Quantum Networking for Secure and Reliable Communication in Space Exploration

Luca Borgianni, Davide Adami, and Stefano Giordano

The authors analyze the potential of quantum networking in addressing future challenges of space communications.

Abstract

In the coming years, space missions will increasingly require communication systems capable of ensuring high-performance, safe, and reliable data transmission between ground stations and spacecraft. Since classical communication systems will be inadequate and have enormous limitations, this article intends to analyze the potential of quantum networking in addressing future challenges of space communications. We introduce well-known phenomena of quantum mechanics, such as non-cloning, entanglement, quantum measurement, and quantum teleportation, which open up a completely new scenario in the design of the communication network. Finally, we propose a network architecture for space exploration, aiming to take a look at the potential of quantum technology to establish communication between Earth and spacecraft by integrating terrestrial and non-terrestrial quantum networks.

Introduction

The desire to explore the vast expanse of space has been an inherent part of our being, driving us to push the boundaries of knowledge and technology in our investigation for understanding the universe. Space exploration is significant for human development and has profoundly impacted our understanding of the cosmos and Earth. Humanity's incursion into space exploration began with the launch of Sputnik, the world's first artificial satellite, by the Soviet Union in 1957. In 1961, Yuri Gagarin became the first human to orbit Earth, followed by Neil Armstrong's historic moon landing in 1969. These achievements were not just symbolic; they demonstrated humanity's ability to conquer the challenges of space travel and expand our horizons. Mars, the Red Planet, has long fascinated humankind, and its pursuit has been a driving force in space exploration. In 1965, Mariner 4 successfully became the first spacecraft to orbit Mars, sending back images of its desolate landscapes. The rovers Spirit, Opportunity, Curiosity, and Perseverance, launched in the 2000s and 2020, have revolutionized our understanding of Mars. They have provided us with detailed images, geological data, and atmospheric samples, revealing a planet with a complex geological history and the potential for past or present habitability. As we venture deeper into the cosmos, the limitations of classical communication become increasingly apparent. The vast distances between celestial bodies, such as Earth and Mars, necessitate robust and reliable communication, secure data transfer, high computational capabilities on board to support edge AI process in case of lack of immediate connection from the Earth ground stations, and synchronization between spacecraft and ground control.

However, deploying emerging quantum services over vast geographical areas faces challenges. This limitation becomes more pronounced in Non-Terrestrial Networks (NTNs), including aerial and space platforms like high-altitude platform stations and satellites, hindering the realization of a global Quantum Internet [1]. Integrating NTNs with terrestrial networks (TNs) has gained acceleration, aided by 3GPP standardization, facilitating implementation within 5G new radio specifications [2]. This integration promises continuous wireless coverage, offering a cost-effective solution for scalable, reliable network coverage across diverse geographies [3]. Due to their low channel losses and negligible decoherence in space, Free-Space Optical (FSO) links in connecting NTN entities are preferred in quantum communications protocols. The authors in [4] have examined and delineated the guidelines for a quantum satellite backbone network comprising satellites functioning as Quantum Repeaters (QRs). Their contributions include the design of an SDN (Software-Defined Networking)-based architectural scheme to control the quantum satellite backbone. Quantum technologies, especially entangled states in satellite networks, offer numerous benefits, such as some quantum sensors with the capability to detect significantly smaller quantities compared to conventional systems. They also offer an enhanced resolution for image capturing processes [5]. Quantum cryptography, especially Quantum Key Distribution (QKD) protocols, has received significant attention for its capability to maintain information security and it is not possible to think about a future scenario of space communication without QKD.

In this article, we give an overview of Quantum Networking (QN) and the quantum technologies that nowadays are facing relevant attention from the research community and big companies. The primary contribution of this article is to provide insight into quantum technologies and communication and their limitations, with a focus on space exploration. The presented architecture aims to show a potential quantum-based solution that poses the basis for NTN and TN integration for space exploration. The rest of the article is

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organized as follows. The following section presents a primer on quantum mechanics. We then introduce the main features of QN and Quantum Internet. Following that, we provide a description of the proposed QN Architecture for space exploration and how it could be helpful in the scenario presented. Then we describe the challenges and open problems. Finally, we conclude the work.

A Primer on Quantum Mechanics

Before introducing the challenges in space exploration and how QN could open new horizons, we provide a brief overview of the main principles of quantum mechanics essential for comprehending the complexities associated with QN design.

