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# Using Satellites for Entanglement-based Advanced Secure Networking

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# Using Satellites for Advanced Secure Networking Applications


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## Summary

Advanced Secure Networking mitigates emergent and future cybersecurity threats using an entanglement-based architecture, integrating physics-based security and complementing updated math-based security, like the new post-quantum cryptography (PQC) algorithms released by NIST in 2024. Expanding the reach of  entanglement-based Advanced Secure Networks is critical to ensuring our communications are secured against new threats. The convergence of entanglement-based technology and satellite infrastructure represents a groundbreaking leap in communication systems, offering unprecedented security with global coverage. With the potential to revolutionize industries ranging from telecommunications to scientific research, the integration of satellite technology with entanglement-based networks marks a pivotal shift towards a more interconnected and secure world. This white paper explores the existing satellite technologies, and projects currently pursuing free-space quantum communication, and the future of using satellites for a global quantum communications infrastructure. Quantum communication leverages the principles of quantum mechanics, particularly superposition and entanglement, to achieve tasks that are impossible or infeasible with classical communication methods. Quantum communication uses qubits, particles encoded with quantum information, to enable a variety of applications, but in this white paper we'll focus on the secure networking use case. Other applications include distributed quantum computing and distributed quantum sensing.

## Introduction

We use satellites in everyday life, whether we realize it or not. In today's digital society, we rely on the global connectivity of devices. Satellites are critical in providing that global connectivity for almost everything: voice, text, internet, TV, radio, Wi Fi, online banking, financial transactions, military and defense applications, Internet of Things, science in metrology, for environmental monitoring, for imaging, for weather forecasting, for GPS. If you've used Apple Maps or Google Maps recently, you've utilized this technology. This infrastructure figures heavily into our everyday life.

## Current satellite communication systems

Today's satellite communication systems are integral to global connectivity, supporting a wide range of applications from telecommunications to navigation and environmental monitoring. Let's dive a little deeper into how these satellite systems work in today's world, starting with an overview of a typical 5G satellite communication system.There's no quantum technology involved in this example, this is a classical application. It’s useful to understand how these satellite communication systems work outside of entanglement-based Advanced Secure Network applications.[LEO]

Every satellite communication consists of at least these three stages:

- Uplink: transmission from ground station to designated satellite
- Transponder: satellite does signal amplification and frequency change
- Downlink: transmission from satellite to ground station(s)

## How does it work?

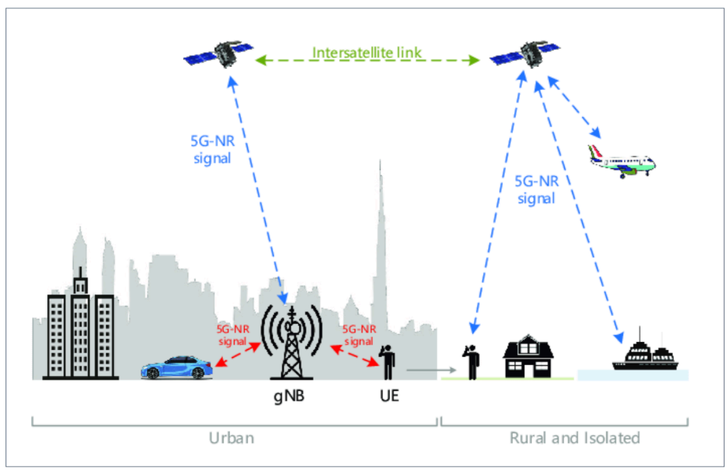
### A Typical 5G Satellite Communication System

Every satellite communication consists of 3 stages:

**Uplink:** transmission from ground station to designated satellite

**Transponder:** satellite does signal amplification and frequency change

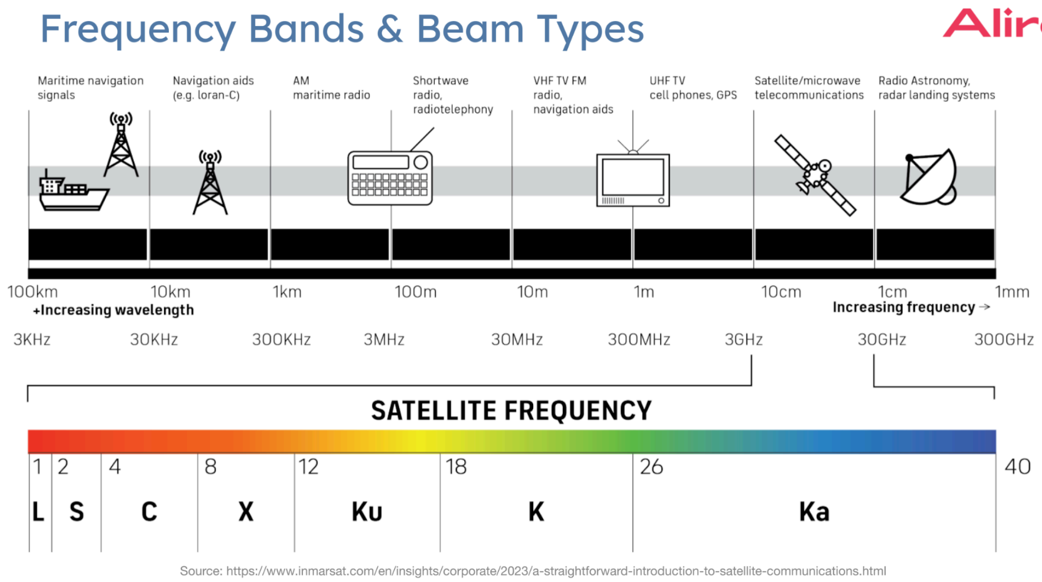
**Downlink:** transmission from satellite to ground station(s)




