Quantum Network Infrastructure

Lisa Wörner, Kai Bongs, Stefanie Bremer, Philipp Kleinpaß, Florian Moll, Davide Orsucci, Jaspar Meister, and Jan-Michael Mol*

Global quantum state distribution has applications in many areas, one of which is global key distribution for secure communications in an era of the threat of quantum computing. Long-distance quantum key distribution requires a global network of optical relay stations, ground stations, and quantum memories. In this study, why quantum memories should be operated in space as untrusted nodes is presented. In addition to quantum key distribution, quantum memories in space are an enabling technology for distributed quantum sensor systems. The requirements for distributed sensors are outlined and the current technology readiness level of relevant systems is referenced. Finally, the possibility of an emerging quantum internet, enabling the coherent combination of quantum computers around the world, is addressed.

1. Introduction

As it happens within physics again and again, some areas attract more attention than others. In this context, the potential of quantum technologies has triggered what is now called the second quantum revolution.[1] Regardless of how the second quantum revolution is defined, entanglement-based systems are certainly part of it. While this includes sensor systems, such as quantum radar[2,3] or quantum lidar,[4] its main focus are systems for quantum computing,[5] distributed sensing,[6,7] and quantum communication, with its dominant application, quantum key distribution (QKD).[8,9] Especially distributed quantum computing[10,11] is currently discussed as the main application of a global 'quantum internet'.[12]

The backbone of all of these systems is similar: A global network that allows distribution of entangled photons coherently. Where the systems differ is in the application of the network:

First, distributed computing or the idea of a quantum internet, seeks to coherently connect quantum computers. The computational power of any quantum computer is limited by the number of coherently entangled qubits. Quantum computers consisting of several hundreds of qubits are the current state of the art.[13,14] Increasing the number of coherent qubits presents a considerable challenge and is a topic of active research. One option to realize large-scale error corrected quantum computers is to establish coherent connections between individual sites.

Second, the connection of several sensors via an optical link could improve their individual performances as well as the overall information gained from the network. This improvement can be used in novel Global Navigation Satellite Systems (GNSS), such as the Kepler constellation.[15] While this particular application foresees a classical optical link, squeezed light could yield additional benefits in sensor performance.[6,7,16] These include improved sensitivity as well as reduction of common noise sources and the possibility to address sensor information otherwise unavailable. The potential improvement ranges from optical clocks to magnetometers, gravimeters, and any other system making use of quantum states. Especially distant clock systems can benefit from a coherent connection, which is effectively a quantum network. A potential implementation of a coherent clock network is depicted in reference.[17] Experimental tests with atomic systems have recently demonstrated the longevity of qubits and thus their deployability as nodes and optical clocks.[18]

Third, a network that aims at global distribution of entangled photons could be used to establish QKD on global scales.[19–22] Quantum key distribution is a technology allowing the production of secure keys between two known partners. The necessity of QKD arises from the emergence of potent quantum computers and their promise to decipher messages secured by classical encryption methods.[23] QKD can be performed with single photons,[24,25] entangled pairs,[26,27] and weak coherent pulses.[28]

L. Wörner
German Aerospace Center DLR e.V.
Institute for Satellite Geodesy and Inertial Sensing
30159 Hannover, Germany
E-mail: lisa.woerner@dlr.de

K. Bongs, J.-M. Mol
German Aerospace Center DLR e.V.
Institute for Quantum Technologies
89081 Ulm, Germany

S. Bremer, J. Meister
German Aerospace Center DLR e.V.
Institute for Satellite Geodesy and Inertial Sensing
25389 Bremen, Germany

P. Kleinpaß, F. Moll, D. Orsucci
German Aerospace Center DLR e.V.
Institute of Communications and Navigation
82234 Weßling, Germany

