Integrated Non-Terrestrial and Terrestrial Quantum Anonymous Networks

Awais Khan, Tinh Thanh Bui, Junaid ur Rehman, Symeon Chatzinotas, *Fellow, IEEE*,
Simon L. Cotton, *Fellow, IEEE*, Octavia A. Dobre, *Fellow, IEEE*, Trung Q. Duong, *Fellow, IEEE*, and
Hyundong Shin, *Fellow, IEEE*

***Abstract*—Due to optical fiber limitations for quantum communication, global-scale quantum networks are possible only by integrating non-terrestrial components in the overall network architecture. Quantum networks are expected to support distributed tasks for quantum information processing, such as quantum sensing, control, communication, and computing. These networks enable emerging applications that are uniquely quantum or augmented by quantum mechanics. Leveraging quantum resources, anonymous networking can be enhanced to such an extent that even an adversary with control over all network resources cannot trace the message source, achieving *perfect untraceability*. To provide this untraceable global connectivity, we demonstrate the integration of non-terrestrial networks (NTNs) and terrestrial networks (TNs) for quantum anonymous communication (QAC), highlighting possible architectures and key challenges in these integrated NTN-TN quantum anonymous networks (QANs). To illustrate and benchmark the design of QAC protocols within integrated networks, we present essential quantum protocols such as anonymous conference key agreement (CKA) and anonymous broadcast. In the first case study, we propose a satellite-to-ground quantum anonymous CKA (QA-CKA) protocol and assess the anonymous key exchange rate. This QA-CKA protocol utilizes low Earth orbit satellites to generate anonymous keys among two distinct TN nodes. In the second case study, we develop an air-to-ground quantum anonymous broadcast (QAB) protocol and examine the anonymous broadcast announcement rate. This QAB protocol exploits unmanned aerial vehicles to enable a broadcasting party to transmit classical information anonymously across two distinct TNs. These QAC protocols are simulated with realistic integrated network parameters to provide practical estimates of achievable performance. Furthermore, we discuss future research directions for enabling integrated NTN-TN QANs.**

***Index Terms*—Integrated non-terrestrial and terrestrial network, conference key agreement, quantum anonymous communication, quantum anonymous network.**

I. INTRODUCTION

QUANTUM information processing systems are expected to revolutionize many industries by providing unprecedented potential applications such as semantic communication in Metaverse [1], anonymous networking in emerging connectivity [2], molecule simulation in drug discovery [3], stochastic modeling in finance [4], large-scale problem solving in optimization [5], and ultra-secure encryption in cryptography [6]. In the long term, the quantum Internet facilitates and enhances these applications by providing ubiquitous connectivity of different classes of quantum information processors. Developing a global-scale quantum Internet and its various components is an ambitious goal that requires concentrated efforts in both theoretical and experimental research, as well as close collaboration between academia and industry.

In contrast to classical information, which is represented by the macroscopic properties of matter and is conventionally transmitted by modulating the macroscopic properties of electromagnetic fields, quantum information is represented and transmitted differently. Quantum information is encoded in the superposition of quantum states, which are associated with microscopic properties such as the polarization of individual photons or the quantized number of photons in a pulse. These quantum states exhibit the unique no-cloning property, which prohibits the perfect duplication of arbitrary quantum states—a cornerstone for secure quantum communication. Once encoded, these quantum microstates are transmitted through a physical medium designed to support their transmission. For example, quantum bits (qubits) can be prepared on single photons and transmitted over a fiber optic (FO) or a free-space optical (FSO) channel. Photons possess several unique properties, such as low interaction with the environment, ease of generation, compatibility with existing infrastructure, and high-speed propagation, making them highly suitable for long-distance transmission [7]. At the physical layer, qubits can be communicated over existing FOs by connecting them to quantum transmitters and receivers. However, without the use of quantum repeaters, the achievable transmission distance through these FO connections is fundamentally limited [8]. The development of efficient quantum repeaters faces significant technical challenges, hindering their inclusion in near- or medium-term plans of quantum networks. Integrating non-terrestrial FSO components with terrestrial FO components appears to be a more practical approach for near- and medium-term quantum networks.

An interesting application for integrated quantum platforms of non-terrestrial networks (NTNs) and terrestrial networks

Awais Khan, and Hyundong Shin (corresponding author) are with the Department of Electronics and Information Convergence Engineering, Kyung Hee University, Yongin-si, Gyeonggi-do 17104, South Korea; Junaid ur Rehman is with the Department of Electrical Engineering and Interdisciplinary Research Center for Intelligent Secure Systems, King Fahd University of Petroleum and Minerals and Dhahran, Saudi Arabia; Simon L. Cotton is with the Department of Electronics, Electrical Engineering, and Computer Science, Queen's University Belfast, BT7 1NN Belfast, U.K.; Symeon Chatzinotas is with University of Luxembourg, 1855 Luxembourg City, Luxembourg; Tinh Thanh Bui, Octavia A. Dobre, and Trung Q. Duong are with the Department of Electrical and Computer Engineering, Memorial University of Newfoundland, St. John's, NL A1B 3X5, Canada, and Trung Q. Duong is also with the Department of Electronics, Electrical Engineering, and Computer Science, Queen's University Belfast, BT7 1NN Belfast, U.K.

(TNs) is the potential for anonymous communication. In this scenario, an adversary—even with arbitrary computational power and complete control over all network resources—cannot trace the source of a message. This high level of security is essential when protecting a communicator's identity is not merely about privacy but also concerns personal and data safety. The combination of a quantum anonymous network (QAN) [2] and the integrated NTN-TN system emerges as a robust defense against widespread surveillance and unauthorized data interception, establishing a new communication standard where privacy is inherently guaranteed. This development aligns perfectly with the growing global demand for privacy-preserving and untraceable communication in both public and private sector applications.

In this article, we first explore the potential and challenges in developing a large-scale integrated NTN-TN quantum network as a precursor to the quantum Internet. We begin by discussing key enablers, core architectural components, and the general architecture of such a network. Next, we consider quantum anonymous conference key agreement (QA-CKA) and quantum anonymous broadcast (QAB) as use cases for this large-scale integrated quantum network to estimate the potential performance in the near term, identify key bottlenecks, and derive insights to optimize network performance.

II. INTEGRATED NTN-TN QUANTUM NETWORKS

Quantum communication networks, envisioned as overlays to classical networks, aim to enhance network utility and enable new applications, such as connecting quantum computers for distributed computing, forming ultra-precise quantum sensing networks, and ensuring high network-wide security. Building a global-scale quantum network faces challenges, particularly due to optical fiber limitations in attenuation and long-distance construction. Integrated NTN-TN quantum networks are proposed to address these issues by combining wired terrestrial quantum components with free-space non-terrestrial elements. This section explores integrated NTN-TN quantum networks, focusing on motivations, key enablers, and potential architectures comprising ground-ground, satellite-satellite, and satellite-air-ground quantum networks.

A. Motivations

The expansive coverage and continuous connectivity offered by satellites and aerial vehicles make them ideal for extending the reach of quantum networks, facilitating long-distance quantum communication links in integrated NTN-TN quantum networks. Satellites, categorized based on altitude into geostationary Earth orbit (GEO) (over $36,000\,\text{km}$), medium Earth orbit (MEO) ($2,000$ to $36,000\,\text{km}$), and low Earth orbit (LEO) (160 to $2,000\,\text{km}$) satellites, are pivotal in this architecture. In low-noise and clear line-of-sight scenarios, FSO channels used by these satellites can surpass the performance of terrestrial FO in terms of attenuation over long distances. Consequently, while terrestrial FO networks are densely deployed in urban areas, non-terrestrial FSO networks link these local systems into a global quantum network. Aerial vehicles further enhance FSO link quality, serving as dynamic repeaters to optimize connections and ensure high fidelity of quantum entanglement.

