Received: 19 November 2022 | Revised: 13 April 2023 | Accepted: 15 May 2023

DOI: 10.1049/qtc2.12060

IET Quantum Communication

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Quantum for 6G communication: A perspective

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Funding information

Engineering and Physical Sciences Research Council, Grant/Award Number: EP/W032627/1

Abstract

In the technologically changing world, the demand for ultra-reliable, faster, low power, and secure communication has significantly risen in recent years. Researchers have shown immense interest in emerging quantum computing (QC) due to its potentials of solving the computing complexity in the robust and efficient manner. It is envisioned that QC can act as critical enablers and strong catalysts to considerably reduce the computing complexities and boost the future of sixth generation (6G) and beyond communication systems in terms of their security. In this study, the fundamentals of QC, the evolution of quantum communication that encompasses a wide spectrum of technologies and applications and quantum key distribution, which is one of the most promising applications of quantum security, have been presented. Furthermore, various parameters and important techniques are also investigated to optimise the performance of 6G communication in terms of their security, computing, and communication efficiency. Towards the end, potential challenges that QC and quantum communication may face in 6G have been highlighted along with future directions.

KEYWORDS

6G communication, quantum communication, quantum computing

1 | INTRODUCTION

The first generation (1G) of cellular networks appeared in the 1980s. Since then, 2G, 3G, and 4G cellular networks have evolved as advanced telecommunication networks. Thereafter, fifth-generation (5G) wireless technologies have been deployed since 2020 with the aim of being mostly software-based by 2025 [1]. The most remarkable aspect of 5G is the micro-service-based cloudification of network architecture, which abstracts physical resources into virtual and logical environments, introducing automated learning management functions. More recently, with the initial commercial deployments of 5G, research in sixth generation (6G) has begun in earnest. Although, it is too early to predict the functioning of 6G, a key attribute of 6G will be the convergence of several critical features, such as high reliability, low latency, high throughput, massive connectivity, and network densification. 6G will support unique use cases with stringent quality of service (QoS) requirements like holographic communication and remote high-precision surgery [2].

The QoS requirements in 6G can be satisfied with the realisation of many emerging technologies, such as artificial intelligence (AI), terahertz (THz) communication, cell-free communication, optical wireless communication, joint communication and sensing, joint information and energy transfer, network virtualisation, blockchain, and quantum technologies [3]. Specifically, quantum technologies have evolved more recently in terms of quantum computing (QC), quantum communication, quantum security, and quantum sensing. It has been envisioned that quantum technologies will play a vital role in enabling future 6G in terms of communication and computing while providing a significant level of security [4].

Faster computing always remains an ambition in information and communication technology (ICT). QC may help in achieving such ambition by leveraging quantum concepts such as superposition. Many different quantum systems, including trapped ions [5, 6], superconducting qubits [7, 8], photons [9, 10], and silicon [11, 12], which can be used to create quantum computers. The supremacy of quantum parallelism leads to the realisation of developing more efficient algorithms, which on one hand helps enhancing computing-intensive applications, while on the other hand provides capabilities to break the security of classical cryptosystems such as Rivest–Shamir–Adleman that are based on prime factoring difficulty. To overcome such security challenges, researchers are investigating post-quantum cryptography, which aims to make ICT systems resilient against security attacks generated from both classical and quantum computers.

Another related area of study is QC-assisted communications, with a significant likelihood of meeting the demanding standards of 6G technologies to deliver exceptionally increasing data rates and link security [13]. QC employs photons (or quantum fields) to encode data in the quantum state (or qubits) and transfers qubits from a quantum emitter to a quantum receiver. Utilising qubits in communications provides numerous benefits, such as communication security, high-speed and low transmission losses in optical and radio media, and reduced decoherence risk, among others. In addition, QC-assisted communication has tremendous potential for long-distance communications. Quantum repeaters can be utilised at great distances to divide the communication link into numerous shorter middle parts and then rectify problems such as photon loss and operation defects in these segments [14]. Future communication systems' link capacity enhancement options, such as power domain multiple access enabled by Successive Interference Cancellation, have extremely high run-time computational power requirements, making QC clearly applicable [15]. A quantum-aided solution to data-packet paths in multi-hop communication networks is an illustration of a challenging multi-objective space, and an exhaustive search problem in communications has already been presented [16]. It is anticipated that 6G would include high data rate applications and a massive number of connected devices [17] including bio and nano-internet of things (IoT), unmanned mobility, haptic communications, unmanned aerial vehicles, and a number of other applications [18, 19]. The quantum-safe cryptography solutions guarantee secure communication in future fully connected world. The secure quantum communication may achieve information-theoretical security by leveraging quantum principles such as entanglement and no-cloning theorem [4]. An example of information-theoretically secure protocol is quantum key distribution (QKD).

An important area of 6G where quantum systems can outperform classical systems is sensing and imaging of a physical environment. Indeed, quantum sensing surmounts the classical sensing due to its ability to detect minute changes in the environment with few physical qubits. This makes quantum systems an ideal choice in realising digital-twin applications, such as the metaverse. Quantum sensing could also help in realising haptic communications [4].

It is worth mentioning that quantum technologies are still evolving, however, they will play a crucial role in achieving the requirements of future 6G systems. This paper discusses the details and importance of quantum concepts, such as QC, quantum communication and quantum security as enablers of future 6G networks. Fundamentals of these leading quantum concepts are discussed along with enabling technologies such as quantum interconnects, and quantum repeaters and quantum-enabled 6G communication system. Towards the end, future research direction, challenges, and technological limitations are investigated to adopt quantum technologies in cellular communication domain.

2 | QUANTUM COMPUTING

Moore's law has accurately predicted the growth in computing power, which states that the number of transistors per integrated circuit doubles every 2 years and has been the guiding principle for the semiconductor industry since 1965 [20]. Nowadays, millions of transistors are integrated in single computer chip, and the continuous progress has open doors for nanotechnology, and the behaviour of such circuits can only be expressed in quantum mechanical terms rather than classical physics which obeys the laws of quantum mechanics. In 1985, Richard Feynman showed quantum computers can perform computations by taking into account the probabilistic weight of each computation and can act as a quantum process simulator, which are impossible to be achieved efficiently through conventional automation [21].

