

Space Quantum Communication: Applications and challenges for building Global Quantum Network

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Abstract. Quantum communications can play a key role in the space systems, secure telecommunications, information processing, navigation and science of the future. Quantum Key Distribution (QKD) is the next step in security evolution which will open new horizons in building and expand Global Quantum Network. Unique properties of the quantum mechanical principles such as superposition, entanglement and teleportation are used to transfer quantum information between quantum devices, but also to generate and distribute secure cryptographic keys. We aim to summarize different challenges and their inventive solutions in free space quantum communications through satellites. Increased investment in the field led to new technological breakthroughs that can enhance Quantum Key Distribution over vast distances through Inter-Satellite and Satellite-Ground quantum communication, but also to connect the future quantum sensors and scalable quantum computers.

1. Introduction

The security of data transmission through classical communication channels becomes more and more challenging on the verge of quantum computing appearance. The different physics behind give them strong advantage over classical cryptographic methods and even at the early stage of implementation they are able to decrypt high end security protected data in fairly short time. In the next few years this will improve, and we should be prepared [1]. Harvest now, decrypt later is a stealing technique that collects sensitive encrypted data today, so when there is a breakthrough in the future the data will be decrypted. Quantum technology gives to this technique new perspective, and we should make counter measures fast.

Quantum communication steps in with a whole new approach for data protection. Involving quantum physics, the key distribution using quantum principles seems unbreakable, since the setup and transmission of quantum information is a subject of specific properties on its reception and reading. The information is sent through qubits (quantum bits) encoded in their wave function that cannot be fully read. In fact, when we read the state of a qubit its wave function collapses, so any consequential readings will return a completely different result. This does not allow quantum information to be copied (No cloning theorem [2]), which gives the quantum technology unique advantage not only for unwanted eavesdropping, but also for detection thereof. Quantum communication approach does not stop here, it is also possible to improve and secure the data



transmission with Superdense coding [3]. Quantum sensors and quantum processors can be connected directly with quantum channels, which will unlock the opportunity to use technologies like Distributed and delegated quantum computing [4], Distributed quantum sensing [5] and Quantum metrology [6]. Space quantum communication will enhance the research of key physical laws and phenomena at relativistic distances and speeds [7].

Building a global quantum network is a challenge that combines variety of new methods and existing technologies to achieve the required reliability and scalability in a communication system. It can be utilized in space agencies, science institutions, telecommunication companies, governments, financial institutions, and healthcare providers. Terrestrial optical fiber networks can connect multiple places over short distances, but we need different approach to reach longer distances, such as mountains, seas and oceans, countries and continents. Bigger ranges can be achieved through satellite communication channels. In this article, we will discuss different challenges and also opportunities in quantum communication through satellite and ground station connections.

2. Quantum information

Unlike classical communication, which uses bits as an information carrier, quantum communication uses qubits (quantum bits). Qubits hold binary values of 0 or 1, which is very similar to classical bits 0 or 1. The difference comes from the possible states of the qubit, denoted as $|0\rangle$ and $|1\rangle$ (also called bra-ket or Dirac notation [8]), which can be also in super position $\alpha|0\rangle + \beta|1\rangle$ i.e., they are 0 and 1 simultaneously. Coefficients α and β denotes the probability of measuring either 0 or 1. Qubit state is described mathematically with a wave function $|\psi\rangle$ [9]:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

In Figure 1 is shown, graphical representation of a qubit's wave function on the Bloch sphere [6]. The qubit state is defined as vectors pointing to the sphere's surface. Mathematical operations on qubits are performed by rotation or projection onto different axes at different angles. (θ and ϕ).

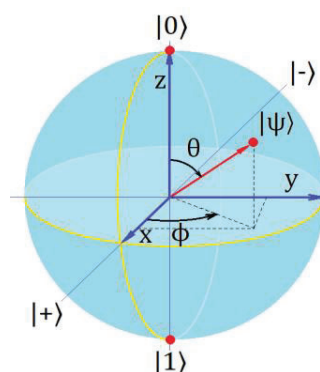


Figure 1. Graphical representation of a qubit on the Bloch sphere.

The quantum states $|0\rangle$ and $|1\rangle$ are located at the opposite points diametrically from each other i.e., to the north and south pole of the sphere respectively. All other points can be derived by a combination of both states with different angles θ ($0 \leq \theta \leq \pi$) and ϕ ($0 \leq \phi \leq 2\pi$). For example, when

$\theta = 0$ then qubit state is $|0\rangle$, respectively when $\theta = \pi$ then qubit state is $|1\rangle$ and when $\theta = \frac{\pi}{2}$ the qubit is in equal superposition between $|0\rangle$ and $|1\rangle$. This means that we have equal probability to be $|0\rangle$ or $|1\rangle$ over the z-axis. In other hand we have angle ϕ between state vector counterclockwise from the positive x-axis. Angle ϕ represents phase between quantum states $|0\rangle$ and $|1\rangle$. When we measure Z-basis (called also computational basis) we get $|0\rangle$ or $|1\rangle$ based on the probability in θ , but we don't know the phase $|+\rangle$ or $|-\rangle$ in ϕ . And vice versa, when we measure X-basis (called also Hadamard basis) we get $|+\rangle$ or $|-\rangle$ based on the phase in ϕ , but we don't know the probability $|0\rangle$ or $|1\rangle$ in θ . This shows that one qubit delivers significantly more information in comparison to the classical bit due to the wide variety of complex numbers that α and β can assign. Even though, we can't get them directly due to the limitations in quantum measurement, they are essential in quantum calculations and can be transmitted over the quantum channels.

Superposition principle lies in the base of quantum entanglement of multiple qubits, where two or more qubits can be entangled in one system with common α and β coefficients of the wave function. For example, quantum system with two entangled qubits can have the following wave functions [2]:

$$|\psi\rangle = \alpha|00\rangle + \beta|11\rangle$$

where α and β coefficients shows probability of the system to collapse in ether $|00\rangle$ or $|11\rangle$. From the equation above we can easily see that there is no probability for the system to collapse in ether $|01\rangle$ or $|10\rangle$. Therefore, the measurement of one qubit from this system will determine the result of the measurement of the other qubit (in this case, it will be the same), regardless of the time and distance between them. This property, unique to the quantum systems, is a particularly useful feature in quantum communications.

