Integrated Non-Terrestrial and Terrestrial Anonymous Quantum Networks

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***Abstract*—Due to limitations of optical fibers for quantum communication, a global-scale quantum network is possible only with the integration of non terrestrial components in the overall network architecture. Quantum networks are expected to support distributed quantum information processing tasks such as distributed quantum sensing and distributed quantum computing. These networks also facilitate the development of novel networking applications that are either uniquely quantum or provide enhancements that are only possible with quantum mechanics. Anonymous communication, with the help of quantum resources, can be enhanced to such an extent that an adversary even with the control over all network resources cannot trace back the source of a message. We consider anonymous quantum key distribution as a use-case of integrated non terrestrial and terrestrial quantum networks to provide global connectivity. In doing so, we highlight possible architectures and key challenges in integrated non terrestrial and terrestrial quantum networks. We also simulate anonymous quantum key distribution in practical quantum networks to obtain realistic estimates on the achievable performance.**

***Index Terms*—anonymous quantum networks, satellite quantum communication, anonymous entanglement, quantum key distribution.**

I. Introduction

QUANTUM information processing systems are expected to revolutionize many industries by providing unprecedented potential applications such as molecule simulation in drug development [1], stochastic modeling in finance [2], large-scale problem-solving in optimization [3], and ultra-secure encryption in cryptography [4]. Quantum internet, in the long term, facilitates and enhances these applications by providing ubiquitous connectivity of different classes of quantum information processors [5]. The development of global-scale quantum internet and its various components is an ambitious goal. This requires several concentrated efforts in theoretical and experimental research as well as close collaborations between involved stakeholders from academia and industry.

In contrast to classical information, which is represented by the macro properties of matter and is conventionally transmitted by modulating the macro properties of electromagnetic fields, quantum information is represented and transmitted differently. Quantum information is encoded within the micro properties of matter, such as the polarization of individual photons or the number of photons within a pulse. These micro states of matter are then transmitted through a physical medium capable of carrying out this transmission. For example, quantum bits (qubits) can be prepared on single photons and then transmitting them over a fibre optic (FO) or a free-space optical (FSO) channel. Photons with several unique properties such as low interaction with the environment, ease of generation, compatibility with existing infrastructure and high-speed propagation, have a high potential for long-distance transmission [6]. On the physical layer, communication of qubits can be carried out over existing FOs by connecting them to quantum transmitters and receivers. However, the achievable distance through these FO connections, without employing quantum repeaters, is fundamentally bounded [7]. Technical and practical challenges in developing efficient quantum repeaters hinder their inclusion in the near- or medium-term plans of quantum networks. Integration of FSO-based non terrestrial component with a FO-based terrestrial component appears to be a more practical approach for near- and medium-term quantum networks.

One interesting application of such integrated non-terrestrial and terrestrial quantum network (INTQN) can be the possibility of anonymous communication, where an adversary—even with arbitrary computational power and complete control over all network resources—cannot trace back the source of a message. This high level of security is essential in cases where protecting a communicator's identity is not merely about privacy but also concerns personal and data safety. Thus, the anonymous quantum network (AQN) and INTQN combination emerges as a robust shield against widespread surveillance and unauthorized interception of data, establishing a new standard in communication where privacy is not merely enhanced, but inherently guaranteed. This development is perfectly in tune with the increasing global demand for secure, private, and untraceable communication methods across both public and private sectors applications.