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/qute.202300415

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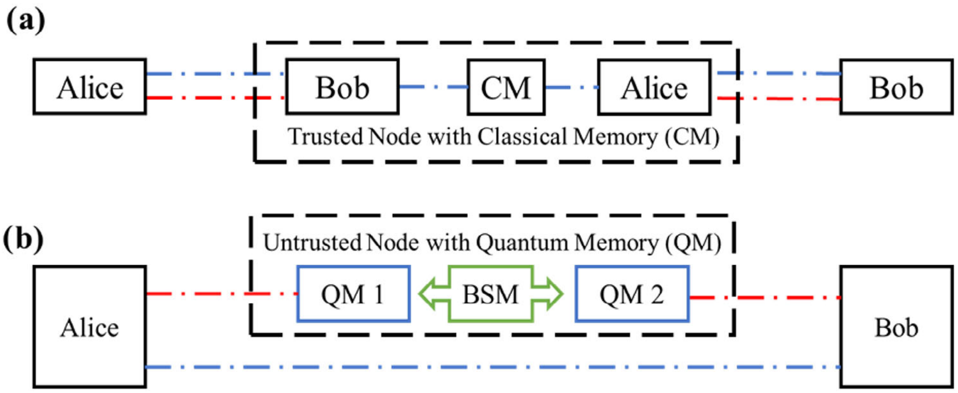

Figure 1. An overview over different network node configurations. The red and blue dotted lines depict the optical and classical connection, respectively. Panel (a) shows an example of a trusted node. In this specific example, the information is deciphered in the node, buffered on a classical memory (CM), encrypted again before being send to the receiver of the information. Panel (b) shows an example of an untrusted node based on a quantum memory (QM). For a full node, the quantum state needs to be transferred between the two quantum memories. This is done via a Bell state measurement (BSM).

There are entanglement-based[29,30] and measurement-device-independent[31] protocols, that operate with completely untrusted source and detection devices, respectively, as well as prepare-and-measure schemes which require trust in both.

With this motivation for global quantum networks, the requirements for such an infrastructure need to be discussed. The following sections describe possible scenarios as well as hardware options to reach this goal.

2. Network Requirements

2.1. Required Network Channels

As motivated in the introduction, global quantum networks can serve many different purposes, all of which require the distribution of photons. While prepare-and-measure and measurement-device-independent key distribution schemes do not require entangled photons, all of the other described scenarios do. Consequently, the following discussion is centered around the ability to distribute entangled photons between Alice and Bob, the two fictional entities usually considered for such exchange.

The individual requirements on additional channels differ for the different areas of application:

Successful **quantum key distribution** requires, in addition to quantum channels allowing the transmission of photonic states, a classical, authenticated channel.[8] It is required for the exchange of information on the measurement basis at both ends and for post-processing of the raw key. Only if the employed basis for both partners match, the measurement is considered for establishing the key. If the detectable error rate in transmission exceeds a certain threshold, the communications channel is deemed compromised and key exchange is aborted and eventually retried. If successful, error correction and privacy amplification are applied to yield the final secure key.

Distributed sensing describes the combination of several sensors by entangled photons. To connect two or more sensors for additional gain, requires optical connections. Ideally, the different sensors operate on the same optical frequency. It is likely that the different sensors are of the same type, looking for similar signals. This could, for instance, be used to improve the measurements of gravitational redshift with optical frequency references[16] or enhance the position accuracy in global navigation satellite systems.[32] In these systems, the individual sensors act as nodes in a network of memories, which supply buffers for network synchronization.

Similarly to distributed sensing, **distributed computing** requires coherent connection between two or more quantum computers.[10] In this scenario, the ensembles of coherent qubits of each system act as the nodes in a network of memories. In difference to the distributed sensing, here, additional Bell state measurements are required. These ensure that the same coherent state is preserved over all involved qubits. This, in turn, allows to benefit from the network and increase the computing power.

2.2. Network Nodes

A quantum network: is comprised of several nodes to allow for long-distance distribution.[33] The nodes include necessarily schemes for the optical transmission and measurement.[34,35] Potential node schemes are depicted in **Figure 1**. The number of nodes between Alice and Bob can be increased by repeating the depicted schemes. In quantum networks one can differentiate between trusted and untrusted nodes:

Trusted nodes: are nodes that are operated by a trusted entity and offer a possibility to access the exchanged information. In terms of quantum networks, a trusted node consists of a transmitter or a receiver, as required for each quantum link that connects to it, and a classical memory to locally store the deciphered information before sending it onward. The concept of a trusted node is depicted in Figure 1a. In this sketch, the classical channel, transmitting the encrypted information is not depicted.

It is possible to build a network architecture based on trusted nodes alone. The main advantage of a network of trusted nodes lies in the distance over which the entangled or prepared state has to be kept. This results in higher end-to-end key generation rates.

