Received: 3 April 2023 | Revised: 14 June 2023 | Accepted: 11 August 2023

IET Quantum Communication

DOI: 10.1049/qtc2.12069

The Institution of Engineering and Technology WILEY

REVIEW

The quantum internet: A synergy of quantum information technologies and 6G networks

Georgi Gary Rozenman[1,2] | Neel Kanth Kundu[3] | Ruiqi Liu[4,5] | Leyi Zhang[5,6] | Alona Maslennikov[7] | Yuval Reches[8,9] | Heung Youl Youm[10]

[1]Faculty of Exact Sciences, Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

[2]Iby and Aladar Fleischman Faculty of Engineering, School of Electrical Engineering, Tel Aviv University, Tel Aviv, Israel

[3]Department of Electrical and Electronic Engineering, The University of Melbourne, Melbourne, Victoria, Australia

[4]Wireless Research Institute, ZTE Corporation, Beijing, China

[5]State Key Laboratory of Mobile Network and Mobile Multimedia Technology, Shenzhen, China

[6]Technology Planning Department, ZTE Corporation, Beijing, China

[7]Raymond and Beverly Sackler Faculty of Exact Sciences, School of Chemistry, Tel Aviv University, Tel Aviv, Israel

[8]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

[9]Center for Light–Matter Interaction, Tel-Aviv University, Tel Aviv, Israel

[10]Department of Information Security Engineering, Soonchunhang University, Asan-si, Korea

Correspondence

Georgi Gary Rozenman and Ruiqi Liu.
Email: garyrozenman@protonmail.com and richie.leo@zte.com.cn

Abstract

The quantum internet is a cutting-edge paradigm that uses the unique characteristics of quantum technology to radically alter communication networks. This new network type is expected to collaborate with 6G networks, creating a synergy that will fundamentally alter how we communicate, engage, and trade information. The improved security, increased speed, and increased network capacity of the quantum internet will lead to the emergence of a broad variety of new applications and services. The current state of quantum technology and its integration with 6G networks are summarised in this study, with an emphasis on the key challenges and untapped possibilities. The main goal is to get knowledge about how the quantum internet might impact communication in the future and alter several economic and societal sectors.

KEYWORDS

cryptography protocols, quantum communication, quantum computing techniques, quantum cryptography, quantum entanglement, quantum information, Rivest–Shamir–Adleman

1 | INTRODUCTION

The area of quantum communication, commonly referred to as quantum cryptography, was founded on the ideas of quantum mechanics and information theory [1–3]. From its initial introduction in the 1970s [4], the idea of exploiting quantum characteristics for secure communication has flourished as a field of study and development. Early quantum communication was primarily restricted to theoretical research and lab experiments [5, 6]. Nonetheless, it has advanced remarkably over the past few decades and is now close to becoming a commercial reality [7].

The ability of quantum communication to provide communication with unconditional security is the primary driving force behind its development [8]. As quantum communication is governed by physical rules as opposed to classical ones, it cannot be intercepted or altered. This makes it a desirable option for use cases like private government communications, encrypted banking transactions, and military communications [9].

Currently, quantum communication is a rapidly developing science with many practical applications, not only a theoretical idea. Advances in quantum technology, such as the creation of high-quality single-photon sources [10] and the realisation of quantum key distribution (QKD) across large distances, have made it easier to construct viable quantum communication systems [11]. These developments have created new opportunities for the commercialisation of quantum communication, which is anticipated to have a significant impact on the development of secure communication in the future [7, 12].

Additionally, QKD is being used in institutions of higher learning [13]. In these circumstances, QKD is used to safeguard sensitive academic intellectual property and research data. A typical QKD system is shown in Figure 1. Universities are now incorporating QKD protocols into their curricula to equip the next generation of quantum engineers and scientists. By doing so, they are providing students with firsthand exposure to cutting-edge developments in the field [13]. In order to support the industrial research and development organisations currently forming the fundamentals of the quantum internet, these activities are essential for the training of the upcoming generation of scientists and engineers in the field of quantum science and technology.

In that regard, a novel idea, shown in Figure 2, called the 'quantum internet' suggests leveraging theoretical and experimental quantum physics, classical and quantum light-matter interactions [14–17], and computer science, to create a new method of information processing and transmission [18]. It is intended to be a network that can safely send quantum data across great distances, such as quantum keys, quantum entanglement, and quantum states, without running the risk of interception or modification. Quantum communication protocols, as outlined in Figure 1, such as BB84, E91, B92 and COW06, would be the foundation of the quantum internet [19]. These protocols make use of the features of quantum physics to facilitate efficient and safe information transfer. A new era of technology and communication may also be ushered in by the development of the quantum internet, which has the potential to open up new opportunities in sectors like

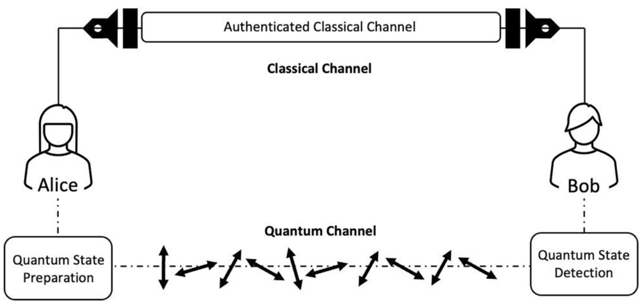

FIGURE 1 Schematic of general quantum key distribution. Secure communication made possible with Quantum Key Distribution—where the principles of quantum mechanics enable the exchange of secret keys over a public channel with ultimate security.

quantum sensing [20], quantum simulation [21], and quantum computing [22]. Although research on the quantum internet is still in its infancy, it shows immense potential for the growth of technology and communication in the future [23].

Starting 2020, fifth-generation (5G) wireless communication systems have been commercialised in different parts of the world. Researchers and telecom engineers have now started investigating the new use cases and the required technologies for the next sixth-generation (6G) communication networks. Apart from high data rates, high reliability, and supporting a massive number of devices, 6G would require to provide unconditional security in the emerging quantum computing era. Quantum technology will play a significant role in the development of 6G wireless networks in order to provide enhanced security, privacy, high data rates, and improved network performance as compared to the current 5G wireless system. Therefore, the 6G wireless network would require seamless integration with the future quantum internet to support end-to-end secure data transmission from the access network to the core network. Furthermore, a quantum-enabled 6G network would allow users to securely access quantum computing services on the cloud. In this study, we present a comprehensive review of the quantum internet and discuss the various applications of quantum information technology in the development of 6G wireless networks. We also present the latest industrial standardisation efforts for quantum-enabled 6G wireless networks.

2 | QUANTUM INTERNET

2.1 | Introduction and overview of quantum internet

There is a possibility that the quantum internet would usher in a new era of capabilities for the field of telecommunications, the likes of which would be difficult to achieve via traditional communication routes [24]. The quantum internet, shown schematically in Figure 2, paves the way for a number of exciting new possibilities, including increased sensing, distributed quantum computing, and communications that are potentially completely secure [25]. A quantum internet will not operate in a manner that is dissimilar to how a classical internet operates; however, instead of disseminating information, a quantum internet will generate entanglement between remote nodes [26]. Entanglement is a form of correlation between different parties [27] that does not have a classical analogue.

A quantum internet, in its standard model, can be seen as a network where each node holds qubits in quantum storage. The connections or links between nodes depict a quantum channel. This channel can generate quantum entanglement between the qubits that reside in the nodes at either end of this link. Such a structure is referred to as a quantum memory network [28].

The first underlying assumption in this model is the practicality of executing two-qubit gates between any pair of qubits housed within the same node. Additionally, it presumes

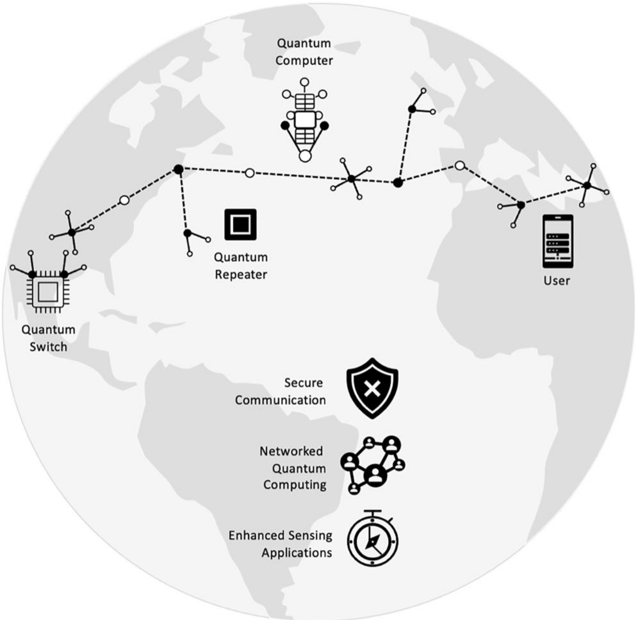

FIGURE 2 A schematic depiction of the quantum internet, which includes a quantum switch, quantum repeaters, quantum computers, and users.

each node is assigned a predetermined number of memory units corresponding to each channel that connects to it.

This section aims to go beyond linear quantum networks and examine how quantum repeaters fit into the future quantum internet concept.

In this part, we will first describe a set of communication activities that can be carried out via a quantum network. Secondly, we correlate these example communication activities with experimental needs and a taxonomy of the quantum internet's phases. Lastly, we study how to assess the utility of quantum networks for each of these activities. For this purpose, we present a simple network model in the form of a graph. The evaluation is expressed in terms of network capacity, or amounts that can be attained under ideal conditions.

Prior to considering how to quantify the usefulness of a quantum network, it is crucial to examine the potential uses of quantum networks and the quantum internet in general. A discussion of a few representative applications is provided below, organised by domain. Yet as the number of users increases, we should expect to find a variety of new applications, much like in the early days of the Internet [29]. A quantum internet may be used to transmit information first. The network's nodes may wish to communicate either conventional or quantum information. Without a quantum network, the latter is plainly unachievable, but the quantum internet can also benefit the former over a traditional network. Specifically, both entangled channel inputs and joint quantum measurements can increase the transmission rate of conventional communication [30]. A quantum internet may also be used to send secret conventional data between two parties [31]. In turn, this makes it possible to distribute secret keys, a process that can only be accomplished using conventional methods. If the parties are willing to rely on assumptions, the security of the rivest shamir adelman cryptosystem depends on the difficulty of the factoring problem, while the security of the wireless physical layer depends on a model of the conditional probability distribution associated with the wireless channel.

Beyond facilitating private communication, quantum networks can also carry out a wide array of cryptographic tasks, often offering significant advantages over their classical counterparts [32]. Among these tasks, QKD is the most widely known. However, there are several others, including certified deletion, conference key agreement, secure money transfer, leader election, and secret sharing [33]. Interestingly, there are certain tasks that neither classical nor quantum resources can efficiently tackle. But if certain assumptions about the potential attacker's storage capabilities—both in terms of quantity and quality—are taken into account, quantum resources can handle these tasks more efficiently. This category includes quantum methodologies for bit commitment, oblivious transfer, and secure identification. One of the standout features of quantum networks is their ability to execute the majority of these cryptographic tasks without making any assumptions about the behaviour of the legitimate parties' equipment. This has led to the emergence of what's known as 'device-independent' implementations, which have become a major line of defence against side-channel attacks [34].

Finally, the research of quantum communication complexity reveals that by delivering quantum information (qubits) rather than classical information, we may drastically reduce the amount of communication necessary (bits) [35]. Communication's quantum advantage is illustrated through quantum fingerprinting. The computing is the fourth significant use of quantum networks. In its most direct meaning, the modular or distributed quantum computer is an alternative paradigm to the monolithic building of a quantum computer [36]. In this paradigm, high-quality, tiny quantum computers are interconnected by entanglement to form a bigger quantum computer [37]. A quantum network can also be used to execute quantum computation on a distant quantum computer without disclosing details about the calculation or underlying data, to do multipartite computation, or to gain a computational advantage in distributed computation jobs. In conclusion, the entanglement propagated by a quantum network can enhance the performance of sensing applications. In this arena, notable applications of entanglement include clock synchronisation and interferometry, where it is used to expand the baseline of telescopes [38].

2.2 | Potential applications and utility of quantum internet

The road to building the quantum internet will be long and difficult. The current standard viewpoint is that the quantum internet will probably develop in stages. There are several ways to divide it into stages.

The classification proposed in is based on the network functionality available to the end nodes. Interestingly, quantum networks where the nodes have very limited functionality are already useful for applications, and new tasks can be implemented as the functionality of the end nodes increases. This means that we expect quantum networks to be useful even in the early stages of development (Figure 3).

2.3 | Phases of quantum internet development

As outlined in Figure 4, in the initial phase, networks of reliable repeaters are established. During this stage, nodes can prepare and broadcast quantum states to their neighbours. This functionality enables the construction of protocols for the distribution of prepared and measurable quantum keys between adjacent nodes. In this manner, it is conceivable, for instance, to establish a network of individual QKD links [39]. Nevertheless, it is not a complete quantum network because quantum information cannot be communicated to non-adjacent nodes. This extremely limited functionality is nonetheless useful: If two end nodes in a network trust the behaviour of the nodes along a path that connects them, then they can exchange secure keys.

In the second phase, preparation and measurement networks are developed from beginning to end. At this phase, nodes can prepare and transmit individual qubits to any other node in the network without assuming confidence. This may incur a cost in the form of post-selection of transmitted signals. Nevertheless, prepare-and-measure networks can be utilised for a variety of new applications, including safe identification in two-party cryptography with noisy quantum memory and key distribution. These include protocols in which entanglement is utilised to ensure security, yet nodes never share an entangled state. Alternatively, it is sufficient for nodes to confirm if entanglement can be communicated if the end nodes have performed a coherent version of a prepared and measured protocol.

Entanglement distribution networks are built in the third phase so that two users can get end-to-end quantum entanglement [40] in either a deterministic or an announced method. End nodes do not require quantum memories at this stage. If the loss is modest enough, this added functionality permits device-independent QKD.