Incorporating hybrid quantum-classical NTN-TN platforms creates ultra-secure networks, where the quantum key distribution (QKD) and conference key agreement (CKA) play a crucial role in maintaining the confidentiality of transmitted information by distributing encryption keys. Current public-key cryptography systems, where encryption and decryption keys are mathematically related, pose a risk of private key deduction from the public key. In contrast, the QKD and CKA overcome this vulnerability by providing secure cryptographic key distribution, enabling information-theoretically secure encryption methods such as the one-time pad.

A global NTN-TN quantum network enhances network security through the CKA and facilitates untraceable anonymous communication and the delegation of computing-intensive tasks without revealing details to cloud servers [9]. In an era dominated by applications such as augmented reality, virtual reality, online gaming, and deep learning, users often face constraints due to limited computing power. Offloading tasks to cloud servers or supercomputers in core networks is a common solution, but it raises the risk of data interception by eavesdroppers. Distributed architectures like mobile-edge computing networks, which bring computing servers closer to users, and fog computing, an extension of cloud computing to network edges, partially address privacy concerns by improving energy efficiency and reducing latency. However, they do not fully protect the invisibility of user information. Quantum anonymous communication (QAC) [1], [2], [5], [10] can offer a robust solution to this issue in the integrated NTN-TN framework. This innovation in quantum networks enables the concealment of user identities and information for both airborne and ground-based stations, thereby creating a network where communication tasks remain completely anonymous, untraceable, and secure.

B. Architectural Components

The hybrid NTN-TN architecture seamlessly integrates three network layers—space, aerial, and ground—into a unified communication system. The terrestrial layer, connected via FOs and wireless links, interfaces with fully functional satellites through gateways. These satellites generate, transmit, store, and measure entangled qubits, establishing robust quantum links for satellite-satellite and satellite-to-ground communications. In the aerial layer, unmanned aerial vehicles (UAVs) and high-altitude platforms (HAPs) serve as quantum repeaters and entangled photon sources, facilitating satellite-air-ground quantum communication. Their mobility ensures seamless integration with both satellite and ground networks, allowing dynamic reconfiguration as needed. On the ground, hybrid stations and gateways connect the terrestrial, aerial, and space networks, supporting both classical and quantum communications. This integrated architecture enables ground-ground, satellite-air-ground, and satellite-satellite quantum networks, with a focus on photonic quantum communication, as shown in Fig. 1.

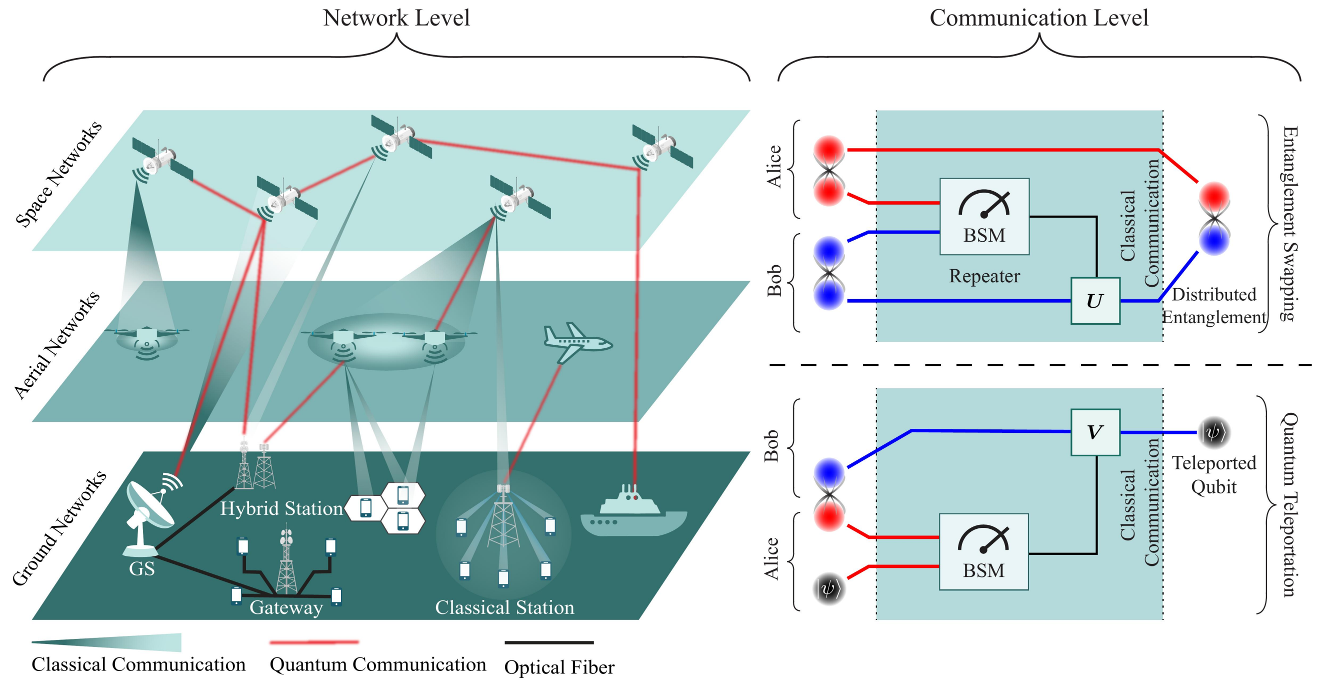


Fig. 1. An integrated NTN-TN quantum network involving the cooperation between quantum and classical communication. Quantum teleportation and entanglement swapping enable long-distance quantum transmission, with classical communication supporting the distribution of Bell-state measurement (BSM) outcomes, where $\boldsymbol{U}$ and $\boldsymbol{V}$ are Pauli operators for swapping and teleportation, respectively.

1) Ground-Ground Quantum Networks: In integrated NTN-TN quantum networks, the ground-ground quantum network is crucial for local quantum information transmission. In this system, qubits encoded by photons in visible or near-infrared frequencies are sent between ground stations (GSs) over optical fibers, which are preferred for their stability and efficiency compared to free-space atmospheric links. However, long-distance transmission leads to significant quantum state attenuation, necessitating the use of quantum repeaters. These repeaters break the distance into shorter, manageable segments, enhancing communication efficiency. Quantum repeaters are integral to this process, creating entanglement across network nodes. They consist of three key components: sources for generating entangled photon pairs, quantum memories for storing these photons, and Bell state measurements (BSMs) for entanglement swapping and extending the quantum link between distant nodes. These repeaters often perform entanglement distillation to enhance the quality of shared entanglement by distilling a smaller amount of highly entangled pairs from a larger number of weakly entangled pairs. However, the effectiveness of this process diminishes over distance due to photon quality attenuation in fiber cables. In densely populated areas like cities, where distances are relatively short, using repeaters and optical fibers remains an effective method for connecting ground quantum nodes.