On the other hand, the scheme relies on deciphering and re-encrypting the information at every node. Thus, the information is no longer secured by quantum mechanical principles and could be intercepted at any one of the nodes, especially if stored to a classical on-board memory. Consequently, the operation of a network of trusted nodes needs to reside within a trusted entity. This infers considerable financial and operational investments and disables the participation of other entities. Additionally, a network of trusted nodes results in several networks being operated and thereby a large number of satellites in orbit. Besides these considerations, a network of trusted nodes does not allow for distributed sensing or distributed computing.

Untrusted nodes: are nodes that are not operated by a trusted entity and could even be operated by a hostile entity. This enables smaller companies and countries to participate in the second quantum revolution by operating individual satellites as opposed to facing the necessity of running a complete network. Thus, for real quantum networks with global participation, untrusted nodes appear most promising.

An ideal untrusted node has no possibility to gain the transmitted information while it is processed. In a quantum network context, this means that the quantum state is kept without the possibility of the operator gaining knowledge of it, instead only providing a means to distribute it to neighboring nodes.

One way to establish an untrusted node is through the usage of entangled photons to connect Alice and Bob. The quantum correlations of entangled photons cannot be forged by a potential hostile entity wishing to intercept and decipher an encrypted message.[36] The divergence from the state distribution expected from using an entangled source can be measured through Bell state measurements or similar error detection protocols. Entanglement distribution has been demonstrated on ground[37] and in orbit.[26,27]

Another example architecture containing untrusted nodes is shown in Figure 1b. Here, the untrusted node contains two quantum memories (QM) and a Bell state measurement (BSM)[38,39] to transfer the quantum state from one memory to the next.

Quantum memories can be established by usage of cold atom ensembles,[40] warm vapor cells,[41] color centers in diamond,[42] rare-earth-ion-doped crystals,[43] single atoms or ions in a trap,[44,45] and any other system that offers coherent storage of photons.

In a full quantum network architecture, quantum memories placed along a network architecture between two parties, can be deployed to increase the end-to-end information transmission rate.[46] The technologies considered for quantum memories can be employed as deterministic sources for entangled photons.[47,48]

Quantum memories allow the operation of nodes in delay-mode. In this mode, the state is transferred into the memory and read out, ideally tending to the needs of the network. The simplest type of delay-memory are optical fibers, which generate a fixed delay in the transmission. Long optical fibers suffer from both signal intensity loss and decrease in fidelity of the polarization state. The signal loss is particularly detrimental and is the main reason why ground-based networks are limited in length or require frequent nodes to improve signal quality and intensity.

Other coherent systems could act as quantum memories and delay the signal. Here, coherence times, fidelity, and on-demand read-out, present open challenges. Different memory types present different advantages and limitations in delay-mode operation.[16]

The five most common systems deployed as quantum memories, outside of optical fibers, are:

1. Warm Vapor Cells
   Warm vapor cells are deployed in a wide variety of applications, especially optical clocks.[49] Due to the potential coherence times, those based on alkaline gases are most prone for usage in quantum memory systems.[50] Coherence times in the order of $50 - 100$ ns have been observed using off-resonance Raman protocols.[51]
2. Degenerate Quantum Gases
   Degenerate quantum gases describe gases in which the external and internal degrees of freedom have been cooled. The most prominent example are Bose–Einstein Condensates (BECs), which represent the cooling into the absolute ground state. BECs have been demonstrated in space.[52,53] Usually these systems are deployed to enable measurements of accelerations, such as gravitational fields.[54]
   The achievable ground state enables longer coherence times if compared to warm vapor cells, while the storage and readout schemes are transferable. Recent developments have shown potential of cold atoms to be deployed as quantum memories.[55,56] First experiments have shown storage times in the order of milliseconds.[40]
3. Rare Earth Ion Doped Crystals (REIDs)
   Crystalline systems offer the potential of compact quantum memories. In these systems, rare-earth ions, usually Europium or Praseodymium, are doped into a crystalline structure, usually a silicate derivative. The material determines the compatibility with the photon wavelength.
   REIDs operate mainly as atomic frequency combs based on spin-waves, which allows for on-demand retrieval. With external cooling in the order of 6 K, storage times in the order of hours have been achieved.[57]
4. Color Centers in Solid State Systems
   The most studied color centers are nitrogen vacancy (NV) centers in diamond. These systems can act as deterministic sources for quantum key distribution[58] and are deployed in many other applications ranging from magnetometry to quantum computing. Consequently, these systems can be used as quantum memories and coherence times in the order of 10 s have been observed.[59]
5. Individual Atoms or Ions
   Quantum computers investigated trapped individual atoms and ions as early on as potential candidates. The optical readout using Raman schemes enables additionally the usage as quantum memories with coherence times in the order of 100 ms.[44]

