadratic speedup by exploiting Grover's search algorithm. In the situation of a public key, Shor's algorithm can recover the private key from the public key by efficiently factorizing large integers with an exponential speedup compared to classical algorithms.

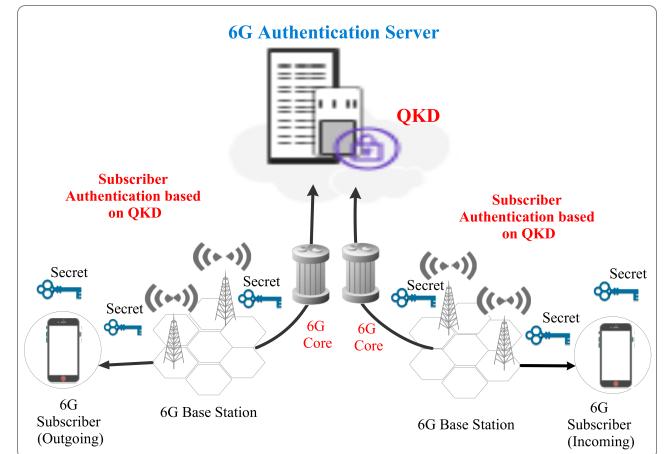


Fig. 3. An illustration of QKD as a service for 6G.

Therefore, quantum cryptographic protocols will enable private communication with perfect information-theoretic between 6G nodes over a freely available "public" channel, allowing provably secured sharing of confidential information over the 6G network. For example, QKD can be used as a service for a 6G network to generate and distribute unconditionally private keys to the various 6G cryptographic components, as illustrated in Fig.3. Furthermore, although the randomness deficiency will be a significant shortcoming for broad algorithms of 6G, QRNG can be used to obtain a true randomness source for 6G infrastructure. Also, quantum secure direct communication (QSDC) can transmit secret messages directly between the communicating nodes without additional classical communication protocols. Also, THz QKD has been demonstrated to achieve the requirements for securing users' privacy against collective attacks, and the required secret key rates have been achieved in the THz regime.

VI. TRANSITION TIMELINE

The expected timeline for developing and defining the 6G technology is about 10 years, and having a large-scale quantum computer capable of these speedups is predicted to be 5-10 years away. The industry must be prepared for that change, and 6G has enough time to prepare and secure

TABLE I
QUANTUM SOLUTIONS FOR BLOCKCHAIN ATTACKS.

Attack Type	Quantum Solution
51% Attack: • A group of attackers can control 51% or more of blockchain's computational resources and perform double-spend attacks.	• Quantum voting (Binary or Anonymous) hides ballots in phases within an entangled state that is unavailable to individual participants but is rather a state's global property.
Denial of Service Attacks/Distributed DOS (DOS/DDOS): • DOS/DDOS can flood the network with transactions, temporarily increase the computational power of a Proof of Work (PoW) or perform a traditional DoS attack against the next block creator on a Proof of Stake (PoS).	• Quantum digital signature can prevent transaction flooding by ensuring the validity and correctness of transactions. Also, quantum random number generation (QRNG) will provide true randomness for PoS consensus, which prevent Block Forger DoS attack.
Eclipse Attacks: • An attacker controls all node connections to the network, allowing the attacker to entirely manage the node's prospect of the distributed ledger and network processes.	• Quantum randomness will improve the probability that, if eclipsed, the attack will be short and detectable. • Quantum trusted nodes can be used as a safelist and always connect to at least one.
Replay Attacks: • An attacker takes an existing transaction and resubmits it to the blockchain like a new transaction. Since the original transaction was legitimate, the digital signature will be valid and acceptable to the blockchain, and the attacker gets paid twice.	• Quantum digital signature will prevent the attacker from copying and resubmitting the original transactions. • Quantum decoy-state can be included in each transaction, so if the attacker tried to change and replay it, the digital signature would be invalid and rejected by the network.
Routing Attacks: • Routing attacks target the underlying communications network used by the blockchain for peer-to-peer communications. If an attacker can control all the communications between two sets of nodes, they can partition the network.	• QML monitors the blockchain network statistics, and as attackers' rerouting and monitoring are likely to increase network latency significantly, QML detects routing attacks efficiently, timely, and accurately. • QCA provides encryption and authentication to ensure that an attacker cannot monitor and change the communications occurring between nodes. So, it will prevent the attacker from finding a way to split the network.
Sybil Attacks: • A Sybil attack occurs when an attacker creates many accounts on the blockchain network. Botnets, virtualization technology, or malware can be used to accomplish this attack.	• Quantum private communication will control and limit the attacker's ability to create accounts on the blockchain. • QML can detect malicious behaviour and fake accounts.
Privacy Leaks: • Blockchain technology uses public-key cryptography to protect the authenticity and integrity of transactions and blocks. However, public-key cryptography's security depends on the security of a user's private keys: anyone with a private key can decrypt messages and generate valid digital signatures on the user's behalf.	• Quantum key distribution (QKD) can generate and distribute unconditionally secure keys that allow the nodes to communicate and exchange transactions securely over the blockchain. Furthermore, it can be used as a source for the other various blockchain cryptographic algorithms.
Broken Authentication and Modification attacks: • Broken authentication could give an attacker control over the network's access controls, and the network may become non-functional or modify the data in transit.	• Quantum digital signature ensures that the transaction was actually generated by the sender and has not been modified in transit. • Quantum Identity authentication manages the communicated nodes' authentication, authorization, and identity.

