Characterizing and Utilizing the Interplay between Quantum Technologies and Non-Terrestrial Networks

Hayder Al-Hraishawi*, Junaid ur Rehman*, Mohsen Razavi†, and Symeon Chatzinotas*

*Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg, L-1855, Luxembourg.
†School of Electronic and Electrical Engineering, University of Leeds, Leeds, LS2 9JT, U.K.

***Abstract*—Quantum technologies have been widely recognized as one of the milestones towards the ongoing digital transformation, which will also trigger new disruptive innovations. Quantum technologies encompassing quantum computing, communications, and sensing offer an interesting set of advantages such as unconditional security and ultra-fast computing capabilities. However, deploying quantum services at a global scale requires circumventing the limitations due to the geographical boundaries and terrestrial obstacles, which can be adequately addressed by considering non-terrestrial networks (NTNs). In the recent few years, establishing multi-layer NTNs has been extensively studied to integrate space-airborne-terrestrial communications systems, particularly by the international standardization organizations such as the third-generation partnership project (3GPP) and the international telecommunication union (ITU), in order to support future wireless ecosystems. Indeed, amalgamating quantum technologies and NTNs will scale up the quantum communications ranges and provide unprecedented levels of security and processing solutions that are safer and faster than the traditional offerings. This paper provides some insights into the interplay between the evolving NTN architectures and quantum technologies with a particular focus on the integration challenges and their potential solutions for enhancing the quantum-NTN interoperability among various space-air-ground communications nodes. The emphasis is on how the quantum technologies can benefit from satellites and aerial platforms as an integrated network and vice versa. Moreover, a set of future research directions and new opportunities are identified.**

I. Introduction

The recent breakthroughs in quantum technology development are opening the way towards establishing novel communications networks based on quantum entanglement and teleportation phenomena, which will be able to interconnect quantum servers for reaching an unprecedented computational capability [1]. Quantum technologies have the potential to offer new development opportunities to the conventional communications systems, such as improved optimization techniques enabled by advances in quantum computing and strictly secure cryptography beyond the capabilities of current classical systems [2]. In this direction, the concept of "Quantum Internet" has emerged, as an upgrade the classical Internet, to provide seamless connection between quantum devices in order to improve the established applications and to motivate innovative quantum use cases [3]–[7]. However, one of the main limitations of deploying quantum services over wide geographical areas is the issue of channel loss. In the case of quantum key distribution (QKD), which is one of the best developed applications of quantum technologies, there is the so-called repeaterless PLOB bound, which sets a limit on the achievable secret key generation rate in a point-to-point link to scale linearly with the transmissivity of the channel [8]. Thus, involving non-terrestrial networks (NTNs), that include aerial and space platforms, such as high-altitude platform stations (HAPS) and satellites, can be seen as a natural development step towards realizing global quantum Internet [9].

The use of NTNs in conjunction with the terrestrial infrastructure can help to address quantum networks expansion challenges and unleash the quantum capabilities. The notion of integrating NTNs with terrestrial networks (TNs) has received a substantial boost from the 3GPP standardization group after approving a dedicated work-item for its implementation within a new set of the fifth-generation (5G) new radio (NR) specifications in Release-16 [10]. Thereby, a continuous and ubiquitous wireless coverage can be attained, which is also a cost-effective solution for network scalability with reliable coverage across different geographies [11]. Further, from an implementation perspective, the free-space optical (FSO) links used in connecting NTN entities are typically preferred in quantum communications protocols owing to the unequivocal benefits of the negligible background thermal radiation at optical frequencies [12]. Thus, given the much lower channel losses and negligible decoherence in the space, NTN elements can be used as intermediate nodes for quantum communication between distant locations. However, the integration of quantum technology into satellite systems entails several deployment challenges, which requires devoting more research efforts to harness this interesting opportunity and construct an integrated system-oriented vision.

Furthermore, by employing quantum technologies, particularly entangled states, into satellite networks, we can offer certain advantages due to the higher sensitivity of quantum systems. Particularly, quantum sensors can measure different physical properties and much smaller quantities with a higher accuracy using miniaturized devices compared to the current sensors [13]. In this context, the national aeronautics and space administration (NASA) paired with Massachusetts institute of technology (MIT)-Lincoln Laboratory to develop a quantum laser system to be used for relaying information from the international space station (ISS) in order to improve Earth-to-space communications [14]. This includes a source of entangled photons of light [15]. This system would allow for high-definition photographs and videos, which in turn would extend the reach of space exploration [16]. On a similar note, quantum technologies would allow for designing light detection and ranging (LiDAR) systems working in the single-photon regime extending the precision in our imaging and detection systems [17].

Over the last few years, a number of interesting survey papers have studied and reviewed the new disrupting technologies that are based on the powerful features and resources of quantum mechanics, such as quantum entanglement [18], teleportation [19], and the no-cloning theorem [20]. Specifically, quantum cryptography schemes, especially QKD protocols, have received a major attention from both the research and industry communities owing to the offered capability to maintain information-theoretic security. QKD utilizes quantum mechanical properties to enable the secret exchange of cryptographic keys and can even alert to the presence of an eavesdropper. In this regard, the research and developments on adopting QKD to satellites are summarized in [21], including protocols, infrastructure, and the technical challenges, as well as briefly reporting the on-going satellite QKD initiatives. Additionally, the recent research advances in continuous-variable QKD for low Earth orbit (LEO) satellite communications are discussed in [5]. Likewise, utilizing communications protocols of QKD based on discrete variable systems are reviewed in [1] with considering the challenging environment in space. Further, the survey article in [22] has provided a vision to utilize space-based systems for establishing a global quantum network with focusing on quantum technologies.

The aforementioned studies have reviewed some combination aspects between the quantum technologies and space-based systems but there are still vital characteristics in the emerging NTNs to be utilized for progressing towards a scalable quantum networked landscape. Correspondingly, the resemblance in the equipment needed for interconnecting the quantum nodes and NTN platforms, e.g. optical links, can be further harnessed for more interesting advances in the realm of NTN structures and functionalities. This observation has motivated us to compose this article to identify and capitalize on the mutual interplay between the evolving NTN architectures and quantum technologies. This review paper is different from the existing ones in that we are explicitly focusing on the prominent quantum technologies and their deployment within versatile space-air-ground communications nodes across different altitudes, layers, and orbits, for enhancing the quantum-NTN interoperability. To better understand these synergies, we will briefly explain the essential features of quantum communications systems and the integration aspects with the NTNs in the next two sections.

As presented in Fig. 1, the remainder of this paper is organized as follows. In Section II, quantum communications prospects are discussed with emphasis on QKD and quantum cryptography schemes. Section III presents the key characteristics and architectures of NTNs in addition to the interconnecting synergies with the quantum devices. Next, the integration challenges that require more research efforts for enabling a wide-ranging quantum integrated network using NTNs are elaborated in Section IV. Future research directions and opportunities are highlighted in Section V. This article is finally concluded in Section VI.

II. Quantum Communications

Current communications systems are secured based on the premise that breaking cryptography is slow using the existing conventional computers. This includes communicating between data centres, inter-governmental communications, or critical financial and energy infrastructures. However, the commonly adopted classical cryptography schemes can be jeopardized by the advent of quantum computers owing to their capability to solve certain computationally intensive problems much faster than conventional computers. Although sufficiently powerful quantum computers are not fully developed yet today, this evolving research area is drawing a growing attention. Generally, the forecasts are optimistic for having the quantum computer as a commercial product in the coming years [23]. Therefore, encryption in current communications systems needs further improvement to face the forthcoming risk of developing a full-scale quantum computer, hence, breaking the current encryption algorithms exponentially faster than the best non-quantum machines. Interestingly, we can use quantum mechanics to create strictly secure cryptography beyond the capabilities of current classical systems. In quantum communication systems, the information is encoded in the quantum-mechanical properties of a system, e.g. the polarization of a photon or the spin of an electron. Employing such quantum-mechanical properties allows the communicating parties to exploit unique quantum effects such as superposition and entanglement to their advantage [24]. In this Section, we provide an overview of quantum communications theory and applications, which will serve as the background for the upcoming sections.

A. *Quantum Information: Basic Theory*

The state of an isolated quantum system is represented by a vector in a Hilbert space. A quantum bit (qubit) is the simplest of such a quantum system, which is represented by

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle = \begin{bmatrix}\alpha \\ \beta\end{bmatrix}, \quad (1)$$

where $\alpha, \beta \in \mathbb{C}$ with $|\alpha|^2 + |\beta|^2 = 1$ for normalization, $|\cdot\rangle$ is the Dirac notation for vectors, and $|0\rangle = \left[\begin{smallmatrix}1\\0\end{smallmatrix}\right]$ and $|1\rangle = \left[\begin{smallmatrix}0\\1\end{smallmatrix}\right]$ are the orthonormal vectors constituting the standard basis $\mathcal{B}_\mathrm{s} = \{|0\rangle, |1\rangle\}$ of the two-dimensional vector space. Any qubit with $\alpha \neq 0, 1$ is said to be in the superposition of $|0\rangle$ and $|1\rangle$.

Once a quantum system is prepared in an arbitrary qubit state $|\psi\rangle$, it can be measured to extract *no more than one bit* of classical information. In the simplest case, a measurement is performed by *projecting* the state $|\psi\rangle$ onto the basis vectors of some orthonormal basis $\mathcal{B} = \{|\phi\rangle, |\phi^\perp\rangle\}$, where $|\phi^\perp\rangle$ denotes the state orthonormal to $|\phi\rangle$. Upon measuring $|\psi\rangle$ of (1), the outcome will correspond to $|\phi\rangle$ with probability $|\langle\phi \mid \psi\rangle|^2$ or to $|\phi^\perp\rangle$ with probability $|\langle\phi^\perp \mid \psi\rangle|^2$, where $\langle\phi| = (|\phi\rangle)^\dagger$ is the conjugate transpose of $|\phi\rangle$. It is easy to verify that measuring $|\psi\rangle$ in $\mathcal{B}_\mathrm{s}$ will give the outcome $|0\rangle$ with probability $|\alpha|^2$ and outcome $|1\rangle$ with probability $|\beta|^2$. More importantly, once