The fourth phase involves the construction of quantum memory networks [41]. End users can store quantum information in their memories and transport quantum information to one another during this phase. The transit time between the two end nodes determines the minimum storage time. It should be noted that operations are done directly on the physical qubits at this phase. There is no room for error. If a remote quantum computer is available, this functionality enables several approaches for blind quantum calculations. It also supports protocols for expanding telescope baselines [42], cryptographic activities such as anonymous quantum communication, secret sharing, easy election of a leader, and some clock synchronisation protocols [43].

The fifth phase involves the construction of few-qubit fault-tolerant networks. Here, the end nodes can perform local quantum operations on a few logical qubits fault-tolerantly. This capability enables the execution of more sophisticated protocols.

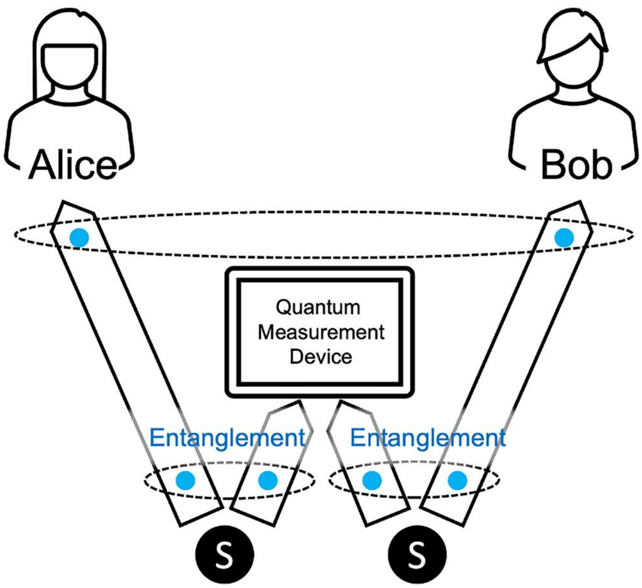

FIGURE 3 Two sources of entangled photons make up the usual quantum repeater schematic architecture. The four photons travel via four distinct fibres that are organised so that two of the photons from each source travel in opposing directions and one photon from each source travels to a quantum measuring device. The two photons that arrive simultaneously are asked, 'Are you identical?', by the quantum measurement equipment. The state that represents the two additional photons' entanglement if the measurement is successful relies on the outcome of the quantum experiment. We have shown the entanglement of two photons separated by a greater distance using this quantum measurement than we could have done with a single source of entangled photons.

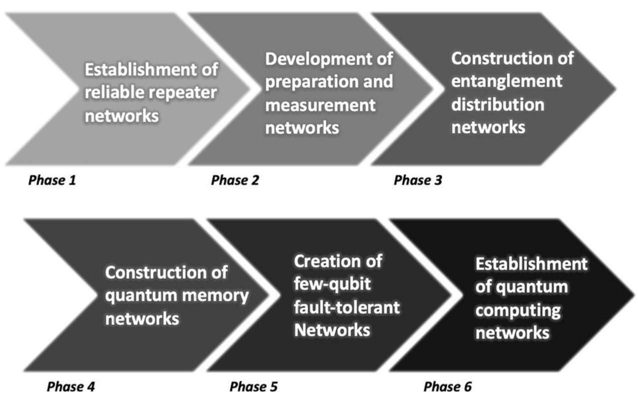

FIGURE 4 Evolution of Quantum Networks: Here, we present the outlines of the six key phases of developing a quantum network. Phase 1: Establishment of Reliable Repeater Networks, where nodes prepare and broadcast quantum states to neighbouring nodes. Phase 2: Development of Preparation and Measurement Networks, introducing the capability of qubit transmission to any other node. Phase 3: Building of Entanglement Distribution Networks, enabling end-to-end quantum entanglement. Phase 4: Construction of Quantum Memory Networks, where end users can store and transport quantum information. Phase 5: Creation of Few-Qubit Fault-Tolerant Networks, enabling local quantum operations on logical qubits. Phase 6: Establishment of Quantum Computing Networks, which allows large-scale fault-tolerant quantum processing. Each phase progressively enables more advanced quantum computations and cryptographic activities.

Specifically, an end node is capable of fault-tolerant execution of a universal gate set on q logical qubits if q is small enough for local quantum processors to be efficiently mimicked by a conventional computer. Given that conventional computing power tends to increase exponentially with time, the value of q that is still accessible by simulation is a function of both time and technology. By connecting the end nodes, this functionality enables the creation of a distributed quantum computer.

In the sixth phase, networks for quantum computing are constructed, enabling large-scale fault-tolerant quantum processing. The terminal node is capable of doing large-scale quantum computations that cannot be efficiently simulated on a conventional computer. This will be the most advanced quantum internet possible [44].

3 | QUANTUM INFORMATION TECHNOLOGIES IN 6G NETWORKS

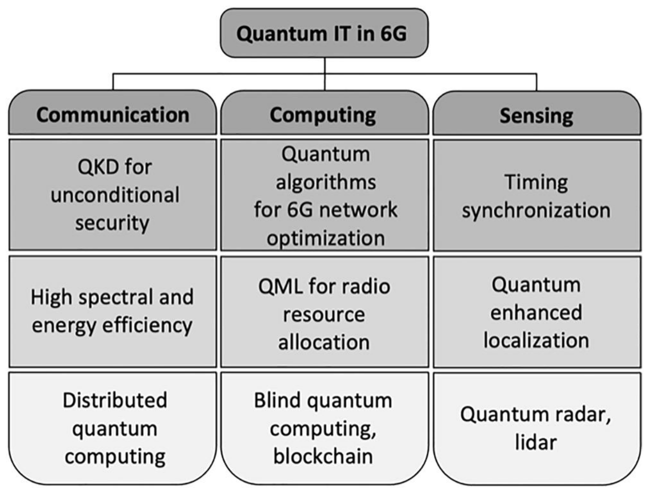

FIGURE 5 Applications of quantum information technology in 6G communications.

Over the past few decades, the development of different wireless communication technologies starting from 1G to 5G has been led by the first quantum revolution where the average or bulk properties of quantum mechanics were used to build transistors, lasers, optical fibres, integrated circuits etc [45]. The first quantum revolution was the backbone of the information technology age we are currently living in. Now, we are entering the so-called second quantum revolution where single quantum objects including photons, electrons, atoms, and molecules can be engineered to develop new communication technologies that might have capabilities beyond those achievable with classical information technology [45, 46].

Quantum technology is poised to play a significant role in the development of next-generation 6G wireless communications [47, 48]. The major applications of quantum information technology in the development of 6G wireless networks can be divided into three categories: Quantum Communications, Quantum Computing, and Quantum Sensing as summarised in Figure 5. By utilising the counter-intuitive properties of quantum physics (superposition, entanglement, and uncertainty), quantum technology can help in achieving ultra-secure communication, enhanced data rates, massive parallel computation, and enhanced localisation and navigation capabilities in next-generation 6G wireless networks.

3.1 | Quantum communications for 6G networks

Quantum communication technology can significantly improve spectral efficiency, energy efficiency, and security of 6G wireless networks.

3.1.1 | Quantum key distribution for 6G

One of the major applications of quantum communications is QKD which can provide unconditional security in 6G networks [7, 49]. 6G is likely to be a three-dimensional (3D) network comprising terrestrial networks, low-earth satellite networks, drones, and high-altitude platform-based networks along with underwater communication networks [50–52]. There are also other promising technologies for 6G networks, such as the reconfigurable intelligent surfaces [53, 54] and full duplex [55]. Therefore, QKD systems that can operate in a 3D network and compatible with other candidate technologies [56, 57] are required for providing quantum security to future networks.

Here, we present a summary of the recent experimental demonstrations of fibre-based and free-space QKD implementations. The technological advancement of fibre-based QKD technology would enable the incorporation of QKD in the 6G core network while free space QKD technology would be important for providing quantum security to the 6G wireless access network. This section also highlights how these experimental QKD demonstrations can support quantum secure data transmission in future 6G networks.

Fibre-based terrestrial QKD networks have reached significant maturity, and various test beds have already been deployed in various parts of the world [7, 49, 58, 59]. Fibre-based QKD systems have also been integrated with the classical optical network in order to support simultaneous high-rate classical communications and QKD [60, 61]. A recent work has experimentally demonstrated a high-rate fibre-based QKD system that can surpass the linear rate-transmittance bound [62]. Since 6G would be required to support high data rate applications, the work in Ref. [62] presents a promising solution for supporting long-distance quantum secure data transmission in the 6G core network. A novel discrete variable (DV)-QKD system using binary phase shift keying (BPSK) signalling has been recently proposed in Ref. [63] that can operate over a hybrid fibre-wireless channel. The hybrid QKD system of Ref. [63] is a promising solution for future 6G networks since 6G would require seamless connectivity between 6G wireless access networks and fibre-based 6G core networks.

The authors of Ref. [64] proposed a novel QKD system using intensity-modulated binary phase keying and direct detection with a dual-threshold receiver that can be implemented using standard terrestrial free space optics (FSO) systems. The FSO QKD system proposed in Ref. [64] is a promising solution for wireless QKD in the initial release of 6G standards since it can be implemented using a standard FSO system without requiring complicated single photon sources and detectors [65]. Some recent works have demonstrated long-distance terrestrial FSO QKD using both discrete variable and continuous variable technology [66, 67]. The authors of Ref. [68] have experimentally demonstrated a high-dimensional QKD protocol using orbital angular momentum that can be used for high-rate QKD applications. The experimental FSO QKD systems developed in Refs [66–68] can operate during both daytime and nighttime, which makes them a promising solution for backhaul QKD links in future 6G networks.

Since the 6G network is likely to be composed of an integrated space-air-ground network [69], novel QKD systems that can seamlessly distribute quantum secure keys between terrestrial, satellite, and high-altitude networks are necessary for future 6G networks. Some of the recent works have demonstrated experimental air-to-ground QKD systems using aeroplanes [70, 71]. The authors of Ref. [72] have carried out a feasibility study of air-to-ground QKD using high-altitude platforms. Some initial progress has also been made in experimental drone-based QKD systems using commercial off-the-shelf multi-copters with optical payloads [73, 74]. Satellite-based QKD systems can distribute quantum secure keys at a global scale that is beyond the reach of fibre-based and terrestrial FSO QKD systems. Recently, considerable progress has been made in experimental satellite-based QKD systems after the launch of the first quantum satellite named Micius [75, 76]. With the initial success of large satellite-based quantum experiments carried out by space agencies, now researchers are focusing on small-satellite-based QKD networks that can support a large number of users in a global quantum communication network [25]. In this regard, recent progress has been made in CubeSats-based QKD networks that operate at low earth orbit and can seamlessly connect with the terrestrial 6G network [77]. Currently, different countries have developed research missions to deploy small satellite-based QKD networks including SpeQtre which is a joint UK-Singapore effort [78], QUARC which is a UK initiative for QKD service in UK [79], QUBE which is a German mission for testing QKD between LEO CubeSat and ground station [80], Q3Sat which is an Austrian quantum CubeSat mission, and QEYSSat which is a Canadian microsatellite mission for quantum encryption and science experiments [81]. Since future 6G networks are likely to be composed of a 3D network comprising of low-earth small satellites, therefore CubeSats-based QKD networks may play an important role in providing quantum security in future 6G networks.

Apart from point-to-point QKD links for backhaul networking, 6G networks would also require quantum access networks for providing wireless QKD service to the last mile. This involves providing quantum communication services to mobile users from cellular base stations (BS) for outdoor applications and WiFi access points for indoor applications. Since terahertz (THz) is a potential frequency band for future networks [82], THz QKD is an attractive solution for providing QKD services to mobile users [83]. Furthermore, similar to classical multiple-input-multiple-output (MIMO) wireless communications, MIMO THz QKD can provide high safe keeping receipt (SKR) and larger transmission distances for 6G QKD applications [84–86]. However, THz quantum sources and detectors are technologically less mature, and significant efforts are required to practically realise THz QKD systems for deployment in future 6G networks. Since quantum hardware is more mature in the optical frequency band, visible light communications (VLC) and LiFi-based systems can provide QKD services to mobile users in the indoor environment [87, 88]. Unlike outdoor FSO systems, VLC and LiFi-based systems use wide-angle transmission and can support mobile users since they do not require delicate tracking and pointing of the user [89] and can support positioning naturally [90]. VLC is envisaged to be potentially combined with some other radio access technologies to provide complimentary large bandwidth for data transmission [91]. The authors of Ref. [92] have theoretically studied the feasibility of CV-QKD protocol using a sub-carrier index modulation-based indoor VLC communication system. Some recent progress has also been made in the experimental demonstration of handheld free space QKD for short-range applications. The authors of Ref. [93] have developed a handheld QKD device that can achieve 30 Kbps SKR over a distance of 0.5 m. Furthermore, the authors of Ref. [94] have developed a low-cost, short-range QKD system for consumer applications that can support a peak SKR of 20 Kbps. With the recent advances in integrated photonics and chip-based QKD [95], considerable progress has been made in the development of handheld QKD terminals [96] that can be used for short-range applications including secure ATM transactions and device-to-device quantum key exchange [97]. Further advancement in chip-based QKD technology would enable the widespread commercialisation of mobile QKD devices in future 6G networks.

The 6G wireless network should seamlessly integrate with the quantum internet in order to provide end-to-end security using QKD. The quantum secure keys need to be distributed from the wireless access network to the core quantum internet which would require the integration of wireless FSO/VLC QKD with fibre optics-based QKD. Once the quantum secure keys are distributed between two users using QKD, the symmetric keys can be used for securing different cryptographic algorithms in the conventional open systems interconnection layers for example, Secure Shell (SSH)/HTTPS in the application layer, Transport Layer Security (TLS)/SSL in the transport layer, IPsec in the internet protocol layer, PPP/IEEE 802.1 MACsec in the media access control (MAC) layer and one-time-pad based physical layer encryption in the PHY layer [49]. Furthermore, QKD can be integrated with other emerging cryptographic algorithms to provide enhanced security. The quantum keys obtained from QKD can be used for implementing post-quantum encryption (PQE) cryptographic algorithms. Therefore, future 6G networks would employ a hybrid encryption scheme utilising both QKD and PQE in order to provide unhackable end-to-end security to the users [98].