2.1 | Basic of quantum computing

The fundamental unit of classical computing is bits, which have two states, zero and one. The bits are given to computers in the form of strings which use gates to switch some of the bits from $0 \rightarrow 1$ and $1 \rightarrow 0$. Quantum computers use qubits, a portmanteau of quantum and bits, like a bit a qubit can be in states zero and one. The qubits states are represented as $|0\rangle$ and $|1\rangle$. Like classical computers, it is initially just a string of zeroes and ones, but these qubits can also be in infinitely many superposition while quantum computer is running between $|0\rangle$ and $|1\rangle$. When the qubit is in superposition, it has some probability of being in state $|0\rangle$ and some probability of being in state $|1\rangle$. The superposition states, when measured, will collapse into a basic state, either $|0\rangle$ or $|1\rangle$. This superposition state allows us to make calculations not only on one state but on multiple states at the same time. This is clear from famous Schrödinger's cat thought experiment, that is, before opening the box, the mythic cat is in a position of alive and dead. But by observing the cat, it is forced to pick a state, alive or dead, not both. Quantum Computer is typically full of Schrödinger's cats [22]. Mathematically, the state vector of unit amplitude can describe the state of the qubit as

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

where $|0\rangle$ and $|1\rangle$ are the zero and one vectors of the qubit, and α and β are the associated probability amplitudes providing the likelihood of one of the states [23]. $P_{|0\rangle} = |\alpha|^2$ will be the probability of $|0\rangle$ and $P_{|1\rangle} = |\beta|^2$ of $|1\rangle$. The value of $P_{|0\rangle}$ and $P_{|1\rangle}$ can only be determined by preparing multiple rounds of the same qubit state as stated in Equation 1 and measuring it to accumulate statistical data of probabilities $|\alpha|^2$ and $|\beta|^2$. For physical implementation of quantum computation, one needs to change the quantum state of the qubit. This can be achieved through the dipole interaction between the qubit and the external microwave drive field.

For efficient implementation of QC systems, following are the key requirements, *long coherence time* (T1 and T2, time duration for which qubit has a fixed state), *high scalability* (capacity to accommodate rising computing demand), *high fault tolerance, and quantum error correction* (quantum error correction [QEC] is used to shield quantum information from errors caused by decoherence and other quantum noise. Entanglement essentially aids in error detection and correction while maintaining the qubit's state, *ability to initialise qubit* (to rapidly reduce the entropy of a quantum system), *universal quantum gates* (set of quantum logic gates), *efficient qubit-state measurement capability* (quickly and accurately detect a qubit's state using quantum mechanics), and *faithfully transmit flying qubits between specified locations* (condition necessary for quantum communication) [24, 25].

3 | QUANTUM COMMUNICATION

Sensitive information is currently encrypted before being transmitted via fibre-optic cables and other channels, along with the required cryptographic keys to decode the information. The data and keys are transmitted using the standard bit format of 0 and 1s. The ability to track down hackers using this communication method is also exceedingly challenging. Quantum communication is the effective way to address this problem. This method uses the laws of quantum physics to safeguard data and make sure that communications are secure. These rules allow for the superposition of particles, typically light photons used for data transmission through optical cables. This allows them to represent several simultaneous combinations of 0 and 1s. The hackers are unable to alter these quantum bits (qubits) without leaving a visible trace of their actions. It may be claimed that this technology has not fully developed yet, and further study is still needed. Notably, several commercial companies have already used quantum physics and its features to build networks for sending extremely sensitive data based on QKD [26–29].

Quantum communication has a distinctive position between quantum mechanics and applied quantum optics. Quantum mechanics is a branch of physics which deals with the behaviour of matter and light on the atomic and subatomic level. At this level, a particle can have more than one quantum state and at the same time may interact with the particles which are very far away. This is mainly due to the quantum principles, which includes, quantization, uncertainty principle, quantum superposition, tunnelling, entanglement and decoherence [26, 30]. Among the mature quantum information techniques is the QKD. In this, two remote users can create private key securely, through which secret messages can be crypt into ciphertext and sent from one user to another [31]. In short, QKD-based communication have two steps, first is establishing the key and second is to use classical channels for ciphered transmission. Another quantum communication is quantum secure direct communication. In this, message can be transmitted directly from the sender to the receiver by condensing QKD and classical communication ciphertext into single quantum communication, and the entire system is quantum mechanical [32].

Quantum communication encompasses a wide spectrum of technologies and applications, ranging from cutting-edge laboratory studies to commercially viable products. QKD and quantum random number generators are two of the most disputed and investigated quantum technologies in this growing subject of commutations. At the same time, there are also significant hurdles in building worldwide quantum communication networks. While some advancements have been made in this area, all of these endeavours are still in their infancy. Important techniques for secure quantum communication are (a) discrete variable system (b) continuous variable system [33].

In classical communications, the greatest amount of information that can be securely sent across an ideal binary communication channel is one bit per channel. With the use of entanglement, it is feasible to double the maximum amount of information in the quantum paradigm. This technique is known as super-dense coding [34]. In addition, the practical design of quantum-assisted communication protocols largely relies on quantum channel/error correction coding in order to get close to the theoretically feasible capacity. Due to the quantum nature of the information transmitted across quantum channels, the encoding and decoding procedures cannot be treated like their conventional counterparts.

Due to the impossibility of duplicating a quantum state, caution must be taken when attempting to apply the ideas of conventional error-correcting codes to quantum systems (no-cloning theorem) [35, 36]. Some of the key technologies that can help realise 6G are depicted in Figure 1. The traditional decision-making process is mostly based on the anticipated utility hypothesis, and its performance is severely impaired in risky and uncertain situations [37]. In the majority of traditional decision-making processes, the likelihood of producing accurate predictions can be significantly impacted by the surrounding environment, such as an unknown stochastic or variable environment. Moreover, in scenarios with limited or partially accurate data or imperfect preference relations, predictions are likely to be qualitative and partial. Quantum Decision Theory (QDT) appears to be a potential technique for addressing this issue, and it has been studied in various published works [37, 38].