Source: *Near Optimal Timing and Frequency Offset Estimation for 5G Integrated LEO Satellite Communication System*
https://ieeexplore.ieee.org/abstract/document/8795582

In the uplink stage, the signal is transmitted from the ground to a designated satellite. So in an urban area, for example, this would perhaps take the form of communicating with a cell tower. That cell tower is responsible for the uplink to a designated satellite. That signal, as it traverses through the atmosphere, may weaken or degrade. In the second stage, the transponder stage, the satellite does what's called signal amplification. At this stage, the satellite can boost the strength of that signal after it has been weakened. It might also do any necessary frequency changing of the signal before moving on to the third stage. At this point, the satellite may communicate with another satellite in orbit, but eventually it is sent to the other node on the ground. This is the downlink stage, where communication is sent from the satellite to a designated ground station. The satellite could also downlink to aerial assets, such as an airplane, and leverage different frequency bands and beam types.

Different frequency bands are used for different types of applications.




The image above shows the frequency bands and types of traffic associated with those bands.[FREQUENCY BANDS] Satellite and microwave telecommunications typically operate in the three gigahertz to 30 gigahertz regime. The L-band at the left is a small band, and it typically carries traffic for applications for radars, for GPS, for internet of things, but also maritime and aviation applications. Moving to the right, the S-band is twice as big. The S-band typically carries traffic for applications in shipping and aviation, as well as the space industry. For example, airplane Wi-Fi is an example of S-band traffic.

Moving into the C-band, this serves a lot of satellite TV traffic and is also responsible for raw satellite feeds and satellite imagery. The largest band is the Ka-band. The Ka-band is carrying the majority of satellite internet traffic, specifically for high bandwidth and high speed applications, such as video calls and streaming webinars.

In addition to different frequency bands and beam types for specific applications, satellites also have different orbits for different applications.[FREQUENCY BANDS]

## Different Orbits for Different Applications

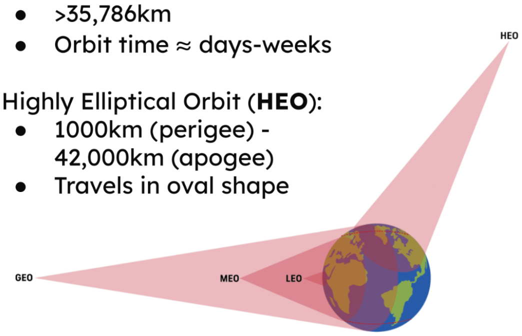
Low Earth Orbit (**LEO**):
- 160-2,000km
- Orbit time ≈ 90min
- 5-7yr lifespan

Medium Earth Orbit (**MEO**):
- 2,000-35,786km
- Orbit time ≈ 2-8hr

Geostationary Earth Orbit (**GEO**):
- 35,786km above equator
- 15+ year lifespan
- Same direction as Earth’s rotation
- Fixed position in the sky

High Earth Orbit (**HEO**):
- >35,786km
- Orbit time ≈ days-weeks

Highly Elliptical Orbit (**HEO**):
- 1000km (perigee) - 42,000km (apogee)
- Travels in oval shape




Source: https://www.inmarsat.com/en/insights/corporate/2023/a-straightforward-introduction-to-satellite-communications.html

The lowest orbit is called Low Earth Orbit. Low Earth Orbit, or LEO orbit, ranges from 160 kilometers to 2000 kilometers above the surface of the earth. The orbit time for LEO satellite is about 90 minutes. These satellites typically have a five- to seven- year lifespan. Starlink deploys LEO satellite constellations to enable global internet coverage.

Medium Earth Orbit, ranges from 2000 kilometers to 35,786 kilometers above the surface of the earth, which sounds like a contrived number but is actually relevant for a geostationary orbit. Medium Earth Orbit time is anywhere from two to eight hours.

In a Geostationary Orbit, or GEO, all of the satellites are located at approximately 35,786 kilometers above the equator. These GEO satellites have a much longer lifespan of at least 15 years. The critical property of GEO satellites is that when traveling in the same direction as Earth's rotation, they have a fixed position in the sky. For any ground station that's communicating with a geostationary satellite, there's no specialized tracking that needs to be performed because the satellite is in a known, fixed position.

Moving further and further from Earth, there are other satellite orbits to consider: the High Earth Orbit, and the Highly Elliptical Orbit. High Earth Orbit satellites can take anywhere from from days to weeks, sometimes even months to orbit Earth. With the Highly Elliptical Orbit, the satellite will be at different distances from Earth throughout its orbit, sometimes closer to Earth and at other times much further away.

These different orbits have different properties - variations in communication latency and signal strength. Because of these differences, they are used in different ways to host a variety of applications.

Low Earth Orbit satellites can enable applications that require global coverage, but because they're closer to Earth, they have a relatively small field of view for reaching a ground station. To work within this constraint, a constellation of LEO satellites can be used to facilitate global coverage. Because LEO satellites are closer to Earth, they have extremely low latency: the signals can traverse between Earth and the satellite much quicker than can be achieved at MEO or GEO. The most popular application for LEO satellites is telecommunications: Internet, 5G broadband, maritime applications, Internet of Things, and emergency response systems.

Further away from Earth, MEO satellites occupy the middle ground between the Geostationary Orbit and Low Earth Orbit. Typically, Medium Earth Orbit is used for GPS systems. GPS systems are really a precise timing system. Position navigation and timing applications use MEO satellites. Medium Earth Orbit satellites are occasionally used to provide internet services to remote areas.