Definition of a Qubit

A quantum bit, also known as a qubit, is used for characterizing a discrete two-level quantum state (Fig. 1). This state can adopt two orthogonal basis states: the zero state (or ground state) and the one state (or excited state), typically represented as $|0\rangle$ and $|1\rangle$.

Following that, we can define the qubit as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $\alpha, \beta \in \mathbb{C}$ with $|\alpha|^2 + |\beta|^2 = 1$ for normalization.

Superposition Principle

The superposition principle is a fundamental concept in quantum computing. While a classical bit can exist in only one of two exclusive states at a time (0 or 1), a qubit can uniquely exist simultaneously in a superposition of both basis states. Imagine a spinning coin as an analogy, a classical coin is either in a head or tail state, while a "quantum coin" in superposition is spinning and can be considered simultaneously in a state of both heads and tails. The qubit is in a superposition of $|0\rangle$ and $|1\rangle$ when $\alpha \neq 0, 1$.

In the example of a photon with a 45-degree polarization, the superposed qubit implies that the photon is in a state that combines the zero state ($|0\rangle$) and the one state ($|1\rangle$). This is a situation where we can define the photon simultaneously horizontally and vertically polarized, as these polarizations correspond to the basis states ($|0\rangle$ and $|1\rangle$. In this way, quantum mechanics enables quantum systems to encode information in an extensively parallel way. Unlike classical bits, where n bits can represent only one of 2^n possible states, n qubits can simultaneously represent all 2^n states.

Entanglement

Entanglement is a phenomenon in quantum physics where systems comprising two or more particles can no longer be described as a combination of independent one-particle states. Instead, they can only be characterized by a common state, typically expressed within a single wave function. The entangled connection persists regardless of the spatial separation between the particles. Remarkably, even if the entangled particles are light-years apart, a change in one particle instantaneously induces a corresponding change in the other. Despite the appearance of instantaneous information transmission, it is essential to note that this does not violate the classical speed of light [6]. Additionally, in the QNs analysis, the entanglement rate is a measured parameter representing a particular form of throughput. It quantifies the number of transmitted

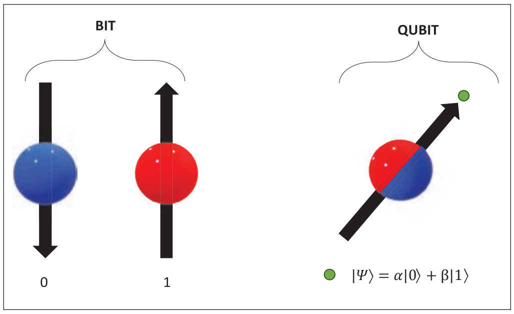

FIGURE 1. A schematic representation of bit and qubit.

entangled states per second, measured in terms of Einstein-Podolsky-Rosen (EPR) pairs per second [7]. EPR pair refers to a pair of subatomic particles correlated based on the quantum properties described in the EPR experiment [8]. These particles are in a state that is a linear combination of states where the measurement of one spin along a particular axis is "up," and the other is "down" (and vice versa), and the combination of states is referred to as an EPR pair state.

In other words, measuring one qubit instantaneously determines the state of the other, regardless of the spatial separation between them. Measuring one qubit within an EPR pair results in an instantaneous alteration of the state of the second qubit, irrespective of the physical separation between the two qubits. In particular, the two particles constituting the EPR pair exist in a superposed state, containing an equal proportion of zero and one. Consequently, by measuring one of the two qubits, there is an equal probability of obtaining either zero or one. However, upon measuring a specific qubit that registers an outcome corresponding to state zero, the second qubit also experiences an immediate collapse into the state zero. This phenomenon exemplifies the entanglement characteristic of quantum particles, illustrating measurement's interconnected and instantaneous influence on entangled quantum systems.

Quantum Measurement

As specified by a core postulate, after measurement, the original quantum state experiences an irreversible collapse into a specific state determined by the measurement result [9]. This phenomenon is inherently probabilistic, offering the potential outcomes of either state zero or state one, contingent upon the proportions of zero and one present in the initial superposed quantum state.

When measuring a superposed qubit resulting in the state zero, an immediate collapse of the qubit into that state occurs. Regardless of the initial quantity of ones in the superposed state, subsequent measurements consistently yield zero as the outcome. Consequently, measuring a qubit enables the extraction of a singular bit of information.