In this article, we first explore the potential and challenges in developing a large-scale INTQN as precursor of quantum internet. To this end, we begin by discussing key enablers, core architectural components, and the general architecture of such a network. Then, we consider anonymous quantum key distribution (QKD) as a use-case of such a large-scale INTQN

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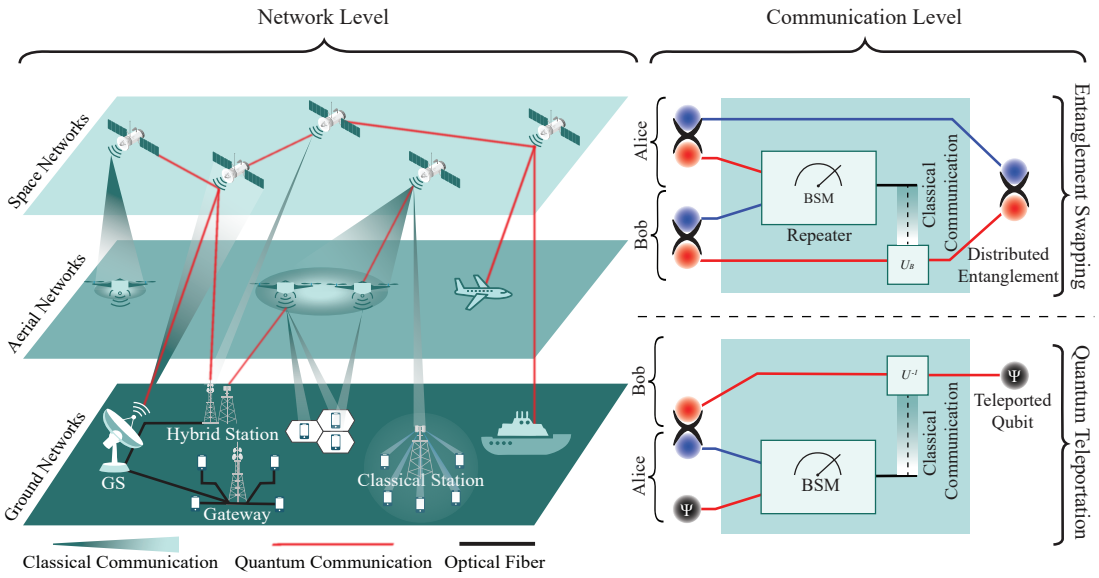

Fig. 1. An integrated non-terrestrial and terrestrial quantum network consists of the cooperation between quantum communication and classical communication. Quantum teleportation and swapping enable long-distance quantum transmission with the support of classical communication for distributing the outputs of BSM.

to estimate the possible performance in the near-term, identify the key bottlenecks, and derive some insights to optimizing the network performance.

The remainder of this article is organized as follows. In Sec. II we outline the architectural components, key enablers, and challenges in INTQNs. In Sec. III we discuss integrated non-terrestrial and terrestrial anonymous quantum networks (INTAQNs) and provide a case study in Sec. IV. We provide some future directions in Sec. V before concluding our discussion in Sec. VI.

II. Integrated Non-Terrestrial and Terrestrial 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 sensor 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. INTQNs are proposed to address these issues by combining wired terrestrial quantum components with free-space non-terrestrial elements. This section explores INTQNs, focusing on motivations, key enablers, and a potential architecture comprising ground-ground, space-air-ground, and space-space quantum networks.

A. Motivation

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 INTQNs. Satellites, categorized based on altitude into geostationary equatorial orbit (GEO) (over 36000 km), medium earth orbit (MEO) (2000 to 36000 km), and low earth orbit (LEO) (500 to 2000 km), are pivotal in this architecture. In scenarios with low noise and clear line-of-sight, FSO channels used by these satellites can surpass the performance of terrestrial FO in terms of attenuation over long distances. Consequently, while FO-based terrestrial networks are densely deployed in urban areas, FSO-based non-terrestrial 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.

Integrating INTQNs with classical integrated non-terrestrial and terrestrial networks (INTNs) creates ultra-secure networks, where QKD is instrumental 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. On the other hand, QKD overcomes this vulnerability by offering a method for secure cryptographic key distribution and enabling the information-theoretically secure encryption methods like the one-time pad.