Because Geostationary Orbit satellites have a fixed position in the sky, they are best suited for more permanent communications links. The field of view for these satellites is approximately one third of the Earth's surface. Not many geostationary satellites are required in order to facilitate global coverage. The application profile of GEO satellites are applications like global imaging, global mobile communications, broadcasting, weather forecasting. GEO satellites also serve as a GPS reference for other MEO GPS satellites. Moving further and further away, High Earth Orbit and Highly Elliptical Orbit facilitate applications that require a global view of Earth: Earth monitoring, as well as deep space applications such as sensing applications, deep space exploration, astronomy and science experiments.

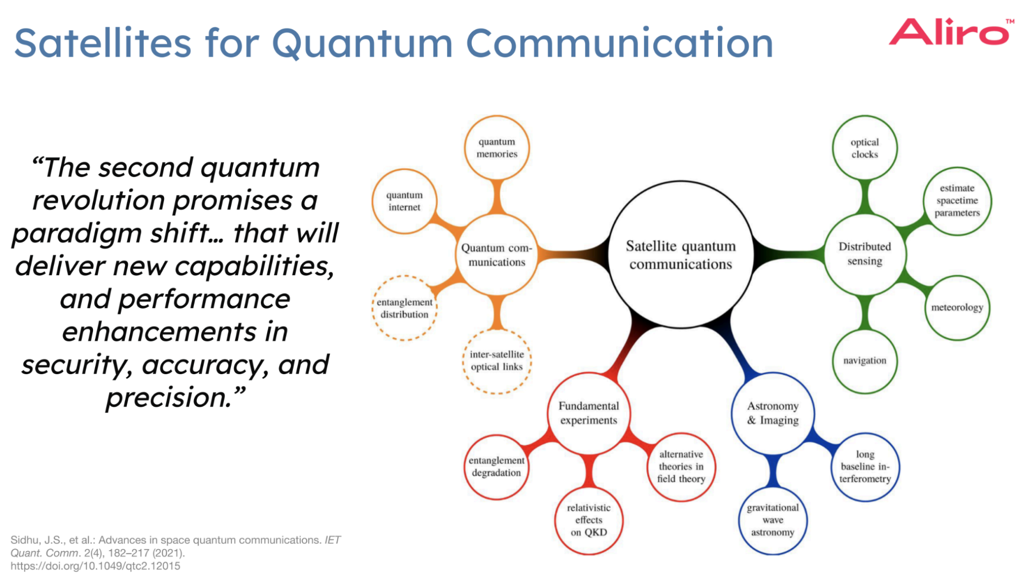
## Radio-Frequency (RF) vs. Free-Space Optical (FSO) Communications

The vast majority of satellite communication systems leverage the radio frequency band. These are more reliable, better for longer distances that can penetrate through atmospheric conditions such as clouds or rain. Recently, free-space optical communications have garnered a lot of interest for satellite communication systems, in classical networking and telecommunications as well as for entanglement-based Advanced Secure Networking and communications. The optical spectrum has very different properties than the RF spectrum. The main constraint in using optical communications is FSO requires line-of-sight between the two endpoints in order to communicate: these communications can't pass through a wall, and it is more sensitive to atmospheric conditions and physical obstructions. However, FSO communications experience less interference with other electromagnetic signals. Another benefit of FSO communications is a much higher data rate than RF is able to achieve. Optical communications applications are typically used to satisfy very high-bandwidth, high-throughput requirements at shorter to medium range distances with a direct line of sight. Because of these different constraints and benefits, certain application profiles are more suitable for the optical domain than the RF domain. The optical spectrum is well-suited for use in quantum communications.

## Advanced Secure Networking with satellites

Entanglement-based Advanced Secure Networking represents a new paradigm for physics-based secure communication, utilizing the properties of quantum physics to establish provably secure connections. Satellites play a crucial role in scaling these networks beyond the constraints of terrestrial fiber networks, enabling global entanglement-based advanced secure network connectivity. Here we'll address the mechanics of quantum communication underpinning this powerful technology, the role of satellites in entanglement distribution, and the current achievements and challenges in satellite-based networks being deployed for quantum communication.

Satellite quantum communications support a suite of very promising applications. This infrastructure of satellite quantum communications will impact a wide range of fields and industries. Quantum secure communications that leverage entanglement distribution will shift how the telecommunications industry operates securely. Quantum satellites could enable distributed quantum sensing applications, having immense impact on optical clocks, and position, navigation, and timing applications. This will also revolutionize what's possible in science and astronomy, pushing the boundaries of fundamental physics forward for astronomical applications, like Long Baseline Interferometry, but also detecting gravitational wave fluctuations. There are many other fundamental experiments that this infrastructure can enable in addition to this listed here.[QN APPLICATIONS]



