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Towards the Quantum Internet: Satellite Control Plane Architectures and Protocol Design

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Abstract: The creation of the future quantum Internet requires the development of new systems, architectures, and communications protocols. As a matter of fact, the optical fiber technology is affected by extremely high losses; thus, the deployment of a quantum satellite network (QSN) composed of quantum satellite repeaters (QSRs) in low Earth orbit would make it possible to overcome these attenuation problems. For these reasons, we consider the design of an ad hoc quantum satellite backbone based on the Software-Defined Networking (SDN) paradigm with a modular two-tier Control Plane (CP). The first tier of the CP is embedded into a Master Control Station (MCS) on the ground, which coordinates the entire constellation and performs the management of the CP integrated into the constellation itself. This second tier is responsible for entanglement generation and management on the selected path. In addition to defining the SDN architecture in all its components, we present a possible protocol to generate entanglement on the end-to-end (E2E) path. Furthermore, we evaluate the performance of the developed protocol in terms of the latency required to establish entanglement between two ground stations connected via the quantum satellite backbone.

Keywords: quantum Internet; quantum satellite internetworking protocol; software-defined networking

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1. Introduction

The future quantum Internet (QI) is expected to interconnect quantum computers (QCs) in order to achieve unprecedented capabilities that are impossible to achieve by using only classical information [1,2]. In a quantum network (QN), a quantum state can be teleported over an arbitrarily long distance, provided that an entangled pair of particles is exchanged through a quantum channel, and a classical communication channel is established over the same link [3–7].

Through the QI, remote quantum devices can communicate and cooperate to solve computational tasks by adopting a distributed computing approach. In fact, as explained in [8–10], through the interconnection of multiple QCs, it is possible to obtain a *single* quantum device with a number of qubits that scales linearly with the number of remote QCs. Moreover, the QI could provide other benefits, such as a near optimal network security.

Nevertheless, despite the significant evolution of quantum technologies, the generation rate of quantum encryption keys decreases exponentially with the distance due to the fiber attenuation; thus, obtaining an efficient entanglement distribution over long distances is still an open challenge [11,12]. In order to mitigate the transmission losses, devices such as quantum repeaters (QRs) must be introduced [2,13]. QRs are equipped with quantum memories to store intermediate quantum states. The QRs divide the long-distance communication channel into several segments, making it possible to generate the entanglement between adjacent nodes by transmitting photons entangled with their own memories [14]. Then, the *entanglement swapping* procedure is performed between adjacent nodes that have acknowledged the existence of entanglement with different QRs by receiving heralding signals from other QRs at long distances [15]. As depicted in Figure 1, the entanglement swapping procedure consists of the conversion of two independent entangled photon pairs—for example, photons α and β, and γ and δ—to a new entangled pair of photons between α and γ that are not originally entangled by performing a Bell State Measurement (BSM) on photons β and δ [16–18].

Considering that the free-space photon usually experiences negligible loss in a vacuum, free-space quantum satellite links have been considered in recent years in order to further address the limitation of optical fibers, making the transmission of photons over thousands of kilometers possible [19–21].