2) Satellite-Air-Ground Quantum Networks: In satellite-ground quantum communication, downlink transmission (satellite to ground) is more efficient than uplink (ground to satellite) due to less atmospheric interference [11]. In uplink transmission, photon path deviations in the troposphere significantly reduce the likelihood of photons reaching satellites. Conversely, in downlink transmission, photons travel mostly through the vacuum, encountering less interference before reaching GSs, resulting in a higher reception probability at GS telescopes. To maximize efficiency, satellites equipped with entangled photon sources can create effective satellite-to-ground quantum links. These satellites generate entangled photon pairs, which are transmitted to the primary GSs and then distributed to the secondary GSs. This approach utilizes only the more efficient downlink transmission and simplifies satellite requirements to just quantum photon sources.

Satellite-to-ground quantum links surpass optical fibers in efficiency only over thousands of kilometers. However, they are vulnerable to atmospheric conditions such as clouds, rain, snow, and solar irradiance noise. To mitigate these disadvantages, the following strategies can be employed:

- **Noise Filtering:** The GSs use various filters to increase fidelity. For example, spatial filters remove off-target photons, while bandpass filters isolate specific wavelengths from satellite sources.
- **Multiple Wavelength Photons:** Satellites equipped with multi-wavelength quantum sources enhance the reception probability at GSs, as different wavelengths react differently to environmental factors.
- **Aerial Platforms:** Aerial systems, such as UAVs, balloons, and HAPs, function as both quantum repeaters and entangled photon sources. These platforms enhance satellite-to-ground quantum communication by improving entanglement quality and expanding connectivity between satellites and GSs [11].

- **Hybrid Networks:** A combination of wireless satellite-to-ground links and optical fibers with repeaters forms a flexible network. Operators switch between routes based on the quantum channel status, optimizing node connectivity.

Integrating these strategies ensures efficient, long-range quantum communication, overcoming the limitations of both satellite and fiber systems.

3) Satellite-Satellite Quantum Networks: Integrating quantum components, such as BSM equipment, quantum memories, and quantum circuits, into satellites adds complexity and weight but provides significant benefits. These fully-functional quantum repeater satellites enable long-distance connections and facilitate connectivity in remote areas. They also efficiently route entangled photons through space, bypassing atmospheric interference. While all satellites are designed to operate as fully-functional nodes in satellite-satellite quantum networks, they can perform specialized single functions in certain scenarios to enhance network performance. For example, a fully-functional satellite can be deployed solely as an intermediate entanglement generator to improve connectivity in specific regions or address specific connectivity demands. This approach ensures network efficiency and flexibility while enabling virtual connectivity, where nodes share maximally entangled photons, allowing qubit transmission independent of the physical channel status [12]. However, the network efficiency can decrease due to the qubit decoherence. Despite these challenges, this architecture holds the potential to create expansive satellite-satellite quantum networks, offering significant benefits that are yet to be fully realized.

C. Key Enablers

To establish integrated NTN-TN quantum networks, two key processes are vital for sharing quantum states between distant nodes: quantum teleportation and entanglement swapping as depicted in Fig. 1. These quantum protocols overcome the limitations imposed by the no-cloning theorem, which prevents the duplication of quantum states, and quantum decoherence, where state collapse due to noise or environmental factors can irreversibly destroy quantum information. Quantum teleportation enables the transmission of quantum information between distant nodes, such as a satellite-GS pair or two GSs. However, photon loss increases with distance, reducing the efficiency of state transmission. To address this, quantum repeaters use entanglement swapping to break long distances into shorter segments, boosting the probability of successful entanglement distribution and improving overall communication efficiency. This approach is crucial for effective long-distance quantum communication in the integrated quantum NTN-TN.

D. Challenges

To develop the proposed quantum network architecture, key research challenges include:

- **Channel Attenuation:** Photon loss in both FO and free-space links escalates with increasing distance, resulting in a significant decrease in entanglement distribution fidelity or a reduction in signal power at the receiver side.
- **Channel Noise:** Sources such as solar irradiance and urban light pollution create high noise levels. LEO satellites and GEO satellites experience sunlight around 70% and 99% of the time, respectively, when orbiting the Earth [13]. This poses a challenge in designing filters to efficiently remove undesired photons.
- **Photon Qubit Decoherence:** Photon qubits have a short decoherence time, rapidly losing coherence due to environmental interactions. This affects both entanglement distribution and quantum memory, where loss of quantum information is critical due to the non-cloning theorem.
- **Quantum Memory Limitations:** The capacity and stability of quantum memory present challenges, with the risk of irreversible quantum information loss.
- **Satellite Integration Complexity:** Quantum functional blocks in satellites require stable, extremely low temperatures for coherence, posing a challenge due to the wide temperature variations in space.
- **Quantum Routing and Resource Allocation:** Establishing and maintaining entanglement in NTN-TN quantum networks is challenging due to the limitations of classical routing protocols. Quantum routing must optimize entanglement generation, storage, and consumption while preserving fidelity and coherence [6], [14]. The dynamic topology of NTN environments, with constantly moving nodes such as LEO satellites, UAVs, and terrestrial stations, requires adaptive quantum-aware algorithms to efficiently manage resources, address quantum link fragility, and ensure robust network performance.
- **Synchronization in Hybrid Networks:** Integrating quantum networks with classical networks requires effective management of control signals, compatible data formats, and coordinated operations. In quantum networks, precise synchronization is essential for quantum information transmission [6]. However, NTN environments, such as satellites and UAVs, introduce latency due to orbital delays and propagation distances. Efficient protocols are necessary to overcome these challenges and ensure seamless interoperability and reliable performance.

These challenges demand innovative solutions in both hardware and software to enhance the resilience and efficiency of integrated NTN-TN QANs.

III. INTEGRATED NTN-TN QANS

In designing future quantum networks, a key challenge is ensuring secure communication between nodes in different locations while safeguarding privacy and anonymity. This involves going beyond traditional encryption methods and focusing on quantum cryptographic protocols to protect both data and the identities of those involved. Successfully building this prototype requires balancing the advancement of communication capabilities with maintaining the highest privacy standards in the quantum realm.

A. Core Components

NTNs serve as a pivotal extension of TNs, facilitating cutting-edge QAC between users across different TNs. The cornerstone of this achievement lies in establishing distributed anonymous entanglement between these TN nodes. This entanglement resource has versatile applications in anonymous quantum teleportation, anonymous private information retrieval, anonymous CKA, and anonymous E-commerce transactions [2]. Such integration of NTNs and TNs with quantum mechanics ushers in a new era of private, secure, and anonymous communication, allowing users to safeguard the confidentiality of their interactions, transcend the boundaries of TNs, and ensure a more private digital realm. In this section, we consider two different types of scenarios for anonymous entanglement distribution between: i) NTN (LEO satellite) and TN nodes; and ii) two TN nodes.

1) Anonymous Satellite-Ground Entanglement: Initially, the connection across the TN is established using pre-shared entaglement between TN nodes, including the GS. Greenberger–Horne–Zeilinger (GHZ) states are employed as the quantum resource for this connection. All TN nodes—except the anonymous TN node (the communicating node to anonymously send a message) and the GS—measure their respective qubit states in the Hadamard basis (i.e., perform the Hadamard operator $\boldsymbol{H}$ followed by the computational-basis measurement). These measurement outcomes are announced, while the anonymous TN node announces a random bit as its measurement result to be anonymized. Then, the anonymous TN node performs a phase-removal (Pauli-$\boldsymbol{Z}$) operator using the announced information. Now, the *one-sided anonymous connection* is established between the anonymous TN and GS nodes. Finally, the GS and the NTN node (LEO satellite) establish a quantum link by sharing Bell pairs as the entangled resource. The GS performs measurements on both qubits to facilitate entanglement swapping, thereby generating anonymous satellite-ground entanglement.