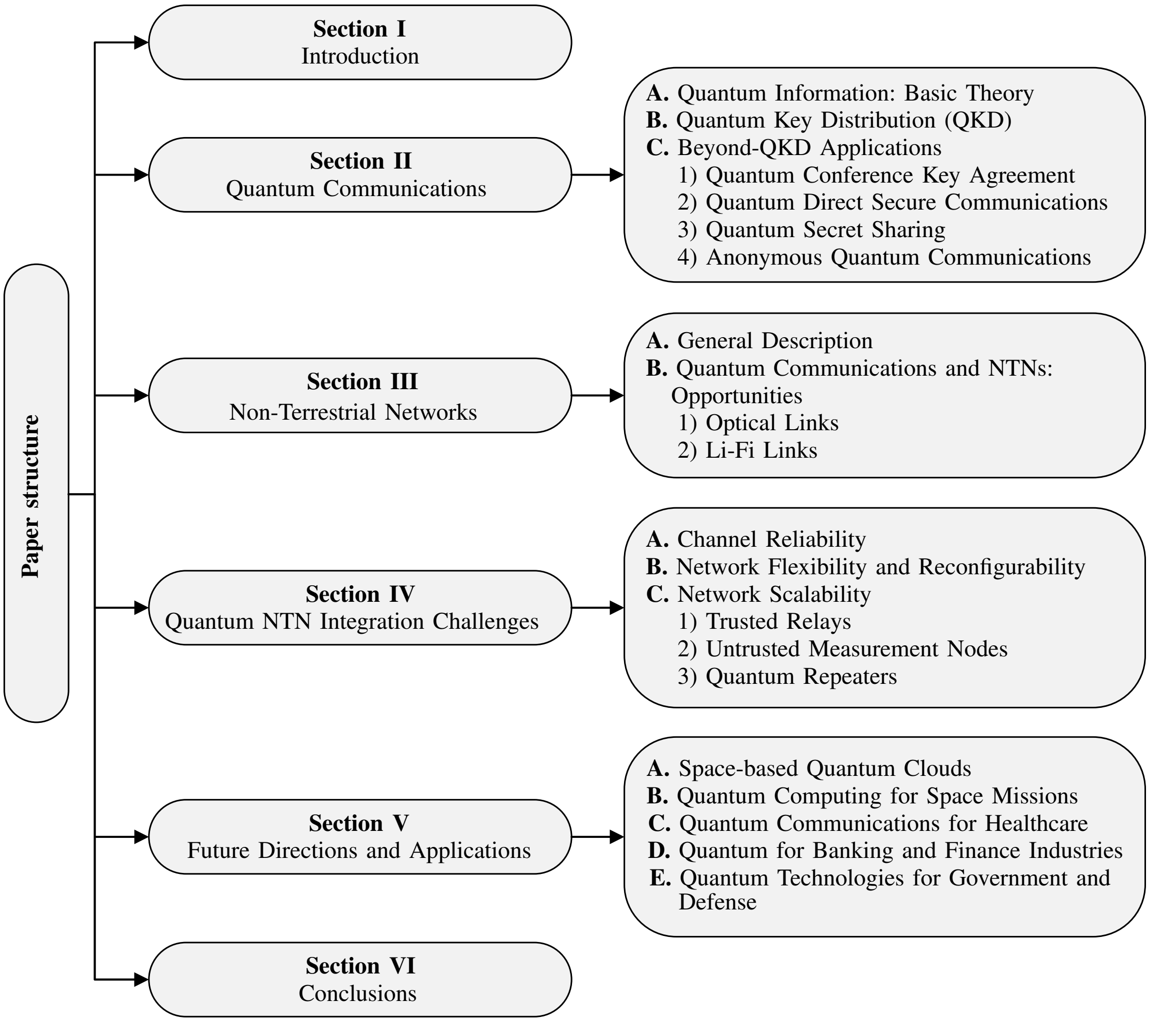

Fig. 1. Structure and organization of the paper.

measured, the state will no longer remain in the superposition of two states. Instead, it will assume the state corresponding to the obtained measurement outcome. In QKD, for instance, this collapse of state upon measurement can be used to detect the presence of an eavesdropper.

More interesting quantum phenomenon can be observed once we consider the state of multiple quantum systems. Entanglement is one such phenomenon, which can be observed in quantum systems consisting of as few as two qubits. The state of an arbitrary two-qubit system can be represented as

$$\begin{aligned} |\psi\rangle_{AB} &= \alpha\,|0\rangle_A \otimes |0\rangle_B + \beta\,|0\rangle_A \otimes |1\rangle_B + \\ &\qquad \gamma\,|1\rangle_A \otimes |0\rangle_B + \delta\,|1\rangle_A \otimes |1\rangle_B \qquad (2) \\ &= \alpha\,|00\rangle_{AB} + \beta\,|01\rangle_{AB} + \gamma\,|10\rangle_{AB} + \delta\,|11\rangle_{AB}\,, \qquad (3) \end{aligned}$$

where the state is normalized as before, subscripts indicate that the first qubit is part of system A and second qubit is part of system B, $\otimes$ denotes the tensor (Kronecker) product, and $|ij\rangle$ is a shorthand notation for $|i\rangle \otimes |j\rangle$.

Consider the two-qubit state of (3) with $\alpha = \delta = 1/\sqrt{2}$ and $\beta = \gamma = 0$, i.e,

$$|\phi^+\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|00\rangle_{AB} + |11\rangle_{AB}\right).$$

The two qubits are correlated and in a joint superposition. Measuring one of the qubits will instantly define the state of the second qubit. This type of state is called an entangled state. Entanglement is a type of correlation that is known and experimentally verified to be stronger than any classical correlation [25]–[29]. It is a key ingredient in long-distance quantum communications and in several representative quantum communications protocols [18]. Another important property of quantum states is established by the quantum no-cloning theorem [30]. This theorem states that there does not exist any physical processes that can perfectly clone an arbitrary unknown quantum state. This theorem is one of the key enablers of quantum cryptography and QKD schemes.

B. *Quantum Key Distribution (QKD)*

The QKD protocols utilize the principle of superposition of quantum states, collapse upon measurement, and the no-cloning theorem to distribute secret bits (keys) between spatially distant nodes [31]–[34]. The main idea behind QKD comes from the fact that it is not possible to perfectly distinguish nonorthogonal quantum states [35], [36].[1] The

[1]Two quantum states $|\phi\rangle$ and $|\psi\rangle$ are said to be orthogonal if $\langle \phi \mid \psi \rangle = 0$.

transmitter, Alice, can encode secret key bits in nonorthogonal quantum states and transmit over a quantum channel to the receiver, Bob. Upon successful reception, Bob measures the qubits in one of the predefined configurations. Next, Alice announces just enough information about the state preparation such that Bob can sift through the measurement configurations to decide which qubits were measured in the configuration compatible with the preparation. Finally, they compare a small subset of decoded key bits to estimate the error rate. Since an eavesdropper, Eve, cannot make perfect copies of transmitted qubits, it is not possible to replicate the measurements performed by Bob without introducing errors. This would enable Alice and Bob to bound the amount of leaked information to Eve based on the observed error rates. If such error rates are sufficiently low, Alice and Bob can use proper privacy amplification techniques to share a secret key among themselves.

These nodes can utilize these secret keys to encrypt their messages to achieve secure communication. Since these keys are secret by the virtue of laws of physics and not by some computational complexity assumption, the achieved security is also called unconditional security [32], [33]. In particular, once combined with well-known information-theoretically secure encryption methods, e.g., the one-time pad, the communicating parties can achieve information-theoretic security. Distribution of unconditionally secure key bits is logistically challenging without using QKD.

During the past decades, QKD has received major attention from both research and industry communities where a remarkable progress has been made in experimental demonstrations. QKD has been realized with optical fibers (OF) and in free-space optics (FSO) using different degrees of freedom of photons including polarization, time-bin, energy and phase. Nevertheless, deploying QKD services worldwide is still a highly intricate task due to the repeaterless bound [8]. A promising solution in optical links is using satellites as trusted relays to assist establishing quantum communications links on global scales through distributing keys among various ground stations separated by larger distance.

C. Beyond-QKD Applications

The QKD is arguably the most mature research topic of utilizing quantum technologies in communications systems. However, there exist other use cases of quantum communications systems that provide unique advantages over their classical counterparts. In particular, some of these applications require the existence of a third-party (TP) with varying levels of trusts (trusted, semi-honest, untrusted). Such a requirement makes them interesting for implementation in an NTN framework where the non-terrestrial components can assume the role of the TP (see Fig. 2). In this subsection, we highlight some intriguing research directions inspired by the quantum NTN integration.

1) ***Quantum Conference Key Agreement:*** QKD offers a bipartite protocol that allows two distant parties to securely establish secret keys. It is possible to utilize QKD to distribute same key among $N \geq 2$ participants by repeated applications

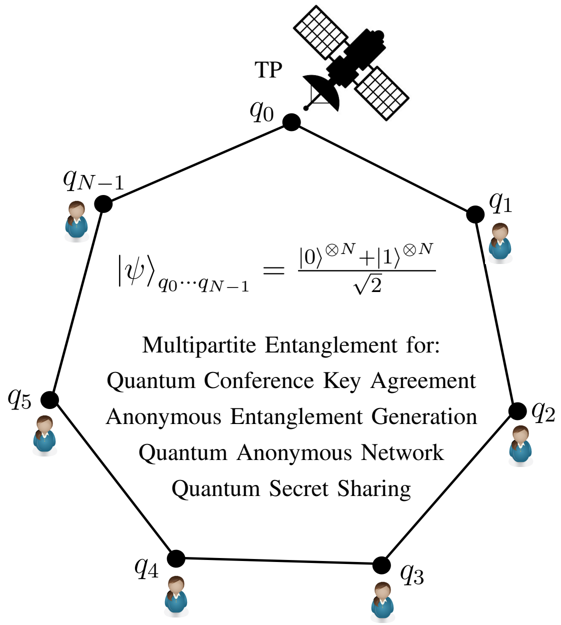

Fig. 2. Quantum conference key agreement, quantum secret sharing, and quantum anonymous communications networks can be implemented in a similar network configuration with multipartite entanglement and NTN component acting as a central node.

of QKD. However, such a setup is resource inefficient, requiring many runs of the QKD protocol. However, the long-term vision of NTN quantum integrated network goes beyond mere bipartite links and includes various nodes. Towards this direction, quantum mechanics allows the distribution of multipartite entanglement in a network, which acts as a common resource for the network participants. Quantum conference key agreement (QCKA) protocols typically leverage the multipartite entanglement to establish a common shared random key among $N \geq 2$ network participants in a single run of the protocol [37]. QCKA allows the users to broadcast secure communications in a network. The rich structure of multipartite entangled quantum states opens the possibility for a wide variety of novel key distribution protocols within the NTN infrastructure, where the quantum correlations can be exploited to devise realistic multipartite schemes.

2) ***Quantum Direct Secure Communications:*** QKD protocols cannot be used directly for transmitting the secret information due to the possibility of information leakage during the communications. For instance, in the intercept-and-resend attack, an eavesdropper can obtain 75% of the exchanged information without any errors. The leakage of information can nevertheless be detected during the classical post-processing, as, for this particular attack, Alice and Bob observe a 25% error rate. In the case of random bits being shared, such a severe leakage of information is not particularly harmful except for requiring to discard the entire key and start over. However, this situation becomes more serious if the leaked information contains the actual message. Quantum secure direct communications (QSDC) protocols allow distant nodes to communicate directly in a secured fashion without requiring them to establish secret keys in advance and it does not require key storage [38]–[40]. Hence, attacks on communication with employing QSDC obtain only random data without any useful information. In the field of NTNs, the feasibility of using QSDC from a GSO satellite to a ground station has been recently demonstrated in [41]. QSDC continues to enhance the security aspects and the value propositions of integrating quantum technologies in the NTN communications systems.

