# Quantum System Methods for Next Generation Satellite Design

Amir reza Fathi[1],Amir reza Kosari[2*],Arash Kosari [3],hadis abidi[4]
1 PhD student at the University of Tehran
2 Associate Professor, University of Tehran
3 Assistant professor, Electrical Engineering and Information Technology Research Institute
4 Master of Engineering ,Malek Ashtar University

## ABSTRACT

*Significant advances in quantum systems have driven quantum physics from a purely theoretical field into the realm of engineering. With the second quantum revolution, concepts such as quantum entanglement and quantum tunneling have entered the engineering domain. Quantum computers and quantum cryptography mark the transition from the modern space age to an era leveraging atomic-scale particles. This paper examines quantum capabilities for next-generation satellite design methods. Currently, the primary design difference between traditional and quantum satellites lies in data transmission. Moreover, fully utilizing quantum technologies requires quantum repeaters, which are not yet in operation. Despite current limitations in quantum technology, rapid scientific progress suggests that these technologies will soon open new avenues for optimized data transmission. With the adoption of advanced technologies, it is anticipated that quantum satellite constellations may eventually form in Low Earth Orbit (LEO) around Earth.*

***Keywords:*** *Quantum, Satellite, system Design*

## 1. *INTRODUCTION*

*The second quantum revolution has enabled the strange phenomena of the quantum world to be harnessed for industrial applications. Information security, along with data transmission speed, has become a significant focus. Currently, the use of quantum technologies in satellites is a compelling and contemporary issue. Quantum technologies can be utilized in the communication links between satellites, quantum space navigation, and space internet. Quantum entanglement allows particles to share information instantaneously. For satellite technology, this could revolutionize communication systems by enabling secure transmission methods, as any attempt to eavesdrop would disturb the entangled state, making interception detectableuantum Communication. The application of entangled particles in quantum key distribution (QKD) can lead to virtually unhackable communication networks. This is particularly significant for satellite communication, where data security is paramount .[1-3]*
*Entanglement can facilitate the development of quantum networks that interconnect satellites, potentially creating a global quantum internet. This could enhance data transmission rates and reliability, overcoming limitations faced by classical communication systems coupled with non-steady-state three-dimensional thermo-mechanical process[4-5]. The creation of the future quantum Internet requires the development of new systems, architectures, and communications protocols. As a matter of fact, the optical fiber technology is affected by extremely high losses; thus, the deployment of a quantum satellite network (QSN) composed of quantum satellite repeaters (QSRs) in low Earth orbit would make it possible to overcome these attenuation problems[6]. Quantum space navigation is a promising technology that aims to use quantum mechanics to enhance navigation accuracy and reliability in space. Quantum sensors, such as atom interferometers, can detect minuscule changes in acceleration and rotation, allowing spacecraft to maintain precise trajectories even in deep space where traditional GPS signals are unavailable clocks are another key innovation, providing highly stable timekeeping that is essential for the synchronization of satellite constellations and interplanetary missions . Additiantum entanglement may enable secure communication and potentially improve positioning accuracy by linking satellites through instantaneous data sharing . These advancemway for a quantum-based navigation framework that could redefine autonomous navigation for spacecraft in both near-Earth and deep-space missions[7]. Earth imaging satellites are a crucial part of our*

*everyday lives that enable global tracking of industrial activities. Use cases span many applications, from weather forecasting to*