Refs. [16, 20] gives a comprehensive overview over the different quantum memory concepts, the necessary schemes and protocols, the state of the art, and limitations in the deployment in space and on ground.

In addition to quantum repeater based around central coherent systems, such as discussed above, concepts for repeater without this inner system are developed.[60–62] These hold the advantage of getting rid of the quantum memory system which is susceptible to external interference, such as cosmic radiation, thermal stability, and external fields. Each of those can lead to a loss

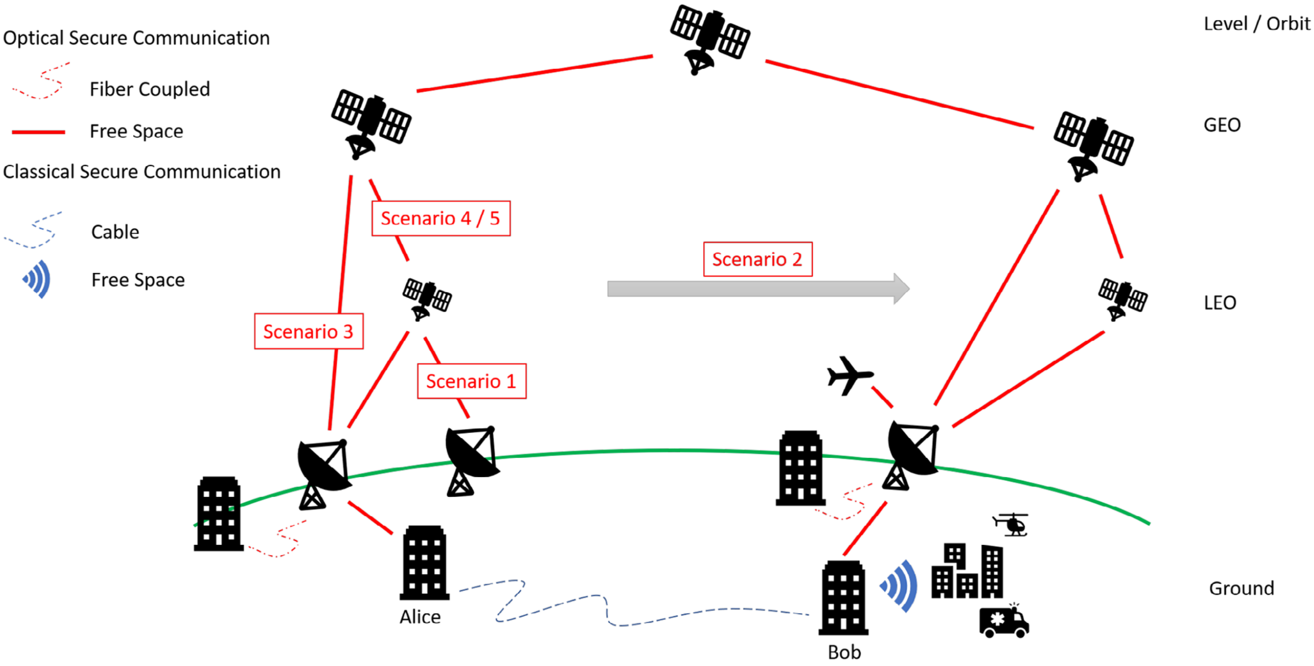

Figure 2. An overview over different scenarios for a quantum network. The individual scenarios are explained in more detail in Table 1. The networks envision combinations of satellites in Geostationary (GEO) and Low Earth Orbits (LEO). The network could be supplemented by satellites in medium Earth Orbit (MEO), which is not displayed.

of coherence in the quantum memory and consequently of the entangled state. The main advantage of memory-based systems lies in the potential to act as transducers and thereby combine different sources and structures, while any loss in complexity aids in the space-readiness of the system.