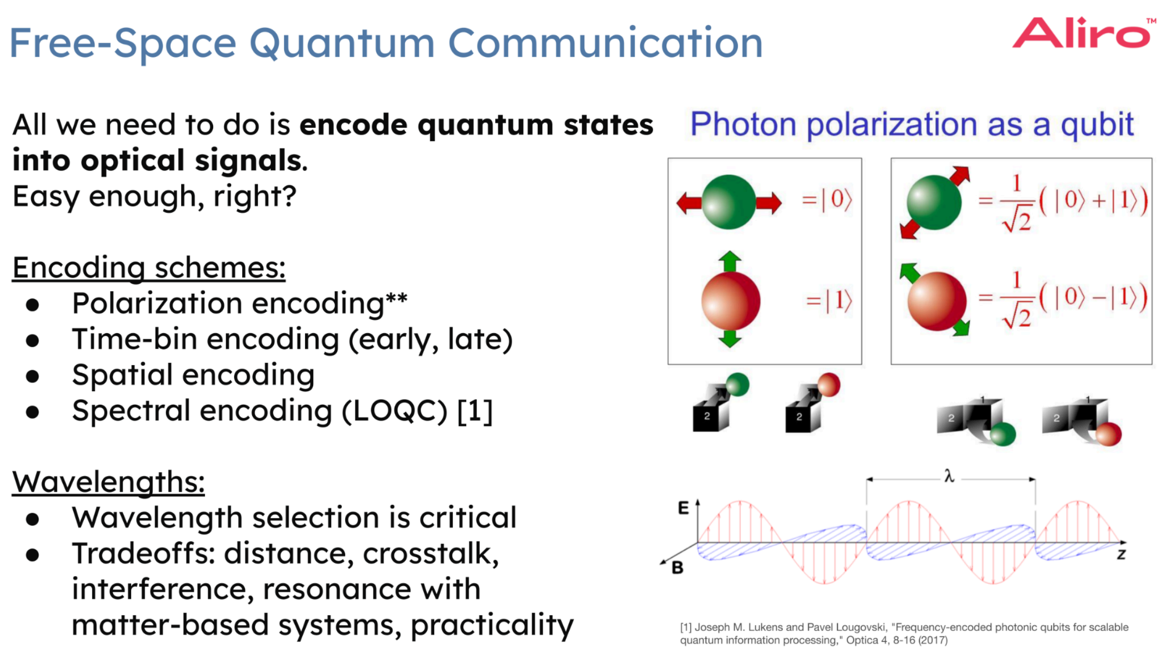

How is free-space quantum communication achieved? Through encoding quantum states into optical signals, or photons. Optical photons have a set of unique properties that make them a particularly great candidate for encoding quantum signals for communications:

- Photons have multiple degrees of freedom that can be used to encode quantum information. Degrees of freedom are independent parameters or ways in which a quantum system can be specified. Each degree of freedom corresponds to an independent state variable that can then be manipulated to encode information. For photons, these degrees of freedom include, but are not limited to frequency, polarization, and phase.
- Photons travel at the speed of light, which is ideal for communication systems.
- These photons can be manipulated with optical components, which are a mature technology that can be bought commercially off the shelf and used to manipulate photons.
- Photons are compatible with telecommunications infrastructure. Leveraging the existing optical fiber networks in the ground will be a significant advantage in adopting quantum communications technology. As entanglement-based networks

and quantum satellites continue to evolve, they will be compatible with existing infrastructure that is already in place.

- Photons operate well at cryogenic temperatures as well as roof temperatures, making them a promising platform for space deployment.
- Optical photons, or photonic qubits, are almost a universal language by which many quantum platforms can communicate. There are many different quantum platforms, in addition to photonic qubits. In quantum computing, for example, there are superconducting qubits, trapped ion qubits, cold atom qubits, and many more quantum information platforms. The properties of photons enable communication across separate, distinct quantum platforms, and make it a very promising spectrum for encoding quantum states for communication.

How are photons encoded with quantum information? There's no one size fits all, no single recipe for the best encoding. The most popular encoding to date is discrete-variable polarization encoding.




In the example above, a quantum state is encoded into the polarization of a single photon.[FREQUENCY-ENCODED QUBITS] The figure is an example encoding in which the ground state, or the $|0\rangle$ state, has been encoded into the horizontal polarization of a single photon. The excited state, or the $|1\rangle$ state, has been encoded into the vertical polarization of a photon. This makes it possible to encode superposition states, which cannot be replicated with any classical system. In the example above, in the top right of the image, the $|+\rangle$ Bell state can be encoded in a diagonal polarization of a photon, and |-⟩ Bell state in the anti-diagonal polarization. This makes it possible to leverage superposition and entanglement via photon interference to create multi-qubit states. This is one of the most popular encoding mechanisms, using the polarization degree of freedom of photons. There are other degrees of freedom that can be used to encode quantum states into photons, including:

- Time-bin encoding is a degree of freedom where the position of the photon in time is used as a dimension to encode the quantum state. Depending on when a single photon is expected to arrive at a certain place, that will determine what the photon state is, for example, an early arrival as the |0⟩ state and a late arrival as the |1⟩ state.
- Space can also be used as another degree of freedom. Optical components can manipulate the path by which a photon will travel in space, allowing different physical paths in space to encode quantum states into the photon. In this degree of freedom, presence or absence decoding is used to detect the state of the photon.
- Frequency encoding can also be used to encode photons. For example, linear optical quantum computing, which is a proposed path for using frequency encoded photonic qubits for scalable quantum information processing.

There is no right way, or single way, to properly encode quantum states into photons: there are many levers that can be pulled, there are many degrees of freedom to encode quantum states, and each has its benefits and limitations.

## Other considerations

To communicate with these systems, certain wavelengths will need to be used Wavelength selection is critical in building space-based quantum communication systems. The wavelength selection is critical because each wavelength comes with benefits and limitations. Depending on the system there could be crosstalk, other traffic in a nearby wavelength regime that may interfere with the quantum signals. Resonance with matter-based systems also must be taken into account. Matter-based quantum systems include trapped ion systems, superconducting circuits, and solid-state defect centers like nitrogen-vacancy (NV) centers in diamond, and many others. To communicate with these systems using photons, certain wavelengths will need to be used, depending on what wavelengths are resonant with that type of matter, or that ensemble. There are practicality considerations as well: available quantum components may be compatible with only a certain wavelength regime.

Cost factors and form factors must also be considered when deploying quantum technology on a satellite. There are two schools of thought on how to encode, manipulate, and measure quantum states: Discrete Variable (DV) encoding and Continuous Variable (CV) encoding. Each of these methods has unique advantages, limitations, and is suited to particular applications.