*digital maps, carbon footprint tracking, and vegetation monitoring. However, there are limitations; satellites are difficult to manufacture, expensive to maintain, and tricky to launch into orbit. Therefore, satellites must be employed efficiently. This poses a challenge known as the satellite mission planning problem, which could be computationally prohibitive to solve on large scales. New articles show notably illustrates that a hybridized quantum-enhanced reinforcement learning agent can achieve a completion percentage of 98.5% over high-priority tasks, significantly improving over the baseline greedy methods with a completion rate of 75.8%. The results presented they work show pave the way to quantum-enabled solutions in the space industry and, more generally, future mission planning problems across industries[8]. All simulations show that also when incorporating improved sensor technologies such as future quantum sensing instruments in extended constellations, temporal aliasing will remain the dominant error source by far, up to five orders of magnitude larger than the instrument errors. Therefore, improving sensor technologies has to go hand in hand with larger satellite constellations together with improved space-time parameterization strategies to further reduce temporal aliasing effects[9]. Quantum Key Distribution (QKD) is an application of Quantum Information theory that obtained a great deal of attention in recent years. It allows to establish secret keys between two or more parties, in a much safer way than that implemented by classical cryptography (based on discrete logarithms and factorization of prime numbers). The most promising way of realizing a QKD network (especially over great distances) in the near future is by a constellation of satellites[10]. Recent research indicates that quantum technologies are making their way into the global space industry, from observational satellites to navigation and communication satellite constellations.*

## 2. *Quantum key distribution*

*A quantum satellite in Low Earth Orbit (LEO) is primarily designed to test and enable quantum communication and quantum key distribution (QKD) over long distances. The close proximity of LEO (typically between 200 and 2,000 kilometers above Earth) makes it an ideal orbit for initial quantum communication experiments, as it provides lower latency, more accessible line-of-sight for ground stations, and reduced power requirements compared to higher orbits.*

- *Quantum Communication Payload: These satellites are equipped with sources of entangled photons, such as laser systems that generate photon pairs. In entanglement-based QKD, one photon from the pair is sent to one ground station while the other photon is directed to a different location (e.g., another ground station or a satellite), enabling secure key distribution by detecting eavesdropping attempts through quantum correlations.*
- *Quantum Communication Payload: These satellites are equipped with sources of entangled photons, such as laser systems that generate photon pairs. These pairs are then used for QKD, where one photon is sent to the satellite and its entangled partner is directed to a ground station, establishing a secure communication link.*
- *Single-Photon Detectors (SPDs): Onboard the satellite, SPDs, in combination with polarization beam splitters and wave plates, are employed to measure the quantum states of individual photons with high precision. These systems ensure the security of transmitted data by enabling the detection of eavesdropping attempts through the analysis of polarization changes and error rates, which are indicative of quantum state disturbances.Orbit Stability and Access: In LEO, a satellite passes quickly over ground stations, offering frequent but short connection windows. This high orbital velocity allows multiple passes over different regions, which is helpful for creating widespread secure networks but requires high precision in tracking and data acquisition.*
- *Atmospheric Interaction: Although LEO reduces atmospheric interference compared to ground-based links, quantum signals still experience challenges such as scattering and loss due to atmospheric particles. Some LEO satellites are specifically equipped to measure and adapt to these atmospheric effects.*
- *Entanglement Distribution and Quantum Repeaters: LEO satellites are working toward distributing entanglement across longer distances. Some experimental LEO missions are also*

*testing quantum repeaters and memory storage capabilities to eventually enable a "quantum internet" that could connect multiple points worldwide.*

*A prominent example of a LEO quantum satellite is China's Micius satellite, launched in 2016. Micius has successfully conducted entanglement-based QKD over distances up to 1,200 kilometers, demonstrating the potential for unhackable, secure communication and paving the way for future applications in secure global communications and potentially inter-satellite quantum networks.*