Quantum state measurement does not follow the same principle as the measurement in a classical system. In a quantum system, we extract a certain property of the physical system, but due to its quantum scale this introduces some interesting features and limitations. The act of measurement leads to a collapse of the wave function $|\psi\rangle$, and the qubit takes a state of $|0\rangle$ or $|1\rangle$, (or $|+\rangle$ or $|-\rangle$ if measured in Hadamard basis) depending on the coefficients α and β , which determines the probability of the outcome. Any further measurements do not give us more information about the qubit's wave function on any other basis, since its quantum state is decayed. Hence, we can perform only one measurement in one basis, and the result is based solely on the qubit's probabilities. This unique property of the quantum communication has no analogue in the classical, deterministic systems. The complete quantum information cannot be extracted by measurement and therefore cannot be recreated or copied (No-cloning theorem [2]). In a system with entangled qubits, which share a common wave function $|\psi\rangle$, the measurement of one of the qubits will collapse the entire system into a new wave function that determines the measurement result of the other qubits.

These unique properties give quantum technology strong advantage over classical approach. Superposition principle allows parallel calculations (so called Quantum parallelism [2]) which together with entanglement lies in the base of Quantum computation. Limitations in the quantum measurements is the key in Quantum cryptography, where the quantum information cannot be copied, and the measurement changes the quantum state which indicates that someone tried to eavesdrop. Quantum entanglement lies in the base of Quantum communication which expand in features like entanglement swapping [10] and quantum teleportation [11].

3. Quantum communication

Microscopic particles like electrons, photons or atoms can be quantum information carriers (qubits), but their physical properties are not easy to be measured. We already have well developed technology for sending and measuring photon polarization. Therefore, we will use photons for quantum information transportation. Photons can be sent over long distances without losing their coherence, which is very convenient for quantum communication. They are already used in terrestrial optical fibers and free space communications. Like in classical communication systems, the main goal of quantum communication systems is to send as much as possible quantum information from one place to another with minimum losses and maximize the distance. Therefore, we have to maintain photon's coherence as long as possible.

Terrestrial quantum communication uses ordinary optical fibers for photon transmission while free space quantum communication use lasers and optical telescopes over open air. In both cases quantum information has been sent through photons. Depending on the application and distance the proper quantum communication channel has to be used, but for building global quantum internet we have to use both – terrestrial and free space channels. We will examine the basic methods for quantum information encoding in photons, their features and applications.

Polarization encoding - Polarization is the most popular method since the polarizing lenses are widespread (polarized glasses, LCD screens and etc.) and the encoded information could be decoded very easily. Superposition can be created with diagonal polarization (45°-polarized) which is in superposition of horizontal and vertical polarization. It is suitable for usage in free space but is hard to be preserved in fiber link.

Path encoding - Path encoding uses different paths of the photon to represent the information [6]. A single photon can be reflected or passed through in the beam splitter - Figure 2. By controlling the splitter ratio in the beam splitter, we can create superposition where the photon has equal probability to take both beam paths. This method is not widely used in quantum communications, because it requires two quantum channels. It is utilized in quantum calculations. Polarization beam splitter is used to make the transfer between polarization and path encoding which reflect or pass through the photon depending on its polarization.

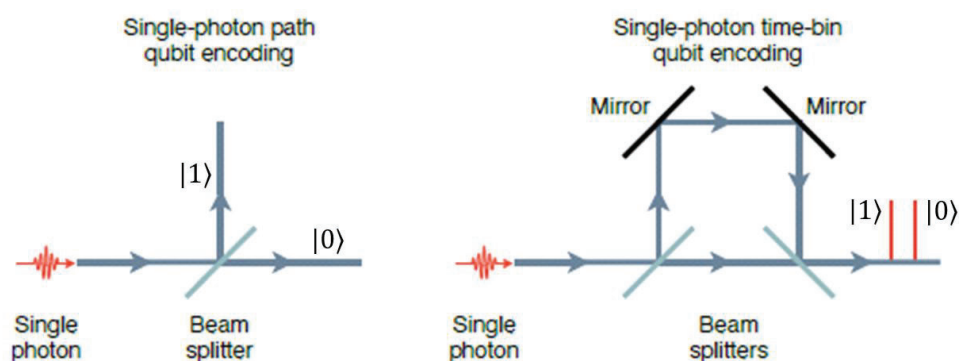


Figure 2. Single-photon path (on the left) and time-bin encoding (on the right).

Time-bin encoding - Time-bin encoding [6] also uses beam splitters to split the path of the photon similarly to the path encoding, but thereafter joins the paths into single one which adds a time delay to the longer path. Thus, the information is encoded in the arrival time of the photon. This method can be used in a single quantum channel, which makes it suitable for optical fiber

communication where the paths are separated by a time delay and the interference is minimal. Polarization beam splitter is also used here as in the path encoding.

Phase encoding - In phase encoding [12], the quantum information is carried through phase modulation of the light beam. Sender sends a sequence of phase encoded photons with information encoded in the relative shift between them. The receiver uses a Mach-Zehnder interferometer and measures the phase differences between successive photons.

Encoding methods can be combined to maximize their strengths and minimize their drawbacks. Combination between *Time-bin and Phase encoding* [13] methods will improve resilience to environment noise which will extend the distance and make it suitable for transmission of Quantum Key Distribution (QKD) protocols like BB84 [1].

Quantum information cannot be copied defined by No-cloning theorem gives us strong advantage in securing the communication by encoding it into the quantum states, but it also becomes a serious drawback. We cannot use the most basic technique for error correction in noisy channels called repetition code, where same information is sent several times. Similarly, we cannot repeat the signal to extend the range like in classical optical fiber communication systems, where the process of repeating of the signal requires read, recreate, and resend of the information. We need a different approach in quantum systems to overcome this drawback. We can use quantum entanglement instead of trying to read and repeat the information, where we extract only the probability part of the information and destroy the rest through the process of reading. In 1985, Asher Peres has proposed the first three-qubit bit-flip code [14], which adds two additional qubits, and it is comparable in performance to the classical repetition code. In quantum systems apart from bit-flip we have phase-flip (sign-flip), which is considered ten year later in Peter Shor's algorithm [15] for error correction with eight additional qubits. This is the first algorithm to correct single-qubit errors.

Although we cannot directly transfer information with quantum entanglement (No-communication theorem [16]), we can use Quantum teleportation algorithm [11] based on it - Figure 3.