One of the main challenges in 6G networks is the high level of complexity and uncertainty due to a large number of connected devices, the diversity of applications and services, and the dynamic and unpredictable nature of the wireless environment. QDT can help address these challenges by providing a more flexible and powerful framework for

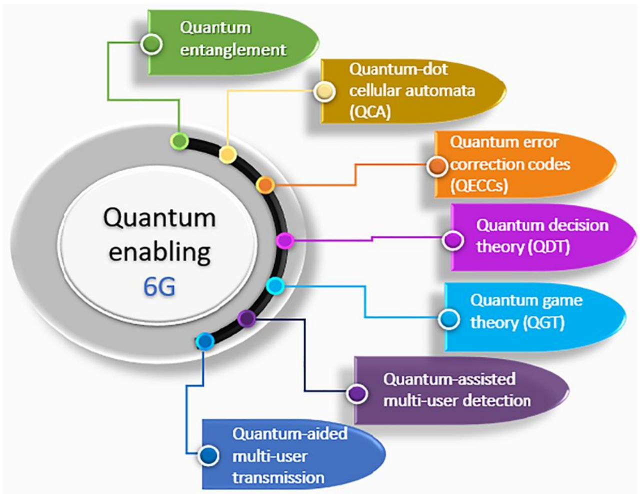

FIGURE 1 Enabling quantum technologies in 6G.

decision-making. For example, QDT can be used to optimise the allocation of wireless resources such as spectrum, power, and bandwidth among different devices and applications [39]. Additionally, QDT can be used to model and analyse the behaviour of network users and applications and to predict their future actions and preferences [40]. Game theory is a strategy for making the appropriate decisions in conflict situations. It has been extensively utilised in economics, the social sciences, and biology to describe decision-making scenarios in which the outcomes depend on the interacting approaches of two or more individuals with competing or, at best, self-interested goals.

Quantum Game Theory (QGT) has the potential to provide new insights and approaches for analysing and designing 6G networks. By combining the principles of quantum mechanics and game theory, QGT can provide a more accurate and comprehensive understanding of the complex interactions between network operators, service providers, and users, leading to more efficient and secure communication protocols. QGT can be used to analyse and optimise communication protocols, design secure QKD schemes, and explore the impact of quantum technologies on network performance and security in 6G networks [41–43].

As an additional crucial point, due to the development of mobile devices like smartphones and tablets, wireless data transfer speeds have skyrocketed. Therefore, it is more important than ever to have communications that conserve power by using multiple-stream detectors with minimal complexity. Create low-complexity soft-input soft-output quantum-assisted multi-user detectors that can be successfully incorporated into state-of-the-art iterative receivers, achieving a bit error rate (BER) of 10^{-5} in the uplink of a rank-deficient multi-carrier interleave division multiple access system that uses realistic imperfect channel estimation at the receiver and allowing for 14 users to transmit QPSK symbols in Ref. [44]. In the difficult rank-deficient scenarios, where the number of transmit antenna elements at the BS is less than the number of users, a new quantum-assisted precoding methodology improves BER performance compared to a classical methodology employing the PSO algorithm while requiring the same computational complexity. Moreover, the proposed quantum-assisted precoder outperforms the conventional precoder when users can only send a small amount of channel state information back to the BS because of the need to quantise the channel states [45]. Quantum security, quantum interconnects, and quantum repeaters are important parts of the evolving field of quantum information technology (QIT), and they are discussed in greater detail below.

3.1 | Quantum security

Quantum cryptography employs quantum physics principles for the secure transmission of information. The transmission of secret messages from one location to another, is an important example. Even if the communication link is unreliable, the cryptographic requirement is that the sent messages remain unavailable to anybody other than the intended recipients. This is typically only guaranteed in traditional cryptography under assumptions of computational difficulty, such as when factoring huge numbers is impossible. In contrast, quantum cryptography relies solely on the laws of quantum mechanics for its security. In this regard, QKD is becoming one of the most promising applications of quantum security [46].

QKD employs a quantum system to protect data, rather than mathematics [47]. In QKD, a quantum communication channel is used along with an authentic channel to construct a secret key between legitimate parties [48, 49]. QKD operates by transmitting photons between legitimate parties via the communication channel such as fibre optic cables. When a photon arrives at its destination, it passes through a beam splitter, forcing it to take one of two paths into a photon collector. To determine which emitter actually sent each photon, the receiving end sends back information about the sequence in which the photons were received. Photons in the wrong beam collector are discarded, leaving only a specific sequence of bits. This bit sequence is then used to encrypt data [50].

There are two main types of QKD, prepare-and-measure and entanglement-based [51, 52]. Prepare-and-measure protocols measure quantum states, which can detect eavesdropping and the amount of data intercepted. On the other hand, entanglement-based protocols focus on quantum states formed by two linked objects. Entanglement means that measuring one object affects the other. If an eavesdropper changes a trusted node, other parties will know. Some of the common protocols built upon QKD are BB84 [53], Silberhorn [54], Decoy state [55], and E91 [56]. Hence, QKD will provide novel approaches to secure 6G networks and technologies.

3.2 | Quantum repeaters

When it comes to quantum communication, quantum repeaters are essential infrastructure. The success rate of direct quantum communication between two parties drops exponentially with the distance between them. Waystations, which function in the communication channel like amplifiers do in traditional channels, are necessary to get around this fundamental constraint. Yet, the no-cloning theorem makes it impossible to amplify a quantum signal, unlike classical signals which can be amplified using conventional amplifiers. To this goal, quantum repeaters create entanglement and then exchange it between waystations in order to broaden the scope of quantum correlations. With the help of quantum repeaters, entanglement can be generated over an entire communication system. Entanglement's integrity can be restored through distillation (purification) if it has degraded [14, 57, 58].