2) Anonymous Ground-Ground Entanglement: In this scenario, we propose a procedure for establishing an anonymous connection between two different TN nodes with the help of an NTN node. The process of creating anonymous TN-TN node entanglement involves the following three steps.

1) **Anonymous TN-NTN Entanglement:** An anonymous TN node (sender) establishes entanglement with an NTN node using a GHZ state and a Bell pair as quantum resources, as detailed in Section III-A1.
2) **Anonymous NTN-TN Entanglement:** Similarly, the same NTN node establishes entanglement with an anonymous TN node (receiver), leveraging the same quantum resources.
3) **Entanglement Swapping:** The NTN node performs entanglement swapping by measuring both qubits.

This anonymous ground-ground entanglement serves as a critical resource for various applications related to untraceable communication and computation.

B. Anonymous Quantum Information Transfer

In an integrated NTN-TN QAN, the established anonymous entanglement is utilized as a critical resource for transmitting quantum information between the distant NTN and TN nodes without revealing the identities of communicating nodes. The transmission of quantum information also requires the classical transmission of measurement information to the receiving node. To maintain anonymity, this classical information is transmitted by utilizing the QAB protocol, which preserves the anonymity of the sending node while broadcasting the classical information. A key feature of this QAC protocol is its traceless nature—ensuring that the communicating operation remains untraceable to its source, even when all network resources are accessible. This unique approach seamlessly transmits quantum information, offering a robust, privacy-preserving communication framework across terrestrial and non-terrestrial domains.

TABLE I
NETWORK SIMULATION PARAMETERS

Parameter	Value
LEO height ($\mathrm{H_s}$)	450 km
UAV height ($\mathrm{H_a}$)	30 km
$\mathrm{GS_1}$-Alice distance	1 km
$\mathrm{GS_1}$-Bob distance	2 km
$\mathrm{GS_1}$-Charlie distance	3 km
$\mathrm{GS_2}$-Hadi distance	1 km
$\mathrm{GS_2}$-Dina distance	2 km
Fiber coupling efficiency	0.9
Fiber loss	0.18 dB/km
Fiber dephasing rate	0.02 Hz
LEO transmit divergence (txDiv)	5×10^{-6} radians
UAV transmit divergence (txDiv)	1×10^{-6} radians
Sigma point	0.5×10^{-6} radians
Beam waist	$1.55 \times 10^{-6}/\,(\mathrm{txDiv} \times \pi)$
Ground aperture	3 m
Wavelength	1.550×10^{-6} m
Speed of light	299792.458 km/s
Atmospheric transmission	1

C. Anonymous Classical Information Transfer

Quantum networks enable the secure transmission of classical information by generating encryption keys using the Bennett-Brassard-1984 QKD protocol. This technology has been partially commercialized using FO equipment. However, anonymous QKD and CKA are still in the early stages of development and deserve more attention due to their wide range of applications. Here, we discuss the satellite-ground QA-CKA protocol, which offers a generalized and group-oriented approach for secure, privacy-preserving communication in integrated NTN-TN quantum networks. The QA-CKA protocol allows an NTN node (e.g., LEO satellite) to share common keys with an anonymous subset of TN nodes. To initiate this protocol, the NTN node (key provider) anonymously notifies the selected TN nodes of their inclusion using the anonymous quantum notification (AQN) protocol. The steps of the protocol are as follows.

1) **Entanglement Distribution:** The GS shares network-wide entanglement (i.e., a multipartite GHZ state) with the TN nodes, while the NTN node shares a Bell pair with the GS.
2) **Hadamard-Basis Measurement:** All network participants measure their entangled particles in the Hadamard basis, except the GS and the initially notified anonymous TN nodes.

3) **Outcome Announcement:** All TN nodes announce their measurement outcomes, except the anonymous parties that announce a binary random number to preserve anonymity.
4) **Phase-Flip Correction:** The GS applies a unitary phase-removal (Pauli-$\boldsymbol{Z}$) operation to correct phase errors introduced during the measurements, establishing anonymous multipartite entanglement between the GS and the anonymous TN nodes.
5) **BSM:** The GS performs a BSM on its particles and announces the result to the NTN node.
6) **Bit/Phase-Flip Correction:** The NTN node applies unitary bit-flip (Pauli-$\boldsymbol{X}$) and phase-flip (Pauli-$\boldsymbol{Z}$) operations to correct errors introduced during the BSM process, creating anonymous GHZ entanglement between the NTN node and the selected TN nodes.
7) **Key Generation:** Finally, all anonymous TN nodes and the NTN node measure their entangled particles in the computational basis to generate a common anonymous key.

Note that a dishonest TN node may attempt to deviate from the protocol by not following it properly. For instance, this dishonest node could skip the measurement in Step 2) and try to obtain the final key. However, such behavior can be easily detected by introducing a random verification of the anonymous entanglement after Step 6). In the verification procedure, the NTN node randomly announces the measurement basis (computational or Hadamard) to be used. The anonymous entanglement is considered valid if it satisfies either of the following criteria.

- When the anonymous TN nodes and the NTN node perform measurements in the computational basis, their outcomes must be identical.
- When these nodes perform Hadamard-basis measurements, the binary (modulo two) sum of their outcomes must be zero.

D. Features

Integrated NTN-TN QANs exhibit the following properties from the principles of quantum mechanics:

- **Unconditional Security:** QAC networks guarantee unconditional security, even against adversaries with powerful computational resources.
- **Anonymity:** These networks enable anonymous communication by dissociating the sender and receiver identities from the information available in the network.
- **Untraceability:** QAC ensures untraceable transactions, as the quantum nature of the communication process prevents the tracking of information back to its source.
- **Inherent Detection Mechanisms:** These networks have built-in mechanisms, such as quantum state collapse and no-cloning theorem, to detect any attempt at interception or tampering, providing a quantum layer of security.
- **Efficiency and Insta-communication:** QANs can transmit information instantaneously and efficiently due to superposition and entanglement.
- **Anti-Interference Capabilities:** QANs bypass conventional channels with anonymous entanglement, strengthening resistance to interference and hacking attempts.
- **Versatility in Medium:** QAC is not restricted by transmission mediums, enabling secure and anonymous communication through air, optical fibers, and even space.
- **Global Security and Anonymity:** The networks are not restricted by the distance between the sender and receiver, allowing for global communication without compromising security and anonymity.

IV. CASE STUDIES: QA-CKA AND QAB

We demonstrate two primary QAC protocols: QA-CKA and QAB within the integrated NTN-TN QANs as case studies. To model these protocols, we utilize the simulation framework developed in [15]. Our simulations consider inherent challenges of FO communications, specifically focusing on optical fiber loss and fiber coupling efficiency, which significantly impact the fidelity of transmitted quantum states. Additionally, we incorporate the dephasing rate, which quantifies the coherence loss of quantum states over time due to environmental interactions, to accurately reflect the operational challenges in a practical quantum communication network. Detailed network parameters are outlined in Table I.