Global INTQN, in addition to enhancing network security through QKD, also facilitates anonymous communication and the delegation of compute-intensive tasks without revealing details to cloud servers [8]. In an era dominated by applications like augmented reality, virtual reality, online gaming, and deep learning, users often find themselves constrained by 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 (MEC) networks, which bring computing servers closer to users,

and fog computing, an extension of cloud computing to the network's edge, partially address privacy concerns by improving energy efficiency and reducing latency. However, they do not fully protect the invisibility of user's information. The advancement in quantum technology introduces quantum anonymous communication within INTNs, offering a robust solution to this issue. This innovation in quantum networks enables the concealment of user identities and information, both for airborne and ground-based stations, thereby creating a network where user exchanges remain completely anonymous and secure.

B. Architectural Components of INTQN

A hybrid INTQN architecture comprises three distinct network components: 1) the space network, 2) the aerial network, and 3) the ground network. In this tri-layered system, the terrestrial layer is interconnected via FOs and wireless links, with gateways bridging connections to satellites for both quantum and classical communications. Satellites function as repeaters, forging quantum links with entangled qubits to facilitate long-distance communication. This setup integrates ground-ground, space-air-ground, and space-space quantum networks, with a focus on photonic-based quantum communications, as depicted in Fig. 1.

1) Ground-ground quantum networks: In INTQNs, the ground-ground quantum network is crucial for local quantum information transmission. Here, qubits encoded by photons in visible or near-infrared frequencies are sent between ground stations (GSs) over optical fibers, preferred for their stability and efficiency compared to free-space atmospheric links. However, long-distance transmission leads to significant quantum state attenuation, making the use of quantum repeaters essential to break the distance into shorter, manageable segments and enhance communication efficiency. Quantum repeaters are integral to this process and create 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.

Quantum repeaters enhance long-distance quantum communication by spreading quantum entanglement between GSs and quantum users via FOs [9]. The primary GSs connect with satellites to distribute entanglement to secondary GSs and ground users. 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) Space-air-ground quantum networks: In space-ground quantum communication, downlink transmission (satellite to ground) is more efficient than uplink (ground to satellite) due to less atmospheric interference [10]. 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 vacuum, encountering less interference before reaching GSs, resulting in a higher reception probability at GS telescopes. To optimize this efficiency, satellites equipped only with entangled photon sources can create effective satellite-to-ground quantum links. These satellites generate entangled photon pairs, transmitted to primary GSs, which then distribute entanglement to secondary GS. 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 fiber in efficiency only over thousands of kilometers. However, they are vulnerable to atmospheric conditions like clouds, rain, snow, and solar irradiance noise. To mitigate these disadvantages, several strategies are employed:

- Noise filtering: 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 GS, as different wavelengths react differently to environmental factors.
- Aerial repeaters: Quantum repeaters can be carried by aerial machines, such as unmanned aerial vehicles (UAVs), balloons, and high-altitude platforms (HAPs) to enhance the quality of entanglement between satellites and GSs [10].
- 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-based systems.

3) Space-space quantum networks: Integrating quantum components like Bell BSM equipment, memories, and circuits in satellites adds complexity and weight but offers significant benefits. Full-functional quantum repeater satellites enable connections over vast distances, which single satellites cannot achieve, and facilitate connectivity in remote areas. They also efficiently route entangled photons through space, avoiding atmospheric interference [11]. To manage the complexity and cost, a constellation comprising both fully functional satellites and simpler, single-function satellites is proposed. The single-function satellites act as intermediate entanglement generators, enhancing the network's reach. This setup enables virtual connectivity, where nodes share maximally entangled photons, allowing for qubit transmission independent of the physical channel's status [12]. However, the network's efficiency decreases with qubit decoherence. Despite challenges, this architecture promises to create expansive space-space quantum networks, offering significant benefits yet to be fully realized.

C. Key enablers

To establish INTQNs, two key processes are vital for sharing quantum states between distant nodes: quantum teleportation and entanglement swapping as depicted in Fig. 1. These methods 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 and a GS, or between two GSs. However, photon loss increases with distance, reducing the efficiency of state transmission. To address this, quantum repeaters use entanglement swapping, breaking long distances into shorter segments to boost the probability of successful entanglement distribution and improve overall communication efficiency. This approach is crucial for effective long-distance quantum communication in INTQN.