Forerunners to full quantum repeaters are the quantum relays. That is, they are rudimentary quantum repeaters that can only do basic tasks. Even though it does not exhibit the scalability of a network based on true quantum repeaters (polynomial resource usage, with the quality of the entangled resource not scaling exponentially with overall communication distance), it is still possible for it to scale polynomially if the quantum memory has an infinite coherence time. The relays typically require single photon sources, single photon detectors, quantum memory, and a qubit-photon interface based on material. Controlling matter qubits via optical transitions like (nitrogen-vacancy) NV centres in diamond and developing lossless fibre-cavity coupling are all necessary. Many of the fundamental hardware components of quantum relays and quantum repeaters are the same, despite the fact that the topologies of the respective communication systems are very different. When compared to a quantum repeater, a quantum relay device does not need to be able to purify entanglement or store photons [59, 60]. Problems limiting the ultimate rates for sending quantum information, entanglement, and secret (cryptographic) keys via quantum repeaters for parties directly connected by a quantum channel are discussed in Ref. [61].

Establishing entangled states whose quality does not degrade exponentially with the number of repeater nodes in a network necessitates that quantum repeaters have at most a polynomial scaling in terms of resources required [62]. Entanglement distribution [63–65], entanglement switching [66, 67], and entanglement distillation (purification and error correction) [68–70] are the three main functions of a quantum repeater system. The error correction used by quantum repeaters is similar to that used in quantum computation, but the implementation is simpler, and fault tolerance is not required [71].

3.3 | Quantum interconnects

Quantum communications systems use quantum interconnects to transfer entanglement between quantum devices. In particular, they offer important advantages in this era of noisy intermediate-scale quantum computing by significantly altering the connectivity for quantum adiabatic computation, quantum annealing, and quantum simulation [72].

Quantum switch (QS), a device that can send optical signals between several channels while maintaining quantum coherence and entanglement, is at the centre of a network of various quantum information systems, as shown in Figure 2. The implementation of quantum interconnects has significant technical challenges: They must transmit quantum information (quantum states) with high accuracy, quick rates, and low loss, frequently across a broad range of energies and do so in a scalable manner. In some situations, a workable candidate quantum interconnect strategy is well established, but implementation requires focussed engineering effort. In other situations, however, novel physical processes must be investigated in order to implement a particular quantum interconnect system. The development of materials, devices, systems, and supporting infrastructure in critical-path domains that support the development of useable quantum technologies will advance significantly with an acceleration of research towards the creation and application of quantum interconnects. Quantum interconnects eventually enable distributed quantum processing. The analysis and development schedule for quantum interconnects are discussed in Ref. [73].

For short distances, without the need for quantum repeaters, quantum interconnects can be built on the chip and between the chips. For instance, 1 m of superconducting cable was used to transmit entangled superconducting qubit [74]. Using photons is anticipated for long-distance quantum interconnects. Effective transducers are needed for the use of non-photonic qubits with photonic quantum interconnects. A network of quantum computers linked together by quantum communication channels is known as the quantum internet. On the quantum internet, quantum computers are coherently networked, allowing for the worldwide distribution and consumption of quantum correlations. The global distribution and consumption of quantum correlations would be possible with such a system of coherently interconnected quantum computers [75].

4 | 6G COMMUNICATION

Beyond 5G and 6G, research has begun in earnest in parallel with the growth of commercial 5G deployments. 6G systems will support novel use applications with demanding Key Performance Indicators, which will be enabled by new facilitating technologies and network designs [76]. This improvement in throughput and delay for 6G will translate into support of more demanding high-speed data applications like immersive (i.e., 360°) 8k video and critical delay-sensitive applications like remote surgery with haptic feedback. 6G is expected to have throughput and latency that will be from 5× to at least 20× better than 5G [77].

This will enable improvements in high-speed data applications and low-delay critical control applications. Moreover, it is interesting to consider the potential device types to be used in 6G by human users (as opposed to M2M and other non-human users). The biggest enhancements in 6G, however,