3.1.2 | Quantum enhanced classical data transmission for 6G

Apart from providing enhanced security, quantum communication technology can be used to improve the performance of classical data transmission in terms of higher spectral efficiency, higher energy efficiency, and lower bit error rates [99, 100]. Recent works have proposed practical quantum enhanced receivers that can surpass the standard quantum limit and achieve lower bit error rates as compared to classical receivers for on-off keying, BPSK, phase shift keying, and pulse position modulation schemes [101, 102]. While classical receivers are based on homodyne, heterodyne, or direct detection, quantum receivers operate at the single photon level and use optimal quantum positive operator value measurements [103].

Under the classical physics regime, the ultimate capacity of communications channels is given by the well-known Shannon's capacity theorem [104]. However, by utilising the quantum mechanical properties of quantum communication channels the ultimate capacity is given by the Holevo capacity [105–108]. The development of classical communication networks from 1G to 5G has focused on achieving Shannon's capacity limits by developing new modulation and coding schemes that work at the classical limits [109, 110], as well as utilising advanced signal processing and resource management schemes to help reaching that limit [111–113]. With the recent developments in the quantum transmitter and receiver design, future communication networks have the possibility to operate at the quantum Holevo limits and support the ever-increasing data rate requirements while requiring lower transmission powers. The classical capacity can further be improved if the transmitter and receiver are equipped with the additional quantum entanglement as a resource [114–116]. The authors of Refs [114, 117] have shown that by operating at the quantum Holevo limit, the energy consumption of optical fibres can be significantly reduced, thereby leading to the development of an energy-efficient and sustainable 6G network.

3.1.3 | Distributed quantum computing for 6G

Apart from transmitting classical information, quantum communication channels can also efficiently transmit quantum information or qubits [118–121]. Quantum communication networks can enable distributed quantum computing by interconnecting different quantum computers through quantum communication channels [19, 37, 122–124]. In the near term with the noisy intermediate state quantum (NISQ) computing era, each quantum computer will consist of only a few hundred qubits [125–130]. The computing capabilities of these distributed NISQ devices can be exponentially increased by interconnecting their qubits using the quantum network [131]. The combined computing power of the interconnected NISQ devices can be used for practical quantum advantage in drug discovery, protein folding, new material discovery, weather forecasting, Artificial Intelligence (AI), financial modelling, and complex optimisation problems [132–137].

A quantum enabled 6G network could provide secure access to the cloud quantum computing services by using hybrid encryption framework that utilises both QKD and PQE [98]. Both 6G networks and quantum internet are currently in the development phase. As both of these technologies mature in the next 10–20 years, 6G and quantum computing will complement each other to support distributed quantum computing.

Globally, scientists are conducting fundamental research and development in the disciplines of 6G and quantum technology [138]. Quantum computers will have demonstrated 'quantum supremacy' over classical computers in specific tasks by 2025, but they are not yet commercially viable [139]. Quantum communication and cryptography are undergoing development as well. Beginning conceptual and theoretical work on 6G, the concentration is on technologies such as AI, machine learning (ML), and advanced forms of network virtualisation and slicing.

Early commercialisation and standards development of QKD might start in 2025–2028. The launch of the first quantum communication satellites paves the way for ultra-secure global data transmission [140]. The release of quantum programming platforms by major technology companies makes it simpler for developers to experiment with quantum algorithms. The initial iteration of the 6G standard is formalised and the first 6G trials and testbeds appear in the telecommunications industry [141]. Theoretical research begins to investigate the intersection between quantum computing and 6G networks.

Early deployment and integration of QKD in 6G might start from 2028 to 2033. During that time, quantum computers might become commercially available, although they are still expensive and predominantly used by large corporations and researchers [142]. At that time, quantum cryptography is being implemented in sensitive applications such as financial transactions and military communications. Around 2030, the first commercial 6G networks will be deployed. These networks support applications such as immersive augmented reality and sophisticated AI applications. During 2032–2033, quantum technologies are beginning to have an impact on 6G, with researchers investigating quantum ML algorithms for network optimisation and quantum cryptography for network security.

At present, the operation of quantum computers requires high power consumption and cost [143]. The requirement of high cost and power consumption is due to the cryogenic refrigerators that are required to maintain millikelvin temperatures for running the superconducting quantum circuits, trapped ion qubits, topological qubits, and Majorana qubits [144, 145]. Therefore, currently, quantum computers are hosted on the cloud by large companies and government organisations only [146]. The future 6G networks can enable users to securely access the cloud quantum computers where the user data is secured using QKD. However, there are some quantum computing hardware technologies that have been proposed or demonstrated to operate at or near room temperature, although they are still in the early stages of development. For example, spin qubits, diamond nitrogen-vacancy (NV) centres, photonic quantum computing, and quantum dot-based qubits [147–150].

As the technological maturity of these quantum computing hardware technologies increases in the next 10–20 years, it is expected that the cost and power requirement of quantum computers would significantly reduce and enable wider adoption of quantum computing in the community [151, 152]. Therefore, it is expected that distributed quantum computing technology would be available in the next decade as the technological maturity of quantum computing and networking increases in the next decade.

3.2 | Quantum computing for 6G networks

Quantum computing can provide exponential speed-up for specific optimisation problems by utilising the superposition principle of quantum mechanics [153, 154]. Furthermore, quantum ML algorithms can improve the performance of classical ML algorithms by utilising superposition and quantum entanglement as computing resources [155, 156]. Quantum algorithms and quantum ML can provide new solutions for many challenging network design problems in future 6G wireless networks as discussed below.

3.2.1 | Quantum algorithms for 6G

Quantum algorithms can efficiently solve complex optimisation problems in 6G that are difficult to solve using classical algorithms. For 6G network design, quantum computing algorithms can help solve complex optimisation problems in resource allocation, user scheduling, network topology design, routing, data detection, and beamforming design [157–159]. In order to support ultra-reliable and low latency communications to the massive number of users in future 6G networks, quantum processors can be used to efficiently solve network optimisation problems within a short processing time. In order to efficiently solve complex optimisation problems that are beyond the reach of current classical computing resources, quantum processors may be deployed at the centralised data centres that jointly process the data from multiple BS [158]. Since the cost and power consumption are high for quantum computers, initially the quantum processors can only be deployed only at centralised data centres. We expect that by the time 6G networks are operational in the next decade, quantum computing technology would be mature enough to support quantum computers at the centralised data centres in about 10 years of time [152]. Furthermore, as other quantum computing hardware emerges that does not require cryogenic cooling, for example, photonic, diamond NV centres, and spin qubits, quantum processors may also be deployed at the BS in the next 15–20 years of time frame [152].

With the deployment of massive MIMO antennas at BS that serve a large number of users, data detection and channel decoding become challenging with classical computing architectures. Recent works have shown promising results for quantum algorithms enhanced MIMO data detection in centralised radio access networks (C-RANs) [160]. Some other recent works have also investigated quantum-inspired and quantum annealing algorithms for near-optimal MIMO data detection [161–163].

Quantum search algorithms have also been investigated for optimal maximum-likelihood (ML) multi-user detection (MUD), and it has been shown that quantum algorithms can achieve a quadratic reduction in computational complexity as compared to classical counterparts [164]. Some other recent works have also shown the applicability of quantum algorithms for computation complexity reduction in ML MUD problems for multiple access schemes including OFDMA, CDMA, and SDMA [165, 166]. Quantum algorithms are also shown to provide enhanced performance for joint channel estimation and MUD for non-orthogonal multiple access (NOMA) wireless communication systems [167, 168]. The authors of Ref. [169] have investigated the applicability of quantum search algorithms to reduce the computational complexity of indoor localisation problems in mm-Wave and VLC communication systems. A recent study has also investigated quantum annealing-based large MIMO precoding for efficiently solving the NP-hard problem of vector perturbation precoding [170].

Furthermore, quantum algorithms are also shown to provide the optimum decoding performance for low-density parity check (LDPC) and polar decoding in a short amount of time [171–173]. Therefore, quantum algorithms can potentially be used for low-latency 6G applications. Quantum approximate optimisation algorithms (QAOA) are hybrid classical-quantum algorithms that can be used for efficiently solving NP-hard combinatorial optimisation problems arising in 6G wireless networks including traffic scheduling, routing, and cluster selection [174–178]. Recent studies have investigated QAOA algorithms for optimal channel decoding [179] and optical multi-dimensional quadrature amplitude modulation [180] whose performance approaches the optimal ML scheme. The authors of Ref. [181] have proposed a variational quantum circuit (VQC)-based turbo decoder for MIMO systems, and it is shown that its performance approaches to that of the optimal ML detection scheme. A recent study has also introduced a VQC-based compressive sensing scheme for joint user identification and channel estimation for a grant-free communication system [182].

3.2.2 | Quantum machine learning for 6G

In recent years, classical ML algorithms have drawn considerable attention from communication engineers to solve complex optimisation problems including wireless channel estimation, data detection, precoding, and channel decoding. Data-driven optimisation algorithms have been shown to improve the performance of communication systems since the inference time is greatly reduced once the ML or deep learning models are trained offline and then deployed at the BS or mobile devices [183, 184]. Quantum ML algorithms can further improve the performance of 6G wireless networks by utilising the counter-intuitive properties of quantum entanglement and superposition [155, 185]. Quantum circuits comprising qubits and quantum gates can extract enhanced features from raw data using the principles of quantum superposition and entanglement that are otherwise not possible with classical computing algorithms. Hybrid quantum-classical ML algorithms use quantum circuits for extracting the features from the data and then apply classical ML or deep learning models on the extracted features to achieve enhanced performance in classification and regression tasks [186, 187].

Quantum neural networks (QNNs) are hybrid classical-quantum ML models that are composed of parametrised quantum circuits (Ansatz) and classical feedforward neural networks that are trained iteratively by minimising a cost function [156]. Recent studies have investigated the applicability of QNNs to reduce training and inference time complexity for wireless resource allocation problems [168, 188, 189]. QNNs have also been investigated for cognitive radio spectrum sensing [190], CDMA MUD [191], and network traffic forecasting [192]. Recent works have also investigated quantum reinforcement learning-based unmanned aerial vehicle trajectory planning that have a better balance between exploration and exploitation and lower computational complexity as compared to classical reinforcement learning [193, 194]. Recent works have also investigated the applicability of QNNs for WiFi sensing where the received RF signals at the WiFi node are used to train a QNN on a cloud quantum computer for enhanced human pose recognition tasks [195–197]. Furthermore, a continuous-variable QNN framework comprising key generation, encryption, and decryption has also been investigated for cryptography application [198].

3.2.3 | Blind quantum computing and quantum blockchain for 6G

With the proliferation of cloud-based quantum computing services, blind quantum computing (BQC) could improve the privacy and security of sensitive user data in future 6G networks [47]. BQC allows users to access cloud-based quantum computing services without revealing the content of their data to the quantum computer. BQC is based on cryptographic algorithms that can enable quantum computation on encrypted data and provide correct solutions without revealing the input, computation, and output to the quantum computer [199]. BQC will also be a major use case of the future quantum internet where a client can carry out quantum processing on the data qubits without revealing its contents to the server [19, 44, 200, 201]. A recent work has demonstrated BQC using the measurement-based quantum computing framework for implementing Deutsch and Gover's algorithm [202]. Quantum homomorphic encryption can support BQC where users can manipulate the encrypted quantum data such that the output of the computation is still encrypted but it can be decrypted to obtain the desired result [203]. BQC could enable users to securely access cloud-based quantum computing services for running quantum AI and ML models without compromising data privacy in future 6G networks.

Blockchain technologies have attained significant attention in recent years due to their ability to provide transparency and accountability using distributed ledger technologies [204, 205]. Blockchain technologies are extensively used in financial services, smart grids, secure healthcare data storage, intellectual property management, secure voting services, and supply chain management [206–208]. Blockchain technology may be used for enabling certain 6G services, for example, decentralised authentication of users and distributed wireless resource sharing among users that might not trust each other [47]. However, classical blockchain technology has certain limitations like low transaction speeds and security threats from malicious users and privacy breaches [209]. Therefore, future 6G networks might require quantum-secured blockchain technologies that leverage the security guaranteed by QKD and post-quantum cryptography protocols [210–212]. Furthermore, entanglement can be used as a resource to design efficient blockchain transaction algorithms in order to reduce communication overhead and increase transaction speed [47].

3.3 | Quantum sensing for 6G networks

Quantum sensing and metrology use the unique properties of quantum mechanics like entanglement and squeezing [213] to achieve high-precision measurements that are not possible with classical measurement schemes [20, 214, 215]. Quantum sensors use unique quantum-mechanical properties to measure and detect physical phenomena with unprecedented sensitivity and accuracy [216]. Quantum sensing and metrology have the potential to significantly improve the performance of 6G wireless networks for enhanced timing synchronisation, localisation, and navigation [47].

3.3.1 | Quantum enhanced timing synchronisation

Timing and phase synchronisation among different nodes is very important for the secure and reliable operation of the different protocols in a communication network. Timing synchronisation is also necessary for network traffic engineering and assessing the network performance metrics. Current communication networks use an atomic master clock for synchronising other slave clocks in the network using a global navigation satellite system (GNSS) [217]. With the exponentially increasing number of connected devices, network traffic, and high data rates requirements, next-generation 6G wireless networks would require more stringent demands on timing and synchronisation technologies for uninterrupted operation. Next-generation quantum clocks can provide increased accuracy in timing synchronisation by utilising quantum entanglement and quantum squeezing operations [218, 219]. There also exist quantum methods for clock synchronisation that can beat the standard quantum limit by using qubit exchange and without requiring entanglement [220]. Furthermore, quantum algorithms can also improve the accuracy of distributed clock synchronisation problems [221]. Apart from theoretical advances in quantum clocks, recent works have also demonstrated experimental quantum clock synchronisation on fibre optic cables that can achieve an accuracy of the order of a few picoseconds [222–224]. Therefore, future 6G networks could deploy quantum master clocks in the network architecture that would transmit ultraprecise (~picoseconds) timing information to the quantum slave clocks [217].