*3) **Quantum Secret Sharing**:* Quantum secret sharing is another interesting application for scalable architectures of quantum communications networks. In these schemes, a secret quantum state is shared among N network participants in such a way that at least $k < N$ participants are required in order to reconstruct the state. In other words, quantum secret sharing splits a secret message of one user, called dealer, into several parts and distributes these parts among other users, called players, with each player receiving a part. The players can gain no information about the state if there are fewer than k players willing for the reconstruction [42], [43]. Recent quantum secret sharing schemes allow assigning unequal weights w_i to each party. Then, the secret can be unlocked if the sum of the weights of the parties willing to unlock the secret is greater than a predefined threshold ω [44]. Further, the work in [45] has analyzed the security and the performance of terahertz continuous-variable quantum secret sharing within ISLs, where the feasibility of a long-distance inter-satellite communications with multiple players has been proved. Accordingly, quantum secret sharing is an essential primitive for large-scale heterogeneous networks such as NTNs in order to secure multiparty communications

*4) **Anonymous Quantum Communications**:* Additional interesting application of quantum communications is the provisioning of anonymity in networking tasks. Hiding the identity of communicating parties can be a desirable property in some scenarios. Entangled states have the unique property that local operations on any of the entangled particle can change the global state of the system regardless of the particle index. This change in the global state can be detected either by a global measurement or local measurements with partial announcement of results. This concept has been used to provide anonymity in several networking tasks including anonymous transmission of classical bits [46], qubits [47], [48], anonymous ranking [49], anonymous notification [50], anonymous collision detection [51], and anonymous private information retrieval [52]. One prominent feature of these protocols is the guarantee of anonymity even when all network messages are monitored by an adversary and/or a malicious agent controls a major part of the network.

Some of the aforementioned protocols have been demonstrated in laboratory conditions. As mentioned above, the requirement of a central node with varying levels of trust makes these protocols particularly suitable for deployment in NTNs. Recent demonstrations of satellite-based entanglement distribution paves the way for implementing these entanglement-based applications in the future [53].

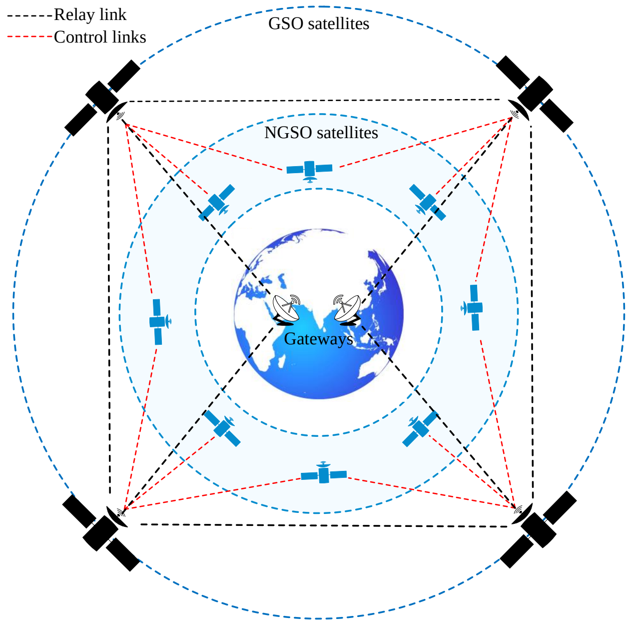

Fig. 3. General schematic diagram of a multi-layer space-based network.

III. Non-Terrestrial Networks

A. General Description

Fundamentally, NTNs include various platforms that have different deployment options but they can be categorized based on their altitudes into two main categories: *space-borne* and *airborne*. The space-born platforms can also be classified based on their orbital geometry into geostationary orbit (GSO) and non-geostationary orbit (NGSO) satellites, see Fig. 3 for an illustration. GSOs are orbiting at the equatorial plane at an altitude of 35,678 km with an almost zero-inclination angle. Whereas, NGSO satellites on a geocentric orbit include the low Earth orbit (LEO), medium Earth orbit (MEO), and highly elliptical orbit (HEO) satellites, which are orbiting constantly at lower altitudes than GSO satellites [54]. Airborne platforms, on the other hand, involve unmanned aerial vehicles (UAVs) that are placed at altitudes between 8 and 50 km, and high altitude platform systems (HAPS) that are deployed within 20 km altitude.

The recent and rapid growth of "NewSpace" industries makes the deployment of satellite mega-constellations feasible through reducing the costs of building, launching and operating small satellites, which significantly increases the number of satellites especially within the lower orbits [55]. Similarly, UAV and HAPS technologies have been growing in popularity and they are being developed and deployed at a very rapid pace around the world to offer fruitful business opportunities and new vertical markets [56]. This large number of diverse platforms imposes exceptional technical challenges on system control and operation, where they need to be built on an autonomous and dynamic network architecture [57]. Therefore, these various space and aerial platforms can be interconnected via inter-aerial links (IALs), inter-satellite links (ISLs) and inter-orbit links (IOLs) to construct a multi-layer integrated NTN systems, which can support real-time communications, massive data transmission, and systematized information services [58].

The satellite research and industrial communities have engaged in the 3GPP standardization process to integrate satellite networks into the 5G ecosystem to accomplish wide coverage and swift expansion as well as to benefit from the economies of scale of the 5G services. In this direction, the 3GPP has specified the main challenges related to the mobility and orbital height of the satellite in Release 16 [59]. Subsequently, Release 17 establishes basic mechanisms to manage the identified challenges in Release 16 and provides a first set of specifications to support NTNs in complementing the 5G system along with the TNs. Further, Release 17 aims at improving 5G system performance, where NTN channel models and necessary adaptations to support NTN are studied and recognized. The main difference among these potential solutions are essentially related to the onboard satellite functionalities, i.e. satellites can act either as relay nodes between 5G user terminals, or as 5G access points (5G-gNodeB) to extend 5G radio access network (5G-RAN) coverage, or as backbone/backhaul supports. In addition, the additional study in [60] investigates the possible employment of satellite networks as active nodes in the 5G access operations. Nonetheless, NTN integration brings about new challenges associated with the deploying and adapting the satellite networks to the technologies that are originally designed for the TNs [61].

Establishing multi-layer NTNs to connect multitude of platforms in different orbits/altitudes will enable combining multiple space/aerial assets to allow a more agile and efficient use of system resources. This NTN architecture is more economically efficient and more suitable for delivering heterogeneous services and serving diversified applications. Furthermore, NTNs can satisfy the increasing complexity of application requirements with a minimum number of gateways on the ground [62]. For instance, utilizing the space-based Internet providers, such as Starlink and SES O3B, to provide broadband connectivity to the airborne and space-borne platforms can be a promising technique for nurturing the development of multi-layer NTN infrastructures. Moreover, developing the seamless connectivity among multipurpose space-air-ground communications nodes over different altitudes, layers, and orbits will enhance the interoperability in future communications networks. Nonetheless, the open connectivity and the interconnection complexity in such an architecture as well as the lower computational capabilities of the small platforms are seen as the most paramount hurdles in this development.

B. Quantum Communications and NTNs: Opportunities

Satellites and aerial platforms in the NTN architecture can assist establishing quantum communications on larger scales beyond the repeaterless bound. Thus, this interesting association between quantum technologies and NTNs can achieve an integrated groundbreaking infrastructure for future communications systems. In this context, several experimental demonstrations have been conducted to investigate the implementation of free-space QKD systems within satellite-based quantum communications. Moreover, quantum communications with orbiting satellites have also been studied by a growing number of feasibility studies [5], [63], [64]. In addition, a demonstration for photon-pair generation and polarization correlation under space conditions has been reported in [65] for in-orbit operation using a 1.65-kg nanosatellite. More importantly, quantum communications via satellites have received a substantial boost after the launch of Micius, the world's first quantum satellite, by the Chinese academy of sciences [66].

A single space-borne or airborne platform can connect two distant points with a maximum limit restricted by the platform altitude and the elevation angle through the atmosphere. Although GSO satellites have the ability to cover approximately a third of the globe, the achievable entanglement rates will be heavily deteriorated due to the vast communication range and low elevations at the extremities of the satellites trajectory, especially when considering dual path losses for non-memory assisted quantum communications. Thus, global quantum connectivity can be realized through multi-segment quantum links, which requires more complicated architectures such as entanglement swapping and quantum memories, *inter alia* [67]. Thus, a constellation of satellites and/or aerial platforms equipped with quantum devices (e.g. entanglement sources and quantum memories) can establish dynamically configurable multi-link connections between any two points within the entire terrestrial and non-terrestrial integrated network.

Indeed, NTNs can be seen as a key driver for the development of robust long-range quantum communications especially when considering the recent remarkable advancements in quantum nonlinear optics, entangled photon generation methodology, and single-photon detection. Generally, quantum communications is conducted by transferring quantum states from one place to another through a quantum channel. Such quantum channels, in the optical domain, include optical fiber, FSO, or Li-Fi channels, as depicted in the schematic diagram in Fig. 4. Within the structure of NTNs, we will next review the offered features and connection schemes that will facilitate developing a global quantum network in a seamless fashion.

*1) **Optical Links**:* Optical communications technologies have an essential role in the multi-layer NTNs, especially within NGSO systems and mega-constellations, to establish efficient architectures using optical IALs, ISLs, IOLs, and ground-to-space/space-to-ground links. Furthermore, optical links can achieve higher data rates than conventional RF communications because the optical band provides much broader bandwidth, and thus, increases network capacity and alleviates the interference issues [68]. Particularly, laser-based FSO ISLs and IOLs offer intrinsic high gains due to the narrow-beam nature of laser beams. Therefore, FSO technology is currently gaining momentum not only in experiments and demonstrations but also for commercial purposes in the context of connecting space missions. To react to this reality, the consultative committee for space data systems (CCSDS) has defined new specifications to deal with coding and synchronization of high photon efficiency links [69]. The objective of CCSDS is developing standards in wavelength, modulation, coding, in-

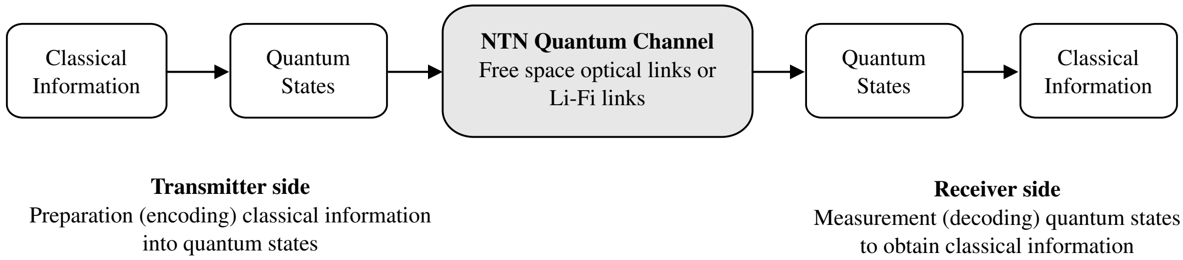

Fig. 4. Basic schematic diagram of an NTN quantum channel including encoding classical information into quantum states, Secure quantum transmission using free space optical or Li-Fi channel, and then, decoding the received quantum states to obtain the classical information.

terleaving, synchronization, and acquisition that are best suited for FSO communications systems [70]. Specifically, some working groups within CCSDS are dedicated on developing the coding and synchronization layer of a waveform supporting optical satellite-to-ground links along with optical modulation schemes to provide higher data rates up to 10 gigabits-per-second (Gbps) [71].