No Cloning Theorem

The no-cloning theorem claims that it is not possible to have an exact copy of an unknown quantum state. It is relevant to understand that this theorem could not be valid when we try to clone two orthogonal states, and it is easy to design a quantum circuit to prove it as presented in [10], as well as the proof of the theorem. If we consider this theorem from a classical mechanics

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point of view, the relevant consequences in the engineering design approach are clear (e.g., the classical error correction techniques need to be revised for quantum states). On the other hand, the no-cloning theorem is essential for quantum cryptography, preventing the creation of copies of a quantum key.

Quantum Network for Space Exploration

Quantum communication and quantum technologies are some of the scientific topics more discussed in recent years, and our perspective is that they will have a relevant impact on space exploration, as NASA and ESA are investing relevant resources in this research area. In this section, we will give an overview of the most common problems in classical communication and whether quantum technologies could or could not have a positive impact. It is crucial to underline that even though the theoretical perspective seems to solve many problems, real-world applications are struggling, and big research challenges need to be addressed. We also present the concept of Quantum Information Network (QIN) and Quantum Internet. In the rest of the section, we introduce the key component of NTN QN with an overview of security in space exploration. To conclude, we present some use cases for quantum space exploration.

Classical and Quantum Space Communication

A complete analysis of the limitations of classic space communication goes beyond the primary purpose of this article, but it is crucial to underline the main problems that pose limits to deep space exploration. These limitations are not intended to be all solved with quantum technologies.

Signal Propagation Delays: As spacecraft travel relevant distances from Earth, the time taken for signals to travel to and from these remote celestial bodies significantly amplifies. For instance, during communication with Mars, signal propagation delays can extend from several minutes to over 20 minutes, depending on the respective positions of Earth and Mars in their orbits. Consequently, it introduces challenges for real-time interaction between ground control and space probes. Immediate decision-making and response to dynamic situations become impractical due to these inherent delays, impacting the agility and responsiveness of space missions.

Vulnerability to Interference: Classical communication signals in space are inherently susceptible to various forms of interference, noise, and signal degradation. The distances crossed by spacecrafts introduce challenges such as cosmic radiation, solar winds, and electromagnetic interference, which can distort and attenuate signals. Additionally, space environments, with their diverse magnetic fields and radiation sources, pose further threats to signal integrity. This vulnerability compromises the reliability of communication links, potentially leading to data corruption, misinterpretation, or loss, and necessitates robust error-correction mechanisms to mitigate these risks.

Bandwidth Constraints: The constrained bandwidth in classical space communication results in slower data rates and necessitates prioritization of transmitted information. As space missions demand increasingly sophisticated instruments capable of generating expansive amounts of data, the existing bandwidth limitations hinder the timely relay of critical information. This becomes particularly problematic in missions involving high-resolution imaging, where the transmission of detailed visual data is crucial for scientific analysis and decision-making.

It is crucial to make the reader aware that not only are these limitations not overcome with the adoption of quantum technologies, but in some cases, the achieved performance is even worse. In fact, at the current stage, it may be more reasonable to think that adopting quantum technology for communication almost causes an increase in latency due to the additional overhead brought by the quantum-based protocol itself and the use of classical communications. Moreover, it is well-known that the use of quantum technologies will make the system much more vulnerable to all kinds of interference (even those that do not affect classical communications) due to the fragility of quantum states.

Quantum Information Network

QIN [11] has garnered growing attention due to its ability to connect quantum devices across vast distances, significantly enhancing their computing, sensing, and security capabilities. At the core of QINs lies quantum state teleportation, which relies on quantum entanglement as a novel form of network capability. This feature requires additional components, such as QRs and quantum memory, for entanglement swapping, making it more reliant on FSO channel communication. Beyond security applications, QIN serves various purposes, such as precise clock synchronization, facilitating services like Time Standards and Frequency Transfer, and enhancing quantum-networked sensors. Improved timing precision is vital for applications like quantum sensing and the next generation of Global Navigation Satellite Systems, as well as for terrestrial applications such as information technology and financial systems, including military applications. Initially, space-based quantum communication is deployed in standalone satellites. However, as technology advances, these systems are likely to integrate with laser communication systems, particularly those under development for military or civil purposes, such as the Starlink constellation. Such integration would offer a dual-layered approach, combining the security of quantum communication with the high-speed data transmission of laser communication. Notably, quantum satellites utilize beacon lasers to establish and maintain the quantum link, presenting challenges and opportunities for technology overlap and integration with advanced laser communication systems. Satellites for quantum communication typically orbit in Low Earth Orbit (LEO) or Geostationary Orbit (GEO). LEO satellites offer greater agility but require more advanced acquisition, pointing, and tracking systems due to their frequent orbit cycles. On the other hand, GEO satellites provide continuous coverage over a fixed area but necessitate more precise laser pointing and focusing, albeit with the advantage of potential 24/7 availability.