3.3.2 | Quantum enhanced localisation and navigation

The GNSS positioning system uses the triangulation method by using the time difference of arrival of signals for determining the location of a mobile user [225]. The positioning accuracy of the GNSS-based navigation system can be significantly improved by using quantum clock synchronisation technologies that have improved clock synchronisation accuracy as compared to the current GNSS system. The classical limits in positioning and ranging accuracy can be overcome by utilising quantum entanglement and squeezing [218]. What is more, by using quantum entanglement-based methods, the position of the legitimate user can be determined in a secure way without leaking any position information to the eavesdropper [226].

Quantum radar works on the principle of quantum illumination where entangled signal-idler pairs are used for enhanced target detection [227]. The signal mode is transmitted towards the target which after reflection is then jointly measured with the idler model stored in a quantum memory to obtain enhanced accuracy in detecting the range and velocity of the target object [228]. The principle of quantum illumination allows the detection of a weakly reflecting target embedded in high background noise by using entangled single photon pulses [229]. Recent works have theoretically established the ultimate quantum-limited precision in simultaneous range and velocity estimation of a target using entanglement as a resource [230]. Quantum lidars using squeezing and frequency-entangled signal and idler beams can provide enhanced precision in the radial velocity estimation of a moving target [231]. Quantum lidar technology can also provide enhanced performance in imaging applications using entangled single photons [232]. Furthermore, atomic quantum sensors that use the quantum mechanical principles of light-matter interaction can be used to build highly sensitive RF sensors [233]. Compared to conventional dipole-antennas, the RF atomic sensors could provide accurate and high-sensitivity electric field measurements that can be used to build improved receivers for radar and communication applications in future 6G networks [234].

Apart from quantum hardware technology using quantum sensors, quantum software technology can also provide enhanced performance in target detection by using quantum-enhanced algorithms for classical target detection in complex environments [235]. Since user localisation, navigation, and sensing are important services in future 6G wireless networks [236–238], quantum-enhanced radar and lidar technology might play an important role in 6G that can significantly improve positioning accuracy and imaging quality.

Quantum radar and quantum lidar can play a critical role in autonomous driving by providing highly accurate and reliable sensing capabilities. Quantum radar can provide highly accurate range and velocity information for objects in the environment [228, 230], which is critical for autonomous vehicles to make safe and efficient navigation decisions. In addition, quantum lidar can provide high-resolution, 3D imaging of the environment [239, 240], which is essential for autonomous vehicles to understand the layout of the road, detect obstacles, and make decisions based on their surroundings. Currently, the prototypes of quantum radar and lidar have demonstrated superior performance in laboratory setups only [239–241]. While quantum lidar using optical frequencies can operate at room temperature [239, 240], quantum radar using entanglement requires cryogenic refrigerators for preserving quantum coherence effects at RF frequencies [241]. Furthermore, the sensitivity of conventional radar systems can be improved by using a Rydberg atomic sensor as a receiver that can detect very faint targets while operating at room temperature [234, 242]. As quantum technology matures in the next decade with the miniaturisation of quantum sources and detectors at optical frequencies, quantum lidar and Rydberg atom-based quantum radar technology have the potential to revolutionise autonomous driving by providing more accurate and reliable sensing capabilities [243].

4 | STANDARDISATION EFFORTS TOWARDS A QUANTUM 6G

Currently the industry is focusing on the full roll-out for 5G networks, and there are only some visional work initiated on 6G. Several major regional and international standard development organisations (SDOs) are contributing to this effort, especially the European Telecommunications Standards Institute (ETSI) and the International Telecommunication Union (ITU)'s Telecommunication Standardisation Sector (ITU-T).

In the ETSI, an industry specification group (ISG) was established to address research and pre-standard issues related to QKD in 2008 [244]. Founded to develop reports and specifications describing quantum cryptography for information and communication networks, the ISG meets regularly and updates the group reports (GRs) and group specifications (GSs). Both GSs and GRs are official deliverables from an ISG, where GRs usually provide a technical overview on specific topics, while GSs can be used as guidelines for system implementations. So far, ISG-QKD has published a series of GRs and GSs, specifying details in QKD deployments, application interface design, optical component characterisation, and other related issues in previous study periods. In the current study period, 10 work items are under progress to compose new GRs and GSs, or update, extend, and revise existing ones. Specifically, GS QKD 005 is revised in response to recent networking developments, where modifications including security definitions, device models, implementation security, and QKD protocols are specified. Apart from those revisions to existing documents, work item GS QKD 010 studies the protection against Trojan horse attacks, and its publication document addressing aspects of the design, construction, characterisation, and operation of QKD systems is expected to be publicly available on November 2023. GS QKD-13, GS QKD-16 and other deliverables are under study as well, and details of their information can be found in Table 1. Although the ETSI is a regional SDO, it has a strong connection to other SDOs such as the third generation partnership project (3GPP). The study reports generated by the ETSI can be taken as input by 3GPP and create a more profound impact on the global standardisation of 6G.

The ITU is an official and global SDO that has great impact to not only researchers and industry players but also policymakers and regulations. From 4G to 6G, visionary works on the next-generation communication systems are first produced in the ITU, following detailed technical studies and specifications in SDOs like the 3GPP.

In the radiocommunication sector of the ITU (ITU-R), security and privacy have attracted a lot of attention from sector members and state members. There is a broad consensus that 6G would require a higher level of security,

TABLE 1 Summary of work items in ETSI ISG-QKD.

Work item reference	Title	Scope
GS QKD 004 V 2.1.1 (2020-8)	Application interface	Describing the application programming interface (API) between the security applications and the QKD key manager
GS QKD 005 V 1.4.3 (work in progress)	Security proofs revision	Summarising security definitions, device models, implementation security and quantum key distribution protocols
GR QKD 007 V 1.4.2 (work in progress)	Vocabulary revision	Collecting definitions and abbreviations used in relation to other documents
GS QKD 010 V 0.4.1 (work in progress)	Implementation security: Protection against Trojan horse attacks in one-way QKD systems	Addressing aspects of the design, construction, characterisation and operation of QKD systems that are intended to protect against Trojan horse attacks and providing related requirements, measurement methods and examples
GS QKD 011 V 1.1.1 (2016-5)	Component characterisation: Characterising optical components for QKD systems	Specifying and providing procedures for the characterisation of optical components in QKD systems
GS QKD 012 V 1.1.1 (2019-2)	Device and communication channel parameters for QKD deployment	Describing the main communication resources in QKD systems and providing a possible architecture for QKD deployment over an optical network infrastructure
GS QKD 013 V 0.1.2 (work in progress)	Characterisation of optical output of QKD transmitter modules	Defining procedures for characterising specific properties of complete QKD transmitter modules
GS QKD 014 V 1.1.1 (2019-2)	Protocol and data format of REST-based key delivery API	Specifying the communication protocols and data format of REpresentational State Transfer (REST) API
GS QKD 015 V 2.1.1 (work in progress)	Control interface of software defined networks	Providing definitions of management interfaces for the integration of QKD in SDN, abstraction models and workflows between an SDN-enabled QKD node and the SDN controller
GS QKD 016 V 1.2.2 (work in progress)	Common criteria protection profile—pair of prepare and measure quantum key distribution modules	Describing complete systems involving point-to-point devices from the physical implementation up to the output of final secret keys and giving high-level requirements
GR QKD 017 V 0.0.11 (work in progress)	Network architectures	Reviewing the variety of architectures that have been proposed for QKD networking
GS QKD 018 V 1.1.1 (2022-4)	Orchestration interface for software defined networks	Providing definitions of orchestration interfaces between SDN orchestrators and SDN controllers of QKD network
GR QKD 019 V 0.0.99 (work in progress)	Design of QKD interfaces with authentication	Summarising designs of classical interfaces for QKD systems that include authentication, including protocols used in discussion channels, auxiliary channels, management interfaces and key delivery interfaces
GS QKD 020 V 0.2.1 (work in progress)	Protocol and data format of REST-based interoperable key management system API	Specifying a representational state transfer (REST) API that allows key management systems to interoperate to pass keys horizontally between two systems located in a common trusted node
GS QKD 021 V 0.0.1 (work in progress)	Orchestration interface of software defined networks for interoperable key management system	Summarising interfaces between the SDN orchestrator and the SDN controller of QKD networks for cooperating key management systems and defining abstraction models and workflows between orchestrators and controllers of QKD SDN

supported by potentially new technical enablers such as QKD. As reflected by the ongoing work developed in ITU-R working party 5D (WP5D) [245], quantum-enabled security is a trendy topic and may play an increasingly critical role in 6G.

Within the ITU-T, a focus group on quantum information technology for networks (FG-QIT4N) was established in 2019 [246]. The major goal of the focus group is to study the evolution and applications of quantum information technologies for networks, with QKD constituting the key technology. As a collaborative platform for pre-standardisation, FG-QIT4N concluded its work on November 2021 and delivered several technical reports related to quantum technologies to ITU-T study group (SG) 13. The primary focus of SG 13 is topics related to future networks, currently on 5G and beyond. With the deliverables from FG-QIT4N, it develops standards for QKD networks (QKDN) and related technologies in work items Y.3800 series. The overall structure and basic functions of a QKDN are first reviewed in work item Y.3800. Then, the requirements and architecture of a QKDN are reviewed in work item Y.3801 and Y.3802, respectively. Based on the defined requirements, functional elements and procedures of key management and network management are then specified in Y.3803 and Y.3804. Since 6G networks are likely to require a large scale of QKD networks to provide the end-to-end QKD service to cover the large areas to the end users, apart from standardising functional requirements and architecture of a single QKDN, it is important to study how to interwork multiple QKDNs to construct a large scale QKDN. In work item Y.3810, two types of interworking interfaces are introduced to support the interworking between QKDN providers, namely gateway nodes (GWN) and interworking nodes (IWN). Based on the reference model, the functional requirements of different layers in QKDNi supported by GWN and IWN are detailed in Y.3813, as the basis for the follow-up development of technical standards. The standardisation works related to QKDNi are still under study. Different from those completed work items with published recommendations, the ongoing projects do not have numerical codes in their work item codes, and the related standards are not available now. The architecture of QKDNi will be further specified in the recommendation published in work item Y.QKDN-iwac. The combination of Software Defined Network (SDN) and QKDNi will be studied in Y.QKDNI-SDNC, and the QoS assurance for QKDNi will be discussed in Y.QKDN-amc. Details of these work items are summarised in Table 2.

ITU-T SG 17 also studies quantum-safe security since the group is focused on security studies. Work item X.1710 published the first standardisation in the series on the security of QKD, where the security framework, requirements, and measures are proposed on the basis of analysing the relevant security threats. Since the key management layer is very important in the layered model of QKDN, work item X.1712 studied security issues of key management and specified related security requirements. Then, the security requirements of key combination and key supply are specified in work item X.1714. Despite these studies, there are still some security issues related to QKDN and QKDNi that have not been specifically addressed, such as the security requirements for trusted nodes in QKDN and QKDN interworking. These requirements are believed to play a significant role in enlarging the key

TABLE 2 Summary of work items on QKD under ITU-T SG 13.

Work item code	Title	Scope
Y.3800	Overview on networks supporting quantum key distribution	Providing conceptual layer structures of QKDN, and defining the basic of different layers in QKDN
Y.3801	Functional requirement for quantum key distribution network	Specifying the functional requirements for different layers in QKDN, including quantum layer, the key management layer, the QKDN control layer and management layer
Y.3802	Quantum key distribution networks—functional architecture	Defining a functional architecture model of QKDN, specifying detailed functional elements and reference points, architectural configurations and basic operational procedures of QKDN
Y.3803	Quantum key distribution networks—key management	Describing key formats functional elements and operations of key management to help the implementation and operation
Y.3804	Quantum key distribution networks—control and management	Specifying control and management functions and procedures of QKDN control, management, and orchestration distribution
Y.3810	Quantum key distribution network interworking—framework	Describing the overview of interworking QKDNs, the reference models, and the functional models of gateway functions (GWFs) and interworking functions (IWFs)
Y.3813	Quantum key distribution networks interworking—functional requirements	Describing the functional requirements for key management layer, QKDN control layer, and QKDN management layer in QKDNi
Y.QKDN-iwac	Quantum key distribution networks interworking—architecture	Specifying functional architecture, functional elements, and basic operational procedures for QKDNi
Y.QKDNi-SDNC	Quantum key distribution network interworking—software defined networking control	Specifying the SDN control for the interworking between QKDN providers, focusing on the functional requirements and architectures for SDN controller in QKDNi
Y.QKDN-amc	Requirements of QoS assurance for QKDN interworking	Specifying the high-level and functional requirements of QoS assurance for QKDNi

TABLE 3 Summary of work items on QKD under ITU-T SG 17.

Work item code	Title	Scope
X.1710	Security framework for quantum key distribution networks	Specifying a simplified framework including security requirements and measures to combat security threats for QKDN
X.1712	Security requirements and measures for QKD networks—key management	Specifying the security threats, security requirements and security measures of key management for QKDN
X.1714	Key combination and confidential key supply for quantum key distribution network	Describing key combination methods for QKDN and specifying security requirements for both key combination and key supply
X.sec_QKDN_AA	Authentication and authorisation in QKDN using quantum safe cryptography	Studying IDs and their management, public key certification supported by the public key infrastructure (PKI), and authentication and authorisation in QKDN
X.sec_QKDN_CM	Security requirements and measures for quantum key distribution networks—control and management	Specifying use cases, security threats in the context of quantum computing, security requirements and security measures for controllers and managers of QKDN
X.sec_QKDN_tn	Security requirements for quantum key distribution networks—trusted node	Identifying the security threats and providing security requirements of trusted node
X.sec_QKDNi	Security requirements for quantum key distribution network interworking (QKDNi)	Specifying security threats for QKDNi, and security requirements for QKDNi including authentication and authorisation aspects

distribution distance and enriching QKD-based applications in the future network, which will be studied and specified in the next study period. The aforementioned work items are summarised in Table 3.