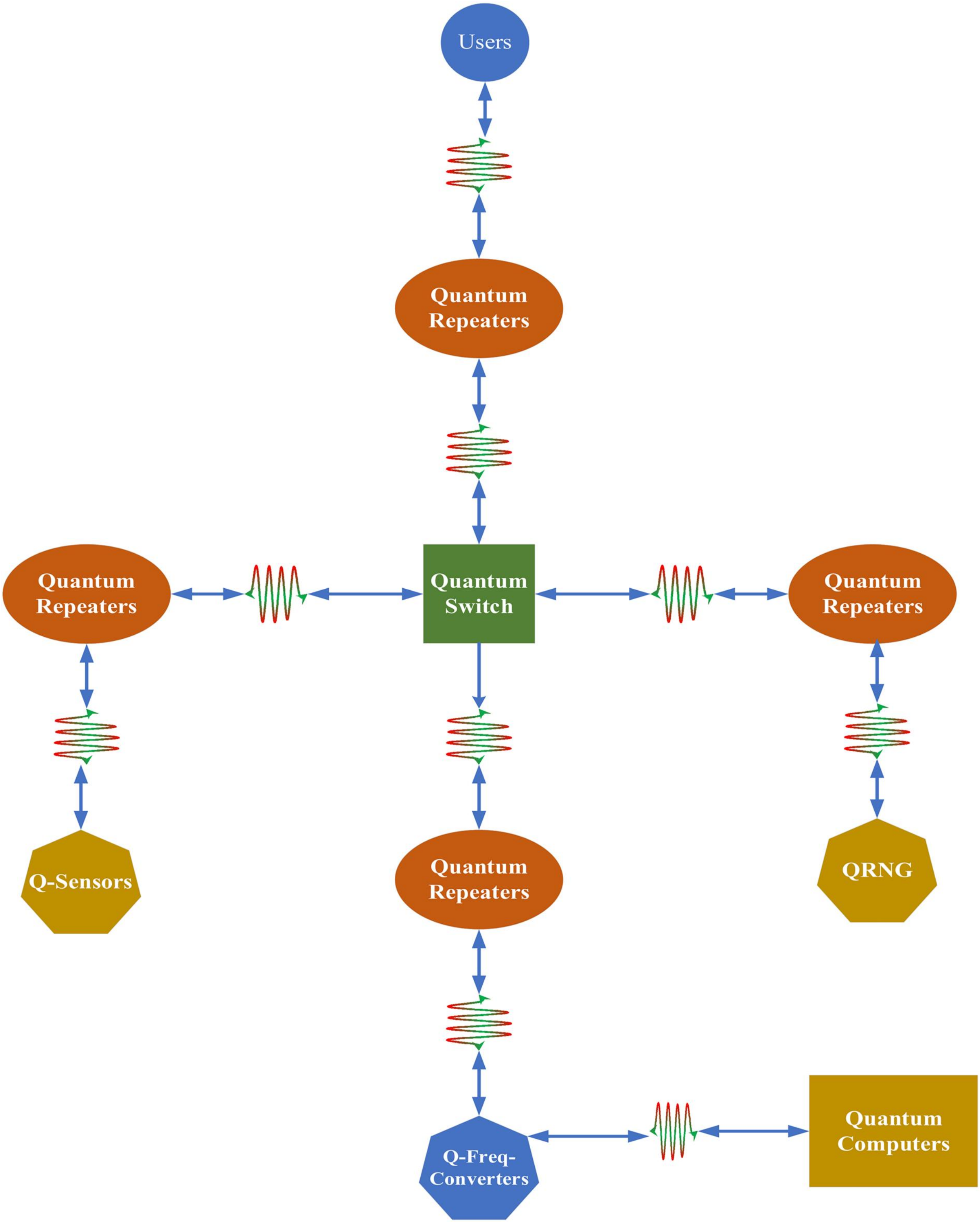

FIGURE 2 The role of quantum interconnects in quantum communication. Quantum interconnects are shown by wave packets that represent photons.

will be in the areas of AI and QIT. 6G networks will need native security and privacy mechanisms, higher efficiency, and ubiquitous intelligence [78].

The jump from fourth generation mobile communications (4G) to 5G was fuelled by an unprecedented increase in connected users, bandwidth requirements, and data intensive services. In particular, ultra-reliable low latency communications have stringent real-time constraints as well. With an eye towards proposed 6G communication frameworks, several technologies have been proposed to address the issues. One of those is providing a machine learning (ML) framework for end-to-end communications.

One of the key areas where quantum technology could be applied in 6G networks is in the development of quantum communication networks. These networks would use quantum cryptography to secure the transmission of data, making it virtually impossible for third parties to intercept or access sensitive information [79]. This is achieved through the use of QKD, which allows for the secure distribution of encryption keys using entangled particles. Another area where quantum technology could be applied in 6G networks is in the development of quantum sensors [18]. These sensors would be capable of detecting and measuring a wide range of physical parameters, including temperature, pressure, and magnetic fields, at a level of precision that is impossible with classical sensors. This would enable a range of new applications, such as ultra-accurate positioning, real-time environmental monitoring, and enhanced imaging capabilities [13]. In addition, QC could be used to optimise the operation of 6G networks. Quantum algorithms could be used to analyse large amounts of data, optimise network performance, and develop new communication protocols that are more efficient and secure.

Parallel to the progression of cellular networks from 5G to 6G, QIT has seen rapid development over the last several years in terms of quantum communications and QC. It is anticipated that QIT will allow and enhance future 6G systems in terms of communication and processing. For instance, secure quantum communications such as QKD may be used to enhance the security of 6G networks. Quantum communication can be useful for the future 6G communication networks. For example, it can enhance the channel capacity, could transmit an unknown quantum state, and to achieve a quantum cryptography by exploiting several advanced communication protocols. Such advanced communication protocols are not possible with the classical techniques [50]. QC enables robust security for 6G wireless communication systems [80]. This is possible by using a quantum key approach, which is based on the uncertainty and the quantum no-cloning principle. QC has the ability to increase the effectiveness of detecting unauthorised users. In addition, quantum communication has the ability to provide a high data rate and robust security against cyberattacks [81].

Quantum techniques can be significantly useful in investigating computationally efficient solutions to classical signal processing problems. One important advantage of utilising the quantum domain in communications is high degrees of freedom. By replacing the conventional physical communications channel with the nano-scale objects, that is, photons, electrons, governed by the quantum principle, in terms of logical values of zero and one, it is possible to utilise the linear combinations of these logical values [82]. It is widely agreed that QEC is a significant technological challenge that has to be handled. As a result, the development of a quantum error-correcting coding scheme is of considerable significance [40]. In addition, the construction of network entities with quantum Internet is considered to be another technical challenge that may be faced by the quantum communication, as it needs QSs/routers and repeaters. To overcome this potential barrier, QSs/routers and repeaters are necessary. One other difficulty is in the capacity measurements of the quantum communication channels [83]. This is due to the fact that quantum channels may have several possibilities in terms of sending information including quantum information and entanglement-assisted classical information [84]. These are the two types of information that can be sent by quantum channels. As a result, substantial amounts of research effort are necessary to make quantum communication physically practicable in the future systems that support 6G communications [15].