Quantum Internet

The Quantum Internet [12] involves transferring quantum entanglement from a quantum source node to a quantum target node through a series of intermediary quantum nodes that act as QRs. This process of entanglement distribution occurs incrementally, beginning with establishing short-distance entangled links between individual quantum nodes. It is important to note that these connections represent the entangled states prepared at each node rather than the physical connections between them.

Subsequently, efforts are made to enhance the level of entanglement within these connections to enable longer-distance entangled links. The level of entanglement within a connection determines the number of quantum nodes spanned by that particular link, known as the hop distance between the source and target nodes. This enhancement is achieved through a procedure referred to as entanglement purification and swapping conducted within the intermediary QRs as detailed in [12].

As introduced earlier, quantum entanglement is based on the concept of correlated states between two or more quantum particles, where information about one particle can instantaneously influence the state of another, regardless of the distance separating them. To illustrate this concept, consider a scenario where two quantum particles, such as photons, are entangled and subsequently separated by great distances. Despite the physical separation, measurements performed on one photon can yield predictive information about the state of its entangled photon. This instantaneous correlation suggests the possibility of transmitting information faster than light. However, despite the apparent instantaneous correlation between entangled particles, this phenomenon does not permit the transmission of information faster than the speed of light. Therefore, it is relevant to highlight that entanglement can not have immediate consequences on the transmission of real-time information to deep space distances, and it is not a communication tool but a mechanism for correlation. On the other hand, quantum entanglement and teleportation could provide unparalleled security and reliability, outperforming conventional space communication.

Key Components for NTN Quantum Networking

The deployment of QRs in space will play a crucial role in extending the entanglement distance, enabling secure quantum communication over vast distances. As described earlier, the No Cloning Theorem handles one of the main problems, which is particularly crucial for long-distance communication, such as in space exploration. Additionally, incorporating quantum enhancements into space exploration has scientific and engineering challenges. The hostile space environment necessitates the development of quantum technologies resilient to radiation, extreme temperatures, and cosmic adversities. QRs ensure data integrity and overcome the challenges posed by the inherent issues of space environments, such as cosmic radiation and electromagnetic interference. The design of these devices is sophisticated, and they allow the extension of the entanglement range between quantum satellites, enabling secure quantum communication over vast interstellar distances. In a quantum scenario, quantum satellites are generally equipped with entanglement sources; these satellites facilitate the creation of entangled pairs necessary for quantum communication. In the same way, the Quantum Sensor acts as a quantum communication gateway, receiving quantum information from space probes or sensors exploring distant celestial bodies. As we will present in the proposed architecture, it is also crucial to have a quantum link and classical nodes that handle classical management, control, and data plane network functions, such as path selection and signaling protocols, to communicate with traditional space exploration instruments.

Enhanced Security in Space Exploration

Security is an extensive and complex field that is crucial for each type of communication, especially space communication. We present the basic idea behind quantum security and how it is also applicable in space exploration with adequate adaptations.

Current security levels, especially for cryptography, rely on the computational capabilities of classical computers, but with the advent of quantum computers, they are at risk. As humanity explores celestial bodies within and beyond our solar system, ensuring the security of interplanetary communication becomes paramount. Improvements are needed in current communication system encryption to contrast the potential risk of quantum computers breaking some existing encryption exponentially faster [13] than non-quantum machines. Quantum communication systems encode information in quantum-mechanical properties, utilizing effects like superposition and entanglement.

Quantum communication leverages the phenomenon of entanglement and offers a QKD mechanism that is crucial for safeguarding sensitive data transmitted between space probes and ensuring the integrity of scientific findings. Traditional cryptographic methods can be vulnerable to sophisticated attacks. Quantum communication provides a fundamentally secure framework through the principles of quantum mechanics, maintaining the confidentiality and integrity of mission-critical information during deep-space exploration.