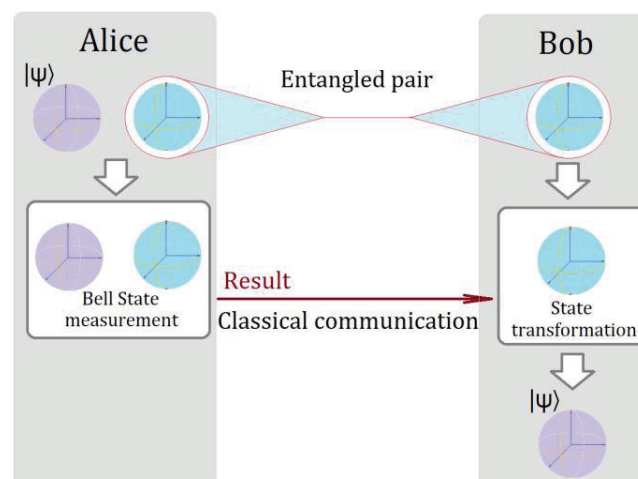


Figure 3. Quantum teleportation algorithm.

In order Alice to send qubit with wave function $|\psi\rangle$ to Bob through quantum teleportation channel, we first need two entangled qubits at both ends. Then Alice will perform Bell state measurement [9] over the new qubit $|\psi\rangle$ and hers entangled qubit. Because Alice and Bob have entangled pair, when Alice did Bell state measurement, she changed not only hers new and entangled qubit, but also the Bob's entangled qubit, which collapsed into a new wave function. Bob's qubit now has the rest of the collapsed wave function of the three-qubit system, and the other part is the result from the Bell state measurement performed by Alice. The result from this measurement is sent through classical communication channel to Bob. Now, Bob will perform state transformation with the result from the Bell state measurement from Alice and his entangled qubit. The outcome will be that the Bob's qubit will now have the same wave function $|\psi\rangle$ as the Alice's qubit that we started with. We need an entangled pair of qubits and a classical communication channel for this method to work.

Furthermore, we can use quantum channel to transmit the classical information with Superdense coding algorithm – Figure 4.

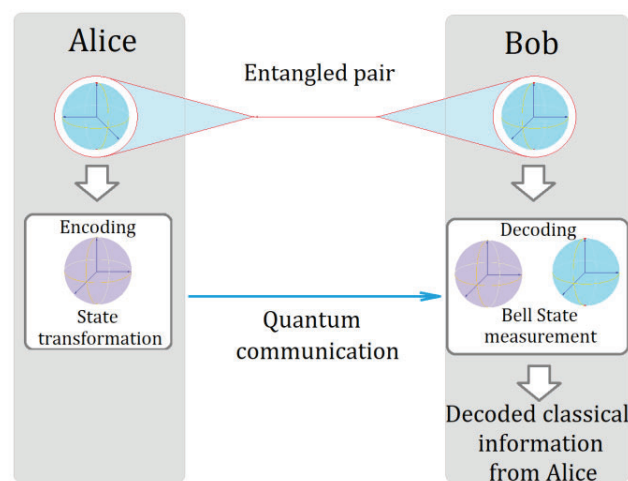


Figure 4. Superdense coding algorithm.

In this algorithm, the entangled pair is again prepared and distributed to Alice and to Bob. Alice will encode two bits of classical information through state transformation (quantum gate operations) with her entangled qubit. After that Alice will send her entangled qubit to Bob through quantum channel. Now, Bob will perform Bell State measurement to retrieve the classical information Alice sent to him. Bob doesn't need to know which quantum gate operations were applied by Alice, but will read the result of it as received information.

Apparently, this method seems effective, since we encode two bits of information in just one qubit, which can also be a photon, but we need first entanglement distribution, and then quantum communication channel to send encoded payload in the qubit. With the current technology progress, the cost of such exchange of qubits is disproportionately higher than the transfer through classical bits, but in fact we achieve quantum-secure communication. This is because only one of the qubits participates in the transfer between Alice and Bob, and both are needed, when the information has to be extracted. Any attempt for eavesdropping of the transmitted qubit will simply destroy the encoded information, because the other qubit does not leave its original "secure" place.

Entanglement swapping [10] is another approach based on Quantum teleportation that we can use to build Quantum repeaters – Figure 5.

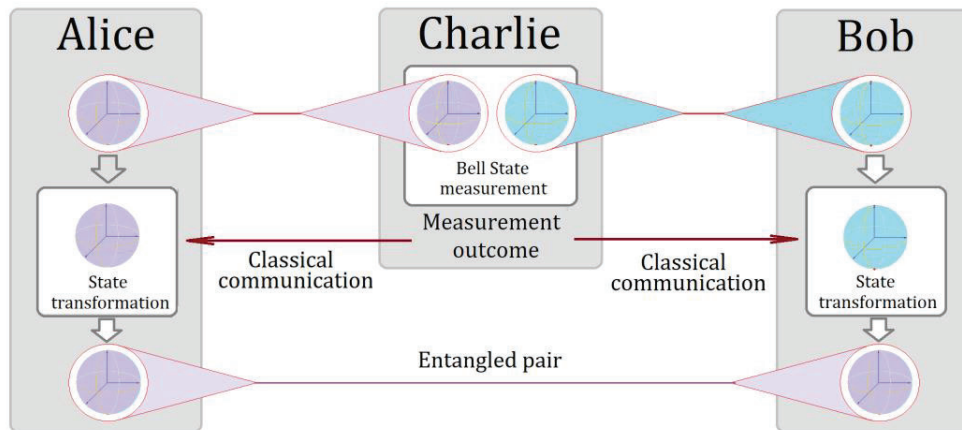


Figure 5. Entanglement swapping algorithm.

In this algorithm we will start with a third node called Charlie that will have an already distributed entangled qubits one from Alice's pair and one from Bob's pair. Charlie will perform Bell state measurement of the received qubits, and he will send the result back to Alice and Bob through classical channel. Now, Alice and Bob will perform state transformation with Charlie's result from the Bell state measurement over their other remaining entangled qubit. The outcome will be an entangled pair of qubits one of which is with Alice and the other with Bob. This algorithm can be used multiple times to extend the range of the quantum channel – Figure 6.