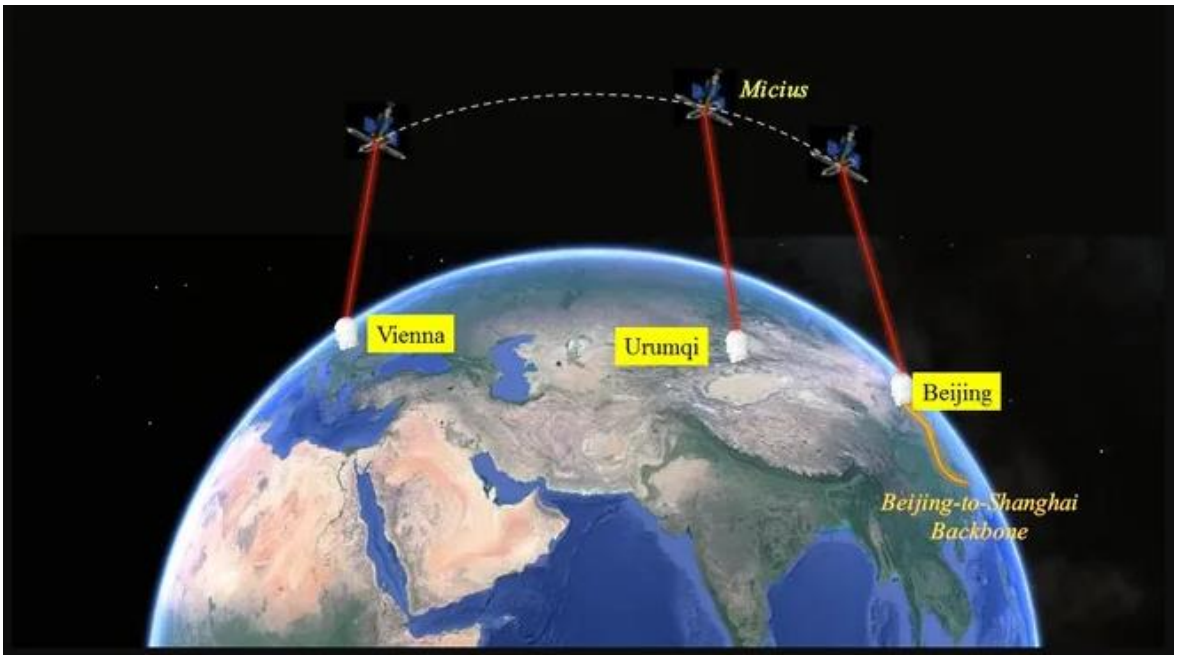


**Fig.1.** *Diagram of message-sending from Vienna to Beijing through space-ground integrated quantum network using China's Micius satellite, which launched in 2016*

*The distance between Vienna, Austria, and Beijing, China, for quantum satellite communication experiments, is approximately 7,400 to 7,600 kilometers. This distance has been successfully bridged using the Chinese quantum satellite Micius during quantum key distribution (QKD) experiments, demonstrating the feasibility of secure intercontinental quantum communication.*

## 3. Traditional communication satellites

*Designing a communication satellite for Low Earth Orbit (LEO) involves specific considerations to optimize for the unique characteristics of this orbital zone. Similar to the previous case, a suitable orbital path needs to be designed for each satellite.*

- *Latency and Bandwidth: LEO satellites are advantageous for low-latency communications, making them ideal for applications that require quick data transfer, such as real-time video streaming, cloud computing, and interactive online activities. The satellite's communication payload, typically including transponders and antennas, must be designed to handle high bandwidth and ensure low-latency performance. Ka-band and Ku-band frequencies are often chosen for their high data capacity.*
- *Power and Thermal Management: Operating in LEO means frequent exposure to sunlight and the cold of space, causing significant temperature variations. Satellite designers implement thermal regulation systems, such as heat pipes and radiators, to maintain stable temperatures. Solar panels and energy storage systems, like batteries, are used to power the satellite's systems, and are sized to meet high power demands during transmission periods.*
- *Durability and Radiation Shielding: Due to the harsh environment of LEO, satellites are exposed to radiation from the Van Allen belts and potential impacts from space debris. Design considerations include radiation shielding for sensitive electronics and a reinforced structure to*

*withstand micrometeorite impacts. Materials and electronic components must be selected for resilience to radiation to prolong the satellite's operational lifespan.*

- *Propulsion and Maneuverability: LEO satellites require propulsion systems for orbital adjustments and collision avoidance, as they frequently encounter space debris. Electric propulsion systems are commonly used due to their efficiency and lightweight design, which helps to extend mission life while reducing fuel mass.*
- *Inter-Satellite Links (ISLs): For efficient data relay across a satellite network, many modern LEO communication satellites incorporate inter-satellite links. These enable satellites to communicate directly with one another, allowing data to be transferred across the constellation before reaching ground stations. This design reduces dependency on ground infrastructure and provides more reliable global coverage.*
- *Onboard Processing: With increasing demand for processing capabilities, LEO communication satellites are often designed with advanced onboard computing systems to process data before transmitting it to Earth. This minimizes data transmission loads and enhances the efficiency of data handling within the satellite constellation.*