In order to encourage possible cooperation on QKD-related standardisation and avoid duplication of work, the joint coordination activities (JCA) on QKDN was set up by the ITU in December 2022 to coordinate standardisation work among ITU-T and other SDOs. It is now working on maintaining a QKDN standardisation roadmap by establishing a database of quantum information technology standards as well as providing analysis on QKDN standards development. Its working progress has been presented in ITU Workshop on 'Future technology trends towards 2030' held in July 2023, which is believed to provide guidelines for the standardisation work of 6G.

5 | CONCLUSION AND OUTLOOK

Important use cases for the quantum internet will be found in sensor networks, upscaling quantum computers, and secure quantum communication. Quantum repeaters are one of the potential building blocks for the quantum internet, and research into them has been substantial. As we have shown, quantum repeaters are necessary in order to successfully construct an effective quantum internet. The 6G network is expected to bring speeds that have never been seen before, decreased latency, more capacity, and enhanced dependability. These advancements will make it possible to launch new apps and services that were not feasible in the past. On the other hand, the quantum internet has the potential to revolutionise the way that we communicate and process information by leveraging the unique properties of quantum mechanics, such as entanglement and superposition, to achieve unbreakable security and faster processing. This could lead to a paradigm shift in how we communicate and how we process information.

While it is anticipated that the 6G network might be put into operation within the next decade, the development of the quantum internet is still in its infancy at this point. Yet, in order for any of these technologies to become a reality, major expenditures in research and development as well as infrastructure are going to be required. In addition, there are a number of technological and practical problems that need to be resolved before these technologies may be used to their full potential.

The advent of 6G network and quantum internet heralds a transformative era in communication, information processing, and business operations. As we navigate through the challenges and uncover new potentials, these groundbreaking technologies promise to shape our future, providing unexplored opportunities and advances. The path forward calls for rigorous research and exploration, which undeniably holds an exciting potential for unforeseen advancements.

The QKD is a technology that is on the verge of commercialisation and has several possible applications for future communication systems. According to what we have thoroughly described in this treatise, even though an unfathomable amount of investment has been poured down for the research and development of QKD, a massive standardisation effort is required to guarantee the sustainability and reliability of near-future deployment and to accommodate a variety of potential use cases and a number of plausible QKD protocols. This is the case despite the fact that an immeasurable amount of investment has been poured down for the research and development of QKD. To be more precise, we have included a summary of the progress made in standardisation as well as the industrial hurdles that stand in the way of the broad application of QKD for our future communication networks. This applies to both DV and CV-QKD systems. The path that leads to the industrialisation of QKD is one that is both lengthy and winding, and it is abundantly evident that this is the case. A multi-disciplinary approach is required in order to conceive the ultimate aim of quantum-safe communications systems. This approach must range from the theoretical investigation of the

QKD use cases to the actual physical implementation of QKD devices. To finish this treatise, we think that close cooperation between academia, industry, and the government will enormously expedite the advancement of standardisation and the adoption of QKD in industrial settings.

We project that the integration of QKD into 6G technology will not only be feasible but highly beneficial. This is because QKD demands secure quantum connectivity to quantum computational resources, a feature that aligns with the advanced capabilities 6G is expected to offer. With traditional computational capacities, deploying QKD on a large scale may present challenges due to its significant reliance on quantum computational resources. However, with 6G providing secure quantum access to these resources, it stands to revolutionise the scalability of QKD systems. In this way, 6G technology could serve as a catalyst for the global advancement and implementation of QKD, enhancing the security and efficiency of future communication networks.

To do this, 6G networks may connect QKD users to quantum computing facilities in a safe and high-throughput way. For this to work, there must be a reliable means of communication that is impervious to snooping, hacking, and other forms of interference.

QKD systems might be made more efficient, scalable, and secure by utilising quantum computing resources, paving the way for broad implementation of quantum encryption for secure communication.

We envision that combining a quantum backbone infrastructure with additional security technologies like encryption, authentication, and access control can provide end-to-end (E2E) safe functioning for 6G devices. Some possible approaches to realising this union are listed below.

i) Post-Quantum Cryptography: While there are many security benefits of quantum computing, traditional cryptography is threatened by it. Together, QKD and post-quantum cryptography can give an extra layer of security to 6G devices, as the latter is immune to assaults from quantum computers.
ii) Authentication: With authentication procedures, we can make sure that only approved devices may connect to the 6G network. Technologies like multi-factor authentication, biometrics, and digital certificates fall within this category.
iii) Safe Protocols: Safe protocols can be used to keep data transmitted between 6G devices and the network safe. TLS and SSH are two examples of protocols that may be used to encrypt data in transit and authenticate communication.

In conclusion, the 6G network, quantum internet, and QKD technologies are fascinating and intriguing innovations with the potential to revolutionise how we communicate and safeguard data.

AUTHOR CONTRIBUTIONS

Georgi Gary Rozenman: Investigation; methodology; visualisation; management; writing – original draft; writing – review and editing. **Neel Kanth Kundu**: Investigation; methodology; visualisation; management; writing – original draft; writing – review and editing. **Ruiqi Liu**: Investigation; methodology; visualisation; management; writing – original draft; writing – review and editing. **Leyi Zhang**: Investigation; writing – original draft; writing – review and editing. **Alona Maslennikov**: Writing original draft; writing – review and editing; visualisation. **Yuval Reches**: Writing – original draft; writing – review and editing. **Heung Youl Youm**: Management.

ACKNOWLEDGEMENTS

Georgi Gary Rozenman is thankful to Prof. Ady Arie for his guidance, wisdom and support. Georgi Gary Rozenman is also thankful to Prof. Wolfgang P. Schleich for his mentorship. Neel Kanth Kundu is thankful to Prof. Matthew R. McKay for his guidance. Yuval Reches is thankful to Prof. Haim Suchowski for his guidance.

CONFLICT OF INTEREST STATEMENT

No conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

The data in this manuscript is available upon a reasonable request.

PERMISSION TO REPRODUCE MATERIALS FROM OTHER SOURCES

Data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Georgi Gary Rozenman https://orcid.org/0000-0002-0799-6520
Ruiqi Liu https://orcid.org/0000-0001-6091-1138

REFERENCES

1. Gisin, N., Thew, R.: Quantum communication. Nat. Photonics 1(3), 165–171 (2007). https://doi.org/10.1038/nphoton.2007.22
2. Pirandola, S., et al.: Advances in quantum cryptography. Adv. Opt. Photon. 12(4), 1012–1236 (2020). https://doi.org/10.1364/aop.361502
3. Bennett, C.H., Shor, P.W.: Quantum information theory. IEEE Trans. Inf. Theor. 44(6), 2724–2742 (1998). https://doi.org/10.1109/18.720553
4. Sergienko, A.V.: Quantum Communications and Cryptography. CRC press (2018)
5. Hirota, O., Tsushima, H.: Quantum communication theory and its applications. IEICE Trans. 72(5), 460–470 (1989)
6. Kremer, I.: Quantum Communication. Citeseer (1995)
7. Liu, R., et al.: Towards the industrialisation of quantum key distribution in communication networks: a short survey. IET Quan. Commun. 3(3), 151–163 (2022). https://doi.org/10.1049/qtc2.12044
8. Kumar, A., Garhwal, S.: State-of-the-art survey of quantum cryptography. Arch. Comput. Methods Eng. 28(5), 3831–3868 (2021). https://doi.org/10.1007/s11831-021-09561-2
9. Abomhara, M., Zakaria, O., Khalifa, O.O.: An overview of video encryption techniques. Int. J. Comp. Theor. Eng. 2(1), 1793–8201 (2010)
10. Somaschi, N., et al.: Near-optimal single-photon sources in the solid state. Nat. Photonics 10(5), 340–345 (2016). https://doi.org/10.1038/nphoton.2016.23
11. Hanschke, L., et al.: Quantum dot single-photon sources with ultra-low multi-photon probability. NPJ Quan. Inf. 4(1), 43 (2018). https://doi.org/10.1038/s41534-018-0092-0

12. Mehic, M., et al.: Quantum key distribution: a networking perspective. ACM Comput. Surv. (CSUR) 53(5), 1–41 (2020). https://doi.org/10.1145/3402192
13. Bloom, Y., et al.: Quantum cryptography—a simplified undergraduate experiment and simulation. Physics 4(1), 104–123 (2022). https://doi.org/10.3390/physics4010009
14. Rozenman, G.G., Peisakhov, A., Zadok, N.: Dispersion of organic exciton polaritons—a novel undergraduate experiment. Eur. J. Phys. 43(3), 035301 (2022). https://doi.org/10.1088/1361-6404/ac50fd
15. Weisman, D., et al.: Diffractive guiding of waves by a periodic array of slits. Phys. Rev. Lett. 127(1), 014303 (2021). https://doi.org/10.1103/physrevlett.127.014303
16. Rozenman, G.G., et al.: Long-range transport of organic exciton-polaritons revealed by ultrafast microscopy. ACS Photonics 5(1), 105–110 (2018). https://doi.org/10.1021/acsphotonics.7b01332
17. Rozenman, G.G., et al.: Long-range transport of organic exciton-polaritons revealed by ultrafast microscopy. In: CLEO: QELS_Fundamental Science. Optica Publishing Group, FM2F.2 (2018)
18. Alléaume, R., et al.: Using quantum key distribution for cryptographic purposes: a survey. Theor. Comput. Sci. 560, 62–81 (2014). https://doi.org/10.1016/j.tcs.2014.09.018
19. Wehner, S., Elkouss, D., Hanson, R.: Quantum internet: a vision for the road ahead. Science 362(6412), eaam9288 (2018). https://doi.org/10.1126/science.aam9288
20. Degen, C.L., Reinhard, F., Cappellaro, P.: Quantum sensing. Rev. Mod. Phys. 89(3), 035002 (2017). https://doi.org/10.1103/revmodphys.89.035002
21. Aspuru-Guzik, A., Walther, P.: Photonic quantum simulators. Nat. Phys. 8(4), 285–291 (2012). https://doi.org/10.1038/nphys2253
22. Gyongyosi, L., Imre, S.: A survey on quantum computing technology. Comp. Sci. Rev. 31, 51–71 (2019). https://doi.org/10.1016/j.cosrev.2018.11.002
23. Tsai, C.-W., et al.: Quantum key distribution networks: challenges and future research issues in security. Appl. Sci. 11(9), 3767 (2021). https://doi.org/10.3390/app11093767
24. Caleffi, M., Cacciapuoti, A.S.: Quantum switch for the quantum internet: noiseless communications through noisy channels. IEEE J. Sel. Area. Commun. 38(3), 575–588 (2020). https://doi.org/10.1109/jsac.2020.2969035
25. Sidhu, J.S., et al.: Advances in space quantum communications. IET Quan. Commun. 2(4), 182–217 (2021). https://doi.org/10.1049/qtc2.12015
26. Fedrizzi, A., et al.: Experimental distribution of entanglement with separable carriers. Phys. Rev. Lett. 111(23), 230504 (2013). https://doi.org/10.1103/physrevlett.111.230504
27. Pal, S., et al.: Experimental localisation of quantum entanglement through monitored classical mediator. Quantum 5, 478 (2021). https://doi.org/10.22331/q-2021-06-17-478
28. Simon, C.: Towards a global quantum network. Nat. Photonics 11(11), 678–680 (2017). https://doi.org/10.1038/s41566-017-0032-0
29. Leiner, B.M., et al.: A brief history of the internet. ACM SIGCOMM Comp. Commun. Rev. 39(5), 22–31 (2009). https://doi.org/10.1145/1629607.1629613
30. Gyongyosi, L., Imre, S., Nguyen, H.V.: A survey on quantum channel capacities. IEEE Commun. Surv. Tutorials 20(2), 1149–1205 (2018). https://doi.org/10.1109/comst.2017.2786748
31. Wahab, O.F.A., et al.: Hiding data using efficient combination of RSA cryptography, and compression steganography techniques. IEEE Access 9, 31805–31815 (2021). https://doi.org/10.1109/access.2021.3060317
32. Rehman, E., et al.: Intrusion detection based on machine learning in the internet of things, attacks and counter measures. J. Supercomput., 1–35 (2022)
33. Broadbent, A., Schaffner, C.: Quantum cryptography beyond quantum key distribution. Des. Codes Cryptogr. 78(1), 351–382 (2016). https://doi.org/10.1007/s10623-015-0157-4
34. Gisin, N., Pironio, S., Sangouard, N.: Proposal for implementing device-independent quantum key distribution based on a heralded qubit amplifier. Phys. Rev. Lett. 105(7), 070501 (2010). https://doi.org/10.1103/physrevlett.105.070501
35. Bedington, R., Arrazola, J.M., Ling, A.: Progress in satellite quantum key distribution. NPJ Quan. Inf. 3(1), 1–13 (2017). https://doi.org/10.1038/s41534-017-0031-5
36. Monroe, C., et al.: Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects. Phys. Rev. 89(2), 022317 (2014). https://doi.org/10.1103/physreva.89.022317
37. Caleffi, M., Cacciapuoti, A.S., Bianchi, G.: Quantum internet: from communication to distributed computing!. In: Proceedings of the 5th ACM International Conference on Nanoscale Computing and Communication, pp. 1–4 (2018)
38. Popkin, G.: The Internet Goes Quantum (2021)
39. Poppe, A., Peev, M., Maurhart, O.: Outline of the SECOQC quantum-key-distribution network in Vienna. Int. J. Quant. Inf. 6(02), 209–218 (2008). https://doi.org/10.1142/s0219749908003529
40. Pirandola, S.: End-to-end capacities of a quantum communication network. Commun. Phys. 2(1), 51 (2019). https://doi.org/10.1038/s42005-019-0147-3
41. Wei, S.-H., et al.: Towards real-world quantum networks: a review. Laser Photon. Rev. 16(3), 2100219 (2022). https://doi.org/10.1002/lpor.202100219
42. Naughton, D., et al.: Design considerations for an optical link supporting intersatellite quantum key distribution. Opt. Eng. 58(1), 016106–016106 (2019). https://doi.org/10.1117/1.oe.58.1.016106
43. Cochran, R.D., Gauthier, D.J.: Qubit-based clock synchronization for QKD systems using a Bayesian approach. Entropy 23(8), 988 (2021). https://doi.org/10.3390/e23080988
44. Cuomo, D., Caleffi, M., Cacciapuoti, A.S.: Towards a distributed quantum computing ecosystem. IET Quan. Commun. 1(1), 3–8 (2020). https://doi.org/10.1049/iet-qtc.2020.0002
45. Hanzo, L., et al.: Wireless myths, realities, and futures: from 3g/4g to optical and quantum wireless. Proc. IEEE 100(Special Centennial Issue), 1853–1888 (2012). https://doi.org/10.1109/jproc.2012.2189788
46. Dowling, J.P., Milburn, G.J.: Quantum technology: the second quantum revolution. Philos. Trans. R. Soc. London, Ser. A 361(1809), 1655–1674 (2003). https://doi.org/10.1098/rsta.2003.1227
47. Wang, C., Rahman, A.: Quantum-enabled 6G wireless networks: opportunities and challenges. IEEE Wireless Commun. 29(1), 58–69 (2022). https://doi.org/10.1109/mwc.006.00340
48. Manzalini, A.: Quantum communications in future networks and services. Quan. Rep. 2(1), 221–232 (2020). https://doi.org/10.3390/quantum2010014
49. Cao, Y., et al.: The evolution of quantum key distribution networks: on the road to the Qinternet. IEEE Commun. Surv. Tutorials 24(2), 839–894 (2022). https://doi.org/10.1109/comst.2022.3144219
50. Bhat, J.R., Alqahtani, S.A.: 6G ecosystem: current status and future perspective. IEEE Access 9, 43134–43167 (2021). https://doi.org/10.1109/access.2021.3054833
51. Calvanese Strinati, E., et al.: 6G in the sky: on-demand intelligence at the edge of 3D networks. ETRI J. 42(5), 643–657 (2020). https://doi.org/10.4218/etrij.2020-0205
52. Zhou, D., et al.: Overview of development and regulatory aspects of high altitude platform system. Intell. Converged Network. 1(1), 58–78 (2020). https://doi.org/10.23919/icn.2020.0004
53. Liu, R., et al.: A path to smart radio environments: an industrial viewpoint on reconfigurable intelligent surfaces. IEEE Wireless Commun. 29(1), 202–208 (2022). https://doi.org/10.1109/mwc.111.2100258
54. Liu, R., et al.: Simulation and field trial results of reconfigurable intelligent surfaces in 5G networks. IEEE Access 10, 122786–122795 (2022). https://doi.org/10.1109/access.2022.3223447
55. Han, X., et al.: Interference mitigation for non-overlapping sub-band full duplex for 5G-advanced wireless networks. IEEE Access 10, 134512–134524 (2022). https://doi.org/10.1109/access.2022.3230836
56. Hu, L., et al.: Reconfigurable intelligent surface-aided secret key generation in multi-cell systems (2023)
57. Kumar, R., Spiller, T.: Full-duplex quantum coherent communication. In: 2019 21st International Conference on Transparent Optical Networks (ICTON), pp. 1–4 (2019)