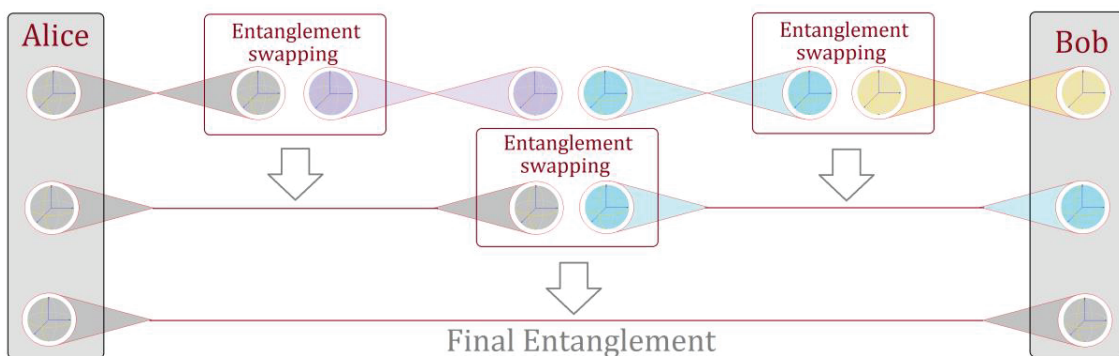


Figure 6. Repeated application of entanglement swapping algorithm.

With these algorithms we can achieve a greater distance but at a cost, for multiple entanglement swapping we use multiple ancillary entangled pairs and we also lose coherence during the errors from algorithm processing. This also needs to be taken into account to achieve a greater distance with minimal losses. The link loss with free space channel is d^2 (30-40 dB over 500-1200km [17]), where the link loss with optical fiber channel is e^d (0.2-0.35 dB/km, so

repeaters will be needed every 100-150km [18, 19, 20]). Therefore, we can see that with satellites we need far less repeaters than with terrestrial optical fiber channels.

4. Space quantum communication

Satellite-based quantum communication will play a major role in Global quantum network. It has already achieved entanglement distribution over 1200 km - Chinese quantum satellite Micius [21]. With Micius, they not only perform Quantum Key Distribution (QKD), but also research fundamental quantum principles.

Satellite-based quantum communication is optical communication implemented with lasers, telescopes and satellites. Lasers will enable better data rates and allow communications systems to become smaller, lighter, and more efficient [6]. As the most suitable method for encoding quantum information in free space is phase encoding and the transmission is established with entangled photon pairs. There are various topologies for quantum signal propagation between ground and orbit – Figure 7.

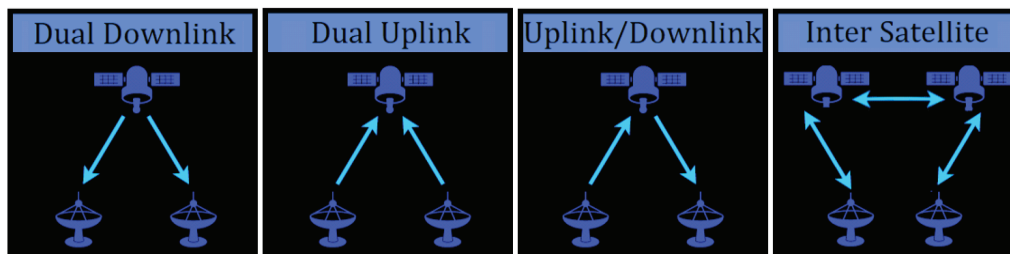


Figure 7. Satellite-based quantum communication topologies.

Dual Downlink – In this topology, the satellite is the primary source of the entangled photon pairs. The ground stations directly receive entangled pairs and there is no need for additional time synchronization. Once the ground stations have entangled pairs they can exchange quantum information through quantum teleportation. Entangled pairs can be directly applied in Quantum Key Distribution (QKD). In this way the satellite plays the role of the quantum repeater.

Dual Uplink – Here, the ground stations send their entangled pairs to the satellite, where Bell state measurement is performed, and the result is sent back to them through classical channels. Then they will build their common entangled pairs through entanglement swapping. This method requires precise time synchronization, because the satellite has to receive the photons at the same. This is not an easy task, because the satellites are flying in orbits at high speeds and the distance varies.

Uplink/Downlink – In this method, the satellite passively reflects the photons to the next ground station without the need of time synchronization [22]. The satellite uses optical components such as mirrors and lenses to redirect the photons back to another ground station without storing or processing any quantum information.

Inter-satellite links – Here, more than one satellite is used to establish the quantum communication between the ground stations. There is a high risk that one or more of the satellites being exposed to the solar radiation, where photon transmission is not possible [23]. Furthermore,

in the most cases only one satellite is enough to build a link between the ground stations, because it has visibility to both of them.

It is important to note, that satellites solely help to build quantum communication links between the ground stations. The actual payload is sent directly between them, which increases the security to a degree not seen in the classical communication systems. Free-space communications are heavily affected by atmospheric conditions and selecting the suitable wavelengths is crucial to minimize those negative effects – 665-685nm, 775-785nm, 1000-1070nm and 1540-1680nm [24]. Better transmission rate is done with higher wavelengths.

5. Applications and challenges

5.1. Applications

We are already exchanging terabits of classical data via terrestrial and space-based classical communication infrastructures. The rapid development of optical communications in space and the exchange of information through optical technologies over vast distances there demonstrate the potential of the future quantum communication in space. In 2024, optical communication was achieved at more than 225 million kilometers distance with the Psyche spacecraft [25]. NASA's deep space optical communication activities over the recent years [6] also shown in Figure 8:

- Laser Communications Relay Demonstration (LCRD) Terminal – accomplished in 2020.
- Optical User Terminal ILLUMA-T – accomplished in 2022.
- Orion Artemis II Optical Communications System (O2O) Terminal – accomplished in 2022.
- Deep Space Optical Communications (DSOC) Terminal – accomplished in 2022.
- Advanced Deep Space Optical Communications (DSOC) Terminal – accomplished in 2024.