Furthermore, FSO communications links have been already experimented by the European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) for satellite-to-satellite link within the SILEX research program (Semiconductor Inter-Satellite Laser Experiment) [72]. In addition, NASA has recently launched the Laser Communications Relay Demonstration (LCRD) to showcase the unique capabilities of optical communications in space. In [73], [74], ground stations have been developed for optical space-to-ground links to investigate data transmission through the atmosphere. Whereas, an optical link between an aircraft and a GSO satellite was established and used to demonstrate a communication link in strongly turbulent and dynamic environment in [75]. All these studies and experimental demonstrations have validated the feasibility of using FSO links to provide an unprecedented performance and the potential of being a favorable candidate for providing high-capacity connectivity to NTNs [76].

The evolution of FSO technology in NTNs can be further utilized by introducing quantum technologies for inter-orbit and intra-orbit connections as well as for downlinking to the gateways on Earth. From an implementation perspective, optical channels are typically used in quantum communications protocols owing to the negligible background thermal radiation at optical frequencies [12]. Fortunately, both FSO connectivity and quantum communications share a symbiotic convergence in terms of the equipment needed for operation, and thus, they can each benefit from the technological developments in the other field. For instance, high-precision pointing systems needed for QKD applications can be used to improve FSO systems, while the adaptive optics modules developed for FSO will also improve the performance of quantum communications systems. Interestingly, there is also a considerable overlap in the design of high-rate encoders/modulators used in QKD and classical FSO systems, as both rely on on-off keying (OOK) and coherent optical modulation schemes. Thus, harnessing the synergetic interaction between these two technologies can pave the way to novel communications paradigms based on an integrated terrestrial and NTN architectures and services.

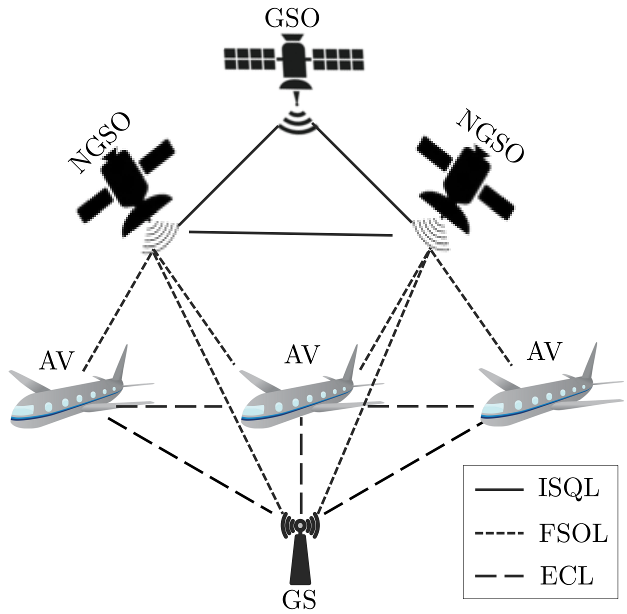

Fig. 5. Multi-layered quantum NTNs can be used for minimizing the communication outage for sensitive equipment. A large number of satellites connected by inter-satellite quantum links (ISQLs) ensure global coverage. FSO links (FSOLs) are used for quantum communications tasks including the QKD. Encrypted classical links (ECLs) are enabled by quantum-secure classical communications.

*2) **Li-Fi Links**:* Light-Fidelity (Li-Fi) technology is based on sending data using light waves as signal bearers with amplitude modulation of the light source. Li-Fi communications systems are able to utilize the vast optical spectrum to achieve peak data rates reaching the 10 Gbps level [77]. Li-Fi extends the concept of visible light communications (VLC) to attain high speed bidirectional and fully networked wireless communications [78]. Moreover, Li-Fi systems offer more tangible benefits comparing to its RF counterpart such as affordable cost, low power operation, easy deployment, and point-to-point high data-rate communications, which provides high bandwidth and operates in license-free wide range optical spectrum. Additionally, Li-Fi communications can be used in RF-restricted areas such as hospitals, mines, and aircraft [79]. To this end, several feasibility studies have been conducted on using Li-Fi links within the satellite systems [80]–[82].

Furthermore, connecting the growing number of small-size, lightweight, low-power and low-cost satellites (e.g. CubeSats and nanosatellites) and aerial platforms in lower altitudes will be challenging due to the increased densification of NTNs [57]. Networking these different NTN entities requires highly survivable links capable of relaying and downlinking data in an efficient and plausible manner. In particular, it is mechanically challenging to deploy large parabolic antennas on small satellites equipped with RF radios in order to support high data rates. Additionally, the required pointing accuracy needed for laser communications presents a challenge to the form factor of CubeSats and nanosatellites due to the stringent size, mass, and power restrictions. Therefore, Li-Fi and VLC technologies can be seen as a potential solution to establish hybrid communications systems that are able to address these connection issues under certain circumstances [82]. Hence, Li-Fi in such scenarios can surmount the NTN platforms' limitations while avoiding the usual interference issues associated with RF systems [83].

Li-Fi technologies can enable wireless access to users of quantum applications. Such techniques have been used to establish a QKD link between a mobile handheld device and a nearby receiver unit [84], [85], which could resemble an automated teller machine in banking applications. Theoretical studies have also proposed indoor wireless optical QKD for end users, and have investigated their feasibility under various conditions [86]–[88]. All this would benefit from advancements in wireless optical communications, as being pursued in the sixth generation of mobile communications systems.

The developments in quantum device technologies can reciprocally benefit Li-Fi and wireless optical systems. Within this context, multiple experimental and research studies explore the effect of different light-emitting diodes (LEDs) on Li-Fi performance. For example, a system based on OOK modulation that uses a white light LED, an analog pre-equalizer, and a post-equalizer is investigated in [89], which achieves high-speed and low complexity VLC links. Similarly, multiple-quantum-well diode is studied in [90] to achieve on-chip optocoupling, which shows the capability of using these diodes for simultaneous emission and photo-detection in a full-duplex VLC system. In addition, the work in [91] demonstrates the performance of a novel cyan LED, a light source for plastic optical fiber (POF) communications, in order to enhance the external quantum efficiency (EQE) and output power of this miniaturized high-speed LED, and thus, this setup improves the fiber coupling efficiency while achieving high data rates. In [92], employing a QKD system for vehicular visible light communications (V2LC) networks is proposed by taking into account the VLC channel characteristics. The obtained results in these studies and experiments prove the feasibility of quantum Li-Fi integrated systems.

From the industrial communications networks, Light Rider company has recently unveiled quantum Li-Fi products that offer an unhackable network connectivity. Further, VLC quantum fusion has been already considered for IoT applications to improve reliability and security [93]. In this setup, quantum dots (QDs) are enabling materials for this integration owing to their easy customizable emission wavelength and superior quantum performance. Similarly, Li-Fi links along with the quantum technologies can be utilized in the emerging Internet of Space Things (IoST), which is a new class of small satellites used for data collection and equipped with limited onboard processing. Accordingly, empowering near future small satellites and the various aerial platforms with the Li-Fi networking capabilities along with embedding quantum technologies can offer further technical and security improvements to establish wide-area quantum networks.

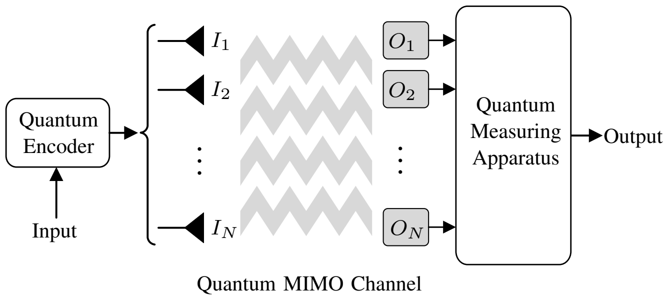

Fig. 6. The schematic model of a quantum MIMO channel.

IV. Quantum-NTN Integration Challenges

Quantum communications over NTNs can overcome the limitations of terrestrial optical networks due to large attenuation in the long-distance fiber channels, and thus, an intercontinental quantum network is attainable. This structure raises a new set of resource allocation and management problems for involving multiple layers, relative motion of various NTN entities, and the distributed ground stations. Therefore, the integration problems of scalability and management are different in this paradigm and require devising new methods for boosting channel reliability and novel strategies for network management and coordination within the multi-layer NTNs. In this section, we will explore the key technical challenges and design issues for deploying efficient quantum NTNs with highlighting some potential solutions.

A. Channel Reliability

FSO links are highly susceptible to atmospheric loss and scintillation effects due to the cloud blockage and the ionospheric electron density along the signal path that result in signal intensity fluctuations at the receiver [94]. The movement of NTN units, and the constant requirement for pointing and tracking of these objects would also add to the overall channel loss. Another important factor in specifying the channel loss is the size and number of telescopes that can be used on a satellite, as well as on the ground stations. The randomness in all the above can also cause channel fading. In addition, the multipath time delay spread leads to time dispersion and frequency-selective fading, whereas Doppler frequency spread leads to frequency dispersion and time-selective fading. Moreover, the random effects of shadowing or diffraction from obstructions result in slow or large-scale fading.

Potential solutions

To enhance channel reliability, multicarrier transmission techniques and spatial diversity strategies, such as site diversity and multiple beam transmissions, can be applied in NTNs and

FSO links [95]. Specifically, multiple-input multiple-output (MIMO) transmission techniques have drawn a significant attention in the satellite communications research due the offered high degrees of freedom [96]. In addition, MIMO transmission has already been considered in quantum optical wireless communications systems and called quantum MIMO by the authors (q-MIMO) [97], although this is not the only way to use MIMO techniques in quantum communications [98]. In contrast to the classical single-beam single-aperture configuration that is called SISO (single-input single-output), MIMO can realize spatial diversity by using a combination of multiple beams at the transmitter and multiple apertures at the receiver. In the setting of [97], MIMO communications is performed over quantum channels where classical information is transmitted through quantum states instead of classical electromagnetic field. The q-MIMO architecture is suitable for applications involving spatial diversity and optimal quantum digital receiver design, which will increase the reliability of quantum communications systems transmitting classical information over quantum channels. This architecture has promising aspects because it allows using positions of quantum antennas at the transmitter and quantum measurement operators at the receiver, which will allow for joined optimum fine-tuning of the overall system performance.

MIMO techniques can also be used to deal with the fading nature of atmospheric channels. For such channels, MIMO techniques are known to improve system performance. However, the advantages achieved by using the MIMO concept come at the cost of utilizing more resources and increased system complexity. The MIMO techniques have not yet been fully investigated within the recent quantum advances and the multi-layer NTN structures, which can be exploited for reliable and secure high-speed communications. Thereby, it is essential to assess the feasibility and advantages of employing MIMO in the context of FSO communications and NTN systems. This could in turn result in performance improvement of both classical and quantum communications systems.