5 | QUANTUM-ENABLED 6G COMMUNICATION

Future 6G systems are expected to benefit from QIT from both a computing and communication standpoint. For instance, 6G security can be enhanced by utilising secure quantum communications techniques like QKD [4]. Quantum mechanics, quantum communications, QC, and quantum sensing and metrology are the four primary subfields of QIT. Quantum entanglement forms the base for many effects such as QKD [85, 86], Quantum dense coding [87], Quantum teleportation [58, 88], and Entanglement swapping [89, 90]. QC has the potential to contribute to wireless communications in several ways, including through the development of quantum optimal algorithms [91, 92] and quantum ML [15]. Quantum optimal algorithms: Quantum optimal algorithms are designed to solve optimisation problems more efficiently than classical algorithms. In the context of wireless communications, quantum optimal algorithms could be used to optimise resource allocation and schedule in wireless networks, which could improve network efficiency and reduce complexity. Channel estimation is a critical aspect of wireless communication, as it is used to estimate the characteristics of the wireless channel and optimise signal transmission. QC could be used to develop more accurate and efficient methods of channel estimation, which could improve network performance and reduce complexity. Overall, while these are just a few examples, QC has the potential to make significant contributions to wireless communications in the future. By developing real-time optimisation, which is made possible by rapidly expanding data analytics and ML, 6G wireless networks will be able to handle immersive services like virtual reality, augmented reality, mixed reality, and tactile Internet [93].

The capacity of current network technology could potentially be significantly increased by quantum network receivers. In contrast to conventional receivers, a quantum receiver's technology operates differently. The latter can access information by decoding a classical (non-quantum) signal that is received. The amount of data that can be decoded with a conventional receiver is nonetheless constrained. This constraint is caused by the fact that the amount of data that can be deciphered is inversely correlated with the energy required to convey it. On a conventional network, the signal that a receiver node receives is also heavily contaminated by noise [94]. In order to determine the best performance parameters at a specific time and in the context of a specific network node, quantum-enabled ML and QC-powered networks may be able to coordinate data inputs as diverse as battery life, throughput, local demand factors, and other significant metrics. This would have a significant impact on the performance of the entire network if replicated across numerous nodes in a single, widely scattered network.

5.1 | Quantum 6G communication system

A quantum-enabled 6G system is depicted in Figure 3 where QIT is used to implement novel 6G functionality and services. Quantum-capable photonic systems like lasers or fibre optic cables connect all nodes. Some nodes will be fully quantum-capable. Yet, many nodes can generate, send, and receive qubits.

As part of 6G, thousands of satellites in low earth orbit, medium earth orbit, and geosynchronous earth orbit will continue to build mesh-like non-terrestrial networks. Free-space optic networks connect satellite nodes, which can house quantum computers. Free-space optics have been used to demonstrate quantum communications between satellite nodes and ground stations [95]. Entanglement distribution for distant satellite nodes must be properly addressed for quantum communications. Powerful satellite nodes with quantum computers can also offer QC to other satellites and ground stations. Yet, a satellite node can be a trust node or quantum repeater to improve quantum communications like satellite-based QKD. QC and communications improve radio access network (RAN) efficiency and security. Open RAN (O-RAN) can use quantum communication for enhanced security. O-RAN components like distribution units (DU) and control units (CU) must be easily deployable and securely coupled. Otherwise, eavesdropping, man-in-the-middle attacks, and other security threats may affect all user traffic passing via O-RAN nodes. QKD can establish security keys between O-RAN components, solving this problem. Pervasive edge computing services will be provided by more edge nodes (e.g., vehicles) in 6G systems. Edge computing environments face security, workload offloading, and resource allocation issues. QC can optimise task offloading and edge resource allocation, while secure quantum communications can ensure secure communications to, from, and between edge nodes [4, 96–98].

Modern data centres use optical fibre and free-space optics for inter-rack communications instead of wireless connectivity to boost data throughput and reduce interference. Quantum channels can use these optical links. Quantum communication and cryptography can increase inter-rack security. QC can solve computation-intensive data centre challenges like efficient data flow and energy consumption management. Blockchain technology uses distributed consensus protocols, distributed databases, cryptography, and hashing to create a decentralised system with transparency and immutability. Blockchain technology enables 6G applications like decentralised authentication and distributed wireless resource sharing between parties that may not trust one other. Blockchain technology also faces security threats from hostile nodes, slow transaction speeds from consensus methods, and privacy breaches from transparent block data. QIT, quantum-assisted blockchain, can fix these difficulties. Quantum communications can improve communication security among blockchain nodes, entangled qubits can simulate block links, and entanglement can be utilised to develop novel consensus methods without high communications overhead and increase transaction speed [99–102].

Massive data from ubiquitous devices and network nodes and AI methods like deep learning, deep reinforcement learning, federated learning, and transfer learning will make 6G systems more intelligent and autonomous. QIT helps wireless AI in numerous ways. First, quantum cryptography can protect model sharing and communications in decentralised AI like federated learning. QC can speed up AI training and inference. Blind QC could enable privacy-preserving AI training. QML may introduce new wireless AI methods [15, 103]. Users can submit QC tasks to cloud-based quantum computers via traditional Internet. Like classical computing as a service, entanglement production, distribution, error correction, memory, and measurement are further quantum capabilities of a full-fledged quantum computer. Other less powerful quantum computers, 6G services and 6G apps may use these quantum capabilities as a service. Quantum measurement as a service might be hosted by the 6G core network (CN), O-RAN central units, or even powerful 6G devices like quantum-capable drones and automobiles. Cars or quantum dock stations could share quantum capabilities with ordinary electronics. QKD-enabled RAN may not have good quantum measurement capability (e.g., quantum measurement hardware like fast and high-fidelity readout) like the CN. Then CU can use CN quantum measurement and can pass all received qubits to the CN via the quantum channel to use the CN's quantum measurement capability. CN receives qubits from CU and measures them randomly using the QKD protocol to produce classical bits. Assuming secure communications, the CN sends the measurement basis and results to CU via the classical channel. CU follows the QKD protocol and transmits designated feedback (e.g., measurement basis) to DU after receiving the measurement basis and findings from the CN. DU receives CU feedback and follows the QKD procedure. CU and DU can finally share a security key [4, 104, 105].