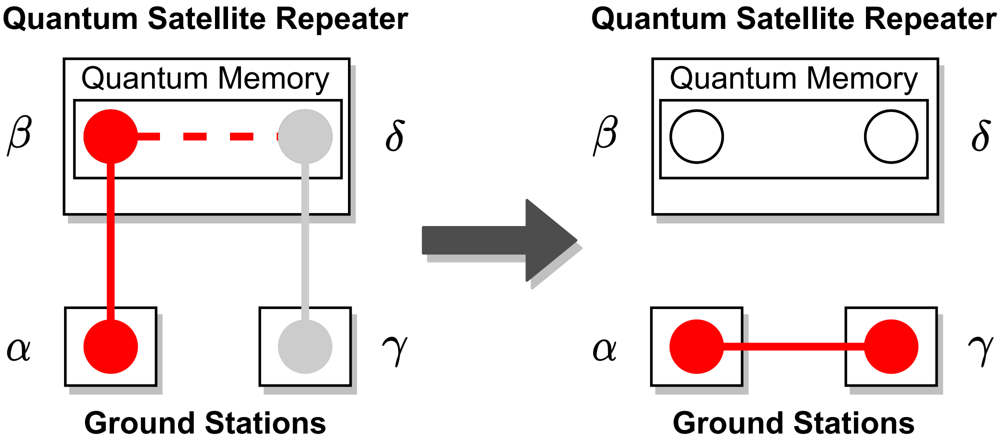

Figure 1. Entanglement swapping performed by a quantum satellite repeater.

However, the realization of a global quantum network requires the development of specific controlled architectures and protocols [22], also considering heterogeneous technologies while ensuring their interoperability, in Service-Oriented Architecture (SOA) [23–26], which also involves distributed computing. In a distributed classical system, different services are located on different machines, and the communication over the network increases the response time [27]. This can also occur in a distributed quantum system, wherein the different operations required by the quantum algorithm need to be properly allocated among the qubits of the different QCs [10]. Furthermore, as explained in [28], considering the limited lifetimes of quantum memories, it is very difficult to build completely distributed quantum network management protocols. This is one of the motivations that make Software-Defined Networking (SDN) a very attractive technology for the management of quantum networks. In fact, in a quantum network, an SDN Controller manages the global strategies for the distribution of long-distance Bell pairs.

According to the previous considerations, we propose a quantum network backbone composed of a constellation of low Earth orbit (LEO) satellites controlled through a *modular two-tier* Control Plane (CP) based on SDN. One tier of the CP consists of an SDN Controller integrated into a Master Control Station (MCS) on the ground, while the remaining component of the CP is deployed into the satellites of the constellation itself. Each satellite of the constellation, which are the elements that compose the Data Plane (DP), is a QR that is able to perform the swapping operations in order to create a path between two stations on the ground [22]. SDN technology is proven to be well suited to handle this type of architecture considering that quantum networks need to be very accurately controlled. In fact, reaching high rates requires a good entanglement generation scheme and efficient swapping procedures [29], which can be easily managed using SDN technology. Furthermore, considering that in specific cases, such as distributed applications, the number of remote operations has to be minimized in order to limit the decoherence effects that disentangle quantum states [30,31] and to reduce the overhead due to the swapping operations [10], we have also developed a Network Layer protocol with the goal of creating E2E entanglement between two ground stations (GSs) in an efficient manner.

The developed protocol is composed of two main phases, and it is adopted by the devices of the overall envisioned architecture that is depicted in Figure 2, which is made up of an MCS on the ground with an SDN Controller embedded that calculates the best path and performs the setup of the satellites that compose the selected path. Besides, the architecture makes use of additional controllers located in the constellation itself that are responsible for managing the operations of entanglement generation and swapping.

Considering that the studies conducted to date on quantum satellite backbone networks include the use of a single SDN controller [22], in this paper, we propose a system for the management of a quantum satellite backbone network consisting of quantum satellite repeaters (QSRs) focusing on the CP, with the following contributions:

- The design of a modular two-tier CP which includes an MCS and multiple controllers belonging to the constellation itself with entanglement generation and management functionalities;
- A Network Layer protocol for E2E entanglement generation specifically designed for the presented architecture;
- A first protocol test with the aim of interconnecting two QCs on a practical LEO constellation.

This paper is organized as follows: in Section 2, the state of the art is described, with a particular focus on architectures and protocols. In Section 3, the overall system model and protocol are described. In Section 4, the protocol validation is presented. Finally, Section 5 concludes the paper and outlines future perspectives.