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 quantum entanglement distribution fidelity or a reduction in signal power at receivers side.
- Channel Noise: Sources like solar irradiance and urban light pollution create high noise levels, LEO satellites and GEO satellites have probabilities of around 70% and 99% in the sunlight zones when they orbit around the Earth [13]. This poses a challenge in filter design to remove efficiently undesired photons.
- Photon Qubit Decoherence: Photon qubits have a short decoherence time, losing coherence rapidly 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 are 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.

These challenges demand innovative solutions in both hardware and software to enhance INTAQNs's resilience and efficiency.

III. Anonymous INTQN

In designing future quantum networks, a key challenge is ensuring secure communication between nodes in different places while safeguarding privacy and anonymity. This involves going beyond traditional encryption, focusing on quantum cryptographic protocols to protect both data and the identities of those involved. To build this prototype successfully, we must balance advancing communication capabilities and maintaining highest privacy standards in the quantum realm.

A. Core Components

Non-terrestrial networks (NTNs) serve as a pivotal extension of terrestrial networks (TNs), facilitating cutting-edge quantum anonymous communication between users across different terrestrial networks. The cornerstone of this achievement lies in establishing distributed anonymous entanglement between these TN nodes. This entanglement resource finds versatile applications in anonymous quantum teleportation, private information retrieval, anonymous conference key agreements, and secure E-commerce transactions. 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, transcending the boundaries of terrestrial networks, and ensuring a more private digital realm. In this section, we consider the two different types of scenarios for anonymous entanglement distribution:

1) Anonymous entanglement distribution between TN node and NTN node (LEO satellite)
2) Anonymous entanglement distribution between two different TN nodes

1) Anonymous space-ground entanglement: A TN-wide entanglement is shared between TN nodes and including the GS. All the TN nodes apply the Hadamard transform on their respective qubit states except the anonymous TN node (communicating node who wants to send anonymous message) and the GS. Then, the measurement is performed by all the parties except the anonymous TN node and the GS. The measurement result is announced by the TN nodes. Anonymous TN node announce some random integer as a measurement result. Then, the anonymous TN node apply phase removal operator (i.e., Pauli-Z operator) based on the announced measurement results. Now, the *one-sided anonymous connection* is established between an anonymous TN node and the GS. The GS shares the bipartite entanglement with the NTN node (LEO satellite). The GS perform the measurement on both of the qubit. This interesting phenomenon is called the entanglement swapping. Finally, the anonymous TN-NTN node entanglement is generated.

2) Anonymous ground-ground entanglement: In this scenario, the procedure of establishing an anonymous connection between two different TN nodes with the aid of NTN node is proposed. The anonymous TN-TN node entanglement contains three steps: 1) The first anonymous TN-NTN node entanglement is generated between anonymous sender TN node and NTN node as explained in scenario 1. 2) Similarly, the second anonymous TN-NTN node entanglement is generated between anonymous receiver TN node and NTN node. 3) The NTN node perform the entanglement swapping phenomenon by performing measurement on both of the qubit. Then, the anonymous TN-TN node entanglement is established and serve as a critical resource for multiple application related to communication and computation.

B. Principle of quantum anonymous information transfer

In an INTAQN, the established anonymous entanglement is utilized as an important resource for transmitting quantum information among the distant terrestrial and non terrestrial nodes without compromising the identities of the sending and receiving node. The transmission of quantum information also requires the classical transmission of measurement information to the receiving node. To maintain the anonymity, this classical information is transmitted by utilizing quantum anonymous broadcast protocol. Quantum anonymous broadcast protocol broadcasts the classical information while preserving the anonymity of the sending node. A key feature of this quantum protocol lies in its traceless nature—ensuring that the encoding operation remains untraceable to its source, even when network resources are accessible. This unique approach seamlessly transmits quantum information, offering a robust, privacy-preserving communication framework across terrestrial and non-terrestrial domains.