58. Sharma, P., et al.: Quantum key distribution secured optical networks: a survey. IEEE Open J. Commun. Soc. 2, 2049–2083 (2021). https://doi.org/10.1109/ojcoms.2021.3106659
59. Boaron, A., et al.: Secure quantum key distribution over 421 km of optical fiber. Phys. Rev. Lett. 121(19), 190502 (2018). https://doi.org/10.1103/physrevlett.121.190502
60. Mao, Y., et al.: Integrating quantum key distribution with classical communications in backbone fiber network. Opt Express 26(5), 6010–6020 (2018). https://doi.org/10.1364/oe.26.006010
61. Alshowkan, M., et al.: Reconfigurable quantum local area network over deployed fiber. PRX Quan. 2(4), 040304 (2021). https://doi.org/10.1103/prxquantum.2.040304
62. Fang, X.-T., et al.: Implementation of quantum key distribution surpassing the linear rate-transmittance bound. Nat. Photonics 14(7), 422–425 (2020). https://doi.org/10.1038/s41566-020-0599-8
63. Pham, T.A., Nguyen, N.T., Dang, N.T.: Quantum key distribution over hybrid fiber-wireless system for mobile networks. In: Proceedings of the 10th International Symposium on Information and Communication Technology, pp. 236–241 (2019)
64. Trinh, P.V., et al.: Design and security analysis of quantum key distribution protocol over free-space optics using dual-threshold direct-detection receiver. IEEE Access 6, 4159–4175 (2018). https://doi.org/10.1109/access.2018.2800291
65. Reches, Y., Elias, E., Suchowski, H.: Detuning modulated composite segments for robust optical frequency conversion. J. Phys. B 55(19), 194002 (2022). https://doi.org/10.1088/1361-6455/ac8b49
66. Heim, B., et al.: Atmospheric continuous-variable quantum communication. New J. Phys. 16(11), 113018 (2014). https://doi.org/10.1088/1367-2630/16/11/113018
67. Liao, S.-K., et al.: Long-distance free-space quantum key distribution in daylight towards inter-satellite communication. Nat. Photonics 11(8), 509–513 (2017). https://doi.org/10.1038/nphoton.2017.116
68. Bouchard, F., et al.: Experimental investigation of high-dimensional quantum key distribution protocols with twisted photons. Quantum 2, 111 (2018). https://doi.org/10.22331/q-2018-12-04-111
69. Guo, H., et al.: A survey on space-air-ground-sea integrated network security in 6g. IEEE Commun. Surv. Tutorials 24(1), 53–87 (2021). https://doi.org/10.1109/comst.2021.3131332
70. Wang, J.-Y., et al.: Direct and full-scale experimental verifications towards ground–satellite quantum key distribution. Nat. Photonics 7(5), 387–393 (2013). https://doi.org/10.1038/nphoton.2013.89
71. Pugh, C.J., et al.: Airborne demonstration of a quantum key distribution receiver payload. Quantum Sci. Technol. 2(2), 024009 (2017). https://doi.org/10.1088/2058-9565/aa701f
72. Chu, Y., et al.: Feasibility of quantum key distribution from high altitude platforms. Quantum Sci. Technol. 6(3), 035009 (2021). https://doi.org/10.1088/2058-9565/abf9ae
73. Tian, X.-H., et al.: Drone-based quantum key distribution. arXiv preprint arXiv:2302.14012 (2023)
74. Wang, Z., et al.: Quantum key distribution by drone. J. Phys. Conf. 2095(1), 012080 (2021). https://doi.org/10.1088/1742-6596/2095/1/012080
75. Liao, S.-K., et al.: Satellite-to-ground quantum key distribution. Nature 549(7670), 43–47 (2017). https://doi.org/10.1038/nature23655
76. Lu, C.-Y., et al.: Micius quantum experiments in space. Rev. Mod. Phys. 94(3), 035001 (2022). https://doi.org/10.1103/revmodphys.94.035001
77. Villar, A., et al.: Entanglement demonstration on board a nano-satellite. Optica 7(7), 734–737 (2020). https://doi.org/10.1364/optica.387306
78. Dalibot, C., Tustain, S.: The preliminary thermal design for the SpeQtre cubesat. In: 2020 International Conference on Environmental Systems (2020)
79. Mazzarella, L., et al.: Quarc: quantum research cubesat—a constellation for quantum communication. Cryptography 4(1), 7 (2020). https://doi.org/10.3390/cryptography4010007
80. Haber, R., et al.: Qube-a cubesat for quantum key distribution experiments (2018)
81. Podmore, H., et al.: QKD terminal for Canada's quantum encryption and science satellite (qeyssat). In: International Conference on Space Optics—ICSO 2020, vol. 11852, pp. 203–212. SPIE (2021)
82. Jian, M., Liu, R.: Baseband signal processing for terahertz: waveform design, modulation and coding. In: 2021 International Wireless Communications and Mobile Computing (IWCMC), pp. 1710–1715 (2021)
83. Ottaviani, C., et al.: Terahertz quantum cryptography. IEEE J. Sel. Areas Commun. 38(3), 483–495 (2020). https://doi.org/10.1109/jsac.2020.2968973
84. Kundu, N.K., et al.: MIMO terahertz quantum key distribution. IEEE Commun. Lett. 25(10), 3345–3349 (2021). https://doi.org/10.1109/lcomm.2021.3102703
85. Kundu, N.K., et al.: Channel estimation and secret key rate analysis of MIMO terahertz quantum key distribution. IEEE Trans. Commun. 70(5), 3350–3363 (2022). https://doi.org/10.1109/TCOMM.2022.3161008
86. Kundu, N.K., et al.: MIMO terahertz quantum key distribution under restricted eavesdropping. IEEE Trans. Quan. Eng. 4, 1–15 (2023). https://doi.org/10.1109/tqe.2023.3264638
87. Elmabrok, O., Ghalaii, M., Razavi, M.: Quantum-classical access networks with embedded optical wireless links. JOSA B 35(3), 487–499 (2018). https://doi.org/10.1364/josab.35.000487
88. Elmabrok, O., Razavi, M.: Wireless quantum key distribution in indoor environments. JOSA B 35(2), 197–207 (2018). https://doi.org/10.1364/josab.35.000197
89. Zia-Ul-Mustafa, R., et al.: Quantum key distribution for visible light communications: a review. In: 2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), pp. 589–594. IEEE (2022)
90. Zhao, H., Wang, J., Liu, R.: High accuracy indoor visible light positioning considering the shapes of illuminators. In: 2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB), pp. 1–4 (2019)
91. Liu, R., Zhang, C.: Dynamic dwell timer for vertical handover in VLC-WLAN heterogeneous networks. In: 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), pp. 1256–1260 (2017)
92. Dang, N.T., et al.: Quantum key distribution solution over indoor visible light communication networks. In: Fourth International Conference on Photonics Solutions (ICPS2019), vol. 11331, pp. 55–63. SPIE (2020)
93. Chun, H., et al.: Handheld free space quantum key distribution with dynamic motion compensation. Opt Express 25(6), 6784–6795 (2017). https://doi.org/10.1364/oe.25.006784
94. Lowndes, D., et al.: A low cost, short range quantum key distribution system. EPJ Quan. Technol. 8(1), 15 (2021). https://doi.org/10.1140/epjqt/s40507-021-00101-2
95. Liu, Q., et al.: Advances in chip-based quantum key distribution. Entropy 24(10), 1334 (2022). https://doi.org/10.3390/e24101334
96. Vest, G., et al.: Quantum key distribution with a hand-held sender unit. Phys. Rev. Appl. 18(2), 024067 (2022). https://doi.org/10.1103/physrevapplied.18.024067
97. Consumer quantum key distribution. https://uknqt.ukri.org/wp-content/uploads/2021/10/Consumer-Quantum-Key-Distribution.pdf
98. Yavuz, A.A., et al.: Distributed cyber-infrastructures and artificial intelligence in hybrid post-quantum era. In: 2022 IEEE 4th International Conference on Trust, Privacy and Security in Intelligent Systems, and Applications (TPS-ISA), pp. 29–38. IEEE (2022)
99. Nötzel, J., Rosati, M.: Operating fiber networks in the quantum limit. J. Lightwave Technol., 1–11 (2023). https://doi.org/10.1109/jlt.2023.3295076
100. Sekavčnik, S., Nötzel, J.: Effects of quantum communication in large-scale networks at minimum latency. In: 2022 IEEE Globecom Workshops (GC Wkshps), pp. 802–807. IEEE (2022)
101. Burenkov, I., Jabir, M., Polyakov, S.: Practical quantum-enhanced receivers for classical communication. AVS Quan. Sci. 3(2), 025301 (2021). https://doi.org/10.1116/5.0036959
102. Sidhu, J.S., et al.: Quantum receiver for phase-shift keying at the single-photon level. Prx Quan. 2(1), 010332 (2021). https://doi.org/10.1103/prxquantum.2.010332
103. Helstrom, C.W.: Quantum detection and estimation theory. J. Stat. Phys. 1(2), 231–252 (1969). https://doi.org/10.1007/bf01007479