3. Potential Network Architectures

Global quantum networks require entangled photon distribution. While those have been demonstrated in networks of ground-based fibers and satellite link distances in the order of several thousand kilometer,[63–65] the losses in free-space and fiber-based transmission are still too severe for global distribution. Various missions have shown the operation of key technologies in space. These include suited telescopes,[66,67] optical links,[26,68,69] entanglement sources,[70,71] and random-number generators for prepare and measure protocols.[72]

Figure 2 shows different network architectures to distribute quantum keys between two partners. The optical channels are marked in red. The figure depicts the combination of fiber-based, dotted lines, and free-space, solid lines, transmissions. It also shows that the network could include vehicles, for instance airplanes, as the final recipient of the information or the key.

The dotted blue line represents the required classical connection necessary for any two partners that want to build a secure key together. Not all of the classical transmissions are depicted to avoid unnecessary cluttering of the image. The classical channel is required to enable the creation of the key and to transmit the encrypted message.

As depicted, it is also possible that vehicles collect a key at the base, which allows transmission of secured messages for a given period.

Figure 2 depicts five different scenarios for quantum key distribution. To reduce losses in the atmosphere, the nodes in the scenarios are primarily set in orbit. A short description of the scenarios is summarized in **Table** 1.

The interfaces between the space and terrestrial networks are realized with optical ground stations. These ground stations are used as antennas, i.e. receive the incident photonic state and

Table 1. Overview over the space aspect of the scenarios depicted in Figure 2.

Number	Name	Description	Section
Scenario 1	Direct Transmission	Direct optical connection between two partners through a satellite	Section 3.1
Scenario 2	Orbital Transport	Storage of quantum states in a space-borne memory for connecting two partners over a distance not allowed by scenario 1	Section 3.2
Scenario 3	GEO Transmission	Direct transmission through several GEO stationary satellites	Section 3.3
Scenario 4	LEO - GEO Network	Transmission through a network of LEO and GEO satellites.	Section 3.4
Scenario 5	Source in LEO Orbit	Production of the entangled photons in LEO with a transmission through a GEO network	Section 3.4

inject it into the fiber network where it is routed to the end node. Alternatively, the end node can also be at the location of the ground station without fiber network in between. Table 1 does not include any of the ground networks necessary for distribution, such as optical fiber connections to the final recipient.

On ground, optical free-space or fiber links could be deployed. The on-ground systems are equally as important as the space segment. Optical links on the ground segment have been demonstrated to be operational deploying flying[73–75] and driving[76] platforms. Those developments represent key components for a functioning global network. As it has been shown in Figure 2, especially flying platforms can be partners in sharing secure information. The involvement of these moving platforms involves challenges with regard to link acquisition and stability and light pollution of the link. The experimental success outlined above increases the relevance of a global network as it is readily understood that especially moving platforms yield high interest in terms of secure communication. Additionally, the demonstration renders further commercialization and additional partners, such as in the aerospace and vehicle industry, possible. The deployment of closed local networks are within reach and could support not only civilian but also military operations.[77] The deployed technology and resulting wavelength can vary for the ground stations depending on the scenario, operational organization, technology development, and other factors.

3.1. Scenario 1: Direct Transmission

Direct transmission networks are the current state of the art. This scenario connects two (optical) ground stations through a single satellite, allowing for a connection between two stations without a direct line of sight. According missions, demonstrating the direct transmission using a trusted node on the satellite have been performed.[78] In these missions the source has been mounted to the satellite. Such a system could be envisioned using a prepare-and-measure protocol or by producing entangled photons on the satellite.

In other configurations, the two end users might create photons that are combined in a Bell state measurement on the satellite. In this case, a classical transmission from the satellite to ground is needed in addition to the optical one.

Finally, the satellite could house a mirror, reflecting the signal created at one of the sites towards the partner. This scenario suffers from atmospheric signal loss twice: first, when the signal is sent to the satellite and, second, when it travels back down to Earth. Other losses may be present if a delay line is employed at the sender. This additional delay can be circumvented in a scenario of prepare-and-measure, in which, the sender does not need to preserve quantum information. Additionally, if the two parties can agree on the photon timing, the need for a quantum memory on ground can be waived. The considerations toward agreeing on the photon timing, equally contribute to the other two schemes described in this scenario.