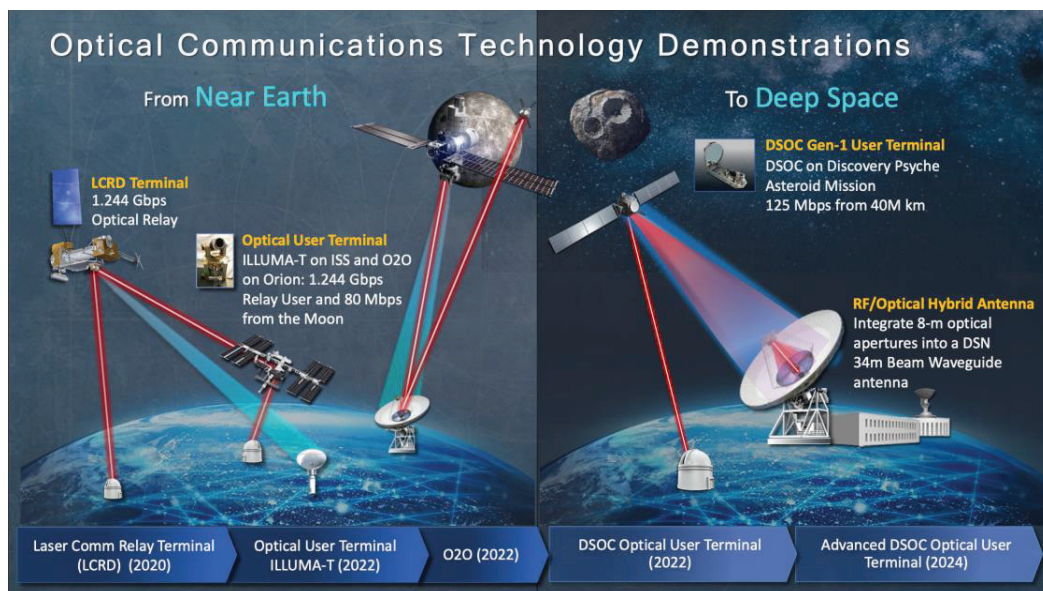


Figure 8. A projected timeline of NASA's deep space optical communication activities [6].

Thousands of satellites are in operation today, used for science, imaging, telecommunications, and navigation. Satellites at LEO orbits provide better signal strength, because they are close to the

ground and create good connections between cities with low latency. Satellites in higher MEO orbits enable intercontinental links potentially with an all-day global quantum communication network. Our ability to control individual quantum systems and to transfer quantum information between them becomes quite promising in the next 10-20 years to witness a technological breakthrough in the practical application areas such as:

Quantum-Enhanced security - The new field of Quantum Cryptography and Quantum Key Distribution is being used to establish keys for secure communications. It is most mature application in quantum communications as many countries and institutions have proof-of-concept demonstrations of commercial QKD systems that are readily available from several vendors. Today the first quantum links are being used to demonstrate quantum applications in cyber security and metrology. Even before a mature quantum internet exists, the development path promises many near-term applications, making both the journey and the end goal worth the investment.

Distributed Quantum Sensing and Quantum Metrology - Quantum metrology has the potential to reach the limit of precision measurements for the systems utilizing quantum resources. Based on unique quantum effects, it will achieve sensitivity that is not possible with the known classical methods. For example, in 2015 gravitational waves were detected for the first time using the Laser Interferometer Gravitational-Wave Observatory (LIGO) which comprises two, very large Michelson interferometers [26]. A space system could be deployed on a massive scale to detect waves at even lower frequencies and to discover and observe new exotic types of sources. In addition, the satellites and space nodes will allow quantum sensors to be interconnected, to achieve extraordinary resolution and precision and to provide valuable insights into Earth and Universe observations. A similar classical approach was used in 2017 to capture the first image of a black hole located in the galaxy M87, a technique known as Very Long Baseline Interferometry (VLBI), effectively creating a virtual telescope the size of Earth by connecting multiple sensors [27]. Quantum sensors connected by entanglement have the potential for unprecedented sensitivity and precision. Quantum technology can speed up convective flow analysis over the Earth's surface [28], which could help us to better understand climate change.

Distributed and delegated quantum computing - Today, quantum computers are sensitive and delicate devices. When they become available to the public, they will likely to be owned by universities, companies, or institutions that will take care of their proper functioning. Users will be able to log in and use the quantum computers remotely, as it is currently the case with IBM's shared quantum processors for popularization and educational purposes [1]. Quantum computing will most likely be distributed among multiple countries or delegated to a country that owns a quantum computer. Quantum computers can be interconnected to multiply the quantum computational power by connecting the quantum processors and sensors. This is an approach that uses the combined computing power of multiple quantum processors allocated in different places. Researchers are working to develop protocols for multi-party delegated quantum computing, which allows multiple clients to securely delegate their computations to the remote quantum server [29].

Scientific breakthroughs - Deep space quantum communication will unlock testing of fundamental physics and quantum mechanics principles over relativistic distances and speeds. In cosmology and astrophysics, it could play a crucial role in our understanding of gravitational fields and their gradients. By analyzing the quantum properties of particles and their interactions, scientists can obtain more scientific data about harder to reach components of the universe such as dark matter and dark energy. New and bold theories of quantum gravity can be tested with such a powerful tool, which could potentially lead to real breakthroughs in the field.

5.2 Current Developments and Future Prospects

Space Communications and Navigation (SCaN) program demonstrates infrastructure for both near-Earth communication and deep space communication that can be used for quantum communication [6]. This is a NASA program, which implements quantum communication via satellites in low Earth orbit and multiple ground stations. Future Plans - Quantum communication between satellites in LEO and MEO orbits and multiple ground stations to enable intercontinental quantum links. Also, for establishing communication networks in deep space, for the purpose of scientific and research missions with a full range of radio frequency communications and navigation capabilities.

Micius Satellite (China) - Launched in 2016, and successfully demonstrated quantum key distribution (QKD) over a distance of 1,200 kilometers, a communication based on quantum entanglement [21]. It appears to be the leading project in the field for now. Future Plans - Building a global quantum communications network in 2030, with more satellites, coverage extension and reliability.

European Quantum Communication Infrastructure (EuroQCI) - Aims to deploy a secure quantum communications infrastructure across Europe, including both ground-based and satellite-based infrastructures, with ongoing efforts to integrate quantum technologies into existing networks [30]. Future Plans - Full deployment by 2030, integrating quantum-based systems into existing communication infrastructures to safeguard sensitive data and critical infrastructures across Europe.

Optical and Quantum Communications – Scylight (ESA) - The European Space Agency's Scylight program is developing satellite constellations to achieve secure quantum communications links over long distances [31]. This program is in the development and demonstration phase. Future Plans - Continued development and in-orbit verification of optical communication technologies, with a focus on creating a "Virtual Fibre in the Sky" system to extend terrestrial networks into space.