## 4. Comparison

*So far, it can be seen that traditional and quantum satellites use almost the same design method. In both, the mission must be specified. and determined the orbit of the satellite based on the mission. And the design of the structure that depends on the space environment will have very little changes. There will be traditional battery and solar cell methods for power generation.*

**Table.1** Comparison of conventional and quantum satellites in design

| *Conventional satellite* | *Quantum satellite* | *Satellite design subsystems* |
|---|---|---|
| ✓ | ✓ | *Structural subsystem* |
| ✓ | ✓ | *ADCS subsystem* |
| ✓ | ✓ | *Power subsystem* |
| ✓ | ✓ | *Orbit subsystem* |
| ✓ | ❖ | *Telecommunication subsystem* |

*The biggest difference in the design of quantum satellites compared to traditional telecommunications satellites lies in their data transmission methods. While traditional satellites primarily use radio waves, quantum satellites employ entangled photon pairs or single photons, generated through techniques like spontaneous parametric down-conversion, for secure quantum key distribution. These keys are embedded in the quantum properties of photons, such as polarization or phase. These quantum properties adhere to the no-cloning theorem, ensuring that any measurement or tampering destroys the original state, thus guaranteeing the security of the generated cryptographic keys. Classical communication channels, such as radio waves or optical links, remain integral for synchronization and error correction*

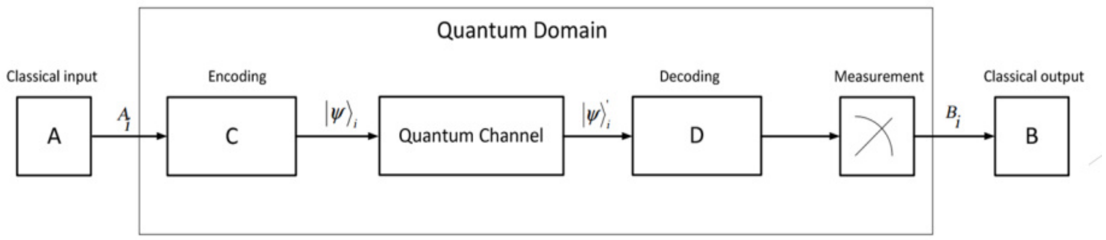


***Fig.2**. Quantum satellite design diagram*

*As it is clear in figure number two, in quantum satellites, in addition to entangled photons, traditional signals are needed to send the complete message.*

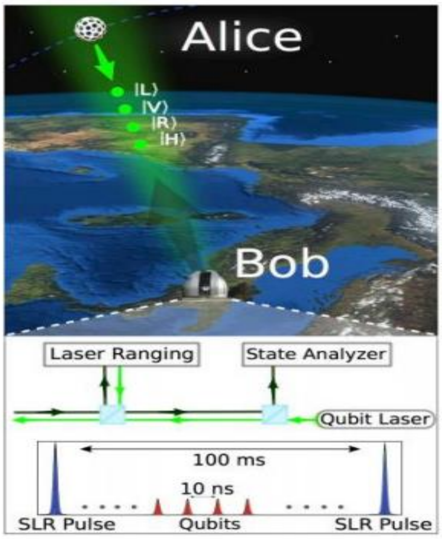


***Fig.3.*** *Qbit pulses are sent and returned at a repetition rate of 100 MHz. Simultaneously using SLR pulses with a repetition rate of 10Hz repetition is done.*