104. Shannon, C.E.: A mathematical theory of communication. Bell Syst. Tech. J. 27(3), 379–423 (1948). https://doi.org/10.1002/j.1538-7305.1948.tb01338.x
105. Caves, C.M., Drummond, P.D.: Quantum limits on bosonic communication rates. Rev. Mod. Phys. 66(2), 481–537 (1994). https://doi.org/10.1103/revmodphys.66.481
106. Holevo, A.S., Werner, R.F.: Evaluating capacities of bosonic Gaussian channels. Phys. Rev. 63(3), 032312 (2001). https://doi.org/10.1103/physreva.63.032312
107. Giovannetti, V., et al.: Electromagnetic channel capacity for practical purposes. Nat. Photonics 7(10), 834–838 (2013). https://doi.org/10.1038/nphoton.2013.193
108. Giovannetti, V., et al.: Ultimate classical communication rates of quantum optical channels. Nat. Photonics 8(10), 796–800 (2014). https://doi.org/10.1038/nphoton.2014.216
109. Zhao, Z., et al.: Regular APSK constellation design for beyond 5G. In: 2022 International Wireless Communications and Mobile Computing (IWCMC), pp. 713–718 (2022)
110. Arıkan, E.: Polar codes: a pipelined implementation. In: Proc. 4th ISBC, vol. 2010, pp. 11–14 (2010)
111. Han, X., et al.: Dynamic resource allocation schemes for eMBB and URLLC services in 5G wireless networks. Intell. Converged Networks 3(2), 145–160 (2022). https://doi.org/10.23919/icn.2022.0011
112. Jian, M., et al.: Reconfigurable intelligent surface aided non-coaxial OAM transmission for capacity improvement. In: 2022 IEEE/CIC International Conference on Communications in China (ICCC), pp. 594–599 (2022)
113. Hou, P., Liu, R.: Statistical QoS guarantee for power-efficient downlink NOMA with statistical CSI. In: 2021 IEEE Wireless Communications and Networking Conference (WCNC), pp. 1–6 (2021)
114. Sekavčnik, S., Nötzel, J.: Scaling of entanglement-assisted communication in amplified fiber links. arXiv preprint arXiv:2211.13296 (2022)
115. Giovannetti, V., et al.: Broadband channel capacities. Phys. Rev. 68(6), 062323 (2003). https://doi.org/10.1103/physreva.68.062323
116. Cox, A., et al.: Transceiver designs to attain the entanglement assisted communications capacity. arXiv preprint arXiv:2208.07979 (2022)
117. Nötzel, J., Rosati, M.: Operating fiber networks in the quantum limit. arXiv preprint arXiv:2201.12397 (2022)
118. Wilde, M.M., Qi, H.: Energy-constrained private and quantum capacities of quantum channels. IEEE Trans. Inf. Theor. 64(12), 7802–7827 (2018). https://doi.org/10.1109/tit.2018.2854766
119. Wolf, M.M., Pérez-García, D., Giedke, G.: Quantum capacities of bosonic channels. Phys. Rev. Lett. 98(13), 130501 (2007). https://doi.org/10.1103/physrevlett.98.130501
120. Arqand, A., Memarzadeh, L., Mancini, S.: Quantum capacity of a bosonic dephasing channel. Phys. Rev. 102(4), 042413 (2020). https://doi.org/10.1103/physreva.102.042413
121. Leviant, P., et al.: Quantum capacity and codes for the bosonic loss-dephasing channel. Quantum 6, 821 (2022). https://doi.org/10.22331/q-2022-09-29-821
122. Pirandola, S., Braunstein, S.L.: Physics: unite to build a quantum internet. Nature 532(7598), 169–171 (2016). https://doi.org/10.1038/532169a
123. Illiano, J., et al.: Quantum internet protocol stack: a comprehensive survey. Comput. Network. 213, 109092 (2022). https://doi.org/10.1016/j.comnet.2022.109092
124. Caleffi, M., et al.: The rise of the quantum internet. Computer 53(6), 67–72 (2020). https://doi.org/10.1109/mc.2020.2984871
125. Ibm unveils 400 qubit-plus quantum processor and next-generation IBM quantum system two [Online]. https://newsroom.ibm.com/2022-11-09-IBM-Unveils-400-Qubit-Plus-Quantum-Processor-and-Next-Generation-IBM-Quantum-System-Two
126. Amazon braket adds support for the new 80-qubit quantum processor from rigetti [Online]. https://aws.amazon.com/about-aws/whats-new/2022/02/amazon-braket-80-quantum-processor-rigetti/
127. Quantum computational advantage with 216 squeezed-state qubits [Online]. https://www.xanadu.ai/products/borealis/
128. Ionq forte: the first software-configurable quantum computer [Online]. https://ionq.com/resources/ionq-forte-first-configurable-quantum-computer
129. Acharya, R., et al.: Suppressing quantum errors by scaling a surface code logical qubit. Nature 614(7949), 676–681 (2023). https://doi.org/10.1038/s41586-022-05434-1
130. What reaching 20 qubits means for quantum computing [Online]. https://www.honeywell.com/us/en/news/2022/06/what-reaching-20-qubits-means-for-quantum-computing
131. Ngoenriang, N., et al.: DQC2O: distributed quantum computing for collaborative optimization in future networks. IEEE Commun. Mag. 61(5), 188–194 (2023). https://doi.org/10.1109/mcom.003.2200573
132. Outeiral, C., et al.: The prospects of quantum computing in computational molecular biology. Wiley Interdiscip. Rev. Comput. Mol. Sci. 11(1), e1481 (2021). https://doi.org/10.1002/wcms.1481
133. Egger, D.J., et al.: Quantum computing for finance: state-of-the-art and future prospects. IEEE Trans. Quan. Eng. 1, 1–24 (2020). https://doi.org/10.1109/tqe.2020.3030314
134. Cao, Y., Romero, J., Aspuru-Guzik, A.: Potential of quantum computing for drug discovery. IBM J. Res. Dev. 62(6), 6:1–6:20 (2018). https://doi.org/10.1147/jrd.2018.2888987
135. Bova, F., Goldfarb, A., Melko, R.G.: Commercial applications of quantum computing. EPJ Quan. Technol. 8(1), 2 (2021). https://doi.org/10.1140/epjqt/s40507-021-00091-1
136. Dunjko, V., Briegel, H.J.: Machine learning & artificial intelligence in the quantum domain: a review of recent progress. Rep. Prog. Phys. 81(7), 074001 (2018). https://doi.org/10.1088/1361-6633/aab406
137. Ajagekar, A., Humble, T., You, F.: Quantum computing based hybrid solution strategies for large-scale discrete-continuous optimization problems. Comput. Chem. Eng. 132, 106630 (2020). https://doi.org/10.1016/j.compchemeng.2019.106630
138. Salahdine, F., Han, T., Zhang, N.: Security in 5G and beyond recent advances and future challenges. Secur. Priv. 6(1), e271 (2023). https://doi.org/10.1002/spy2.271
139. Primqulov, O.: The pursuit of quantum supremacy: challenges and implications. Innovative Develop. Educ. Activit. 2(7), 200–205 (2023)
140. Hasan, S.R., et al.: Quantum communication systems: vision, protocols, applications, and challenges. IEEE Access 11, 15855–15877 (2023). https://doi.org/10.1109/access.2023.3244395
141. Jahid, A., Alsharif, M.H., Hall, T.J.: The convergence of blockchain, IoT and 6G: potential, opportunities, challenges and research roadmap. J. Netw. Comput. Appl. 217, 103677 (2023). https://doi.org/10.1016/j.jnca.2023.103677
142. Sigov, A., Ratkin, L., Ivanov, L.A.: Quantum information technology. J. Ind. Inf. Integrat. 28, 100365 (2022). https://doi.org/10.1016/j.jii.2022.100365
143. Elsayed, N., Maida, A.S., Bayoumi, M.: A review of quantum computer energy efficiency. In: 2019 IEEE Green Technologies Conference (GreenTech), pp. 1–3. IEEE (2019)
144. Spivey, R.F., et al.: High-stability cryogenic system for quantum computing with compact packaged ion traps. IEEE Trans. Quan. Eng. 3, 1–11 (2021). https://doi.org/10.1109/tqe.2021.3125926
145. Hornibrook, J., et al.: Cryogenic control architecture for large-scale quantum computing. Phys. Rev. Appl. 3(2), 024010 (2015). https://doi.org/10.1103/physrevapplied.3.024010
146. IBM quantum (2021) [Online]. https://quantum-computing.ibm.com/
147. Arroyo-Camejo, S., et al.: Room temperature high-fidelity holonomic single-qubit gate on a solid-state spin. Nat. Commun. 5(1), 4870 (2014). https://doi.org/10.1038/ncomms5870
148. Prawer, S., Greentree, A.D.: Diamond for quantum computing. Science 320(5883), 1601–1602 (2008). https://doi.org/10.1126/science.1158340
149. Takeda, S., Furusawa, A.: Toward large-scale fault-tolerant universal photonic quantum computing. APL Photon. 4(6), 060902 (2019). https://doi.org/10.1063/1.5100160
150. Li, Q., et al.: Room-temperature coherent manipulation of single-spin qubits in silicon carbide with a high readout contrast. Natl. Sci. Rev. 9(5), nwab122 (2022). https://doi.org/10.1093/nsr/nwab122

151. Sevilla, J., Riedel, C.J.: Forecasting timelines of quantum computing. arXiv preprint arXiv:2009.05045 (2020)
152. Mizuno, H.: Quantum computing from hype to game changer. In: 2023 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits), pp. 1–4. IEEE (2023)
153. Martyn, J.M., et al.: Grand unification of quantum algorithms. PRX Quan. 2(4), 040203 (2021). https://doi.org/10.1103/prxquantum.2.040203
154. Bharti, K., et al.: Noisy intermediate-scale quantum algorithms. Rev. Mod. Phys. 94(1), 015004 (2022). https://doi.org/10.1103/revmodphys.94.015004
155. Duong, T.Q., et al.: Quantum-inspired machine learning for 6G: fundamentals, security, resource allocations, challenges, and future research directions. IEEE Open J. Veh. Technol. 3, 375–387 (2022). https://doi.org/10.1109/ojvt.2022.3202876
156. Abbas, A., et al.: The power of quantum neural networks. Nat. Comput. Sci. 1(6), 403–409 (2021). https://doi.org/10.1038/s43588-021-00084-1
157. Duong, T.Q., et al.: Quantum-inspired real-time optimisation for 6G networks: opportunities, challenges, and the road ahead. IEEE Open J. Commun. Soc. 3, 1347–1359 (2022). https://doi.org/10.1109/ojcoms.2022.3195219
158. Kim, M., et al.: Heuristic quantum optimization for 6G wireless communications. IEEE Netw. 35(4), 8–15 (2021). https://doi.org/10.1109/mnet.012.2000770
159. Botsinis, P., et al.: Quantum search algorithms for wireless communications. IEEE Commun. Surv. Tutorials 21(2), 1209–1242 (2018). https://doi.org/10.1109/comst.2018.2882385
160. Kim, M., Venturelli, D., Jamieson, K.: Leveraging quantum annealing for large MIMO processing in centralized radio access networks. In: Proceedings of the ACM Special Interest Group on Data Communication, pp. 241–255 (2019)
161. Ducoing, J.D.L., Nikitopoulos, K.: Quantum annealing for next-generation MU-MIMO detection: evaluation and challenges. In: ICC 2022-IEEE International Conference on Communications, pp. 637–642. IEEE (2022)
162. Kim, M., et al.: Physics-inspired heuristics for soft MIMO detection in 5G new radio and beyond. In: Proceedings of the 27th Annual International Conference on Mobile Computing and Networking, pp. 42–55 (2021)
163. Singh, A.K., et al.: Ising machines' dynamics and regularization for near-optimal MIMO detection. IEEE Trans. Wireless Commun. 21(12), 11080–11094 (2022). https://doi.org/10.1109/twc.2022.3189604
164. Botsinis, P., et al.: Noncoherent quantum multiple symbol differential detection for wireless systems. IEEE Access 3, 569–598 (2015). https://doi.org/10.1109/access.2015.2432015
165. Botsinis, P., et al.: Low-complexity soft-output quantum-assisted multiuser detection for direct-sequence spreading and slow subcarrier-hopping aided SDMA-OFDM systems. IEEE Access 2, 451–472 (2014). https://doi.org/10.1109/access.2014.2322013
166. Botsinis, P., et al.: Iterative quantum-assisted multi-user detection for multi-carrier interleave division multiple access systems. IEEE Trans. Commun. 63(10), 3713–3727 (2015). https://doi.org/10.1109/tcomm.2015.2458857
167. Botsinis, P., et al.: Quantum-aided multi-user transmission in non-orthogonal multiple access systems. IEEE Access 4, 7402–7424 (2016). https://doi.org/10.1109/access.2016.2591904
168. Narottama, B., Hendraningrat, D.K., Shin, S.Y.: Quantum-inspired evolutionary algorithms for NOMA user pairing. ICT Express 8(1), 11–17 (2022). https://doi.org/10.1016/j.icte.2022.01.014
169. Botsinis, P., et al.: Quantum-assisted indoor localization for uplink mm-wave and downlink visible light communication systems. IEEE Access 5, 23327–23351 (2017). https://doi.org/10.1109/access.2017.2733557
170. Kasi, S., et al.: Quantum annealing for large MIMO downlink vector perturbation precoding. In: ICC 2021-IEEE International Conference on Communications, pp. 1–6. IEEE (2021)
171. Kasi, S., Jamieson, K.: Towards quantum belief propagation for LDPC decoding in wireless networks. In: Proceedings of the 26th Annual International Conference on Mobile Computing and Networking, pp. 1–14 (2020)
172. Kasi, S., Kaewell, J., Jamieson, K.: The design and implementation of a hybrid classical-quantum annealing polar decoder. In: GLOBECOM 2022-2022 IEEE Global Communications Conference, pp. 5819–5825. IEEE (2022)
173. Piveteau, C., Renes, J.M.: Quantum message-passing algorithm for optimal and efficient decoding. Quantum 6, 784 (2022). https://doi.org/10.22331/q-2022-08-23-784
174. Choi, J., Oh, S., Kim, J.: Energy-efficient cluster head selection via quantum approximate optimization. Electronics 9(10), 1669 (2020). https://doi.org/10.3390/electronics9101669
175. Tran, T., et al.: A hybrid quantum-classical approach to solving scheduling problems. Proc. Int. Symp. Comb. Search 7(1), 98–106 (2016). https://doi.org/10.1609/socs.v7i1.18390
176. Choi, J., Oh, S., Kim, J.: Quantum approximation for wireless scheduling. Appl. Sci. 10(20), 7116 (2020). https://doi.org/10.3390/app10207116
177. Yoo, Y., Cha, R.J.: Wireless packet scheduling with quantum computing. Bull. Am. Phys. Soc. (2023)
178. Kim, J., et al.: Quantum scheduling for millimeter-wave observation satellite constellation. In: 2021 IEEE VTS 17th Asia Pacific Wireless Communications Symposium (APWCS), pp. 1–5. IEEE (2021)
179. Matsumine, T., Koike-Akino, T., Wang, Y.: Channel decoding with quantum approximate optimization algorithm. In: 2019 IEEE International Symposium on Information Theory (ISIT), pp. 2574–2578. IEEE (2019)
180. Koike-Akino, T., et al.: Variational quantum demodulation for coherent optical multi-dimensional qam. In: 2020 Optical Fiber Communications Conference and Exhibition (OFC), pp. 1–3. IEEE (2020)
181. Liu, B., et al.: Learning to learn quantum turbo detection. arXiv preprint arXiv:2205.08611 (2022)
182. Liu, B., et al.: Variational quantum compressed sensing for joint user and channel state acquisition in grant-free device access systems. In: ICC 2022-IEEE International Conference on Communications, pp. 1775–1780. IEEE (2022)
183. Dai, L., et al.: Deep learning for wireless communications: an emerging interdisciplinary paradigm. IEEE Wireless Commun. 27(4), 133–139 (2020). https://doi.org/10.1109/mwc.001.1900491
184. Huang, H., et al.: Deep learning for physical-layer 5G wireless techniques: opportunities, challenges and solutions. IEEE Wireless Commun. 27(1), 214–222 (2019). https://doi.org/10.1109/mwc.2019.1900027
185. Nawaz, S.J., et al.: Quantum machine learning for 6G communication networks: state-of-the-art and vision for the future. IEEE Access 7, 46317–46350 (2019). https://doi.org/10.1109/access.2019.2909490
186. Li, Z., et al.: Experimental realization of a quantum support vector machine. Phys. Rev. Lett. 114(14), 140504 (2015). https://doi.org/10.1103/physrevlett.114.140504
187. Chalumuri, A., Kune, R., Manoj, B.: A hybrid classical-quantum approach for multi-class classification. Quant. Inf. Process. 20(3), 119 (2021). https://doi.org/10.1007/s11128-021-03029-9
188. Narottama, B., Shin, S.Y.: Quantum neural networks for resource allocation in wireless communications. IEEE Trans. Wireless Commun. 21(2), 1103–1116 (2021). https://doi.org/10.1109/twc.2021.3102139
189. Narottama, B., Duong, T.Q.: Quantum neural networks for optimal resource allocation in cell-free MIMO systems. In: GLOBECOM 2022-2022 IEEE Global Communications Conference, pp. 2444–2449. IEEE (2022)
190. Liu, K.: Optimization algorithm of cognitive radio spectrum sensing based on quantum neural network. Automat. Control Comput. Sci. 50(5), 324–331 (2016). https://doi.org/10.3103/s0146411616050072
191. Li, F., Zhao, S., Zheng, B.: Quantum neural network for cdma multi-user detection. In: Advances in Neural Networks–ISNN 2005: Second International Symposium on Neural Networks, Chongqing, China, May 30-June 1, 2005, Proceedings, Part III 2, pp. 338–342. Springer (2005)
192. Huang, W., et al.: Backbone network traffic prediction based on modified EEMD and quantum neural network. Wireless Pers. Commun. 99(4), 1569–1588 (2018). https://doi.org/10.1007/s11277-018-5292-6