QKD leverages quantum principles to distribute secret keys between distant nodes. Using the principles of superposition, state collapse upon measurement, and the no-cloning theorem, QKD achieves unconditional security. QKD protocols, demonstrated in optical fibers and FSO, enable secure communication by detecting potential eavesdropping through observed error rates.

Use Cases for Quantum Space Exploration

One of the primary obstacles faced in operating small satellites at lower altitudes stems from the limited computing power of their onboard processors. This inherent constraint poses challenges in executing complex computing tasks, such as real-time optimization of resource allocation strategies, data processing for Earth observation applications, and data aggregation for Internet of Things (IoT) applications. To overcome this limitation, authors in [14] exploit an approach that involves leveraging quantum technologies and a constellation of CubeSat. In this way, the computational workload of small satellites can be offloaded, paving the way for enhanced processing capabilities. In this context, constructing a space QN, interconnecting satellites via FSO links, becomes feasible. The utilization of FSO, generally with a 1550 nm wavelength, offers several advantages over Radio Frequency systems, and this is a technology that enables quantum com-

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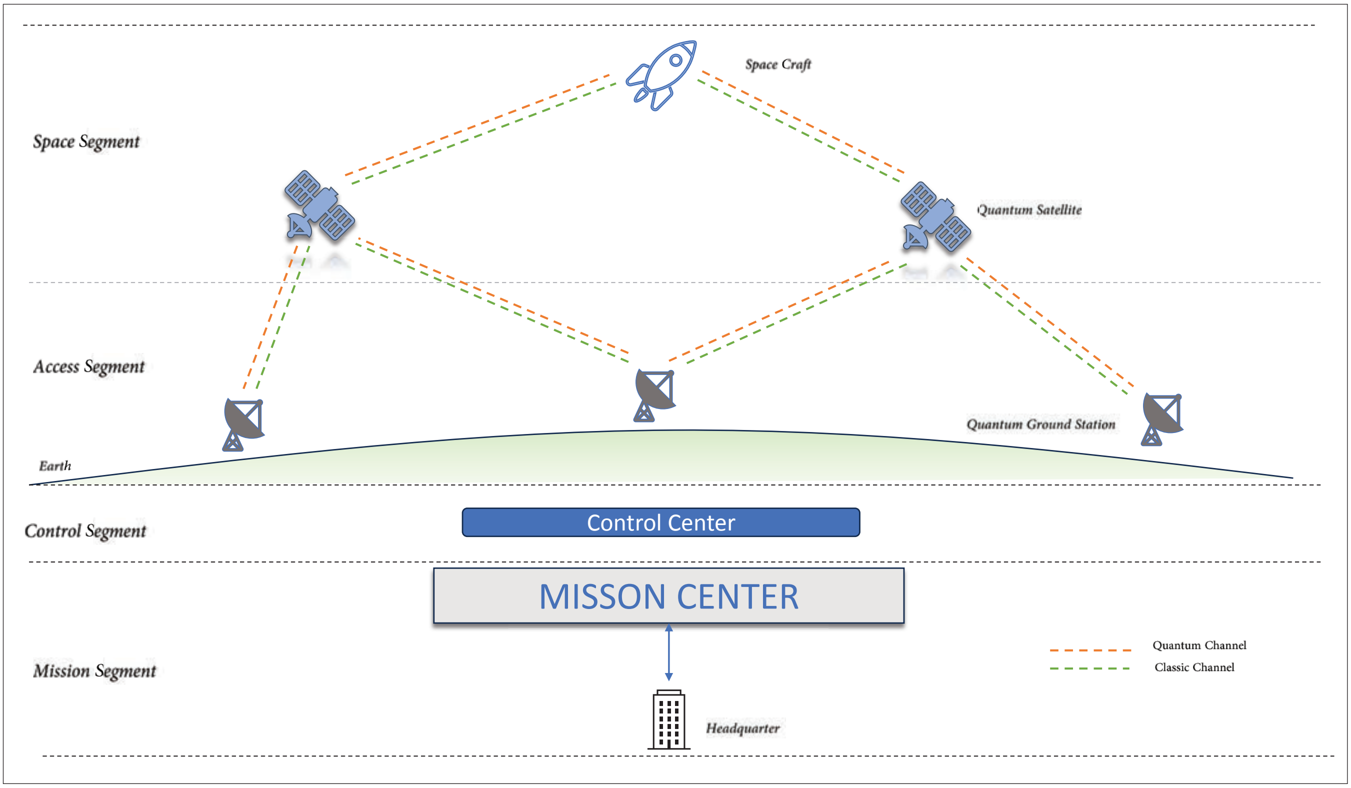