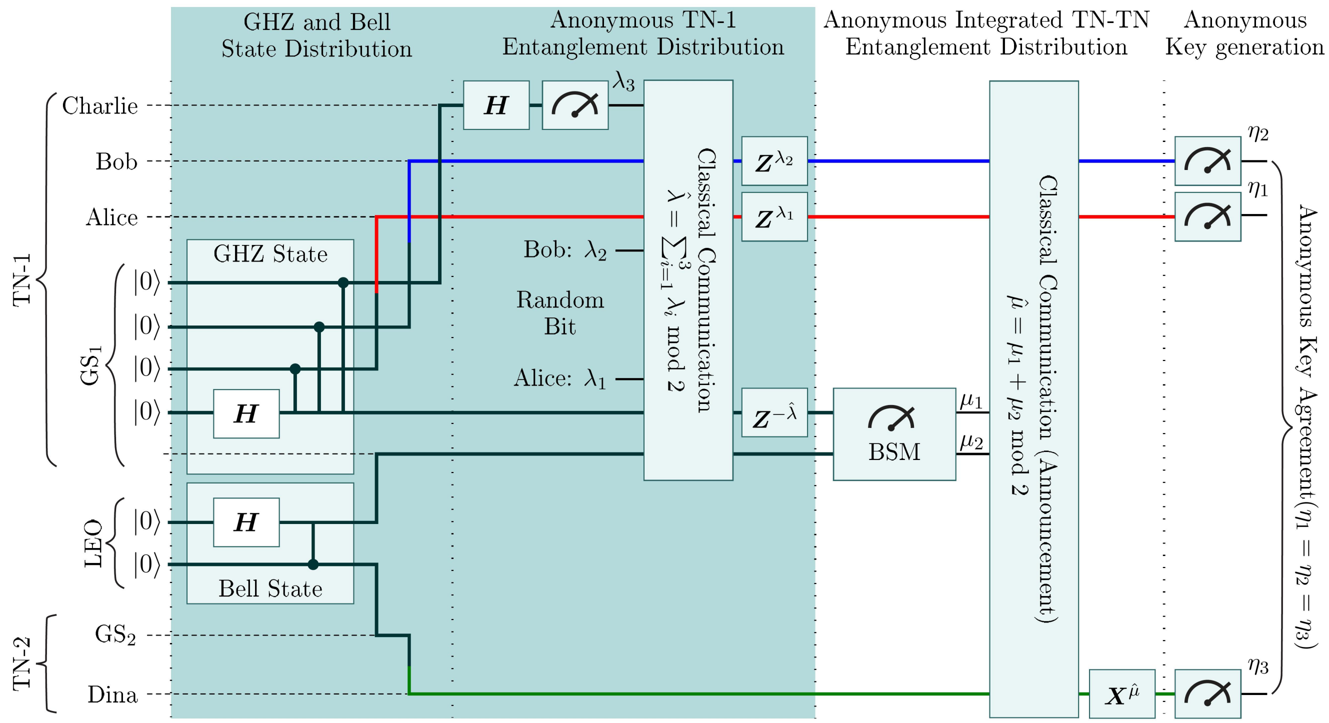
A. Integrated Satellite-To-Ground QA-CKA

In the first case study, we present an integrated satellite-to-ground QAN protocol, which facilitates the distribution of anonymous quantum conference keys among users (Alice, Bob, and Dina) across two distinct TNs, as shown in Fig. 2(a). As a prerequisite, Dina anonymously informs Alice and Bob about this upcoming task using the AQN protocol.

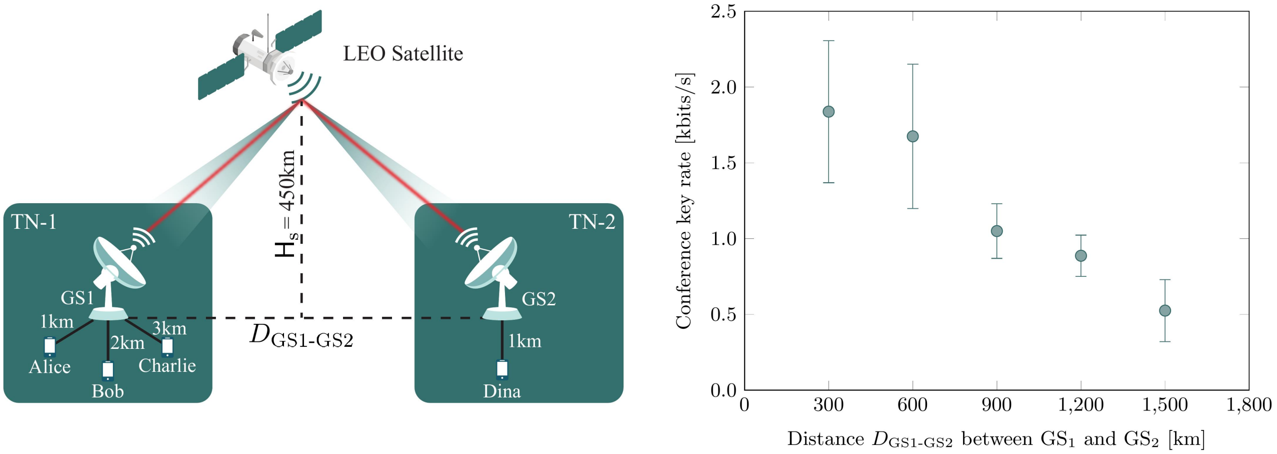
1) System Model: The network architecture of the system is illustrated in Fig. 2(b). It consists of two TNs. The first network, TN-1, includes Alice, Bob, and Charlie as users, all connected to the first terrestrial GS_1 via a FO link. In the second network, TN-2, the user Dina is connected to the second GS_2. A LEO satellite, positioned at an altitude of 450 km above Earth's surface, serves as a central hub, linking GS_1 and GS_2 to integrate both networks.

2) Protocol: This integrated satellite-to-ground QA-CKA protocol follows the steps shown in Fig. 2(a).

- **Carrier-State Distribution:** GS_1 prepares and distributes the four-partite GHZ state among the users in TN-1 via a FO link. In this communication scenario, FO factors such as the fiber coupling efficiency, fiber loss, and fiber dephasing rate are considered, as detailed in [15] and summarized in Table I. To establish a link between the two TNs, the LEO satellite generates a Bell pair and distributes it between GS_1 and GS_2. GS_2 subsequently forwards the photons received from the LEO satellite to Dina. The efficiency of satellite-to-ground communication primarily depends on atmospheric transmittance, taking into account factors such as satellite altitude, prevailing atmospheric conditions, and signal wavelength. These parameters are crucial and are carefully considered during the transmission of the Bell pair.



(a) Protocol



(b) System network architecture

(c) Anonymous conference key rates

Fig. 2. Integrated satellite-to-ground QA-CKA. (a) The GHZ state is distributed within TN-1, while a Bell state links GS_1 and GS_2 shared via the LEO satellite. GS_2 forwards its photon to Dina, while Charlie performs the following sequence of operations: a Hadamard operation ($\boldsymbol{H}$), computational-basis measurement, and announcement of the measurement outcome λ_3. Alice and Bob also announce their random bits λ_1 and λ_2 as their respective measurement outcomes. GS_1, along with Alice and Bob, applies a phase-flip operation (Pauli-$\boldsymbol{Z}$ gate) based on the announced results. Then, GS_1 performs a BSM on its photons and announces the outcomes. Using these outcomes, Dina applies a bit-flip operation (Pauli-$\boldsymbol{X}$ gate) to establish an integrated anonymous link between TN-1 and TN-2. Finally, Alice, Bob, and Dina measure their photons in the computational basis to generate a shared anonymous key. (b) The system network architecture is depicted for this anonymous CKA. (c) The anonymous CKA rate in kbit/s is plotted as a function of the distance $D_{\text{GS1-GS2}}$ between GS_1 and GS_2.