Security And cryptoGraphic mission (SAGA) (ESA) - SAGA focuses on demonstrating and validating space-based quantum technologies [32]. It aims to improve the security of communication networks through quantum cryptography. Future Plans - Enhancing the security of communication networks through advanced quantum cryptography, with ongoing missions to test and refine these technologies.

Singapore's Quantum Cryptography Satellite - is working on developing a quantum cryptography satellite, set to launch in 2025 [33]. This satellite will be equipped with QKD technology. Future Plans - Establishing a secure system for transferring encryption keys for confidential information in fields such as security and finance. This project is led by the Singaporean company SpeQtral, in collaboration with international partners.

5.3 Challenges

Decoherence - Attenuation and decoherence are one of the major problems for any type of quantum communication. Free-space channel links has their unique challenges such as atmospheric conditions, turbulence, diffraction, solar noise and cosmic radiation causes significant loss of quantum information. Even in the closer Low-Earth orbit the quantum communication is almost not possible at daytime. Selecting the wavelengths can reduce some of the atmospheric negative effects - Figure 9. Several transmission windows are evident, within which optical transmission would experience low loss. Better transmission rate is done with higher wavelengths and with 90 degrees angle from the horizon.

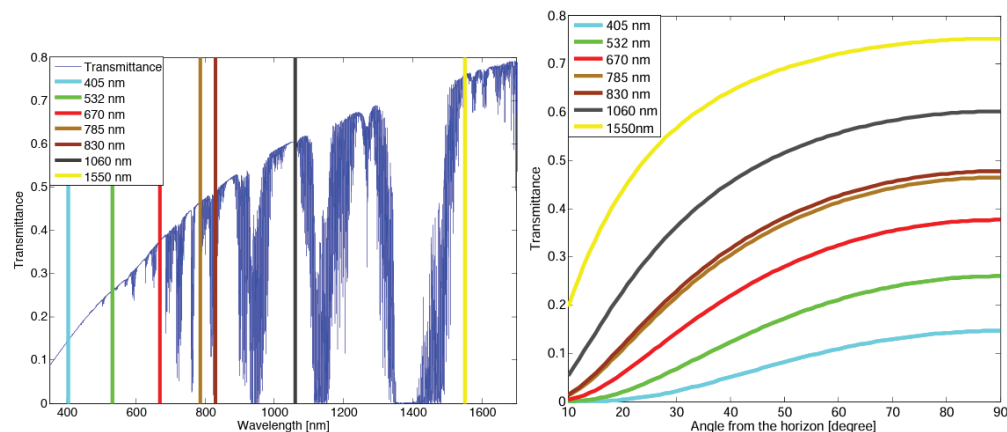


Figure 9. Simulated atmospheric transmittance at a typical rural location, for propagation at zenith (left) and for different elevation angles (right) [24].

Technological limitations of current technology - In addition to the high cost of space facilities, there are also challenges posed by the underdeveloped technologies in this area. Although there are concepts for quantum repeaters, they are still under test and proof of concept stages. Satellites and ground stations require specific and much more precise equipment, such as high-resolution clocks and synchronization devices, single photon emitters and receivers, single photon frequency and bandwidth modulators, quantum memories and quantum transducers. Most of these devices are still in the labs, too noisy and too heavy, especially for space usage, so it will take time for it to become enough stable and mature. Estimated timeline for several quantum technology functional elements adapted from the Workshop on Space Quantum Communications and Networks hosted by NASA in 2020 [34]. The estimates here remain valid at time of writing [6]:

- Entanglement swapping between moving sources - expected 2025.
- Feed-forward operation on teleported qubit - expected 2025.
- High-efficiency, low-jitter photon detectors in space - expected 2025.
- High-resolution clock and sync - expected 2025.
- Single-photon frequency and bandwidth conversion - expected 2025.
- Quantum memory - expected 2030.
- Quantum transducer - expected between 2025 and 2030.
- Fault-tolerant quantum repeater - expected 2035.
- Full-scale, error-corrected quantum processor - expected between 2030 and 2040.

Distance limitations - Geosynchronous orbit (GEO) orbit is still not reachable for quantum communication due to its distance (35 586km to 35 986km). It is hard to preserve the quantum state from decoherence in such huge distance. Medium-Earth orbit (MEO) and Low-Earth orbit (LEO) has a potential for quantum communication, but the relative speed and angle between the transmitter and receiver is still e huge technological challenge.

Infrastructure and costs - It is expensive to build and to launch satellites with such sensitive equipment. Also, this needs international cooperation for the quantum network to become global.

Standardization and regulation - Because this technology is still young and mostly operating in labs, it will take time for it to be well understood and popularized enough to be standardized and regulated - Figure 10. This is crucial to ensure interoperability and security.

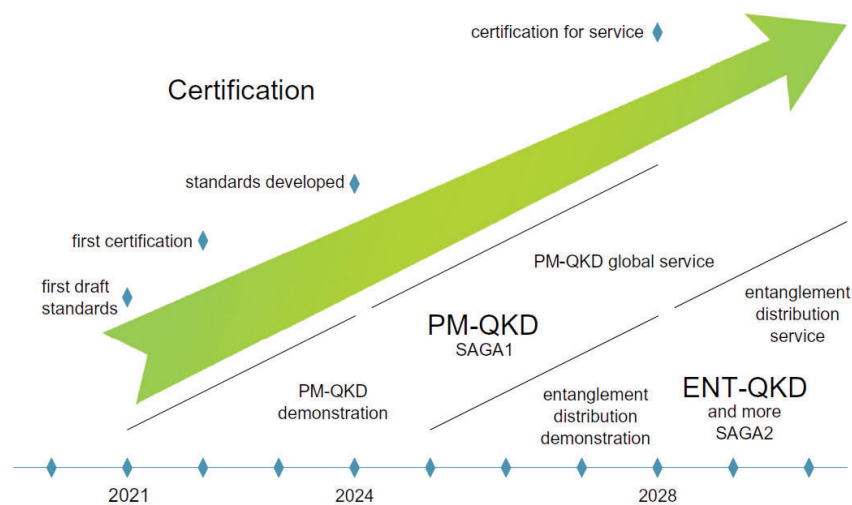


Figure 10. The envisioned timeline for the proposed roadmap [35].