by design for the quantum computing threats. The transition process can be achieved inexpensively; the problem is that it is not going to be just a simple plug and play to replace a new algorithm with an old one; each application will need to be analyzed to understand how it can be transitioned. Therefore, design 6G to adapt post-quantum cryptography and advantages of the new capabilities of quantum technologies require a long-term plan as in Fig.4.

A. Quantum Resistant Network

Implementing quantum-resistant schemes which are purely classical and can run on today's computer after being standardized by NIST will be the first step. However, this process will have a huge effect on 6G technology since it is not well understood how these algorithms will impact it, and the standardization migration process of these algorithms is complex [10].

B. Hybrid quantum-classical Network

It refers to a set of practices that integrate quantum and classical components into one framework to obtain quantum technology's promising advantages, as shown in Fig. 4. It includes approaches such as hybrid cryptography and hybrid quantum machine learning. The hybrid approach will require access to existing tested quantum devices (such as QRNG and QKD) and manipulating a few qubits.

C. Fully Quantum Network

Finally, the ultimate goal is to implement a large-scale fully quantum 6G fault-tolerant network which will require substantial infrastructure transformations across all 6G layers. Complex quantum devices (such as repeater, memory and quantum THz detectors) will be integrated, so all required 6G operations and solutions will be performed according to quantum information. Furthermore, when compared to conventional THz detectors, quantum THz detectors have higher detection sensitivity, faster response,

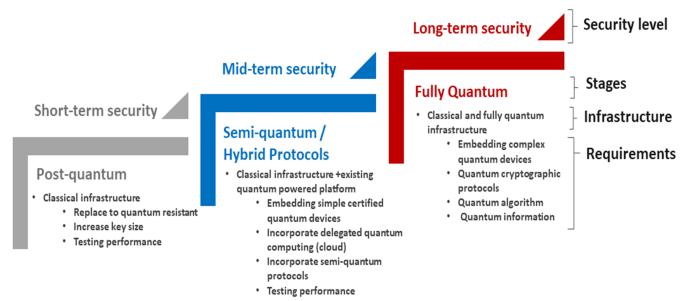


Fig. 4. The transition timeline toward a fully 6G-Quantum.

mature manufacture, smaller size, and easier integration. So, they will be well suitable for 6G high-speed exposure and imaging purposes. Nodes can additionally implement quantum computations, quantum-to-classical interfaces (i.e., measurements), quantum-to-quantum interfaces (i.e., switching data between different physical systems), quantum memories or any quantum process in general. Achieving the global quantum internet and perfect 6G-quantum satellite communication system is the main objective of this stage [15]. Fig.5 shows an example of the required process and operations to have a fully QSDC approach in vehicular commutation.

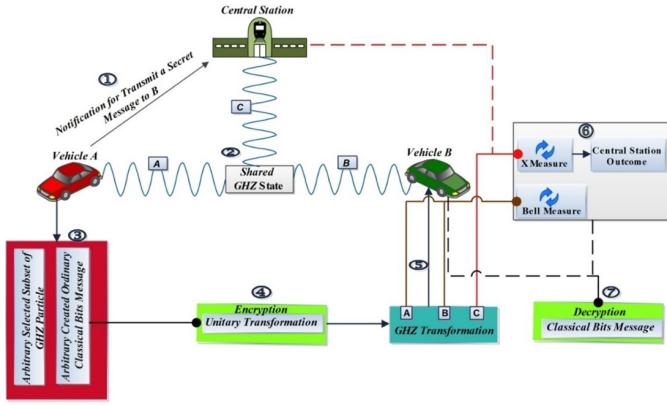


Fig. 5. An example of a fully QSDC approach in V2V commutation.