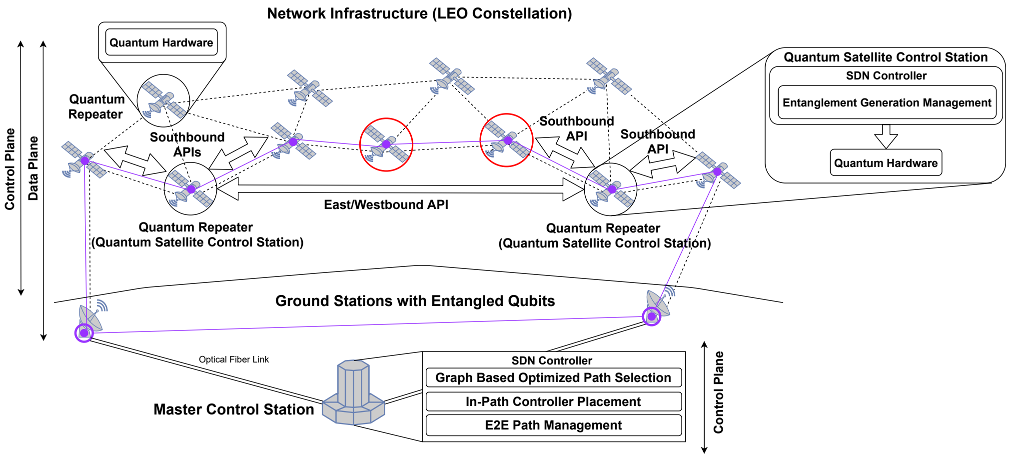

Figure 2. Quantum SDN backbone architecture. A Bell pair is generated between GSs through operations driven by the controllers embedded in the LEO constellation.

2. Related Works

The next development in the field of quantum communications is the creation of a global network of quantum computers, which might allow computations that are beyond the reach of even the most powerful single future quantum computers. As explained in [32], this goal is now much closer thanks to developments in satellite and quantum memory.

In [33], the properties of the photonic networks that can be generated by satellite-based quantum communications are compared with those of the optical fibers. In [20], a detailed analysis of quantum communication channels considering different disturbance effects is provided.

The Micius satellite, which launched in 2016 and is positioned in low orbit, has been used as a trusted relay in order to distribute secure keys among different locations deployed on a continental scale scenario. Furthermore, it has also been possible to perform some experiments on quantum teleportation between the ground stations and the satellite [34,35]. Additionally, in [21], the feasibility of the BB84 protocol [36] from satellite to ground with the qubits encoded in four different polarization states has been proved.

Free Space Optics (FSO) technology has been used in many experiments in the field of quantum communications. For instance, it has already been used for quantum communications on Earth, connecting a transmitter station (at the Jacobus Kapteyn Telescope (JKT) of the Isaac Newton Group on La Palma) and a receiver station (at the Optical Ground Station (OGS) of the European Space Agency on Tenerife), separated by 143 km [37]. This technology has also been used on inter-satellite links as explained in [38]. However, despite the atmospheric factors and beam wandering limiting the performance of FSO significantly [39], especially in the case of Earth-to-satellite communications, adequate performance can be achieved in fair weather conditions using the 193.415 THz frequency [40]. FSO has also been used in the experiment described in [41], where laser connections were made using the 193.415 THz frequency with High-Throughput Satellites (HTS) positioned in geostationary orbit with the aim of reaching speeds of 10 Gbps.

In [42], different Quantum Key Distribution (QKD) protocols were tested on a three-satellite quantum network that utilizes entanglement as a resource.

Besides this, in [43], a double-layer architecture of quantum satellite networks was proposed and a Joint GEO-LEO Routing and Key Allocation algorithm was designed to resolve the E2E key distribution problem.

Many satellite configurations with continuous coverage have been studied in order to balance both the total number of satellites and entanglement distribution rates [44].

In [22], an architecture consisting of a single ground controller that manages the entire constellation was introduced. The CP consists of a single controller deployed in an MCS on the ground, whereas the DP consists of numerous QSRs. The performances of some constellations composed of QSRs were analyzed in [45]. In [46,47], a quantum network stack and a link layer entanglement generation protocol were proposed. Moreover, in [28], the SDN was considered to be a very attractive technology in order to control future quantum networks. The experiments carried out to date have concerned individual links between a ground station and a single satellite, requiring the realization of Data Link Layer protocols such as those in [48], but when the first constellations are launched, it will also be necessary to address an efficient Network Layer protocol.