3.2. Scenario 2: Orbital Transport

In this scenario, the state is transported on board of a system in a satellite.[79] This requires a delay system in orbit. Delay systems could be set into effect by using quantum memories. Optical fibers cannot be effectively used as simple memory systems, since they preserve quantum information only for tens of microseconds. Fibers offer very precise timing of the delay at the price of signal loss.

Other memory types promise longer delays in orbit. Depending on the memory type, fidelity, coherence time, and read-out on demand present challenges to the development and deployment in any of the following scenarios.

3.3. Scenario 3: GEO Transmission

Transmission could be performed using satellites in a geostationary orbit (GEO). Albeit the transmission losses are much higher than those typical for links to satellites in low Earth orbit (LEO) due to the increased link distances, this configuration presents certain advantages. In particular, the satellites position can be chosen in a way that it connects to the relevant ground stations at all times. This allows for long sequence transmission with no lag times.

Furthermore, a system of quantum repeaters in a geostationary orbit could be coupled with global navigation satellite systems (GNSS), to improve the performance of the optical clocks on board.[16] Frequency references of GNSS satellites have been deployed for fundamental tests in the past.[80] Improved performance of the frequency references by connecting several of the satellites coherently, could improve the measurement results further.

3.4. Scenario 4/5: LEO - GEO Network

In addition to the system purely in a geostationary orbit, a combination of satellites in LEO and GEO could allow the exploration of different advantages. As discussed in the other scenarios, both LEO and GEO constellations yield certain advantages. To maximise these, it is easy to envision a combination of nodes in LEO and GEO:

The higher orbit, as described in scenario 3, Section 3.3, allows for transmission to relevant ground stations at all times and thereby to the reduction of lag times.

The lower orbit could improve the signal quality by usage of quantum memories, connect additional ground stations to the network, allow for easier access and participation of companies in the network, and render it more relevant for distributed sensing.

Usually, sensors should be as close to the target as possible. Any sensor, measuring a property of the Earth, should therefore be as close to ground as possible, while making use of the benefits of space flight, for instance global coverage or a wide field of view. To integrate those into a distributed sensor network requires optical inter-satellite links between the nodes in GEO and in LEO. Additionally, a low Earth orbit allows to connect ground-based sensors in remote locations to the network.

Finally, low Earth orbit is easier to access. This means, that tests of systems can be performed easier and node replacement is simpler. Furthermore, the reduced link distance results in reduction of the transmission loss caused by beam divergence. Consequently, this enables a wider variety of companies to participate in the network and to benefit from financial, sensory, and communication implications.

Scenario five, in difference to scenario four, foresees sources in orbit. In scenario four everything is managed through quantum memories, delay-lines, or mirrors to transmit the required photons.

4. Open Challenges

4.1. Loopholes

Practical QKD will face the issue of loopholes, which could endanger the security of the final key.[81] Loopholes include attacks based on time-shifts[82] and a mismatch in the spatial-mode detection efficiency.[83] The vulnerability to potential attacks increases significantly in the presence of loopholes. These become more prevalent the further two partners are apart and the more systems are introduced in between the final recipients. The impact of loopholes can be reduced by the use of fully-device-independent QKD protocols,[84] for which quantum repeater technologies are a key enabler. Furthermore, quantum memories can be introduced to delay the final measurement and thereby allow for synchronization of the measurement basis and allow for more efficient quantum key generation.

4.2. Quantum Memory Readiness

As described in Section 2.2, different systems can be used as quantum memories. Depending on their properties, these memories differ in achievable coherence times and fidelity, as well as read-out properties.[16] In addition to their differences in systematic and operation, they vary in achieved technological readiness. The best experiments up to date have demonstrated quantum state transmission with memories over a distance of 50 km.[85] At this time, no space-based memory has been developed and even ground-based memories remain a challenge tackled in laboratories all over the world.

As discussed above, a quantum network will have to rely on untrusted nodes in space for operation and to counteract transmission losses. Consequently, quantum memories, ideally alongside according Bell state measurements, will need to be set in space.