B. Network Flexibility and Reconfigurability

The success of integrating quantum technologies into NTNs depends to a large extent on the flexibility and adaptability of the existing network architectures [11]. Moreover, establishing a quantum link within NTN entities requires precision timing and time-tagging of the received photons, accurate pointing, robust filtering, and knowledge of the location, velocity, and range of both transmitter and receiver, which is an intricate task considering the dynamic propagation environment of NTNs. More importantly, the routing mechanism for coordinating quantum transmissions and classical communications is a crucial part for this integration, which should consider the unique features of both types of communications within this variable network's topological structure. Furthermore, relaying the quantum keys among different network elements entails the need of quantum devices to communicate with the network control in order to enable flexible and efficient routing based on applications' QoS profiles and secret key rate generation of

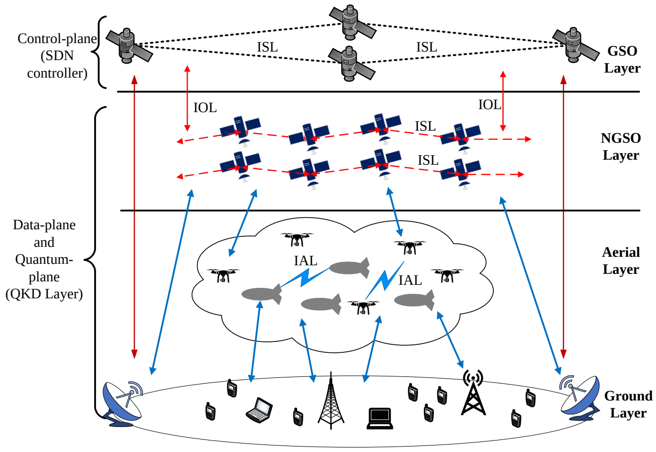

Fig. 7. Quantum software-defined internetworking architecture in the terrestrial and non-terrestrial integrated systems.

the links [99]. Additionally, resource management for the quantum plane, data plane, and control plane is a conundrum that needs to be adequately addressed through flexible and cognizant resource allocation strategies. Particularly, safeguarding NTN communications with QKD requires a quantum signal channel and a public interaction channel for secure key synchronization along with the traditional data channel [100]. Thus, serving these three types of channels has to be conducted via effective algorithmic solutions.

Potential solutions

Software defined networking (SDN) is a well-known paradigm for enabling flexible and programmable network configuration in order to improve system performance, management, and monitoring [101]. SDN enables agile and efficient network services through innovative and advanced resource management techniques. Within NTN context, SDN can play an important role owing to the offered operational flexibility, scalability, and the end-to-end service provisioning [58]. Furthermore, embedding SDN into satellites and aerial platforms can facilitate the interaction between non-terrestrial and terrestrial wireless networks, which allows addressing several coexisting challenges. Additionally, SDN paradigm seems to be more suitable to deal with the complexity and dynamicity of multi-layer NTNs, where SDN controllers can be distributed over higher orbits to simultaneously manage both the classical and quantum parts of the network within the active space and aerial nodes in lower altitudes as shown in Fig. 7. For instance, the SDN architecture can be designed to allow a controller to centrally orchestrate the quantum resources for optimizing the key allocation and systematizing the establishments of a direct channel or multi-hop links based on demands, visibility, and channel conditions.

The SDN technology can help with the management of different tasks we need to control in quantum communications systems. This includes key exchnage mechanisms, entanglement generation/distribution schemes, and efficient swapping procedures. In all cases, embedding SDN technologies into quantum networks would allow for provisioning of accurate control and management. Several research works in the open literature have shown that SDN integration is beneficial to QKD networks by customizing network configuration and designing efficient routing protocols [102]. Specifically, SDN can provide a constant instantaneous monitoring of the quantum parameters such as quantum bit error rate and secret key rate, and flexible configuration of optical paths to ensure the continuous distribution of quantum keys in the network. Furthermore, SDN allows the deployment of advanced resource allocation and control algorithms for load balancing, network slicing, and quantum-aware path computation, regardless of the underlying infrastructure. Thus, introducing the SDN model is a mutually beneficial arrangement that opens the road to a seamless convergence between NTNs and quantum technologies.

C. Network Scalability

Despite the many appealing solutions offered by NTN for scaling up quantum communications networks, there are still considerable technical hurdles for reaping the benefits of this integration. Specifically, FSO and Li-Fi links to ground transmit through atmospheric channels as a propagating medium whose properties are random functions of space and time. This renders the quantum communication to a random process depending on weather and geographical locations [103]. Additionally, several unpredictable environmental factors such as clouds, snow, fog, rain, haze, among other things, may cause signal attenuation and shorten the communication distance. That said, space-based communications links have the advantages of negligible propagation losses for the signal transmitted through the vacuum [104]. Namely, ISLs and IOLs are not subject to weather conditions because satellite orbits are typically far above the atmosphere but the main challenge here is caused by the link availability when satellites are moving with different relative velocities. Thus, these inevitable transmission losses in real optical channels along with challenges in ISL and IOL communications may reduce or even totally destroy the quantum entanglement across remote nodes, and hence, jeopardize the scalability offered by NTNs for realizing the long-range quantum networking.

Potential solutions

In the direction to overcome these limitations, multiple quantum devices and technologies can be utilized within the NTN infrastructure. Next, we will present the most promising approaches for provisioning the foreseeable scalability and ensuring consistent hybrid deployment landscape.

1) Trusted Relays: Reliable and efficient transmission of quantum information at global distances is a daunting task. However, for some specific applications of quantum communications, it is possible to somehow decode-reencode the (classical) message encoded in the quantum states at trusted relays placed between the communicating nodes. QKD is one example of such applications. For establishing a key between Alice and Bob, with a trusted relay, Charlie, one can use two runs of QKD. Charlie establishes two random keys k_1 and

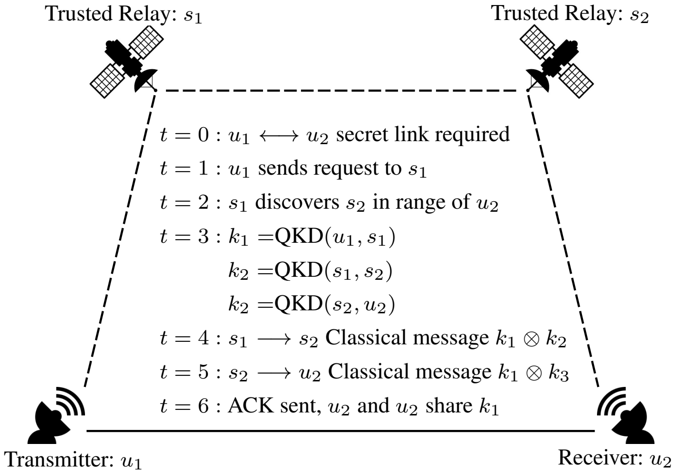

Fig. 8. Trusted-relay based quantum NTNs can extend the distance of QKD beyond the reach of ordinary links. Here an example scenarios is depicted where two satellites s_1 and s_2 assist two distant ground stations u_1 and u_2 to establish secret keys.

k_2 with Alice and Bob by QKD, respectively. Then, Charlie sends the bit-wise exclusive-OR of the two keys to either of the two communicating parties, who can now obtain the key established with the other party. This key can be used for subsequent secret communication between Alice and Bob. Fig. 8 shows an example scenario with two satellites and two ground users. As it is clear from the above procedure, this approach is completely scalable with two serious drawbacks: 1) this approach is not generally applicable to all quantum communications protocols, and 2) very high level of trust is assumed, which may be hard to justify in general. However, this is one of the currently feasible solutions, which has been demonstrated with a LEO satellite assuming the role of a trusted relay and establishing secure keys between two ground stations 7600 km apart [104].

2) Untrusted Measurement Nodes: Measurement device independent (MDI) is an important framework to constitute a quantum network with an untrusted network server/relay, which can provide an enhanced security performance compared to traditional QKD [105]. Thereby, even with untrusted NTN platforms, quantum security can still be guaranteed in some cases using the MDI concept. The main idea in MDI QKD is to design the communications protocol in such a way that no assumption on the trustworthiness of measurement devices is required. Both communications parties prepare and send their signals to the untrusted measurement device, which announces the measurement outcomes. The protocol is designed in such a way that the announcement of incorrect measurement results would show itself in the observed error rates, indicating malice or malfunction. Whereas, the announcement of correct measurement results does not pass any information to Eve/untrusted node about the actual key bits being exchanged between the two parties.

The implementation of MDI QKD in the NTN setting is not without its own challenges. First, it requires us to use the uplink configuration, which is known to be more lossy than the downlink one, in satellite-to-ground settings. It also requires to have the measurement devices on board the satellite, which are often more complicated systems than the source in the MDI-QKD protocol. Synchronization is also a challenge given that the photons sent by the two users have to reach the satellite at the same time. That said, implementation of MDI QKD via a satellite node is a prelude to the implementation of memory-assisted QKD [106], [107] and quantum repeaters in space, and can therefore be part of the global efforts to make quantum communications services accessible worldwide.

3) Quantum Repeaters: The fundamental solution to the issue of scalability is utilizing quantum repeaters, which are the essential parts of future quantum communications systems [108], [109]. In the case of QKD, quantum repeaters enable end-to-end security for QKD users. Conventional quantum repeaters aim at creating entanglement within smaller segments, followed by entanglement swapping (ES) at intermediate nodes to extend the entanglement to longer distances [110]. Embedding quantum repeaters in NTNs allows for realizing entanglement distribution over large distances with a smaller number of intermediate nodes as compared to terrestrial communications systems [111]. In principle, quantum repeater nodes can be placed on board a satellite or an aerial platform, with photonic channels enabling entanglement distribution among orbiting/flying nodes. ES procedures can then be done at such nodes [1]. Creating an end-to-end entangled state, when the nodes are moving in space, would inevitably add an extra layer of complexity to the design of the NTN based system. Therefore, it is critical to efficiently optimize the quantum repeater schemes, which is nontrivial because the number of possible schemes that can be performed grows exponentially with the number of links or nodes [112].

Quantum repeaters enable the implementation of all quantum networking tasks that require preshared entanglement between distant nodes as an important prerequisite; see Sec. II-C for some examples. This makes the ability of quantum nodes, i.e. end nodes and repeaters alike, to store and efficiently utilize quantum entanglement a crucial functionality. More importantly, tasks such as quantum teleportation and entanglement swapping are elementary and fundamental in nature for the basic working of a quantum communications network [113]. To fulfil the requirement of preshared entanglement, quantum memories that are capable of storing quantum information from generation to utilization while maintaining acceptable fidelity levels are required. A quantum memory is a device that can store an incoming photon and efficiently retrieve the same photonic state on-demand without disturbing the quantum state. Thus, an NTN-deployable quantum memory would be essential for long-range quantum communications and for performing QKD across global distances without intermediate trusted nodes.

The development and deployment of quantum memories, by itself, is a huge technical challenge even for terrestrial applications. One of the key issues is the required coherence time of quantum memories. The authors in [114] consider a quantum repeater network with a large number ($\gg 1$) of quantum memories at each node to minimize the waiting time due to classical communications. Their optimistic estimates indicate that coherence times in the excess of 10 ms are sufficient for a 1000 km fiber-based repeater network. Meanwhile, experimental demonstrations have been performed for quantum memories of coherence times well above this limit, e.g., from 1.3 s to six hours [115], [115], [116]. However, these quantum memories typically store quantum information in matter qubits and/or require cryogenic temperatures. Storage in matter qubits requires development of efficient interfaces between flying and matter qubits, which in itself is a challenge [117]. Requirement of cryogenic temperatures make utilization of quantum memories a challenge in non-laboratory conditions. Availability of practical quantum memories with sufficient coherence times will enable not only the long-distance quantum communications but also will greatly diversify the suite of useful quantum communications protocols that can be implemented in such networks.