C. Principle of classical anonymous information transfer

Classical information is securely transmitted in the quantum network environment thanks to the revolutionary QKD method coined as the BB84 protocol. This technology has been partially commercialized based on equipment utilizing optical fibers. However, the anonymous QKD is still in the early stages of development and deserves more attention due to its vast majority of applications. Here, we will discuss the anonymous quantum conference key agreement (AQCKA) protocol due to its generalized nature and its utilization in group-wise privacy-preserved communication scenarios. AQCKA protocol allows NTN node (e.g., LEO sattelite) to share common keys among the subset of anonymous TN nodes. To initiate, the NTN node (key provider) anonymous notifies the subset of TN node via anonymous notification protocol. AQCKA protocol takes the three steps: 1) the GS share the network wide entanglement (i.e., multipartite GHZ state) with TN network nodes and NTN node shares the bell pair with GS. 2) All of the network parties perform the Hadamard operation on their entangled particle and perform the measurement, except GS and anonymous parties (those are notified initially). 3) All the parties announced the measurement result except the anonymous parties. The anonymous parties announce binary random number. 4) Then, the phase removal unitary is applied by the GS. 5) This will share the anonymous entanglement between anonymous TN node wiht GS. 6) Then, the GS performed the Bell state measurement on both of his particles and announced the result to the NTN node. 7) The NTN node perform the phase removal unitary to based on the measurement result. 8) To generate a common anonymous key, all anonymous parties and GS perform the measurement in computational basis. This AQCKA protocol inherits the property of anonymity and untraceability.

D. Properties of anonymous quantum network

Integrated NTN-TN anonymous quantum network inherit the following properties based on the principles of quantum mechanics:

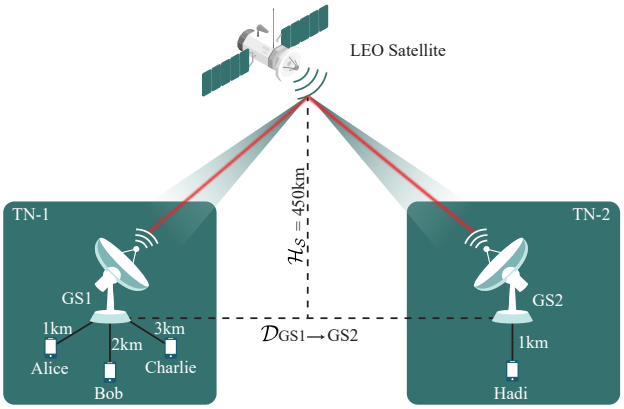

Fig. 2. System network architecture for simulated model

- Unconditional Security: Unconditional security is guaranteed by quantum anonymous communication networks even against adversaries with powerful computational resources.
- Anonymity: These networks enable anonymous communication by dissociating the sender's and receiver's identity from the information available in the network.
- Untraceability: Quantum anonymous communication 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 mechanism (i.e., Quantum state collapse and no cloning theorem) to detect any attempt at interception or tampering, providing an additional layer of security.
- Efficiency and speed: Quantum anonymous communication network due to the superposition and entangled state can transmit information faster and more efficiently than classical methods.
- Anti-Interference Capabilities: Utilizing the inherent properties of quantum entanglement, quantum communication networks not only bypass conventional channels, strengthening resistance to interference and hacking attempts, but also exhibit strong anti-interference capabilities, guaranteeing the reliability of communication channels.
- Versatility in Transmission Mediums: Quantum anonymous communication is not restricted by transmission mediums, enabling secure and anonymous communication through air, optical fibers, and even in space.
- Global Secure and Anonymous Communication: Quantum communication uses the principles of quantum mechanics to enable secure communication through various transmission mediums, such as air, optical fibers, and even in space. These networks are not restricted by the distance between the sender and receiver, allowing for global communication without compromising security and anonymity.