- **Anonymous TN-1 Entanglement Distribution:** Charlie applies the Hadamrd operation $\boldsymbol{H}$ on his entangled particle and measures it in the computational basis, subsequently announcing the measurement outcome λ_3 via classical communication. Meanwhile, Alice and Bob each generate binary random number λ_1 and λ_2, respectively. To preserve anonymity, Alice and Bob declare these random numbers as their respective measurement outcomes. GS_1, Alice, and Bob perform a phase-removal (Pauli-$\boldsymbol{Z}$) operation based on the announced results to rectify the phase flips introduced during this process. This procedure successfully establishes an anonymous link among GS_1, Alice, and Bob.
- **Satellite-Ground QA-CKA:** Next, GS_1 performs a BSM on the photons in its possession and announces the measurement outcomes via classical communication. Dina

then applies a bit-flip (Pauli-$\boldsymbol{X}$) unitary operation, if necessary, to correct any bit-flip errors introduced during the measurement process. This entanglement-swapping process establishes anonymous entanglement between two TNs (Dina, Alice, and Bob). Notably, Dina can perform random verification to detect any malicious behavior by the other nodes (see Section III-C for details). Finally, all anonymous users perform the computational-basis measurements on this tripartite anonymously entangled state to obtain the same key.

3) Anonymous Conference Key Rates: We employ the simulation framework developed in [15] to simulate this scenario under realistic atmospheric conditions shown in Table I, incorporating considerations of measurement and fiber losses. Fig. 2(c) shows the anonymous CKA rate in kbit/s as a function of the distance $D_{\text{GS1-GS2}}$ between the two TN stations GS_1 and GS_2. Here, the anonymous conference keys are shared between three parties from two distinct TNs: Alice and Bob from TN-1 and Dina from TN-2. As the distance $D_{\text{GS1-GS2}}$ increases, the key exchanging rate decreases, where error bars show its one standard deviation.

B. Integrated Air-To-Ground QAB

Now, we present the case study of integrated air-to-ground QAB, which allows any user in one TN to broadcast its classical information ζ among TNs without revealing its identity, as shown in Fig. 3(a).

1) System Model: The network architecture consists of two TNs connected via an UAV, which serves as a bridge between the networks, as depicted in Fig. 3(b). In the TN-1, users Alice and Bob are connected to the first GS_1 via a FO link, with GS_1 directly linked to the UAV. In the TN-2, users Hadi and Dina are connected to the second GS_2 in the same manner, GS_2 is also linked to the UAV.

2) Protocol: We assume that Alice is an anonymous broadcaster. The integrated air-to-ground QAB protocol takes the following series of steps, as depicted in Fig. 3(a).

- **Broadcast Carrier Distribution:** The GSs prepare and distribute the tripartite GHZ state among their respective TN nodes, keeping one photon of the GHZ state for themselves. This establishes a link within each TN. To integrate the TNs, the UAV prepares and distributes a Bell pair between the GSs of both TNs. The GSs perform the BSM on the photons in their possession and announce the measurement outcomes within their respective TNs. Using these announcements, Alice and Hadi apply the phase-removal Pauli-$\boldsymbol{Z}$ gate on their respective photons to correct any phase flips introduced during the BSM process. Then, the GHZ link is established between the two TN nodes and serves as a broadcast carrier.
- **Broadcast Modulation:** All nodes in both TNs perform the Hadamard operation $\boldsymbol{H}$ on their respective photons. As a result, the broadcast carrier state becomes a superposition of all 2^3 four-partite states whose binary sum is equal to zero. Then, all users measure their photons in the computational basis, generating a binary random string due to the basis change introduced by the Hadamard operation. Alice, Bob, Dina, and Hadi record their binary measurement outcomes as λ_1, λ_2, λ_3, and λ_4, respectively. Alice then encodes her classical information ζ into her measurement outcome λ_1 by performing a binary sum modulation, producing $\hat{\lambda}_{\text{A}} = \zeta + \lambda_1 \mod 2$, similar to the one-time pad method.
- **Broadcast Decoding:** All nodes, except Alice, announce their measurement outcomes λ_2, λ_3, and λ_4 using classical communication, while Alice announces the encoded bit $\hat{\lambda}_{\text{A}}$ as her measurement result. Finally, any party in TNs can calculate a binary (modulo two) sum of these announcements $\hat{\lambda}_{\text{A}}$, λ_2, λ_3, and λ_4 to decode the broadcast information without revealing the broadcaster's identity (i.e., Alice).

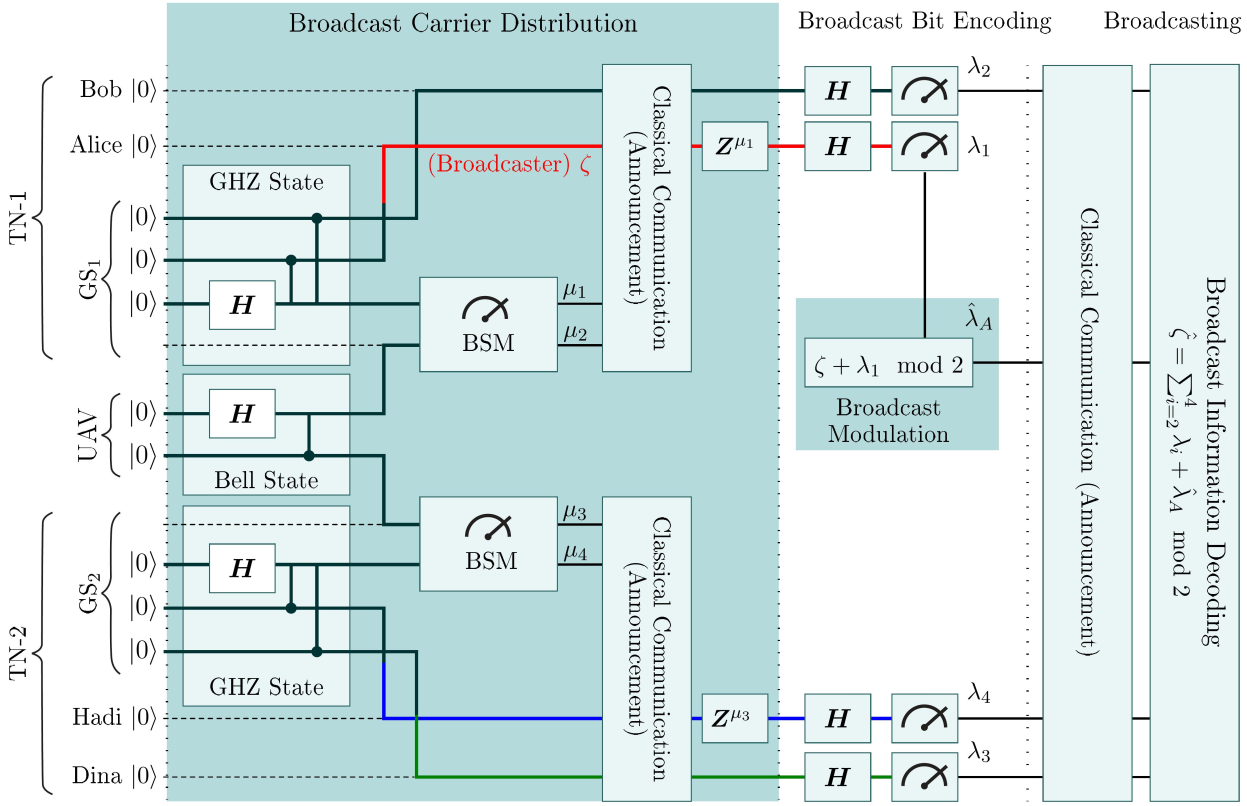
3) Anonymous Broadcast Rates: For sources, detectors, and fiber links compatible with current or near-term technologies, we simulate the QAB protocol with integrated network parameters outlined in Table I. This simulation follows the network architecture illustrated in Fig. 3(b). In the first TN-1, the GS_1 is connected to Alice and Bob via a FO link. Similarly, in the TN-2, the GS_2 is connected to Hadi and Dina. Additionally, to bridge these two networks, an UAV is deployed at the height of 30 km to generate and distribute a Bell pair between the GSs. This entanglement distribution enables a quantum link between the GSs of the two networks, facilitating quantum communication across the distinct segments. Fig. 3(c) illustrates the anonymous broadcast rate in kbits/s as a function of the distance $D_{\text{GS1-GS2}}$ between GS_1 and GS_2. As expected, the anonymous broadcast bit rate decreases with the slant distance. This decline can be attributed to the increasing path loss and atmospheric attenuation encountered over longer transmission distances.