There are multiple competing approaches that are being considered as candidates for quantum memories with different strengths and weaknesses [115], [118]. In this direction, a variety of different dopant/host combinations have been studied for various quantum mechanical phenomena, and many elements necessary for a practical quantum memory have been shown, such as long storage times and high efficiency optical storage and recall. However, the research still focuses on optimizing single parameters, while a system demonstrating all necessary aspects simultaneously remains to be developed. To this end, there are ongoing efforts for the integration of these memories in quantum networks such that the modality of quantum memory can be made independent of the operating modality of the quantum network [119]. Once developed, these quantum interconnects will allow seemless interface between quantum nodes working with different modalities. The experimental developments can be boosted by the improved funding opportunities and allocation of more funds targeting the key components of the quantum network architecture. Meanwhile, theoretical efforts can be concentrated to the development of useful quantum technologies realizable with currently available hardware. Prepare-and-measure type protocols, e.g., BB84 are well within the reach of current experimental capabilities. Developments of novel quantum applications with the same structure can provide a boost in the utilization of quantum technologies in near future.

The above developments could, however, take years to be space ready. Another challenging task in the adoption of quantum communications networks in NTNs is then the limited number of demonstrable network tasks of practical interest. Most applications we mentioned in earlier sections, e.g., quantum secret sharing, as well as other emerging ones such as quantum secret comparison, quantum oblivious transfer, and quantum voting, require quantum resources beyond current technological reach, e.g., large amounts of long-term entanglement and error-corrected communication and storage [120]. These quantum resources are not likely to be available very soon [121]. In the mean time, it is essential to develop quantum network applications that are less resource-demanding and can be demonstrated with the currently available or near-term quantum communications equipment.

V. Future Directions and Applications

The disruptive potentials of the convergence between quantum technologies and NTNs do not lay only in provisioning secure communications but it also promises to open new frontiers for digital innovation. In this section, several promising research directions and novel applications will be presented.

*1) **Space-based Quantum Clouds**:* The concept of space-based clouds is developed to further boost information service systems by utilizing satellites not only as relay devices but also for establishing data storage paradigms over GSO and/or NGSO satellites. The main advantage of space-based data centres is the absolute immunity against natural disasters occurring on the ground. In the realm of multi-layer NTNs, the geographical boundaries and terrestrial obstacles are not deterrent factors for transferring data globally, and thus, mega-corporations that have intercontinental sites will be able to share massive data through a space-based cloud and benefit from the faster transmissions comparing to the terrestrial cloud networks. Beyond this, empowering space-based clouds with quantum technologies improves the security aspects and offers quantum computing capabilities for big data applications. This ecosystem will create an accessible quantum algorithm development environment for the quantum developers around the world and may also lead to emerging quantum-as-a-service providers. Moreover, given the extreme high costs of hosting and building quantum computing services, space-based quantum clouds can improve the financial viability through allowing simultaneous access for multiple beneficiaries and users, and hence, increase machine utilization.

*2) **Quantum Computing for Space Missions**:* One of the major challenges in the operation of the CubeSats and small satellites in lower altitudes is the rather low information processing capabilities of the onboard processors [122]. Consequently, complex processing tasks, such as online optimization of the resource allocation strategy, data processing for Earth observation applications, or data aggregation for IoT, can hardly be executed using a single satellite processor. Alternatively, quantum technologies along with space-based quantum clouds can be utilized in such scenarios in order to offload the computational burden from small satellites. Thus, a space quantum network can be structured and interconnected via FSO links, which will benefit from several advantages of FSO over RF systems and the extraordinary computational capacity of the quantum servers with certainly enhanced security performance. This setup can also alleviate the latency issue especially for resource-hungry and delay-sensitive applications. In addition, small satellites can be deployed as space-based quantum sensors to enhance the practical performance of navigation and Earth observation systems. In particular, these quantum sensors on the small satellite nodes would to a large extent improve the knowledge of our planet through Earth observation missions that can measure small-scale variations of Earth's gravitational field resulted from water flows, movement of ice, continental drifts, and so forth.

*3) **Quantum Communications for Healthcare**:* One of the sensitive issues in digital healthcare is encryption and security of data. Quantum communications provides methods of secure exchange of health records by QKD and anonymous private information retrieval systems [52]. Additionally, security of medical media is imperative for patient safety and confidentiality, and thus, recently the concept of quantum medical image encryption has attracted a significant attention from both scientists and healthcare system designers [123]. In this framework, medical images and records can be securely communicated within different health centers using quantum encryption/decryption algorithms. Another interesting feature is to offer certified deletion of health records that generates a classical certificate of deletion of health records [124]. These features make quantum communications systems attractive for digital healthcare solutions and other databases of sensitive nature. Furthermore, quantum computing can also help in this context via optimizing the healthcare system models to advance the patient care experience, improve the population health, and minimize per capita healthcare costs [125].

*4) **Quantum for Banking and Finance Industries**:* Banking and finance industry have strict requirements for encryption due to sensitive nature of their operations and data. On the one hand, banks and financial institutions require real-time encryption capabilities for the large-volume of their real-time transactions, which is a major growing challenge. Introducing quantum to NTNs offers a solution to this challenge in the form of satellite-based QKD with the possibility of global connectivity. On the other hand, quantum computing also offers appealing solutions for the finance sector in the form of quantum algorithms for risk-based asset management, portfolio optimization, and other complicated financial procedures [126], [127]. Specifically, quantum computing can further develop the investment industry via applying quantum-based machine learning algorithms for managing massive numbers of underlying assets while considering various sets of relevant data for learning, adapting, and enhancing investment decisions. Beyond this, with the availability of cloud quantum computers and the possibility of blind quantum computation, there exists an opportunity to put these quantum solutions to test and harness their benefits [128].

*5) **Quantum Technologies for Government and Defense**:* Communication within the governmental organizations and defense establishments are under persistent threats of espionage and cyber-attacks. The unconditional security offered by the QKD and other quantum encryption techniques is an effective countermeasure to protect against these threats. Furthermore, quantum technologies including communications, computing, and sensing are offering a set of beneficial tools and mechanisms for defense and military applications [129]. For instance, quantum sensors can be used to detect submarines and stealth aircraft [130]. Specifically, utilizing quantum sensors for positioning, navigation and timing can induce reliable inertial navigation systems, which empower navigation without the need for external references. A gravimeter based on quantum sensing has been proposed in [131] to detect changes in the gravitational field. This gravimeter uses a quantum magnetomechanical system consisting of a magnetically trapped superconducting resonator, and it is a passive system that probes without transmitting signals. This allows the detection of objects, which may not emit any kind of electromagnetic signals, by only observing the surrounding transient gravitational changes.

VI. Conclusions

In this paper, we have discussed how quantum technologies interplay with, benefit from, and shape the future of NTN research within the wireless communications landscape. Amalgamation of quantum information technologies with NTN can provide benefits to both NTNs and quantum technologies. On the one hand, NTNs can benefit from the secure communication offered by quantum technologies. On the other hand, quantum communications networks supported by the NTN infrastructure can be more resilient and operated at the global scale. In this direction, the key integration challenges are elaborated with providing some intriguing potential solutions. In particular, channel reliability in such dynamic propagation environment, scalability and networking issues, resource management and coordination problems are discussed along with the theoretical and experimental complications. Afterwards, various innovative visions and research directions motivated by utilizing quantum technologies in the non-terrestrial communications systems are pointed out. Ultimately, this article covers the quantum communications aspects and the integration challenges with NTNs to constitute a global-spanning quantum network, in the hope that it would trigger more in-depth investigations and serve as a continuous incentive for further quantum communications research activities.

References

[1] S. Pirandola *et al.*, "Advances in quantum cryptography," *Adv. Opt. Photon.*, vol. 12, no. 4, pp. 1012–1236, Dec 2020.

[2] C. De Lima *et al.*, "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges," *IEEE Access*, vol. 9, pp. 26 902–26 925, 2021.

[3] H. J. Kimble, "The quantum internet," *Nature*, vol. 453, no. 7198, pp. 1023–1030, Jun 2008.

[4] S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: A vision for the road ahead," *Science*, vol. 362, no. 6412, p. eaam9288, 2018.

[5] N. Hosseinidehaj, Z. Babar, R. Malaney, S. X. Ng, and L. Hanzo, "Satellite-based continuous-variable quantum communications: State-of-the-art and a predictive outlook," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 881–919, 2019.

[6] A. S. Cacciapuoti *et al.*, "Quantum internet: Networking challenges in distributed quantum computing," *IEEE Netw.*, vol. 34, no. 1, pp. 137–143, 2020.

[7] J. Illiano, M. Caleffi, A. Manzalini, and A. S. Cacciapuoti, "Quantum internet protocol stack: A comprehensive survey," *Computer Networks*, vol. 213, p. 109092, 2022.

[8] S. Pirandola, R. Laurenza, C. Ottaviani, and L. Banchi, "Fundamental limits of repeaterless quantum communications," *Nat. Commun.*, vol. 8, no. 1, p. 15043, Apr 2017.

[9] C. Simon, "Towards a global quantum network," *Nat. Photonics*, vol. 11, no. 11, pp. 678–680, 2017.

[10] 3GPP TR 38.821 V16.0.0, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16)," 3rd Generation Partnership Project, Tech. Rep., 2019.

[11] M. Giordani and M. Zorzi, "Non-terrestrial networks in the 6G era: Challenges and opportunities," *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, 2021.

[12] A. Trichili, M. A. Cox, B. S. Ooi, and M.-S. Alouini, "Roadmap to free space optics," *J. Opt. Soc. Am.*, vol. 37, no. 11, pp. A184–A201, 2020.

[13] C. L. Degen, F. Reinhard, and P. Cappellaro, "Quantum sensing," *Reviews of modern physics*, vol. 89, no. 3, p. 035002, 2017.

[14] B. L. Edwards and D. J. Israel, "Update on NASA's laser communications relay demonstration project," in *SpaceOps Conf.*, 2018, p. 2395.

[15] S. A. Hamiltona *et al.*, "Overview of NASA's national space quantum laboratory program," *International Astronautical Congress (IAC)*, Oct 2019.

[16] A. Thoss, V. Henderson, M. Krutzik, and A. Wicht, "Laser systems enable quantum technology in space," www.laserfocusworld.com/lasers-sources/article/14188837/laser-systems-enable-quantum-technology-in-space, accessed 22-07-2022.

[17] J. Tachella *et al.*, "Real-time 3D reconstruction from single-photon LIDAR data using plug-and-play point cloud denoisers," *Nat. Commun.*, vol. 10, no. 1, pp. 1–6, 2019.

[18] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, "Quantum entanglement," *Rev. Mod. Phys.*, vol. 81, no. 2, p. 865, 2009.

[19] S. Pirandola, J. Eisert, C. Weedbrook, A. Furusawa, and S. L. Braunstein, "Advances in quantum teleportation," *Nat. Photonics*, vol. 9, no. 10, pp. 641–652, 2015.

[20] M. G. Kuzyk, "Quantum no-cloning theorem and entanglement," *Am. J. Phys.*, vol. 87, no. 5, pp. 325–327, 2019.

[21] R. Bedington, J. M. Arrazola, and A. Ling, "Progress in satellite quantum key distribution," *npj Quantum Inf.*, vol. 3, no. 1, pp. 1–13, 2017.