Discrete-Variable vs. Continuous-Variable Quantum Communication

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| | Discrete-Variable (DV) | Continuous-Variable (CV) |
|---|---|---|
| Nature | Discrete quantum states (e.g., photon polarization, spin states) | Continuous variables (e.g., quadrature amplitudes of EM field, amplitude/phase) |
| Encoding Schemes | Qubits are the fundamental unit of QI. Use orthogonal bases (e.g. computational basis, Hadamard basis) | CVs are used to encode QI. Use Gaussian states, squeezed states, coherent states. Infinite Hilbert space |
| State Preparation & Measurement | Standard quantum logic gates for manipulation + single-photon detection | Non-Gaussian operations: squeezing, displacement + homodyne detection |
| Protocols | DV-QKD, Entanglement swapping, teleportation | Daytime CV-QKD, teleportation with Gaussian states |

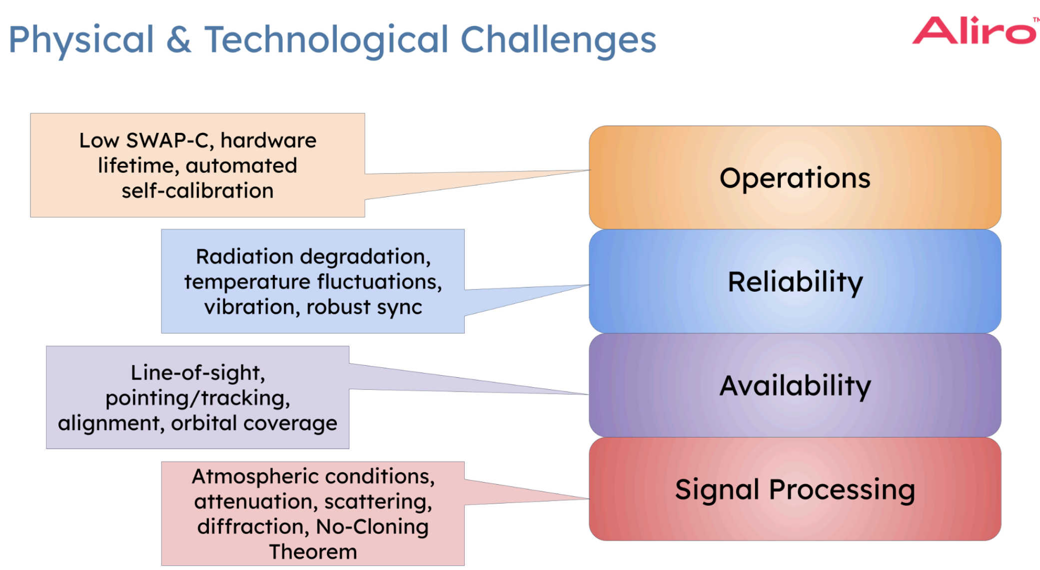
DV encoding encodes quantum information into discrete quantum states of a physical system, such as the polarization states of a photon. This type of encoding uses a finite-dimensional Hilbert space for representing quantum states. The information is encoded in distinct, countable states, typically $|0\rangle$ and $|1\rangle$, along with their superpositions. When a discrete qubit is measured, the result is either a 0 or a 1: the observables are a discrete set of values corresponding to distinct quantum states. This finite-dimensional Hilbert space is useful for the manipulation of quantum states through well-defined quantum gates and operations, facilitating the implementation of quantum algorithms and protocols.

CV encoding uses continuous variables, or continuous degrees of freedom, to encode quantum states. For example, the quadrature amplitudes of an electromagnetic field where the amplitude or phase is a dimension by which quantum information is encoded.

CV encoding still uses photons, but leverages different kinds of coherent light and different ways of processing it. In CV encoding, the Hilbert space is infinite, and observables (physical quantities that can be measured, such as the position, momentum, or quadrature amplitudes of a quantum system) can lie on a spectrum and can have a continuous range of values. To measure such continuous observables, CV encoding relies on homodyne detectors for measurement and decoding.

In terms of the protocols used in these encoding schemes, there is a lot of overlap. Both encoding schemes can support a variety of common protocols, such as quantum key distribution. There are also applications that are better suited for one type of encoding versus another. For example, recently, it's been shown that continuous variable encoding may be beneficial for daytime environments when communicating over free-space. CV encoding is also ideal for quantum metrology and sensing and any application requiring integration with existing optical technologies. DV encoding is particularly useful in applications that require high fidelity, discrete quantum operations, and long-distance quantum secure communication.

## Challenges in deploying quantum-enabled satellites




There are both physical challenges and also technological challenges to consider when deploying a quantum-enabled satellite.

A free-space quantum communication system needs to be practical and have a good return on investment. The requirements for attaining this level of free-space quantum communication system are:

- Low SWAP-C. System components must have the lowest possible size, weight, power, and cost.
- Quantum satellites need to be operational for years without breakdown. Low Earth orbit satellites typically have a five to seven year lifespan, so quantum hardware deployed on a satellite must have an equal or greater lifespan.
- Free-space quantum communication systems must function with very little manual intervention. Automated self-calibration will minimize this type of intervention.
- These systems must be highly reliable. All the environmental factors that result from space deployment need to be considered, such as: the effects of radiation and how that may degrade certain quantum components; large temperature fluctuations as the satellite is orbiting the Earth; vibrations.
- Quantum satellites must have a robust synchronization system.
- Quantum satellites must be accessible through line-of-sight: efficient pointing and tracking systems are needed to ensure the signals are sent to the designated ground station or satellite.
- Proper alignment of all of the optical components within a satellite is critical for capturing the relevant signals and eliminating as much noise as possible.
- Orbital coverage is important to maintaining line-of-sight, and dependent on the application: the level of coverage to achieve your communication objective might call for global coverage or may call for a much smaller footprint.
- Signal processing is impacted by factors unique to free-space communication: how the signal may scatter, attenuate, or diffract as it's passing through clouds, fog, or rain.
- Quantum signals are fragile, and they cannot be amplified by copying the quantum information and boosting or regenerating the signal.