V. FUTURE DIRECTIONS AND CONCLUSION

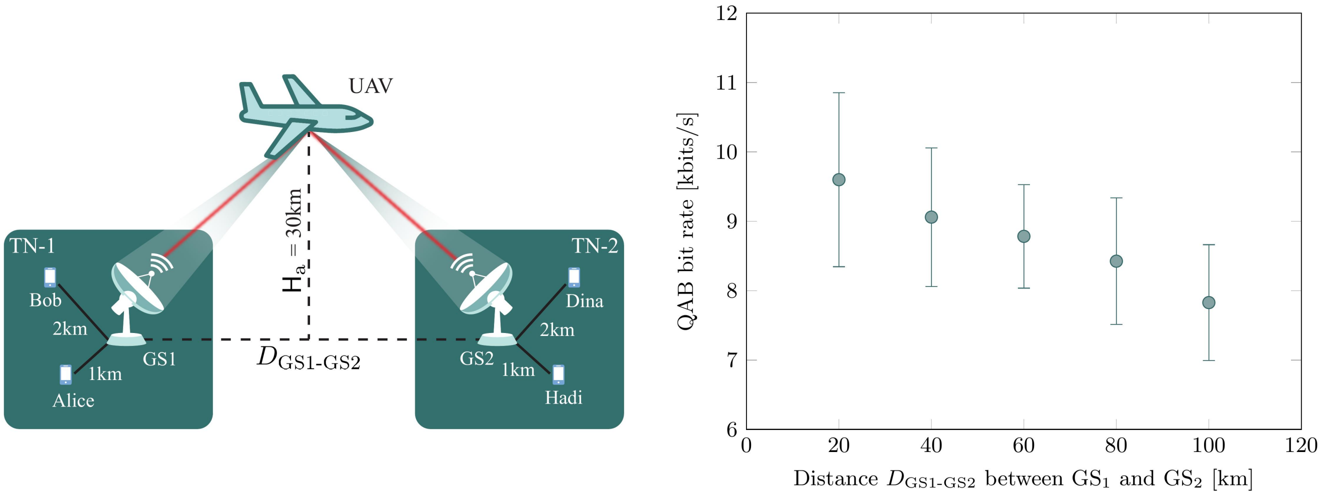
Although integrated NTN-TN QANs have unprecedented benefits, such as providing a new resource, global connectivity between quantum computers, and highly secure anonymous connections, key research topics must be addressed to realize their full potential. In this section, we propose future directions in the sequence of constructing a new network: hardware design for network elements, network deployment, and communication cooperation.

A. Hardware Design

Realizing integrated QANs requires advanced developments in hardware design to overcome the aforementioned challenges. Firstly, quantum light sources need improvement to efficiently generate high-quality entangled photons that can withstand temperature fluctuations and highly noisy environments. Additionally, further studies on telescopes capable of detecting weak quantum photons from long-distance transmissions are essential. Secondly, quantum memories, which play a key role in enabling repeaters to create quantum entanglement over long distances, require further research to buffer quantum signals for extended periods. Moreover, feasible solutions for integrating quantum functional blocks into satellites are crucial, as satellite materials endure vibrations, accelerations, and extreme temperatures compared to ground devices.



(a) Protocol



(b) System network architecture

(c) Anonymous broadcast rates

Fig. 3. Integrated air-to-ground QAB. (a) GHZ states are distributed among TN nodes, while a Bell state links GS_1 and GS_2 via a UAV. The following sequence of operations is performed: BSMs by GS_1 and GS2, and a phase-flip operation (Pauli-$\boldsymbol{Z}$) by Alice and Hadi to create an entanglement link (GHZ state). All nodes (Alice, Bob, Dina, and Hadi) measure their photons in the Hadamard basis, generating outcome strings λ_1, λ_2, λ_3, and λ_4. Classical broadcast information ζ is encoded using a one-time pad method (i.e., $\hat{\lambda}_\text{A} = \zeta + \lambda_1 \mod 2$) and decoded through the binary modulo summation of the announced measurement results, enabling anonymous information broadcasting across the network. (b) The system network architecture is depicted for this anonymous QAB, where a single UAV is deployed to effectively distribute a Bell state between two GSs at a rate of approximately 10^6 pairs per second via a free-space channel. The reliability of this communication depends on factors such as atmospheric transmission, transmit divergence, and beam waist, as outlined in Table I. (c) The QAB bit rate in kbit/s is plotted as a function of the distance $D_{\text{GS1-GS2}}$.

B. Network Deployment

With the development of classical satellite networks, many existing satellites orbit the Earth to provide classical communication. Therefore, adding more quantum-functional satellites requires new optimal solutions to avoid collisions and ensure the efficiency of quantum networks. Additionally, integrated NTN-TN QANs may use multiple types of quantum channels. Making optimal decisions on the best route for connecting any two quantum nodes can significantly improve quantum network performance. For example, two ground quantum nodes can be connected through a direct optical link, satellite quantum links, or indirect optical links using ground repeaters. Optical links can be used during the day when there are many noisy photons from sunlight, while satellite quantum links can be chosen for quantum information exchange during the night.

C. Hybrid Quantum-Classical Communication

Currently, hybrid quantum-classical communication networks represent a crucial research direction for enabling quantum networks. Classical communication plays a key role in allowing the quantum receiver to select the precise operation for reconstructing the original quantum state at the sender. Additionally, hybrid systems leverage the strengths of both classical and quantum communications to enhance network performance. For instance, to create highly secure communication, QKD and CKA utilize classical communication to transmit large amounts of data encrypted by quantum keys with exchange through quantum channels. Furthermore, satellite communications are gaining attention for building global classical networks due to their unique properties. Instead of constructing quantum and classical networks separately, integrating them can reduce costs and provide new global services, such as ultra-secure connections and cloud quantum computing. However, to achieve seamless interaction between classical and quantum communications, quantum-classical interface protocols, hybrid architectures, and processing techniques need to be further developed and improved.