193. Li, Y., Aghvami, A.H., Dong, D.: Intelligent trajectory planning in uav-mounted wireless networks: a quantum-inspired reinforcement learning perspective. IEEE Wireless Commun. Lett. 10(9), 1994–1998 (2021). https://doi.org/10.1109/lwc.2021.3089876
194. Silvirianti, S., Narottama, B., Shin, S.Y.: UAV coverage path planning with quantum-based deep deterministic policy gradient (2023)
195. Koike-Akino, T., Wang, P., Wang, Y.: Quantum transfer learning for wi-fi sensing. In: ICC 2022-IEEE International Conference on Communications, pp. 654–659. IEEE (2022)
196. Koike-Akino, T., Wang, P., Wang, Y.: AutoQML: automated quantum machine learning for Wi-Fi integrated sensing and communications. In: 2022 IEEE 12th Sensor Array and Multichannel Signal Processing Workshop (SAM), pp. 360–364. IEEE (2022)
197. Koike-Akino, T., et al.: Quantum feature extraction for THz multi-layer imaging. In: 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz), pp. 1–2. IEEE (2022)
198. Shi, J., et al.: An approach to cryptography based on continuous-variable quantum neural network. Sci. Rep. 10(1), 2107 (2020). https://doi.org/10.1038/s41598-020-58928-1
199. Fitzsimons, J.F.: Private quantum computation: an introduction to blind quantum computing and related protocols. NPJ Quan. Inf. 3(1), 23 (2017). https://doi.org/10.1038/s41534-017-0025-3
200. Van Meter, R., et al.: A quantum internet architecture. In: 2022 IEEE International Conference on Quantum Computing and Engineering (QCE), pp. 341–352. IEEE (2022)
201. Gyongyosi, L., Imre, S.: Advances in the quantum internet. Commun. ACM 65(8), 52–63 (2022). https://doi.org/10.1145/3524455
202. Barz, S., et al.: Demonstration of blind quantum computing. Science 335(6066), 303–308 (2012). https://doi.org/10.1126/science.1214707
203. Ouyang, Y., Tan, S.-H., Fitzsimons, J.F.: Quantum homomorphic encryption from quantum codes. Phys. Rev. 98(4), 042334 (2018). https://doi.org/10.1103/physreva.98.042334
204. Yli-Huumo, J., et al.: Where is current research on blockchain technology?—a systematic review. PLoS One 11(10), e0163477 (2016). https://doi.org/10.1371/journal.pone.0163477
205. Xu, M., Chen, X., Kou, G.: A systematic review of blockchain. Financial Innovation 5(1), 1–14 (2019). https://doi.org/10.1186/s40854-019-0147-z
206. Al-Megren, S., et al.: Blockchain use cases in digital sectors: a review of the literature. In: 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), pp. 1417–1424. IEEE (2018)
207. Alladi, T., et al.: Blockchain in smart grids: a review on different use cases. Sensors 19(22), 4862 (2019). https://doi.org/10.3390/s19224862
208. Agbo, C.C., Mahmoud, Q.H., Eklund, J.M.: Blockchain technology in healthcare: a systematic review. Healthcare 7(2), 56 (2019). https://doi.org/10.3390/healthcare7020056
209. Edwards, M., Mashatan, A., Ghose, S.: A review of quantum and hybrid quantum/classical blockchain protocols. Quant. Inf. Process. 19(6), 1–22 (2020). https://doi.org/10.1007/s11128-020-02672-y
210. Kiktenko, E.O., et al.: Quantum-secured blockchain. Quantum Sci. Technol. 3(3), 035004 (2018). https://doi.org/10.1088/2058-9565/aabc6b
211. Gao, Y.-L., et al.: A secure cryptocurrency scheme based on post-quantum blockchain. IEEE Access 6, 27205–27213 (2018). https://doi.org/10.1109/access.2018.2827203
212. Fernandez-Carames, T.M., Fraga-Lamas, P.: Towards post-quantum blockchain: a review on blockchain cryptography resistant to quantum computing attacks. IEEE Access 8, 21091–21116 (2020). https://doi.org/10.1109/access.2020.2968985
213. Hurvitz, I., Karnieli, A., Arie, A.: Frequency-domain engineering of bright squeezed vacuum for continuous-variable quantum information. Opt Express 31(12), 20387–20397 (2023). https://doi.org/10.1364/oe.489606
214. Kundu, N.K., McKay, M.R., Mallik, R.K.: Machine-learning-based parameter estimation of Gaussian quantum states. IEEE Trans. Quan. Eng. 3, 1–13 (2021). https://doi.org/10.1109/tqe.2021.3137559
215. Giovannetti, V., Lloyd, S., Maccone, L.: Advances in quantum metrology. Nat. Photonics 5(4), 222–229 (2011). https://doi.org/10.1038/nphoton.2011.35
216. Pirandola, S., et al.: Advances in photonic quantum sensing. Nat. Photonics 12(12), 724–733 (2018). https://doi.org/10.1038/s41566-018-0301-6
217. Granelli, F., et al.: A novel architecture for future classical-quantum communication networks. Wireless Commun. Mobile Comput. 2022, 1–18 (2022). https://doi.org/10.1155/2022/3770994
218. Giovannetti, V., Lloyd, S., Maccone, L.: Quantum-enhanced positioning and clock synchronization. Nature 412(6845), 417–419 (2001). https://doi.org/10.1038/35086525
219. Ilo-Okeke, E.O., et al.: Remote quantum clock synchronization without synchronized clocks. npj Quan. Inf. 4(1), 40 (2018). https://doi.org/10.1038/s41534-018-0090-2
220. de Burgh, M., Bartlett, S.D.: Quantum methods for clock synchronization: beating the standard quantum limit without entanglement. Phys. Rev. 72(4), 042301 (2005). https://doi.org/10.1103/physreva.72.042301
221. Chuang, I.L.: Quantum algorithm for distributed clock synchronization. Phys. Rev. Lett. 85(9), 2006–2009 (2000). https://doi.org/10.1103/physrevlett.85.2006
222. Hong, H., et al.: Demonstration of 50 km fiber-optic two-way quantum clock synchronization. J. Lightwave Technol. 40(12), 3723–3728 (2022). https://doi.org/10.1109/jlt.2022.3153655
223. Quan, R., et al.: Implementation of field two-way quantum synchronization of distant clocks across a 7km deployed fiber link. Opt Express 30(7), 10269–10279 (2022). https://doi.org/10.1364/oe.451172
224. Quan, R., et al.: Demonstration of quantum synchronization based on second-order quantum coherence of entangled photons. Sci. Rep. 6(1), 30453 (2016). https://doi.org/10.1038/srep30453
225. Hegarty, C.J., Chatre, E.: Evolution of the global navigation satellite system (GNSS). Proc. IEEE 96(12), 1902–1917 (2008). https://doi.org/10.1109/jproc.2008.2006090
226. Giovannetti, V., Lloyd, S., Maccone, L.: Quantum cryptographic ranging. J. Opt. B Quantum Semiclassical Opt. 4(4), S413–S414 (2002). https://doi.org/10.1088/1464-4266/4/4/330
227. Maccone, L., Ren, C.: Quantum radar. Phys. Rev. Lett. 124(20), 200503 (2020). https://doi.org/10.1103/physrevlett.124.200503
228. Luong, D., Rajan, S., Balaji, B.: Entanglement-based quantum radar: from myth to reality. IEEE Aero. Electron. Syst. Mag. 35(4), 22–35 (2020). https://doi.org/10.1109/maes.2020.2970261
229. Shapiro, J.H.: The quantum illumination story. IEEE Aero. Electron. Syst. Mag. 35(4), 8–20 (2020). https://doi.org/10.1109/maes.2019.2957870
230. Huang, Z., Lupo, C., Kok, P.: Quantum-limited estimation of range and velocity. PRX Quan. 2(3), 030303 (2021). https://doi.org/10.1103/prxquantum.2.030303
231. Reichert, M., et al.: Quantum-enhanced Doppler lidar. NPJ Quan. Inf. 8(1), 147 (2022). https://doi.org/10.1038/s41534-022-00662-9
232. Zhao, J., et al.: Light detection and ranging with entangled photons. Opt Express 30(3), 3675–3683 (2022). https://doi.org/10.1364/oe.435898
233. Simons, M.T., et al.: Rydberg atom-based sensors for radio-frequency electric field metrology, sensing, and communications. Measurement: Sensors 18, 100273 (2021). https://doi.org/10.1016/j.measen.2021.100273
234. Fancher, C.T., et al.: Rydberg atom electric field sensors for communications and sensing. IEEE Trans. Quan. Eng. 2, 1–13 (2021). https://doi.org/10.1109/tqe.2021.3065227
235. Weichman, P.B.: Quantum-enhanced algorithms for classical target detection in complex environments. Phys. Rev. 103(4), 042424 (2021). https://doi.org/10.1103/physreva.103.042424
236. De Lima, C., et al.: Convergent communication, sensing and localization in 6G systems: an overview of technologies, opportunities and challenges. IEEE Access 9, 26902–26925 (2021). https://doi.org/10.1109/access.2021.3053486
237. Wymeersch, H., et al.: 6G radio requirements to support integrated communication, localization, and sensing. In: 2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), pp. 463–469. IEEE (2022)

238. de Lima, C., et al.: 6G white paper on localization and sensing (2020)
239. Staffas, T., et al.: 3D scanning quantum LiDAR. In: CLEO: Applications and Technology. Optica Publishing Group, AM2K–1 (2022)
240. Haase, J.F., et al.: A 32x24 pixel SPAD detector system for lidar and quantum imaging. In: Photonic Instrumentation Engineering VIII, vol. 11693, pp. 83–93. SPIE (2021)
241. Luong, D., et al.: Receiver operating characteristics for a prototype quantum two-mode squeezing radar. IEEE Trans. Aero. Electron. Syst. 56(3), 2041–2060 (2019). https://doi.org/10.1109/taes.2019.2951213
242. Gordon, J.A., et al.: Weak electric-field detection with sub-1 Hz resolution at radio frequencies using a Rydberg atom-based mixer. AIP Adv. 9(4) (2019). https://doi.org/10.1063/1.5095633
243. Malaney, R.: The quantum car. IEEE Wireless Commun. Lett. 5(6), 624–627 (2016). https://doi.org/10.1109/lwc.2016.2607740
244. Dahmen-Lhuissier, S.: Our group on quantum key distribution for users (QKD) [Online] https://www.etsi.org/committee/1430-qkd
245. ITU WP 5D [Online]. https://www.itu.int/md/R19-WP5D.AR-C/en
246. Focus group on quantum information technology for networks (fg-qit4n) [Online]. https://www.itu.int/en/ITU-T/focusgroups/qit4n/Pages/default.aspx

How to cite this article: Rozenman, G.G., et al.: The quantum internet: a synergy of quantum information technologies and 6G networks. IET Quant. Comm. 4(4), 147–166 (2023). https://doi.org/10.1049/qtc2.12069