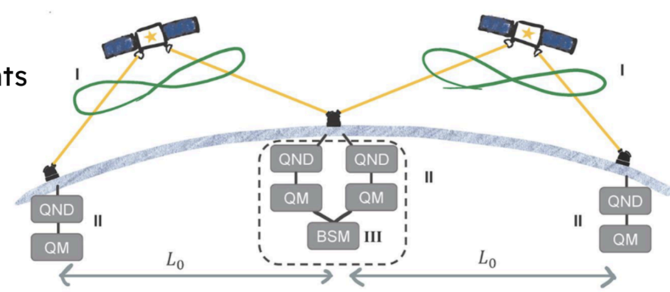
## Successful free-space quantum communication

Despite the challenges free-space quantum communication presents, there are successful examples of this architecture. In 2016, a landmark event in free-space quantum communication was achieved with the Micius satellite that was launched by China into Low Earth Orbit. The satellite demonstrated entanglement between two distant ground stations in China about 1200 kilometers apart. In 2017, China used the Micius satellite to facilitate the first quantum encrypted virtual conference between Vienna and Beijing. This achievement was notable for the quantum community as well as for the broader science community: the news made the front cover of Science Magazine in June 2017. China is investing money and resources into developing their quantum communications infrastructure, with their terrestrial footprint being quite large, and leading the way in space-based quantum communication.

## Using satellites for entanglement distribution

### Satellites for Entanglement Distribution

- A global Advanced Secure Network requires a combination of terrestrial and space-based segments
- Optical ground stations receive photons from downlinks
- High-altitude UAVs have the potential to connect satellites with ground networks




Entanglement distribution with a terrestrial repeater

Sidhu, J.S., et al.: Advances in space quantum communications. *IET Quant. Comm.* 2(4), 182–217 (2021). https://doi.org/10.1049/qtc2.12015

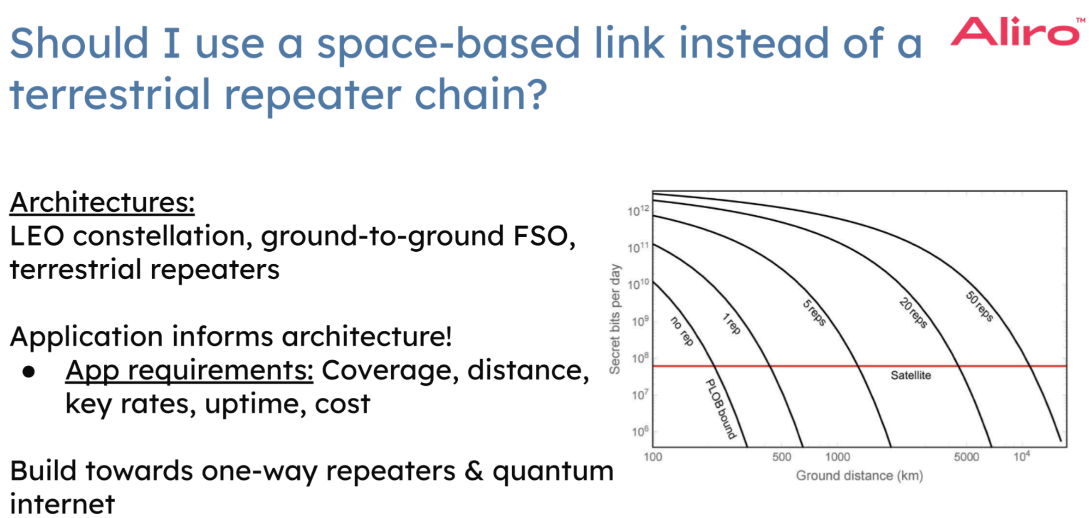
Above is an example of how satellites could be leveraged to distribute entangled pairs of photons to very distant ground stations on Earth.[SPACE QUANTUM COMM] A global Quantum Internet, and even larger regional entanglement-based networks, will require a combination of both terrestrial networks on the ground and space-based segments. In the setup pictured above, there are a set of optical ground stations, which are responsible for receiving the photons from, for example, a photon source that sits on the satellite. This example shows entanglement distribution with a terrestrial repeater. The objective is to connect two ground stations on Earth with entanglement. They're very far apart - too far apart for a purely terrestrial link. To achieve this, two satellites, each with an entangled photon pair source, emit a pair of photons. One goes to the end node, and the other goes to the terrestrial repeater node. The middle node here is responsible for capturing the incoming photons, one from each pair emitted from the two satellites, and performing entanglement swapping. This process effectively stitches together the entanglement from the first node to the middle node with the entanglement from the last node to the middle node - creating a single long range entanglement from the first node to the last node.This is one way to deliver entanglement to very distant ground stations using satellites.

There are different architectures to consider here. The example above used two satellites with downlinks to distribute entanglement, but there are uplink architectures in which the ground stations emit entangled photon pairs up to the satellite, in which case the repeaters would be located on the satellite. There are trade-offs for each of these architectures, so choosing the right one will depend on the particular objective and implementation constraints.

There has also been demonstrated potential for using high altitude UAVs as a way to more effectively connect satellites with these terrestrial entanglement-based networks.