6. Conclusions

In this paper, we started from the smallest, but most important element in the quantum system – the qubit. Its unique properties give us the opportunity to explore different aspects of the quantum communication where different encoding schemes were deployed: polarization encoding, path encoding, time-bin encoding, phase encoding. These methods also can be combined to maximize their strengths and minimize their drawbacks. And the most promising combination is Time-bin and Phase encoding, which improve resilience to noise and extend the distance. Further in our research we showed important features in quantum technology like quantum teleportation, superdense coding and entanglement swapping, which are used to build quantum communication links through terrestrial optical fiber and free space satellite channels. Quantum Key Distribution is our core technology to securely link different places together. Satellites give us strong advantage by extending the range in compare to the ground fiber connections. They also give us the opportunity to deploy a trusted party between the ground links, which will further enhance the security. As of today, satellites at LEO orbits are the subject of deployment of such novelty network. This will enhance applications such as Distributed Quantum Sensing, Quantum Metrology, Distributed and Delegated Quantum Computing. Projects currently in progress in this field are Space Communications and Navigation (SCaN), Micius Satellite (China), European Quantum Communication Infrastructure (EuroQCI), Optical and Quantum Communications (Scylight), Security And cryptographic mission (SAGA) and Singapore’s Quantum Cryptography Satellite. This is of course coming at a cost and challenges are arising such as decoherence, distance limitations, infrastructural costs, standardization and regulation.

The satellites are the key nodes in building a sustainable quantum entanglement distribution chain, which will connect different ground station links over long distances. Satellite constellations, equipped with quantum sensors with entangled atomic clocks could become an important tool to research further the dark matter with their super-resolution imaging and distributed quantum lights. By controlling quantum systems a wide range of applications opens up across computing, sensing and cryptography. There are many challenges around building Global Quantum Network, but the current progress and investments are quite promising and the next 10-20 years we may

become witnesses to a technological breakthrough for practical applications in areas such as entanglement swapping between moving sources, feed-forward operation on teleported qubit, high-efficiency low-jitter photon detectors in space, high-resolution clock and sync, single-photon frequency and bandwidth conversion, quantum memory, quantum transducer, fault-tolerant quantum repeater and full-scale error-corrected quantum processor.

Quantum technologies will become more and more accessible to the end user and will continue to enhance our daily life. Quantum cloud services have the biggest potential to provide services with unprecedented high level of security. Various quantum sensors with very high sensitivity will help to research new fields of science. In the next years we are expecting to reach longer distances in our quantum communication links, which will help us to finally build a global quantum internet.

References

- [1] M. AbuGhanem, "IBM Quantum Computers: Evolution, Performance, and Future Directions", arXiv, 2024, doi: 10.48550/arXiv.2410.00916
- [2] M. A. Nielsen and I. L. Chuang, "Quantum Computation and Quantum Information", 10th edition, Cambridge University Press, 2010, isbn: 978-1-107-00217-3
- [3] K. Mattle, H. Weinfurter, P. G. Kwiat and A. Zeilinger, "Dense Coding in Experimental Quantum Communication", Physical Review Letters, Vol. 76, No. 25, pp. 4656-4659, American Physical Society, 1996, doi: 10.1103/PhysRevLett.76.4656
- [4] E. T. Campbell and J. Fitzsimons, "An introduction to one-way quantum computing in distributed architectures", International Journal of Quantum Information, Vol. 08, No. 01n02, pp. 219-258, World Scientific, 2010, doi: 10.1142/s0219749910006198
- [5] Z. Zhang and Q. Zhuang, "Distributed quantum sensing", Quantum Science and Technology, Vol. 6, No 4, pp. 043001, IOP Publishing, 2021, doi: 10.1088/2058-9565/abd4c3
- [6] H. Semenenko, S. Wright, M. Lollie, J. Florez, M. Hoban and F. Curchod, "Quantum Communication 101", NASA, 2024
- [7] D. Rideout, T. Jennewein, G. Amelino-Camelia, T. F. Demarie, B. L. Higgins, A. Kempf, A. Kent, R. Laflamme, Xian Ma, R. B. Mann, E. Martin-Martinez, N. C. Menicucci, J. Moffat, C. Simon, R. Sorkin, L. Smolin and D. R. Terno, "Fundamental quantum optics experiments conceivable with satellites — reaching relativistic distances and velocities", Classical and Quantum Gravity, Vol. 29, No. 22, pp. 224011, IOP Publishing, 2012, doi: 10.1088/0264-9381/29/22/224011
- [8] P. A. M. Dirac, "A new notation for quantum mechanics", Mathematical Proceedings of the Cambridge Philosophical Society, Vol. 35, No. 3, pp. 416-418, Cambridge University Press, 1939, doi: 10.1017/s0305004100021162
- [9] I. B. Djordjevic, "Quantum Communication, Quantum Networks, and Quantum Sensing", 1st edition, Academic Press by Elsevier, 2022, isbn: 9780128229422
- [10] M. Zukowski, A. Zeilinger, M. A. Horne and A. K. Ekert, "'Event-ready-detectors' Bell experiment via entanglement swapping", Physical Review Letters, Vol. 71, No. 26, pp. 4287-4290, American Physical Society, 1993, doi: 10.1103/PhysRevLett.71.4287
- [11] C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres and W.K. Wootters, "Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels", Physical Review Letters, Vol. 70, No. 13, pp. 1895-1899, American Physical Society, 1993, doi: 10.1103/physrevlett.70.1895
- [12] Z. L. Yuan, A. Plews, R. Takahashi, K. Doi, W. Tam, A. W. Sharpe, A. R. Dixon, E. Lavelle, J. F. Dynes, A. Murakami, M. Kujiraoka, M. Lucamarini, Y. Tanizawa, H. Sato and A. J. Shields, "10-Mb/s Quantum Key Distribution", Journal of Lightwave Technology, Vol. 36, No. 16, pp. 3427—3433, IEEE, 2018, doi: 10.1109/JLT.2018.2843136
- [13] A. Boaron, G. Boso, D. Rusca, C. Vulliez, C. Autebert, M. Caloz, M. Perrenoud, G. Gras, F. Bussieres, Ming-Jun Li, D. Nolan, A. Martin and H. Zbinden, "Secure Quantum Key Distribution over 421 km of Optical Fiber", Physical Review Letters, Vol. 121, No. 19, pp. 190502, American Physical Society, 2018, doi: 10.1103/PhysRevLett.121.190502
- [14] A. Peres, "Reversible Logic and Quantum Computers", Physical Review A, Vol. 32, No. 6, pp. 3266-3276, American Physical Society, 1985, doi: 10.1103/PhysRevA.32.3266
- [15] P. W. Shor, "Scheme for reducing decoherence in quantum computer memory", Physical Review A, Vol. 52, No. 4, pp. R2493-R2496, American Physical Society, 1995, doi: 10.1103/physreva.52.r2493