5.2 | Quantum-classical network evolution

Classical information and communication technologies (CICT) and QIT will work together to improve hybrid classical-quantum systems. Quantum computers require conventional computers or circuits for quantum unit control. The most difficult part is partitioning classical and QC units. Pre-, post-, and co-processing require well-specified quantum and classical modules. No hardware prototype has tested classical-quantum hybrid approaches on wirelessly networked system challenges. Hybrid classical-quantum architectures aim to enable ultra-high throughput networks. How to partition sequential computational tasks into classical or quantum units and assign them to

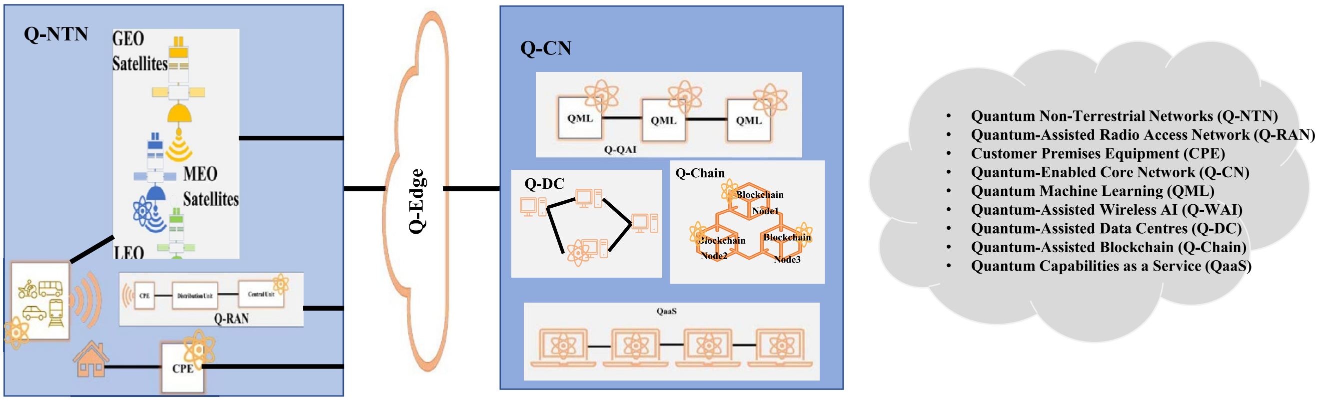

FIGURE 3 Quantum-enabled 6G communication system.

staged processing units is critical [106, 107]. Quantum networks communicate qubits over long distances via a physical layer, like classical networks. Due to their speed, ease of avoiding interactions, and availability of fibre-optic cable conduits, photons are the only suitable particle for transferrable qubits. Photons absorb and scatter like other particles, so a long transmission will reduce propagation efficiency on Earth [108]. As a result, a hybrid architecture is anticipated for the quantum-enabled 6G. The difficulty comes from creating QIT and CICT to cohabit in an effective, modular, and scalable framework. This calls for a comprehensive evaluation and understanding of the pros and cons of each technology in order to determine optimal matching scenarios and solutions to accommodate different user requirements (such as security requirements and expected quantum fidelity), different hardware component constraints (such as classical technologies and QIT equipment cooling requirements), and existing CICT infrastructure (e.g., types of physical fibre links, data centre configurations) [4].

6 | CHALLENGES AND FUTURE DIRECTIONS

In order to get ready for the potential challenge that QC would provide in the 6G era in the future, scientists have already begun researching quantum resistant hardware and encryption solutions. To investigate prospective breakthroughs in 6G design, the 6G architecture can be divided into four blocks: ‘platform,’ ‘functional,’ ‘specialisation,’ and ‘orchestration.’ To accelerate hardware and improve data flow centrality, heterogeneous clouds must establish an open, scalable, and agnostic run-time environment as part of the ‘platform’ of the 6G architecture [109]. The demand to communicate at ever-increasing data speeds will continue indefinitely. To achieve data speeds of terabits per second, it is necessary to operate at higher and higher frequency bands. The increasing pathloss and other propagation phenomena necessitate the use of very large-scale antenna arrays, which require the assistance of numerous hardware components, such as signal mixers, analogue-to-digital converters and digital-to-analogue converters, power amplifiers, etc. [110].

Moving up in the frequency, the device physics changes drastically and the approach of using a metal-based antenna has several limitations, chief among them is the low mobility of electrons in the nanoscale metallic structures. This results in the antennas being highly lossy at the resonant frequencies, which would result in a high attenuation and subsequently, poor efficiency of the overall system [111]. To address this lossy behaviour, meta-material-based nanostructures have emerged as attractive solutions [112]. Graphene is an atomically thin, 2D material crystalline form of carbon in which the carbon atoms are arranged in a hexagonal lattice structure (see Figure 4b,c). On the other hand, the design of signal processing algorithms is impacted by the high cost and power consumption of these components at the mm Wave and THz bands, making it impossible to employ standard transceiver architectures. Partnering across the hardware and algorithm communities will be essential for designing systems of this complexity. What this indicates is that hardware-algorithm co-design has to be promoted. The design of transceiver systems needs to be both algorithm and hardware friendly [113].

Recent advances in cutting-edge circuits, antennas, and metamaterial-based structures, as well as the rapid rise of AI techniques, such as ML, data mining, and data analysis, have explored a new path for overcoming the obstacles that radio networks will encounter on the path to 6G. For this reason, it is of importance to provide intelligence above and beyond the well-established intelligent spectrum access for cognitive radio networks in order to solve new problems in radio communication. Therefore, state-of-the-art AI/ML approaches will be required for the ideal intelligent radio (IR) to deal with issues including precise channel modelling and estimation, modulation, beamforming, resource allocation, optimal spectrum access, and automated network deployment and administration. Thus, IR's incorporation into 6G will shorten the implementation time and drastically cut the price of new algorithms and hardware [114].