VII. CHALLENGES

A. Cost and Availability

Implementing quantum technology with 6G will require substantive modifications across the entire 6G infrastructure ranging from quantum state preparation and measurement to achieving a scalable quantum system with good enough processing power to utilize the quantum algorithms to its full performance. The quantum devices used to prepare, process, and measure quantum states are still in early stages, and quantum-based processors require extensive cooling systems to work efficiently. Furthermore, it can be difficult to control the prepared quantum states since they can be entangled with the surrounding environment and decohered very quickly. Therefore, it will be costly with constrained availability to reach a fully quantum-6G network during a few years [13].

B. Data Encryption Lifetime

It is a common requirement for 6G sensitive data with specifications to have acceptable encryption algorithms and security levels. When developing a 6G solution, it's necessary to consider whether it supports the necessary levels of encryption and whether data can be encrypted without impacting the functionality of the 6G. Longer-term, an organization needs to consider the required length of time the data must be encrypted. Any data added to a 6G should be encrypted at a level that ensure it will not be exposed for the length of time that the data remain sensitive.

C. Lack of Standardization

The development of quantum and 6G devices is still in the early stages and require significant certification and device characterization standards to work properly. Also, there is no clear standard or guidance about choosing the right and compatible quantum-resistant protocol to implement on 6G since no protocol fits all solutions. Some of them are very fast but have huge keys, and others have small keys but large ciphertext. So, the best strategy for transition to a 6G quantum-resistant world is to analyze each case and test the various protocols to achieve the proper one, which will leave the 6G at risk [12].

D. Hardware Requirements

A major concern for developing 6G-Quantum applications is the hardware requirement, and error mitigation levels are the advantages of speedup. Various 6G devices will not have the ability to handle the quantum operations since their power and processing capabilities are low. The absence of quantum devices such as repeater and memory will affect achieving the goal of quantum internet over a 6G network. Quantum repeater will retransmit the quantum information when there is no direct communication between the nodes over the 6G network, creating longer-distance links to extend the network's coverage. Furthermore, the probability of realizing THz quantum cryptographic communication over long-distance is restricted since the required hardware devices are less well-developed. Given that communications links in quantum networks are expected to be optical, an issue of central importance is optical stability when signals from remote sources interfere or interact with local quantum states. Similar observations apply to many other protocols involving entangling measurements or multiphoton interference.

E. Noisy Environment

The current quantum computers and devices are imperfect and experiencing technical difficulties, making it a major challenge to implement 6G-Quantum in the near term. In the case of noisy intermediate-scale quantum devices, hybrid quantum-classical algorithms to train a parameterized quantum circuit can be used due to its simplicity and hardware efficiency. Unfortunately, these algorithms are unsuitable for a large number of qubits because of the gradient estimation complexity and the exponential dimension of the Hilbert space. Therefore, the 6G network will require a large number of qubits to process the various operations and achieve the intended objectives effectively. Moreover, the generated number of stable qubits is still insufficient to satisfy the scalability requirement since most of these qubits will be used to manage and correct the induced error of the quantum components.

F. Linearity of Quantum Mechanics

Non-linear activation functions are often used in machine learning since they allow the neural networks to approximate a class of functions that do not follow linearity. Modern complex neural networks in 6G are often used to process

large data sets with nonlinearity and high dimensionality. To create complex mappings between the network's inputs and outputs, which is essential for such tasks, a non-linear activation function is required. However, as quantum mechanics is inherently a linear theory because of the unitarity of the operators, it is tricky to incorporate nonlinearity into QML. This will increase the complexity and overhead while implementing QML with 6G to gain the advantages of QML algorithms.

VIII. CONCLUSION

This article discussed the fundamental opportunities and challenges for deployment 6G in the presence of QC. We have shown that the QC can be a threat on one side and another as an opportunity for 6G. QC could improve the whole performance of 6G, such as expediting the classification of massive amounts of data and identifying unseen patterns, THz detection and imaging, data integrity verification and content authentication with higher accuracy and securing communication. With significant progress in building a 'workable' quantum computer and the ongoing commercialization of quantum technologies, the telecom industry should well prepare for both short- and long-term transition processes since it will encounter various serious challenges to adapt to this change.

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