- [16] N. Gisin and A. Peres, "Maximal violation of Bell's inequality for arbitrarily large spin", *Physics Letters A*, Vol. 162, No. 1, pp. 15-17, Elsevier, 1992, doi: 10.1016/0375-9601(92)90949-M
- [17] J.-P. Bourgoin, B. L. Higgins, N. Gigov, C. Holloway, C. J. Pugh, S. Kaiser, M. Cranmer and T. Jennewein, "Free-space quantum key distribution to a moving receiver", *Optics Express*, Vol. 23, No. 26, pp. 33437, Optical Society of America, 2015, doi: 10.1364/OE.23.033437
- [18] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues and P. Trojek, "Entanglement-based quantum communication over 144 km", *Nature Physics*, Vol. 3, No. 7, pp. 481-486, Nature Publishing Group, 2007, doi: 10.1038/nphys629
- [19] H. Takesue, S. W. Nam, Q. Zhang, R. H. Hadfield, T. Honjo, K. Tamaki and Y. Yamamoto, "Quantum key distribution over a 40-dB channel loss using superconducting single-photon detectors", *Nature Photonics*, Vol. 1, No. 6, pp. 343-348, Nature Publishing Group, 2007, doi: 10.1038/nphoton.2007.75
- [20] D. Stucki, N. Walenta, F. Vannel, R. T. Thew, N. Gisin, H. Zbinden, S. Gray, C. R. Towery and S. Ten, "High rate, long-distance quantum key distribution over 250 km of ultra low loss fibres", *New Journal of Physics*, Vol. 11, No. 7, pp. 075003, IOP Publishing, 2009, doi: 10.1088/1367-2630/11/7/075003
- [21] Chao-Yang Lu, Yuan Cao, Cheng-Zhi Peng and Jian-Wei Pan, "Micius quantum experiments in space", *Reviews of Modern Physics*, Vol. 94, No. 035001, American Physical Society, 2022, doi: 10.1103/RevModPhys.94.035001
- [22] S. Goswami and S. Dhara, "Satellite-Relayed Global Quantum Communication without Quantum Memory", *Physical Review Applied*, Vol. 20, No. 2, pp. 024048, American Physical Society, 2023, doi: 10.1103/PhysRevApplied.20.024048
- [23] M. Er-long, H. Zheng-fu, G. Shun-sheng, Zhang Tao, D. Da-sheng and G. Guang-can, "Background noise of satellite-to-ground quantum key distribution", *New Journal of Physics*, Vol. 7, No. 215, IOP Publishing, 2005, doi: 10.1088/1367-2630/7/1/215
- [24] J.-P. Bourgoin, E. Meyer-Scott, B. L. Higgins, B. Helou, C. Erven, H. Huebel, B. Kumar, D. Hudson, I. D'Souza, R. Girard, R. Laflamme and T. Jennewein, "A comprehensive design and performance analysis of low Earth orbit satellite quantum communication", *New Journal of Physics*, Vol. 15, No. 2, pp. 023006, IOP Publishing, 2013, doi: 10.1088/1367-2630/15/2/023006
- [25] "NASA's Optical Comms Demo Transmits Data Over 140 Million Miles", NASA, 2024, url: <https://www.nasa.gov/missions/psyche-mission/nasas-optical-comms-demo-transmits-data-over-140-million-miles/>
- [26] "LIGO's Interferometer", Caltech, url: <https://www.ligo.caltech.edu/page/ligos-ifo/>
- [27] Songbai Chen, Jiliang Jing, Wei-Liang Qian and Bin Wang, "Black hole images: A review", *Science China Physics, Mechanics & Astronomy*, Vol. 66, No. 260401, Springer, 2023, doi: 10.1007/s11433-022-2059-5
- [28] R. Velichkova and S. Antonov, "Analysis of occurrence and distribution of convective flow in the environment", *AIP Conference Proceedings*, Vol. 2505, No. 1, pp. 080011, 2022, doi: 10.1063/5.0100653
- [29] E. Kashefi and A. Pappa, "Multiparty Delegated Quantum Computing", *Cryptography*, Vol. 1, No. 2, pp. 12, MDPI AG, 2017, doi: 10.3390/cryptography1020012
- [30] F. Wissel, O. Nikiforov, D. Giemsa and M. Gunkel, "The Opportunities and Challenges of EuroQCI", *IEEE Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, USA, 2024, isbn: 979-8-3503-7758-3
- [31] H. Hauschildt, C. Elia, H. L. Moeller and D. Schmitt, "ScyLight — ESA's secure and laser communication technology framework for SatCom", *IEEE International Conference on Space Optical Systems and Applications (ICSOS)*, pp. 250-254, Japan, 2017, doi: 10.1109/ICSOS.2017.8357400
- [32] A. M. Lewis and M. Travagnin, "A secure quantum communications infrastructure for Europe – Technical background for a policy vision", *European Commission: Joint Research Centre, Publications Office of the European Union*, 2022, doi: doi.org/10.2760/180945doi.org/10.2760/180945
- [33] "Securing Global Networks in the Quantum Era", *SpeQtral Pte*, url: <https://speqtralquantum.com/>
- [34] "Workshop on Space Quantum Communications and Networks", NASA SCaN, 2020, url: <https://www.nasa.gov/centers-and-facilities/johnson/workshop-on-space-quantum-communications-and-networks-proceedings/>
- [35] R. Kaltenbaek, A. Acin, L. Bacsardi, P. Bianco, P. Bouyer, E. Diamanti, C. Marquardt, Y. Omar, V. Pruneri, E. Rasel, B. Sang, S. Seidel, H. Ulbricht, R. Ursin, P. Villoresi, M. van den Bossche, W. von Klitzing, H. Zbinden, M. Paternostro and A. Bassi, "Quantum technologies in space", *Experimental Astronomy*, Vol. 51, pp. 1677–1694, Springer, 2021, doi: 10.1007/s10686-021-09731-x