*In Fig. 3, we explain how satellites equipped for quantum communication often combine two types of laser systems to handle both secure data transmission and satellite positioning. High-frequency quantum bit (qubit) pulses, transmitted at a rapid rate of 100 million times per second (100 MHz), are used to securely transmit sensitive information by encoding data in the quantum properties of photons. At the same time, slower Satellite Laser Ranging (SLR) pulses, sent at just 10 pulses per second (10 Hz), help track the satellite's position precisely by measuring the time it takes for laser signals to return after bouncing off the satellite. This dual-purpose approach ensures that satellites remain accurately aligned while enabling secure and efficient quantum communication. The two systems are carefully managed to avoid interference, allowing both to operate seamlessly*

*One of the methods used in quantum satellites is the use of BB84 protocol. In this protocol, Alice's information is in the form of bits 0 and 1, and for each bit, it randomly selects one of the pairs of axes H, V or D, A, and according to the axis and the value of the bit, it provides a photon with a certain polarization. The photon is sent to Bob. Bob chooses one of the pairs of axes at random and then measures the polarization of the photon based on the selected axes. After sending a certain number of photons, Alice and Bob send each other their chosen axes. In cases where the same axes are selected, the desired bit will be saved except for the code key and vice versa.*

| Alice's random bit | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 |
|---|---|---|---|---|---|---|---|---|
| Alice's random sending basis | + | + | × | + | × | × | × | + |
| Photon polarization Alice sends | ↑ | → | ↘ | ↑ | ↘ | ↗ | ↗ | → |
| Bob's random measuring basis | + | × | × | × | + | × | + | + |
| Photon polarization Bob measures | ↑ | ↗ | ↘ | ↗ | → | ↗ | → | → |
| PUBLIC DISCUSSION OF BASIS | | | | | | | | |
| Shared secret key | 0 | | 1 | | | 0 | | 1 |

***Fig*.4.***BB84 Protocol*

*Despite the convenience of implementing the BB84 protocol, this protocol is not effective in long ranges.*

**Table.2** Advantages and disadvantages of the BB84 protocol

| **disadvantages** | **Advantages** |
|---|---|
| *Limited range (due to photon loss and noise over distance)* | *Simplicity of implementation (BB84 is conceptually simple)* |
| *Simplicity of implementation (BB84 is conceptually simple)* | *Provides theoretically unbreakable security through quantum key distribution (QKD)* |
| *Need for a single-photon transmission source (which is difficult to maintain and requires precise equipment)* | *Can be implemented using various quantum phenomena, such as photon polarization or spin* |

## 5. conclusion

*In this article, the design of quantum satellites and their differences from traditional satellites were compared. It is observed that the primary current difference in design between these two types of satellites lies in data transmission. It has been established that, even for data transfer via quantum methods such as quantum entanglement, radio waves are still necessary for the complete transmission of messages. Furthermore, fully leveraging quantum technologies requires quantum repeaters, which have not yet been fully deployed. Despite existing limitations in quantum technologies, the rapid scientific advancements in this field suggest that in the near future, these technologies will open new possibilities for optimized data transmission. Quantum satellites are expected to form constellations in Low Earth Orbit (LEO).*

.

**REFERENCES**


[1] R. Gisin, "Quantum cryptography," Physical Review Journals, 2002.

[2] S. &. L. R. Pirandola, "Towards a Quantum Internet.," Nature Photonics, 2012.

[3] B. M, "Entangled photons for secure communication in satellite networks," Applied Physics Letters, 2020.

[4] A. P.Van Loock, "Quantum information with continuous variables," Reviews of Modern Physics, 2017.

[5] H.J.Kimble, "The quantum internet," Nature, 2008.

[6] Francesco Chiti, "Towards the Quantum Internet: Satellite Control Plane Architectures and Protocol Design," Future Internet, 2021.

[7] B. e. al, "This study from the UK National Quantum Technology Hub focuses on the role of quantum clocks and sensors," American Institute of Physics, 2019.

[8] S. Rainjonneau, "Quantum Algorithms Applied to Satellite Mission Planning for Earth Observation," IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2023.

[9] R.D. Philipp Zingerle, "Constellation design and performance of future quantum satellite gravity missions," Earth, Planets and Space, 2024.

[10] F. D. Grossi, "Orbit design of satellite quantum key distribution constellations in different ground stations networks," Advances in Space Research, 2024.