It is therefore worthwhile to discuss the current technological readiness level of quantum memories in space. As mentioned before, the current state of the art in memory development are laboratory settings on ground. However, some systems under investigation as potential quantum memories have been operated in space. In particular, optical components are flown on satellites and inside of the international space station in various experiments, so much so that radiation hardening of optical fibers has become an important business and focus of developments.[86,87] Other developments include warm vapor cells, primarily investigated as optical frequency references[88,89] and magnetometers,[90] degenerate quantum gases for tests of fundamental physics,[52,53,91] and nitrogen vacancy centers for magnetometers.[92] It should be noted, that these systems require substantial adaptations and to increase their technology readiness level to be deployed as quantum memories in space. Especially the implementation of protocols and connection of systems will require further ground-based investigation before quantum memories can be prepared for space.

4.3. Frequency Transducers

An aspect of quantum networks that has not been fully addressed so far is the compatibility of memories and potential sources. The use of free-space connections enables more flexibility in the choice of the wavelength, while for optical-fibre connections one is restricted to the use of telecom wavelengths, around 1550 nm.[93]

The main challenge arises with quantum memory operation in large networks. Quantum memories operate at various different wavelengths, some of which yield high potential losses in the atmosphere. Not only quantum memories require different wavelengths, but also applications of quantum networks for distributed sensing or distributed computing necessitate photons of wavelengths other than 1550 nm.

Consequently, a quantum network requires frequency transformation. Frequency combs have been operated in space on board of sounding rockets[88] and are currently prepared for the operation in orbit on the international space station. However, these systems are not designed to keep a potential quantum mechanical state intact, as it would be necessary for a quantum network.

This results in a necessity for quantum frequency transducers. Recent developments have demonstrated ground-based operation of frequency transducers.[94] Within these experiments, the transformation of coherent states over a distance of 40 km using ${}^{40}Ca^{+}$ atoms has been shown.

4.4. Transmission Rates

Transmission rates of quantum states are low compared to classical channels. Of course, as mainly a key is generated, high rates are not of the same level of concern as for classical communication, in which information is transmitted. The term "quantum internet" speaks to the expected reality of parallel operation of nodes in any global quantum network. But, if global quantum networks are to be considered seriously, the challenge of transmission rates and parallel transmission has to be addressed.

Most of the quantum memory systems discussed above allow for the storage of a single state, let alone the transmission of several sequences for true global quantum key distribution. Some of these challenges can be overcome by targeting individual atoms or defects in a memory, as opposed to the entire system. The challenge is further complicated by the required frequency conversion discussed above.

4.5. Transmission Mode

As discussed above, the transmission rate is an important part of a functional network. In addition to the storage capabilities and operational modes of the quantum memories, the emission mode plays a central role in maximum distance that can be covered between two partners.

In addition to the distance and implicated expected signal loss, the limitations of quantum memories have to be taken into account. Based on the storage capability of most memories, it appears most feasible to conceive the network deploying a discrete variable approach. The signal loss should, in part, be mitigated by the closely spaced quantum memory network. However, future developments may alleviate some of the restrictions imposed by the memory architecture and allow for a continuous variable approach.

4.6. Detection Timing

The timing of detection of two photons inside the network is crucial to establish a valid key between two partners. With increasing transmission length, such as in a global quantum network, this becomes increasingly challenging. One possibility is the adaptation of timing by additional delay-mode memories in the network to align the timing between two partners. Additionally, concepts based on an initialization sequence could be considered to agree on detection times. For most of the current applications, synchronization of the signal is realized through clocks at the distant partners. The detection timing needs to be in accordance with the exclusion of loopholes discussed in Section 4.1.

5. Conclusion

Global quantum networks are on the rise. Several local quantum networks have been successfully established and commercially exploited. A true global quantum network faces additional challenges, such as distributing entanglement in the face of high end-to-end transmission losses. If it is established, however, it yields advantages, not only in global quantum key distribution, but also in distributed sensing and distributed computing, the latter leading to a quantum internet. This paper summarizes different network architectures, outlines their requirements and discusses open challenges. We have especially addressed the necessity for quantum memories as well as their use for improved sensing beyond the current state of the art. Especially, space-based quantum memories appear of high significance, as they offer the operation of untrusted nodes and allow the transformation of frequencies inside the network to incorporate sensors or quantum computers.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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