IV. Case Study: Key Agreement in INTAQN

We present a case study of an INTN anonymous quantum network, which facilitates the distribution of anonymous quan-

TABLE I
NETWORK SIMULATION PARAMETERS

Parameters	Value
Satellite Height ($\mathcal{H}_s$)	450 km
GS_1 to Alice distance ($\mathcal{D}_{GS_1 \to A}$)	1 km
GS_1 to Bob distance ($\mathcal{D}_{GS_1 \to B}$)	2 km
GS_1 to Charlie distance ($\mathcal{D}_{GS_1 \to C}$)	3 km
GS_2 to Hadi distance ($\mathcal{D}_{GS_2 \to H}$)	1 km
Fiber coupling efficiency (f_c)	0.9
Fiber loss (f_{loss})	0.18 dB/km
Fiber dephasing rate (f_{dr})	0.02 Hz
Transmit Divergence (txDiv)	5×10^{-6} radians
Sigma Point (sigmaPoint)	0.5×10^{-6} radians
Beam Waist (W_0)	$(1.550 \times 10^{-6}/(\text{txDiv} \times \pi))$
Ground Aperture (rx_aperture_ground)	3 meters
Wavelength (λ)	1.550×10^{-6} meters
Speed of Light (c)	299792.458 km/s
Atmospheric Transmission (T_{atm})	1

tum conference keys among users of two distinct terrestrial networks. These networks are seamlessly integrated via a LEO satellite, positioned at an altitude of 450 km above the Earth's surface. The system network architecture is depicted in Fig. 2 and employ the simulation framework developed in [14] to simulated this scenario.

1) Generation of Terrestrial Network Link: In this scenario, we are considering two terrestrial networks. The first network, designated as TN-1, includes users Alice, Bob, and Charlie. These users are connected to the first ground station, GS_1, via an optical fiber link. GS_1 has a direct link to a LEO satellite. In the second terrestrial network, TN-2, the user Hadi is similarly connected to the second ground station, GS_2, which is also linked to the satellite. Detailed network parameters are outlined in Table I.

The GS_1 is tasked with distributing 4-partite GHZ states among TN-1 users, while GS_2 forwards the photons received from the satellite to Hadi. During this communication scenario, factors such as fiber coupling efficiency, fiber loss, and fiber dephasing rate are taken into consideration as presented in [14].

2) Integration of TN-TN nodes: The LEO satellite facilitates the integration of two terrestrial networks by generating an entangled pair and distributing it between both ground stations, located $\mathcal{D}_{GS_1 \to GS_2}$ apart. The efficiency of satellite-to-ground communication is primarily dependent on atmospheric transmittance, taking into account factors such as the satellite's altitude, prevailing atmospheric conditions, and the wavelength of the signal. These factors are crucial and are carefully considered during the transmission of the EPR pair.

3) Integrated NTN-TN AQCKA: We assume that Hadi from TN-2 wishes to share anonymous conference keys with Alice and Bob, who are users of TN-1. The first step involves establishing an anonymous entanglement link between GS_1 and both Alice and Bob. The method for generating this anonymous entanglement has been previously described. Simultaneously, GS_2 sends the EPR pair photon to the Hadi. Following this, GS_1 performs a BSM on the photons in their possession. This action results in the creation of anonymous entanglement among Hadi, Alice, and Bob, a process known as entanglement swapping. Then, all the anonymous users perform the measurement in a computational basis on this anonymous entanglement to get the keys. We have simulated this scenario under realistic atmospheric conditions, incorporating considerations of measurement and fiber losses. We plotted the raw anonymous conference key rate $\mathcal{K}_r$ (kbit/s) vs the distance between the two ground stations $\mathcal{D}_{GS_1 \to GS_2}$ in Fig. 3.