## Satellites for scaling entanglement-based networks

A central question to consider as entanglement-based Advanced Secure Networks scale is “Should a space-based link be used to scale an entanglement-based Advanced Secure Network, or should a terrestrial repeater chain using fiber in the ground be used instead?” The figure below begins to address this exact question.




The Quantum Internet will be a combination of both free-space links and terrestrial networks. There is no one-size-fits-all architecture for scaling entanglement-based Advanced Secure Networks. The application informs the architecture needed to scale: the link and hardware setup that is best suited to the application will dictate the requirements of growing the network. The application may require a certain coverage: full global connectivity, regional connectivity, and metropolitan region connectivity would each have different needs to meet for coverage. For example: to achieve quantum secure communication from London to New York, a satellite link is likely to be more viable than a chain of terrestrial repeaters. Distance between nodes, coverage, and key rates will all factor into the considerations for architecture. For quantum key distribution, the throughput, network uptime, and the cost of implementation will all factor heavily into determining the appropriate architecture.

There are many other applications that quantum satellites will enable beyond secure communication. Higher satellite orbits enable new applications and different application profiles. At low earth orbit, it's been demonstrated that satellites can be used for secure communications. Constellations of Low Earth Orbit satellites could scale this application to global quantum connectivity. Pushing this technology to orbits further from Earth, it's possible to enable applications that press the field of fundamental physics forward, with capabilities at the intersection of quantum physics and relativity, developing a theory for quantum gravity, and other critical questions about the nature of our universe.

Quantum satellites are a promising platform for expanding the impact of quantum technology enabled by entanglement-based networks.

Building for scalability, leaning towards the vision of a global Quantum Internet, requires building for diverse applications to run on the network, and also preparing for advancements in technology: from improvements to quantum hardware and protocols to the engineering of quantum repeaters and robust quantum satellites. Taking a hardware-agnostic, multipurpose-application approach to entanglement-based Advanced Secure Networks will help to create the most flexibility for scaling.

# Free-space quantum communication projects at a glance

## Global Efforts

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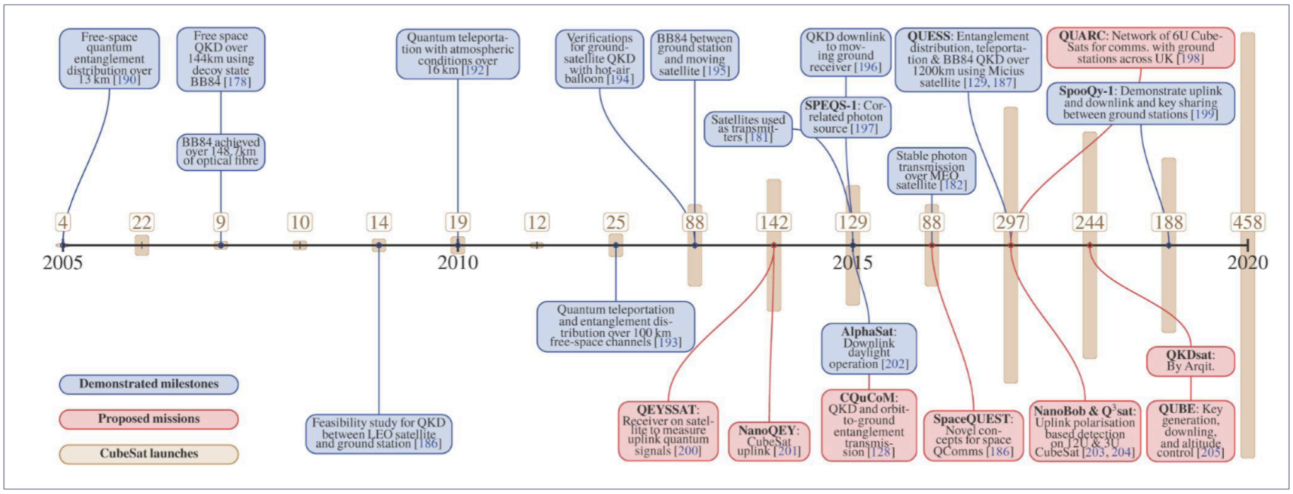
### Public-private-academic collaborations




Timeline of key milestones in satellite QKD

Sidhu, J.S., et al.: Advances in space quantum communications. IET Quant. Comm. 2(4), 182–217 (2021). https://doi.org/10.1049/qtc2.12015

There are many quantum satellite efforts across the globe.

Above is a timeline of different global efforts around free-space physics-based communication.[SPACE QUANTUM COMM] The first free-space entanglement distribution happened in 2005. Over 13 kilometers, this was a terrestrial demonstration. In blue are demonstrated milestones: quantum teleportation has been demonstrated, quantum key distribution has been demonstrated. In red are proposed missions going forward. Most of these projects involve a number of collaborators, both with public participation from government agencies, private companies, satellite companies, startups and bigger corporations, as well as universities and academics. Some notable projects include:

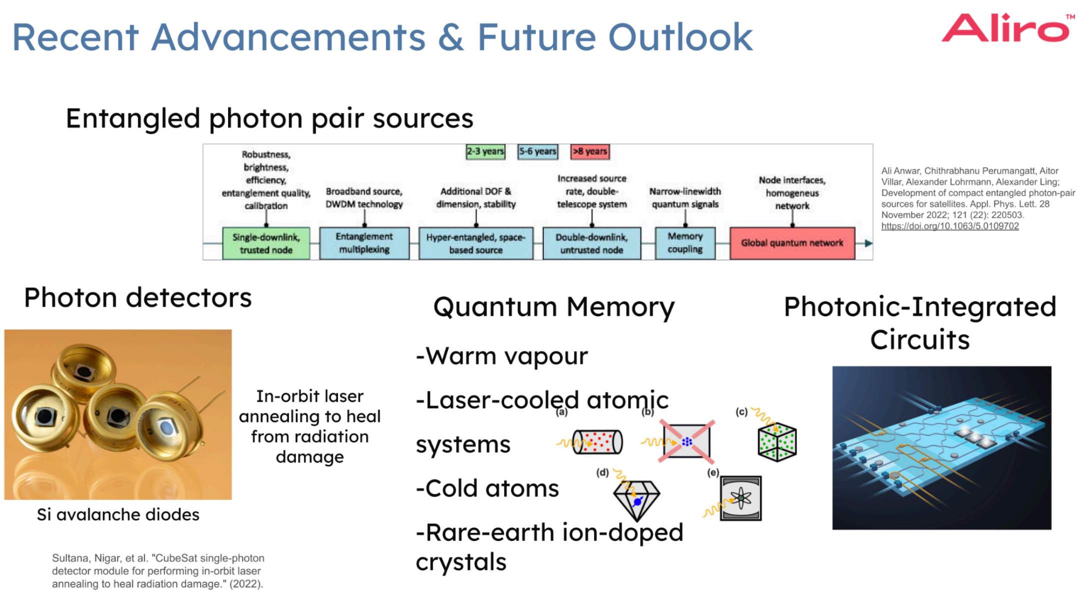
- QEYSSat (Quantum EncrYption and Science Satellite) driven by the Canadian Space Agency, with planned launch in 2025. The goal for this project is to launch three Low Earth Orbit satellites to study, demonstrate, and validate space-based quantum secure communications.
- Eagle-1, driven by the European Space Agency, launches in 2024. This will build the first European end-to-end space-based QKD system, a step toward future European quantum communications.

- QKDSat (Quantum Key Distribution Satellite) launched in 2023 by ARQIT and collaborators in the UK. This project aims to demonstrate how a space-based quantum infrastructure can be used to exchange sensitive information between several parties.
- Shenzhou 16 is the follow up project launched by China in 2023. This project will go on to launch a Geostationary satellite in 2026.
- SpooQySats projects launched in 2018 and 2020 to demonstrate entanglement generation on a satellite. This project is led by the National University of Singapore Center for Quantum Technologies, in collaboration with a company called SpeQtral.
- There's a collaboration between Oak Ridge National Labs and University of Illinois, Urbana Champaign to study how satellites could enable more efficient and secure quantum networks through experiments, emulation, and simulation. This study concluded in 2023.
- The Deep Space Quantum Link project, led by NASA, aims to establish long-baseline quantum links between the Lunar Gateway moon-orbiting space station and nodes on, or near, the Earth.
- QUDICE is a project led by ThalesAlenia Space, but is a large collaboration of partners in the public sector, private sector, and in academia. This project has several goals:
    - Launch two sources for QKD: one for discrete variable encoding, and one for continuous variable encoding in order to explore the trade off between these different mechanisms for encoding quantum information.
    - Study the effects of quantum random number generators.
    - Develop satellite pointing, acquisition, and tracking systems.
    - Use a 5G communication system to perform the necessary post processing for QKD.

This is not an exhaustive list, but gives a sense of the breadth and depth of the projects being pursued to implement free-space quantum communication. Each of these projects has a different approach to space-based quantum communications.

## Relevant advancements and the future of space-based quantum communication

Recent advancements are moving us toward better space-based quantum communication. Photon sources are critical in any quantum communication system. Entangled photon pair sources were deployed on satellites back in 2016, with the Micius satellite. So what's next?




The timeline above gives a sense of the near- and medium-term advancements on the horizon:

- Entangled photon sources will be developed to leverage multiplexing.
- From there, technology moves from a focus on entangled photon pairs to hyper-entangled states and multi-dimensional entanglement.
- Protocols with fewer trust assumptions about nodes will be developed.
- Development of photon sources capable of efficiently interfacing with our quantum memory systems.
- Photon detectors will continue to improve, and become more hardened to the environment of space. For example, radiation degrades the quality of photon detectors. Self-calibrating and self-healing photon detectors will need to be implemented on satellites. This is an advancement that is already being pushed forward experimentally today.
- Quantum memories are crucial for scaling quantum systems and entanglement-based networks, and they enable a suite of protocols that aren't

possible without the storage capabilities of a quantum memory. There are several promising platforms for a quantum memory:

    - Warm vapor
    - Laser-cooled atomic systems
    - Cold atoms
    - Rare-earth ion-doped crystals

- Photonic integrated circuits are another promising technology for free-space quantum communication due to their small footprint. Photonic integrated circuits are on a chip, light weight, don't consume a lot of power, and the optics functionality is built in.

The ideal quantum satellite is one that has a hyper-entangled photon source: a source that is capable of preparing highly entangled states with many output ports, enabling it to communicate with many other satellites and many other ground stations. It is equipped with very efficient detectors that are self-healing from radiation. It should also be equipped with quantum memories that can store quantum photons, which can  then be retrieved at any time, as well as optical components for manipulating these quantum states. While many advancements are needed to build the ideal quantum-enabled satellite, this technology is already being deployed for secure communications.

Quantum satellites are the next frontier of quantum technology. Free-space entanglement-based networking will scale small local area networks and metropolitan scale terrestrial networks to achieve a global Quantum Internet. Now is a great time to shape your organization’s quantum strategy. There are national security implications with this technology as well. Quantum satellites can enable better military applications for position, navigation, and timing, and also sensing and metrology, in addition to cybersecurity applications. Free-space quantum communication is the new space race.

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