As networks become more complex and heterogeneous, software only will no longer be effective for 6G. To support

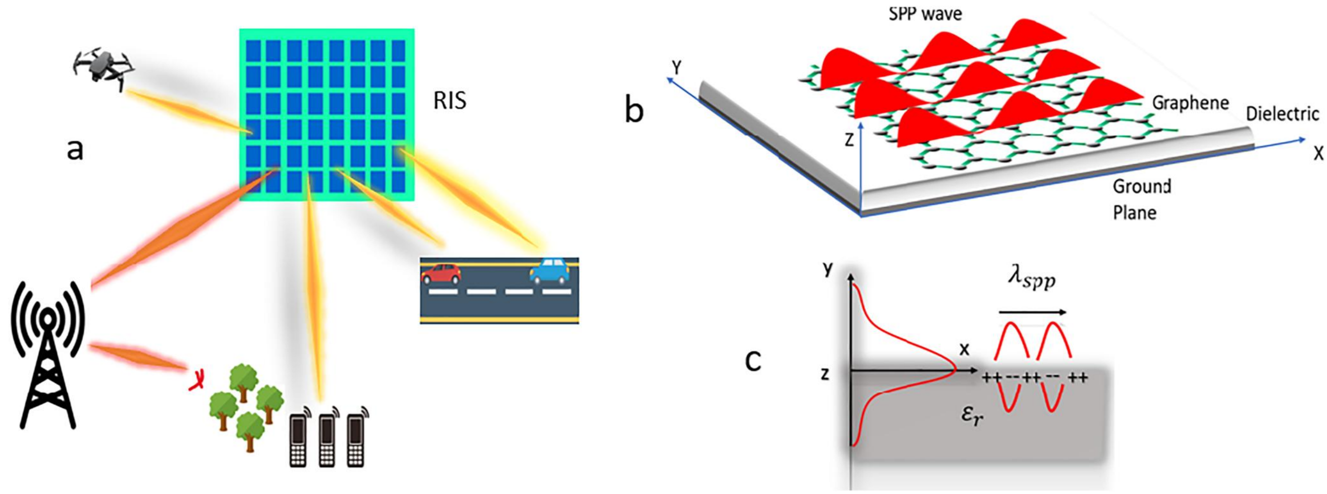

FIGURE 4 (a) RIS-enabled non-line-of-sight transmission. (b), (c) Schematic representation of an electron density wave propagating along a metal–dielectric interface (Graphene). RIS, reconfigurable intelligent surface.

AI-based applications, network entities must support a wide range of capabilities, such as communications, content caching, computing, and even wireless power transfer. In addition, 6G will incorporate new radio access interfaces such as THz communications and intelligent surfaces. It must also support more advanced IoT functions such as sensing, data collection, analysis, and storage [1]. All of the aforementioned challenges necessitate a flexible, adaptive, and, most importantly, intelligent architecture. Physical layer security (PLS) approaches, such as the deployment of active relays or friendly jammers that employ artificial noise (AN) for security provisioning, may entail on higher hardware cost and power consumption, and must be evaluated in conjunction with 6G security issues. Moreover, acceptable secrecy performance cannot always be assured in poor wireless propagation settings, even with the employment of AN. Therefore, it would be desired to adaptively manage the propagation parameters of wireless channels in order to assure the security of wireless communications, which cannot be achieved with current communication technologies. By intelligently regulating the phase shifts of reconfigurable intelligent surface (RIS), the reflected signals may be coherently combined at the target receiver to improve the quality of the received signal [115].

With the development of metamaterials and microelectromechanical systems, RISs have emerged as a viable solution for tackling the security, energy, and spectrum efficiency issues of intelligent environments. RIS is a software-controlled metasurface composed of a planar array of several passive, low-cost reflecting components whose reflective coefficients can be altered in real-time as shown in Figure 4a. This allows them to regulate the amplitude and/or phase shift of reflected wave, hence enhancing the transmission of wireless communications [114, 116].

In recent years, Quantum dot-based materials with desired properties have been developed, such as tuneable absorption band gap, practical physical size, minimal crosstalk, low dark current, and solution-based processing enabling straightforward device integration. As a result, research on THz imaging chips benefit from the introduction of quantum dot-based materials, which produce cheap detectors. In Ref. [117], colloidal quantum dots were utilised as the active layer to create a 3D microstructure array in order to introduce the surface plasmon polariton effect and increase the THz field's limiting impact. This process enhanced the THz detector's performance in 6G technology. Converging THz waves within a concave structure provided the constructed device with a high responsiveness and low equivalent noise power.

7 | CONCLUSION

QC is envisioned to revolutionise the wireless resource optimisation challenges in 6G communication systems in terms of their security, efficiency, and intelligence and is believed to be a vital enabling technology. This paper provides a visionary description and in-depth research of QC, which has the potential to minimise the computational complexity of future 6G communication systems. In addition, the significance of quantum interconnects, quantum repeaters, and quantum security has also been discussed in detail, which is considered to be incredibly useful and important in the development of QIT. In this study, it is also established that the quantum technology is still gradually evolving, and 6G communications enabled by QC may face some challenges in designing efficient and secure quantum communication equipment for 6G communication systems. The study also highlights those challenges which quantum-enabled 6G network may encounter, as well as its potential future possibilities. In a nutshell, the findings of this review paper are expected to be beneficial for researchers and scientists working in QC discipline for the deployment of future quantum-enabled 6G networks.

AUTHOR CONTRIBUTIONS

Conceptualisation: Muhammad Zulfiqar Ali, Abdoalbaset Abohmra, and Qammer H. Abbasi. **Writing—Original Draft Preparation**: Muhammad Zulfiqar Ali, Abdoalbaset Abohmra,

Muhammad Usman, and Adnan Zahid. **Writing—Review & Editing**: Muhammad Zulfiqar Ali, Abdoalbaset Abohmra, Muhammad Usman, Adnan Zahid, Hadi Heidari, Qammer H. Abbasi, and Muhammad Ali Imran. **Supervision**: Qammer H. Abbasi and Muhammad Ali Imran. **Project Administration**: Qammer H. Abbasi and Muhammad Ali Imran. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGEMENTS

This work was supported in parts by The Engineering and Physical Sciences Research Council (EPSRC) grant no Ep/W032627/1.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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How to cite this article: Ali, M.Z., et al.: Quantum for 6G communication: a perspective. IET Quant. Comm. 4(3), 112–124 (2023). https://doi.org/10.1049/qtc2.12060