D. Concluding Remarks

We have investigated the integrated NTN-TN framework with QAC. Motivated by the quantum advantage in networking, particularly in terms of security and privacy, we have put forth QANs in the integrated forms of non-terrestrial and terrestrial networks. These networks involve essential functional modules such as anonymous entanglement distribution, anonymous teleportation, anonymous CKA, and anonymous broadcast among NTN-TN and TN-TN parties. Additionally, we have presented the salient features and challenges of this integration. In summary, this work serves as a stepping stone in developing globally secure and anonymous quantum networks.

ACKNOWLEDGEMENT

The fundamental research described in this paper was supported, in parts, by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2025-2021-0-02046), by the Convergence security core talent training business support program (IITP-2025-RS-2023-00266615) supervised by the IITP (Institute for Information & Communications Technology Planning & Evaluation), by the project Lux4QCI under Grant GA 101091508 funded by the Digital Europe Program, and by the project LUQCIA funded by the Government of Luxembourg/SMC.

REFERENCES

[1] U. Khalid, M. S. Ulum, A. Farooq, T. Q. Duong, O. A. Dobre, and H. Shin, “Quantum semantic communications for Metaverse: Principles and challenges,” *IEEE Wireless Commun.*, vol. 30, no. 4, pp. 26–36, Aug. 2023.

[2] S. N. Paing, J. W. Setiawan, T. Q. Duong, D. Niyato, M. Z. Win, and H. Shin, “Quantum anonymous networking: A quantum leap in privacy,” *IEEE Netw.*, vol. 38, no. 5, pp. 131–145, Sep. 2024.

[3] J. Li, R. O. Topaloglu, and S. Ghosh, “Quantum generative models for small molecule drug discovery,” *IEEE Trans. Quantum Eng.*, vol. 2, no. 6, pp. 1–8, Aug. 2021.

[4] D. Herman, C. Googin, X. Liu, Y. Sun, A. Galda, I. Safro, M. Pistoia, and Y. Alexeev, “Quantum computing for finance,” *Nat. Rev. Phys.*, vol. 5, no. 8, pp. 450–465, Aug. 2023.

[5] S. Tariq, U. Khalid, B. E. Arfeto, T. Q. Duong, and H. Shin, “Integrating sustainable big AI: Quantum anonymous semantic broadcast,” *IEEE Wireless Commun.*, vol. 31, no. 3, pp. 86–99, Jun 2024.

[6] M. Mehic, M. Niemiec, S. Rass, J. Ma, M. Peev, A. Aguado, V. Martin, S. Schauer, A. Poppe, C. Pacher *et al.*, “Quantum key distribution: a networking perspective,” *ACM Comput. Surveys*, vol. 53, no. 5, pp. 1–41, Sep. 2020.

[7] T. Northup and R. Blatt, “Quantum information transfer using photons,” *Nat. Photonics*, vol. 8, no. 5, pp. 356–363, May 2014.

[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] F. Zaman, S. N. Paing, A. Farooq, H. Shin, and M. Z. Win, “Concealed quantum telecomputation for anonymous 6G URLLC networks,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 7, pp. 2278–2296, Jul. 2023.

[10] M. Christandl and S. Wehner, “Quantum anonymous transmissions,” in *Proc. Int. Conf. Theory Appl. Cryptol. Inf. Secur.*, Berlin, Heidelberg, Germany, Dec. 2005, pp. 217–235.

[11] T. Gonzalez-Raya, S. Pirandola, and M. Sanz, “Satellite-based entanglement distribution and quantum teleportation with continuous variables,” *Commun. phys.*, vol. 7, no. 1, p. 126, Apr. 2024.

[12] J. Illiano, M. Caleffi, A. Manzalini, and A. S. Cacciapuoti, “Quantum internet protocol stack: A comprehensive survey,” *Comput. Netw.*, vol. 213, p. 109092, Aug. 2022.

[13] S.-K. Liao, H.-L. Yong, C. Liu, G.-L. Shentu, D.-D. Li, J. Lin, H. Dai, S.-Q. Zhao, B. Li, J.-Y. Guan *et al.*, “Long-distance free-space quantum key distribution in daylight towards inter-satellite communication,” *Nat. Photonics*, vol. 11, no. 8, pp. 509–513, Jul. 2017.

[14] Z. Li, K. Xue, J. Li, L. Chen, R. Li, Z. Wang, N. Yu, D. S. Wei, Q. Sun, and J. Lu, “Entanglement-assisted quantum networks: Mechanics, enabling technologies, challenges, and research directions,” *IEEE Commun. Surveys Tuts.*, vol. 25, no. 4, pp. 2133–2189, Fourthquarter 2023.

[15] R. Yehia, M. Schiavon, V. M. Acosta, T. Coopmans, I. Kerenidis, D. Elkouss, and E. Diamanti, “Connecting quantum cities: Simulation of a satellite-based quantum network,” *New J. Phys.*, vol. 26, no. 7, p. 073015, Jul 2024.

Awais Khan received his Ph.D. degree from Kyung Hee University (KHU), South Korea, in February 2023. Since March 2023, he has been working as a Postdoctoral Fellow in the Department of Electronics and Information Convergence Engineering at KHU. His research interests include quantum anonymous communication, quantum secure computation, and quantum networks.

Tinh Thanh Bui received his B.Eng. and M.Eng. degrees in Telecommunications Engineering from Vietnam National University – Ho Chi Minh City University of Technology, Vietnam. He is currently pursuing a Ph.D. degree in the Department of Electrical and Computer Engineering at Memorial University, Canada. His research interests include optimization, machine learning, and wireless communication systems.

Junaid ur Rehman received his Ph.D.degree from the Kyung Hee University, South Korea in 2019. Currently, he is an assistant professor with the Department of Electrical Engineering at King Fahd University of Petroleum and Minerals. His research interests include quantum information sciences, including quantum communications and quantum computing.

Symeon Chatzinotas [F] is a Full Professor / Chief Scientist I and the Head of the research group SIGCOM at the Interdisciplinary Centre for Security, Reliability, and Trust, University of Luxembourg. He is also an Adjunct Professor at the Norwegian University of Science and Technology, an Eminent Scholar at Kyung Hee University, Korea, and a Collaborating Scholar at National Center for Scientific Research "Demokritos".

Simon L. Cotton [F] received his Ph.D. degree in electrical and electronic engineering from Queen's University Belfast, Belfast, U.K., in 2007. He is currently a Full Professor and the Director of the Centre for Wireless Innovation (CWI) at Queen's University Belfast, U.K.

Octavia A. Dobre [F] is a Professor and Canada Research Chair Tier-1 at Memorial University, Canada. Her research interests include technologies for next generation wireless networks, as well as optical and underwater communications. She is an elected member of the European Academy of Sciences and Arts, a Fellow of the Engineering Institute of Canada, a Fellow of the Canadian Academy of Engineering, and a Fellow of the Royal Society of Canada.

Trung Q. Duong [F] is a Canada Excellence Research Chair (CERC) and a Full Professor at Memorial University, Canada. He is also an adjunct professor at Queen's University Belfast, UK, and a visiting professor at Kyung Hee University, South Korea.

Hyundong Shin [F] is a Professor at Kyung Hee University, South Korea. He received IEEE Guglielmo Marconi Prize Paper Award and IEEE William R. Bennett Prize Paper Award. He was an Editor of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS and IEEE COMMUNICATIONS LETTERS.