FIGURE 2. Quantum Network Architecture for Space Communication.

munication even for vast distances, such as in our space exploration scenario. Combined with the computing power of quantum servers, it ensures significantly improved security performance.

Quantum Network Architecture for Space Exploration

In the context of a space mission, the Quantum Software-Defined Networking (QSDN) paradigm emerges as a game-changer. The centralized control provided by QSDN allows for dynamic and adaptive management of quantum devices, optimizing the Quantum Data Plane and Classical Data Plane. This intelligent orchestration ensures that the mission's communication needs are met efficiently, even in the unpredictable environmental conditions of space. Furthermore, the integration of FSO technology in Quantum Satellite backbones enhances performance, mitigating atmospheric challenges and reducing the need for numerous QRs. This innovative combination of quantum principles, SDN adaptability, and FSO technology results in a space mission communication architecture that is secure, reliable, highly efficient, and adaptable to the dynamic conditions of outer space.

To foster quantum communication, two distinct channels are generally employed, each serving specific purposes:

•*Quantum Channel:* This channel acts as a link to generate an entangled pair between two directly connected QRs.

•*Classical Channel:* This channel establishes a link between classical nodes in the network. Its functionalities encompass background protocols, such as path selection and signaling protocols for end-to-end entanglement generation. The classical channel is also utilized to communicate classical bits of information integral to entanglement swapping and teleportation processes.

The quantum satellite can theoretically manage both quantum and classical communication through a unified transponder [15]. Quantum signals, typically sent on downlinks, consist of single polarized photons traveling through a quantum channel. Meanwhile, uplinks on the classical channel are utilized for measurement-basis signals, key-relay services, and potential future data services. To ensure compatibility with classical communications, a multi-beam system is employed for inter-satellite communication, enabling the transmission of quantum and data signals on separate laser beams within the same optical link.

Considering the architecture proposed in [11], we present its adaptation to the space exploration scenario, encompassing four elements: the Space Segment, Access Segment, Control Segment, and Mission Segment, as illustrated in Fig. 2.

The Space Segment involves satellites and spacecraft in orbit. Spacecraft transmits entangled photon pairs to satellites through quantum optical beams, establishing a quantum channel. As we have described above, the presence of classical communication channels (radio frequency or optical) that are established between spacecraft and receivers on the satellites for applications data exchanges is also essential.

The Access Segment consists of QGSs (Quantum Ground Stations) directly serving spacecraft or connecting to a local terrestrial QIN. Each QGS has optical terminals, quantum receivers, entanglement processors, storage units, and maintenance workstations. It collects photons through telescopes, stores entangled states and enables non-real-time usage of entanglement resources.

The Control Segment comprises a Control

Feature	Possibile application in space exploration
Secure Communication	Creation of secure communication channels. QKD ensures a secure exchange of cryptographic keys, enhancing overall cybersecurity. Additionally, quantum encryption protocols could be employed to safeguard data transmission between spacecraft.
Quantum Sensing	Quantum sensors can be utilized for precise measurements in navigation, gravitational field mapping, and environmental monitoring. Quantum sensing technologies enable high-resolution measurements of various physical parameters crucial for space exploration missions.
Quantum Computing	Quantum computing in space exploration holds the potential to accelerate specific tasks for navigation, data analysis, and simulations. However, it is important to note that current quantum computing technologies are primarily experimental and not yet ready for deployment in space missions. Research in this area is ongoing to overcome scalability, error correction, and environmental robustness challenges.
Remote Sensing	Quantum technologies enhance remote sensing capabilities. Quantum sensors can detect and analyze distant objects, providing valuable data for scientific exploration.
Interferometry	Quantum interferometry enables high-precision measurements for tasks like gravitational waves detection and celestial objects studies.

TABLE 1. Summary table of quantum networking features for space exploration.