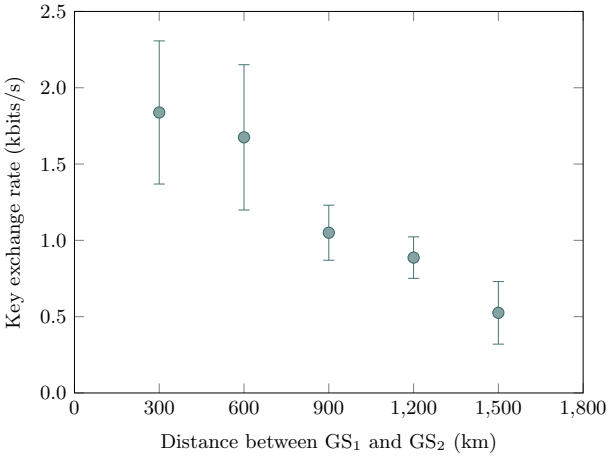

Fig. 3. This plot shows the raw anonymous key rate, $\mathcal{K}_r$ in kbit/s (averaged over eight runs), when the anonymous conference keys are shared between the users of two distinct TN users: Alice and Bob from TN-1 and Hadi from TN-2. As the distance between the two GS $\mathcal{D}_{GS_1 \to GS_2}$, increases, the $\mathcal{K}_r$ decreases. Error bars show one standard deviation of key exchange rate.

V. FUTURE DIRECTIONS

Although INTAQNs have unprecedented benefits to make a revolution in communications such as providing a new resource, global connectivity between quantum computers, and high-security anonymous connections, some key research topics need to be conducted to realise 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

Hardware design can be seen as the foundation for quantum communication development. Realizing INTAQNs requires advanced developments in hardware design to overcome the aforementioned challenges. Firstly, quantum light sources need to be improved to generate efficiently high-quality entangled photons which can withstand temperature fluctuation and high-noise environments. Besides, it is also essential to have more studies on telescopes that can detect weak quantum photons from long-distance transmission. 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 in extended periods. Additionally, the feasible solutions for the integration of quantum functional blocks into satellites are crucial since materials on satellites suffer vibrations, accelerations, and extreme temperatures compared to ground devices.

B. Network deployment

With the development of classical satellite networks, there are many existing satellites orbiting the Earth to provide classical communication. Therefore, adding more quantum functional satellites requires new optimal solutions to avoid collision, and guarantee the efficiency of quantum networks. Besides, there can be multiple types of quantum channels being used in INTAQNs. Optimal decisions on choosing the best route for connecting any two quantum nodes can improve significantly the quantum network performance. For example, two ground quantum nodes are connected through a direct optical link, satellite-based quantum links, and undirect optical links using ground repeaters. The optical links can be used during the day when there are many noisy photons from sunlight, while the satellite-based quantum links can be chosen for quantum information exchange during the night.

C. Classical-Quantum Hybrid Communication

Currently, the hybrid classical communication (CC) and quantum communication (QC) networks is an important research direction to enable quantum networks. Classical communication plays a key role in allowing the quantum receiver to choose the precise operation for reconstructing the original quantum state at the sender. Additionally, with the hybrid system, the strengths of both can be leveraged to enhance the network performance. Indeed, to create highly secure communication, QKD uses CC for transmitting a high amount of data which is encrypted by a quantum key exchanged through quantum channels. Besides, satellite communications are currently drawing attention in building global classical networks by their unique properties [15]. Thus, instead of constructing quantum networks and classical networks separately, they can be built together to reduce cost and provide new global services such as ultra-secure connection, cloud quantum computing, and remote simulation for materials science. However, to achieve seamless interaction between CC and QC, quantum-classical interface protocols, hybrid architectures, and processing techniques need to be further designed and improved.

VI. Conclusion

We investigated the INTQNs with anonymous quantum communication. Initially, we briefly introduced the terrestrial and non-terrestrial networks, highlighting their potential advantages and significant bottlenecks. Motivated by the quantum advantage in networking, particularly in terms of security and privacy, we proposed an INTAQN. This network involves key functional modules such as anonymous entanglement distribution, anonymous quantum teleportation, and AQCKA among NTN-TN and TN-TN nodes. Additionally, we presented the salient features and challenges of this integration. In summary, this work serves as a stepping stone in developing a global secure and anonymous quantum network.

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