[22] J. S. Sidhu *et al.*, "Advances in space quantum communications," *IET Quantum Communication*, vol. 2, no. 4, pp. 182–217, 2021.

[23] G. J. Alberts *et al.*, "Accelerating quantum computer developments," *EPJ Quantum Technology*, vol. 8, no. 1, p. 18, 2021.

[24] M. M. Wilde, *Quantum Information Theory*, 2nd ed. UK: Cambridge University Press, 2017.

[25] J. S. Bell, "On the Einstein Podolsky Rosen paradox," *Phys. Phys. Fiz.*, vol. 1, pp. 195–200, Nov 1964.

[26] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, "Proposed experiment to test local hidden-variable theories," *Phys. Rev. Lett.*, vol. 23, pp. 880–884, Oct. 1969.

[27] B. Hensen *et al.*, "Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres," *Nature*, vol. 526, no. 7575, pp. 682–686, Oct 2015.

[28] C. Abellán *et al.*, "Challenging local realism with human choices," *Nature*, vol. 557, no. 7704, pp. 212–216, May 2018.

[29] A. S. Cacciapuoti, J. Illiano, S. Koudia, K. Simonov, and M. Caleffi, "The quantum internet: Enhancing classical internet services one qubit at a time," *IEEE Netw.*, vol. 36, no. 5, pp. 6–12, 2022.

[30] W. K. Wootters and W. H. Zurek, "A single quantum cannot be cloned," *Nature*, vol. 299, no. 5886, pp. 802–803, Oct 1982.

[31] C. H. Bennett and G. Brassard, "Quantum cryptography: Public key distribution and coin tossing," in *Proceedings of IEEE International Conference on Computers, Systems, and Signal Processing*. Bangalore, India: IEEE, Dec. 1984, pp. 175–179.

[32] M. Curty *et al.*, "Finite-key analysis for measurement-device-independent quantum key distribution," *Nat. Commun.*, vol. 5, Apr. 2014.

[33] M. Tomamichel, C. C. W. Lim, N. Gisin, and R. Renner, "Tight finite-key analysis for quantum cryptography," *Nat. Commun.*, vol. 3, p. 634, Jan. 2012.

[34] Y. Cao *et al.*, "The evolution of quantum key distribution networks: On the road to the qinternet," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 2, pp. 839–894, 2022.

[35] K. M. R. Audenaert *et al.*, "Discriminating states: The quantum Chernoff bound," *Phys. Rev. Lett.*, vol. 98, p. 160501, Apr. 2007.

[36] J. Calsamiglia, R. M. noz Tapia, L. Masanes, A. Acín, and E. Bagan, "Quantum Chernoff bound as a measure of distinguishability between density matrices: Application to qubit and Gaussian states," *Phys. Rev. Lett.*, vol. 77, p. 032311, Mar. 2008.

[37] G. Murta, F. Grasselli, H. Kampermann, and D. Bruß, "Quantum conference key agreement: A review," *Adv. Quantum Technol.*, vol. 3, no. 11, p. 2000025, 2020.

[38] K. Boström and T. Felbinger, "Deterministic secure direct communication using entanglement," *Phys. Rev. Lett.*, vol. 89, p. 187902, Oct 2002.

[39] S. Qaisar, J. ur Rehman, Y. Jeong, and H. Shin, "Practical deterministic secure quantum communication in a lossy channel," *Prog. Theor. Exp. Phys.*, vol. 2017, no. 4, pp. 1–12, Apr. 2017.

[40] T. Li and G.-L. Long, "Quantum secure direct communication based on single-photon bell-state measurement," *New J. Phys.*, vol. 22, no. 6, p. 063017, jun 2020.

[41] X.-f. Wang *et al.*, "Transmission of photonic polarization states from geosynchronous Earth orbit satellite to the ground," *Quantum Eng.*, vol. 3, no. 3, p. e73, 2021.

[42] M. Hillery, V. Bužek, and A. Berthiaume, "Quantum secret sharing," *Phys. Rev. A*, vol. 59, pp. 1829–1834, Mar 1999.

[43] R. Cleve, D. Gottesman, and H.-K. Lo, "How to share a quantum secret," *Phys. Rev. Lett.*, vol. 83, pp. 648–651, Jul 1999.

[44] Y.-H. Chou, G.-J. Zeng, X.-Y. Chen, and S.-Y. Kuo, "Multiparty weighted threshold quantum secret sharing based on the Chinese remainder theorem to share quantum information," *Sci. Rep.*, vol. 11, no. 1, p. 6093, Mar 2021.

[45] C. Liu *et al.*, "Continuous-variable quantum secret sharing based on thermal terahertz sources in inter-satellite wireless links," *Entropy*, vol. 23, no. 9, 2021.

[46] M. Christandl and S. Wehner, "Quantum anonymous transmissions," in *Advances in Cryptology - ASIACRYPT 2005*, B. Roy, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 217–235.

[47] V. Lipinska, G. Murta, and S. Wehner, "Anonymous transmission in a noisy quantum network using the w state," *Phys. Rev. A*, vol. 98, p. 052320, Nov 2018.

[48] A. Unnikrishnan *et al.*, "Anonymity for practical quantum networks," *Phys. Rev. Lett.*, vol. 122, p. 240501, Jun 2019.

[49] W. Huang *et al.*, "Quantum anonymous ranking," *Phys. Rev. A*, vol. 89, p. 032325, Mar 2014.

[50] A. Khan, J. ur Rehman, and H. Shin, "Quantum anonymous notification for network-based applications," *Quantum Inf. Process.*, vol. 20, no. 12, p. 397, Nov 2021.

[51] A. Khan, U. Khalid, J. ur Rehman, K. Lee, and H. Shin, "Quantum anonymous collision detection for quantum networks," *EPJ Quantum Technol.*, vol. 8, no. 1, p. 27, Dec 2021.

[52] A. Khan, U. Khalid, J. ur Rehman, and H. Shin, "Quantum anonymous private information retrieval for distributed networks," *IEEE Trans. Commun.*, vol. 70, no. 6, pp. 4026–4037, 2022.

[53] J. Yin *et al.*, "Satellite-based entanglement distribution over 1200 kilometers," *Science*, vol. 356, no. 6343, pp. 1140–1144, 2017.

[54] ITU-R, "Simulation methodologies for determining statistics of short-term interference between co-frequency, codirectional non-geostationary-satellite orbit fixed-satellite service systems in circular orbits and other non-geostationary fixed-satellite service systems in circular orbits or geostationary-satellite orbit fixed-satellite service networks," International Telecommunication Union, Standard, 2003, ITU-R S.1325-3.

[55] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas, and S. Chatzinotas, "A survey on non-geostationary satellite systems: The communication perspective," *IEEE Commun. Surveys Tuts.*, 2022.

[56] T. Alladi, Naren, G. Bansal, V. Chamola, and M. Guizani, "SecAuthUAV: A novel authentication scheme for UAV-ground station and UAV-UAV communication," *IEEE Trans. Veh. Technol.*, vol. 69, no. 12, pp. 15 068–15 077, 2020.

[57] H. Al-Hraishawi, S. Chatzinotas, and B. Ottersten, "Broadband non-geostationary satellite communication systems: Research challenges and key opportunities," in *IEEE Int. Conf on Commun. (ICC)*, Jun. 2021, pp. 1–6.

[58] H. Al-Hraishawi *et al.*, "Multi-layer space information networks: Access design and softwarization," *IEEE Access*, 2021.

[59] 3GPP TR 38.821 V16.0.0, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16)," 3rd Generation Partnership Project, Tech. Rep., 2019.

[60] 3GPP, "Study on using satellite access in 5G," 3rd Generation Partnership Project, Tech. Rep., 2018.

[61] M. Bacco *et al.*, "Networking challenges for non-terrestrial networks exploitation in 5G," in *IEEE 2nd 5G World Forum (5GWF)*, 2019, pp. 623–628.

[62] N. U. L. Hassan, C. Huang, C. Yuen, A. Ahmad, and Y. Zhang, "Dense small satellite networks for modern terrestrial communication systems: Benefits, infrastructure, and technologies," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 96–103, 2020.

[63] C. Cheng, R. Chandrasekara, Y. C. Tan, and A. Ling, "Space-qualified nanosatellite electronics platform for photon pair experiments," *J. Lightw. Technol.*, vol. 33, no. 23, pp. 4799–4804, 2015.

[64] L. Moli-Sanchez, A. Rodriguez-Alonso, and G. Seco-Granados, "Performance analysis of quantum cryptography protocols in optical earth-satellite and intersatellite links," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1582–1590, 2009.

[65] Z. Tang *et al.*, "Generation and analysis of correlated pairs of photons aboard a nanosatellite," *Phys. Rev. Appl.*, vol. 5, no. 5, p. 054022, 2016.

[66] S.-K. Liao *et al.*, "Satellite-to-ground quantum key distribution," *Nature*, vol. 549, no. 7670, pp. 43–47, 2017.

[67] L. Bacsardi, "Resources for satellite-based quantum communication networks," in *IEEE 22nd Int. Conf. on Intell. Eng. Syst. (INES)*, 2018, pp. 000 097–000 102.

[68] S. Gong *et al.*, "Network availability maximization for free-space optical satellite communications," *IEEE Wireless Commun. Lett.*, vol. 9, no. 3, pp. 411–415, 2020.

[69] CCSDS, 142.0-B-1, *Recommended standard - Optical Communications Coding Synchronization*, August 2019.

[70] CCSDS, 141.0-B-1, *Recommended standard + Pink Sheets for O3K - Optical Communications Physical Layer*, February 2020.

[71] B. L. Edwards, "Latest status of the CCSDS optical communications working group," in *IEEE Int. Conf. on Space Optical Systems and Applications (ICSOS)*, 2022, pp. 1–6.

[72] T. Tolker-Nielsen and G. Oppenhauser, "In-orbit test result of an operational optical intersatellite link between artemis and spot4, silex," in *Free-Space Laser Communication Technologies XIV*, vol. 4635. International Society for Optics and Photonics, 2002, pp. 1–15.

[73] M. R. Garcia-Talavera *et al.*, "Preliminary results of the in-orbit test of ARTEMIS with the optical ground station," in *Free-Space Laser Communication Technologies XIV*, vol. 4635. International Society for Optics and Photonics, 2002, pp. 38–49.

[74] M. Toyoshima *et al.*, "Results from phase-1, phase-2 and phase-3 kirari optical communication demonstration experiments with the NICT optical ground station (KODEN)," in *25th AIAA Int. Commun. Satellite Syst. Conf.*, 2007.

[75] V. Cazaubiel *et al.*, "LOLA: A 40000 km optical link between an aircraft and a geostationary satellite," in *ESA Special Publication*, vol. 621, 2006.

[76] M. Giordani and M. Zorzi, "Non-terrestrial networks in the 6g era: Challenges and opportunities," *IEEE Netw.*, vol. 35, no. 2, pp. 244–251, 2020.

[77] A. Sevincer, A. Bhattarai, M. Bilgi, M. Yuksel, and N. Pala, "LIGHTNETs: Smart LIGHTing and mobile optical wireless NETworks — a survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1620–1641, 2013.