Center and Telemetry, Tracking, and Control stations. It also receives mission requests from the Mission Segment and converts them into precise commands for spacecraft operations. It controls spacecraft orbit and attitude, receives telemetry data, and communicates with the Mission Center, which schedules transmissions and handles mission monitoring data, ensuring the seamless integration of spacecraft into the QIN in space.

The Mission Segment comprises a Mission Center, the master controller of the system. It also receives status data from spacecraft, and the Access Segment is responsible for operations and building instructions for the Control Center. This configuration addresses latency issues, particularly for applications demanding substantial resources and real-time responsiveness, and opens up the possibility of deploying small satellites as space-based quantum sensors. This approach also advances the practical performance of navigation and Earth observation systems. Specifically, integrating quantum sensors on small satellite nodes can significantly enhance our understanding of Earth through observation missions. These missions can effectively measure small-scale variations in Earth's gravitational field resulting from water flows, ice movement, continental drifts, and more.

Challenges and Open Issues

In this article, we presented QN as a future protagonist to help humanity explore deep space. The spontaneous question should be: Why is it not so widely implemented? The journey toward practical QN for space exploration is fraught with scientific hurdles. Quantum decoherence, a fundamental challenge in maintaining quantum coherence over long distances, becomes even more pronounced in the extreme conditions of space. The fragile nature of quantum states demands innovative solutions to shield against environmental factors such as cosmic radiation, extreme temperatures, and magnetic fields. Developing advanced QRs and quantum memory becomes imperative to fight the dangerous effects of decoherence in the vacuum of space. Quantum error correction, an intricate task due to the no-cloning theorem, takes on added complexity in the space environment. The finite quantum resources available for space missions, including entangled pairs and qubits, necessitate efficient resource management strategies to ensure the reliability of quantum computations and communications. Moreover, the integration of QNs with existing classical communication systems in space exploration missions poses a unique set of challenges, requiring interoperability and compatibility. The distribution of entangled qubits across vast distances becomes a critical challenge in the cosmic quest for knowledge and exploration. Overcoming quantum noise and minimizing interference in the face of cosmic radiation and other external factors is essential for establishing robust and efficient quantum communication protocols for space missions.

Despite these challenges, the vision of QN for space exploration remains a promising horizon, and the promising features (Table 1) of QN will be key to foster the development of cutting-edge technologies in space exploration.

Conclusion

In the pursuit of expanding human presence beyond Earth, classical communication for space exploration faces critical challenges. As we continue to push further and further the limits of space exploration, QN will take part in outperforming these limitations and opening up new horizons for discovery and innovation. In this article, we discussed and introduced quantum technology as a key enabling factor for future communications infrastructure specifically designed for space exploration and integrating TNs and NTNs. The proposed architecture shows the flexibility and the directions in which the scientific community can enlarge humanity's potential in the field of space exploration.

Acknowledgments

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Luca Borgianni received Bachelor's and Master's degrees in Telecommunication Engineering from the University of Pisa (Italy) in 2020 and 2022, respectively. He is currently a Ph.D. student in the Department of Information Engineering at the same university. His studies and research activities focus on traffic measurement and network control for high QoE in interactive multimedia applications. His current research interests are in the field of Software-Defined Wide Area Networks with a particular focus on Reinforcement Learning algorithms to improve QoS. He is also involved in support of teaching activities for FPGA laboratories and Mininet laboratories. Other research interests include Network traffic prediction, Quantum Networking, and Networked Music Performance.

Davide Adami received the degree in electronic engineering from the University of Pisa, Italy, in 1992. From 1993 to 1997, he was with Consorzio Pisa Ricerche, taking part in many research and technology transfer projects funded by the EU, such as the MAESTRO ACTS Project. In 1997, he joined CNIT, where he is a Senior Researcher in telecommunication networks. He has conducted research for several research projects funded by ASI, ESA, EU (FP6 RINGRID, FP7 DORII, FP7 OFELIA, FP7 Fed4FIRE, FP7 SCOUT, H20202 UMI-SCI-ED), and the Italian MIUR. He has authored over 100 papers in scientific journals and international conference proceedings. His research mainly concerns SDN and NFV, especially in cloud data centers, and the design and development of innovative solutions for integrating Cloud applications, IoT architectures, and sensor networks. Finally, he is a lecturer at the School of Engineering and Dept. of Computer Science of the University of Pisa.

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