[78] G. S. Spagnolo *et al.*, "Optical wireless communication and Li-Fi: A new infrastructure for wireless communication in saving energy era," in *IEEE Int. Workshop on Metrology for Industry 4.0 IoT*, 2020, pp. 674–678.

[79] X. Wu, M. D. Soltani, L. Zhou, M. Safari, and H. Haas, "Hybrid LiFi and WiFi networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1398–1420, 2021.

[80] P. Pavarangkoon *et al.*, "Bandwidth utilization enhancement using high-performance and flexible protocol for INTELSAT satellite network," in *IEEE 7th Annual Inf. Technol., Electronics and Mobile Commun. Conf. (IEMCON)*, 2016, pp. 1–7.

[81] M. Leba, S. Riurean, and A. Lonica, "LiFi-the path to a new way of communication," in *IEEE Conf. on Inf. Syst. and Technol. (CISTI)*, 2017, pp. 1–6.

[82] P. M. Kalaivaanan *et al.*, "On-the-move measurement analysis for Ka-band high throughput satellite and LiFi communication networks in tropical region," *IEEE Access*, vol. 9, pp. 71 344–71 355, 2021.

[83] D. N. Amanor, W. W. Edmonson, and F. Afghah, "Link performance improvement via design variables optimization in LED-based VLC system for inter-satellite communication," in *IEEE Int. Conf. on Wireless for Space and Extreme Environments (WiSEE)*, 2017, pp. 7–12.

[84] J. L. Duligall, M. S. Godfrey, K. A. Harrison, W. J. Munro, and J. G. Rarity, "Low cost and compact quantum key distribution," *New Journal of Physics*, vol. 8, no. 10, p. 249, 2006.

[85] H. Chun *et al.*, "Handheld free space quantum key distribution with dynamic motion compensation," *Optics Express*, vol. 25, no. 6, pp. 6784–6795, 2017.

[86] O. Elmabrok and M. Razavi, "Wireless quantum key distribution in indoor environments," *JOSA B*, vol. 35, no. 2, pp. 197–207, 2018.

[87] O. Elmabrok, M. Ghalaii, and M. Razavi, "Quantum-classical access networks with embedded optical wireless links," *JOSA B*, vol. 35, no. 3, pp. 487–499, 2018.

[88] S. Bahrani, O. Elmabrok, G. C. Lorenzo, and M. Razavi, "Wavelength assignment in quantum access networks with hybrid wireless-fiber links," *JOSA B*, vol. 36, no. 3, pp. B99–B108, 2019.

[89] H. Li, X. Chen, J. Guo, and H. Chen, "A 550 Mbit/s real-time visible light communication system based on phosphorescent white light led for practical high-speed low-complexity application," *Opt. Express*, vol. 22, no. 22, pp. 27 203–27 213, 2014.

[90] Y. Jiang *et al.*, "Simultaneous light-emitting light-detecting functionality of InGaN/GaN multiple quantum well diodes," *IEEE Electron Device Lett.*, vol. 38, no. 12, pp. 1684–1687, 2017.

[91] J.-M. Wun *et al.*, "GaN-based miniaturized cyan light-emitting diodes on a patterned sapphire substrate with improved fiber coupling for very high-speed plastic optical fiber communication," *IEEE Photon. J.*, vol. 4, no. 5, pp. 1520–1529, 2012.

[92] H. T. Le, H. T. T. Pham, H.-C. Le, and N. T. Dang, "Satellite quantum key distribution for vehicular visible light communication networks," in *IEEE Eighth Int. Conf. on Commun. and Electron. (ICCE)*, 2021, pp. 45–50.

[93] G. Suciu, A. Scheianu, I. Petre, A. Drosu, and R. Darabană, "VLC quantum fusion," in *Int. Workshop on Antenna Technology (iWAT)*, 2020, pp. 1–4.

[94] H. Kaushal and G. Kaddoum, "Optical communication in space: Challenges and mitigation techniques," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 57–96, 2016.

[95] E. Erdogan *et al.*, "Site diversity in downlink optical satellite networks through ground station selection," *IEEE Access*, vol. 9, pp. 31 179–31 190, 2021.

[96] K.-X. Li *et al.*, "Downlink transmit design for massive MIMO LEO satellite communications," *IEEE Trans. Commun.*, pp. 1–1, 2021.

[97] M. Gabay and S. Arnon, "Quantum key distribution by a free-space MIMO system," *J. Lightw. Technol.*, vol. 24, no. 8, pp. 3114–3120, 2006.

[98] N. K. Kundu, S. P. Dash, M. R. McKay, and R. K. Mallik, "MIMO Terahertz Quantum Key Distribution," *IEEE Communications Letters*, vol. 25, no. 10, pp. 3345–3349, 10 2021.

[99] E. Hugues-Salas *et al.*, "Monitoring and physical-layer attack mitigation in SDN-controlled quantum key distribution networks," *Journal of Optical Communications and Networking*, vol. 11, no. 2, pp. A209–A218, 2019.

[100] Y. Zhao *et al.*, "Resource allocation in optical networks secured by quantum key distribution," *IEEE Commun. Mag.*, vol. 56, no. 8, pp. 130–137, 2018.

[101] S. Xu, X.-W. Wang, and M. Huang, "Software-defined next-generation satellite networks: Architecture, challenges, and solutions," *IEEE Access*, vol. 6, pp. 4027–4041, 2018.

[102] R. Picchi, F. Chiti, R. Fantacci, and L. Pierucci, "Towards quantum satellite internetworking: A software-defined networking perspective," *IEEE Access*, vol. 8, pp. 210 370–210 381, 2020.

[103] X. Deng, C. Tian, X. Su, and C. Xie, "Avoiding disentanglement of multipartite entangled optical beams with a correlated noisy channel," *Sci. Rep.*, vol. 7, no. 1, pp. 1–9, 2017.

[104] S.-K. Liao *et al.*, "Satellite-relayed intercontinental quantum network," *Phys. Rev. Lett.*, vol. 120, p. 030501, Jan 2018.

[105] F. Xu, "Measurement-device-independent quantum communication with an untrusted source," *Phys. Rev. A*, vol. 92, p. 012333, Jul 2015.

[106] C. Panayi, M. Razavi, X. Ma, and N. Lütkenhaus, "Memory-assisted measurement-device-independent quantum key distribution," *New Journal of Physics*, vol. 16, no. 4, p. 043005, apr 2014.

[107] M. Gündoğan *et al.*, "Proposal for space-borne quantum memories for global quantum networking," *npj Quantum Information*, vol. 7, no. 1, p. 128, Aug 2021.

[108] M. Mastriani and S. S. Iyengar, "Satellite quantum repeaters for a quantum internet," *Quantum Eng.*, vol. 2, no. 4, p. e55, 2020.

[109] M. Ghalaii and S. Pirandola, "Capacity-approaching quantum repeaters for quantum communications," *Phys. Rev. A*, vol. 102, no. 6, p. 062412, 2020.

[110] M. Razavi, M. Piani, and N. Lütkenhaus, "Quantum repeaters with imperfect memories: Cost and scalability," *Phys. Rev. A*, vol. 80, no. 3, p. 032301, 2009.

[111] C. Liorni, H. Kampermann, and D. Bruß, "Quantum repeaters in space," *New J. Phys.*, vol. 23, no. 5, p. 053021, 2021.

[112] K. Goodenough, D. Elkouss, and S. Wehner, "Optimizing repeater schemes for the quantum internet," *Phys. Rev. A*, vol. 103, p. 032610, Mar 2021.

[113] A. S. Cacciapuoti, M. Caleffi, R. Van Meter, and L. Hanzo, "When entanglement meets classical communications: Quantum teleportation for the quantum internet," *IEEE Trans. Commun.*, vol. 68, no. 6, pp. 3808–3833, 2020.

[114] M. Razavi, M. Piani, and N. Lütkenhaus, "Quantum repeaters with imperfect memories: Cost and scalability," *Phys. Rev. A*, vol. 80, p. 032301, Sep 2009.

[115] M. Zhong *et al.*, "Optically addressable nuclear spins in a solid with a six-hour coherence time," *Nature*, vol. 517, no. 7533, pp. 177–180, Jan 2015.

[116] M. Rančić, M. P. Hedges, R. L. Ahlefeldt, and M. J. Sellars, "Coherence time of over a second in a telecom-compatible quantum memory storage material," *Nat. Phys.*, vol. 14, no. 1, pp. 50–54, Jan 2018.

[117] D. Awschalom *et al.*, "Development of quantum interconnects (quics) for next-generation information technologies," *PRX Quantum*, vol. 2, p. 017002, Feb 2021.

[118] Y. Wang *et al.*, "Single-qubit quantum memory exceeding ten-minute coherence time," *Nat. Photonics*, vol. 11, no. 10, pp. 646–650, Oct 2017.

[119] D. Awschalom *et al.*, "Development of quantum interconnects (QuICs) for next-generation information technologies," *PRX Quantum*, vol. 2, p. 017002, Feb 2021.

[120] H. Zhang, Z. Ji, H. Wang, and W. Wu, "Survey on quantum information security," *China Commun.*, vol. 16, no. 10, pp. 1–36, 2019.

[121] J. Preskill, "Quantum Computing in the NISQ era and beyond," *Quantum*, vol. 2, p. 79, Aug. 2018.

[122] T. M. Lovelly *et al.*, "A framework to analyze processor architectures for next-generation on-board space computing," in *IEEE Aerosp. Conf.*, 2014, pp. 1–10.

[123] A. A. Abd El-Latif, B. Abd-El-Atty, and M. Talha, "Robust encryption of quantum medical images," *IEEE Access*, vol. 6, pp. 1073–1081, 2018.

[124] T. Hiroka, T. Morimae, R. Nishimaki, and T. Yamakawa, "Quantum encryption with certified deletion, revisited: Public key, attribute-based, and classical communication," in *Advances in Cryptology –*

ASIACRYPT 2021, M. Tibouchi and H. Wang, Eds. Cham: Springer International Publishing, 2021, pp. 606–636.

[125] P. Jayanthi, B. K. Rai, and I. Muralikrishna, "The potential of quantum computing in healthcare," in *Technology Road Mapping for Quantum Computing and Engineering*. IGI Global, 2022, pp. 81–101.

[126] M. Hodson, B. Ruck, H. Ong, D. Garvin, and S. Dulman, "Portfolio rebalancing experiments using the quantum alternating operator ansatz," 2019.

[127] J. Cohen, A. Khan, and C. Alexander, "Portfolio optimization of 40 stocks using the dwave quantum annealer," 2020.

[128] J. F. Fitzsimons, "Private quantum computation: an introduction to blind quantum computing and related protocols," *npj Quantum Inf.*, vol. 3, no. 1, p. 23, Jun 2017.

[129] M. Krelina, "Quantum technology for military applications," *EPJ Quantum Technol.*, vol. 8, no. 1, p. 24, Nov 2021.

[130] S. J. Gamberini and L. Rubin, "Quantum sensing's potential impacts on strategic deterrence and modern warfare," *Orbis*, vol. 65, no. 2, pp. 354–368, 2021.

[131] M. T. Johnsson, G. K. Brennen, and J. Twamley, "Macroscopic superpositions and gravimetry with quantum magnetomechanics," *Sci. Rep.*, vol. 6, no. 1, pp. 1–13, 2016.