Only a few studies have been conducted so far on path selection for terrestrial and satellite quantum networks [22]; however, the application of a networking protocol on quantum networks based on LEO satellites is a research direction that is worth exploring. In this paper, in addition to defining a possible architecture, we propose a networking protocol for the generation of entanglement between two GSs through the use of multiple QSRs.

3. System Model

The design of an efficient quantum satellite backbone requires extremely accurate control, and the use of SDN technology could be fundamental to achieve this goal. In order to increase the generation rate of Bell pairs on the selected path, an appropriate path selection algorithm is required. These are the functions of the MCS depicted in Figure 2. Moreover, considering that the management of swapping procedures could increase the overhead, it is relevant to minimize this, especially for distributed operations [10]. This goal can be achieved by the efficient management of entanglement generation and swapping operations by the CP integrated into the constellation itself.

The following sections describe in detail the architecture together with the protocol and the related exchanged messages.

3.1. Presented Architecture

Several satellites in low orbit are considered in the presented architecture to overcome the distance problem, as shown in Figure 2 [2,22,45]. The use of a dense constellation close to the Earth's surface allows the distance problem to be addressed, as described in [45]. In fact, as explained in [2], the probability of success in entanglement generation decreases exponentially as a function of distance, and the time required to generate the entanglement between two adjacent nodes strongly depends on this probability and the characteristics of the medium. Therefore, in our paper, we considered a single LEO constellation in which all elements can embed SDN controllers. The elements that are part of the DP—i.e., the QSRs and the GSs, as depicted in Figure 2—operate in the frequency range of FSO, described in [22]. Atmospheric factors and beam wandering limit the performance of FSO significantly [39], especially regarding Earth-to-satellite communications, but adequate performance can be achieved in fair weather conditions using the 193.415 THz frequency. Optical technology can be used not only for the quantum channel but also for the control channel. In fact, all nodes in a quantum network are assumed to have classical connectivity between each other in order to perform background protocols, such as path selection, as well as signaling protocols to set up the E2E entanglement generation [49]. Furthermore, at the considered frequencies, the space vacuum has a much higher attenuation length of 9,261,376 compared with optical fibers. For these reasons, we have considered the realization of a satellite backbone managed by an MCS on the ground with an SDN controller embedded that derives the matrices of intersatellite distances. Then, a *graph-based optimized path selection algorithm* that calculates the best path is applied to the derived matrices [45]. The MCS calculates and manage the best path while communicating with the satellites through the southbound APIs. This architecture, shown in Figure 2, also includes the use of multiple controllers embedded in the constellation, whose proper placement helps to reduce the delays between them and the satellites acting as QRs, thus making it possible to completely avoid the terrestrial routes and, in particular, the Earth–satellite link, which is the most critical due to atmospheric phenomena. As explained in [50], the starting point from which to start generating Bell pairs [51] affects the speed of entanglement propagation over the entire path. A first attempt which considers the use of SDN technology to address this problem was made in [22], in which an architecture is described wherein the satellite *in the middle* is detected by a single controller on the ground, which sends the necessary instructions to the selected satellites to start the propagation procedure, interfacing with them through the southbound APIs.

However, with the proposed architecture shown in Figure 2, which uses a modular two-tier CP based on SDN, it is also always possible, thanks to the intervention of the MCS, to activate the control process on an appropriate satellite along its domain, which is composed of several satellites that compose the path. The satellites that delimit the borders between one domain and another are identified as *border QSRs*, highlighted with a red circle in Figure 2. The satellite controller manage the operations of entanglement generation and swapping, reducing both the time required for the propagation of the L2L entanglement and the propagation delays of signaling packets. The placement of the controller in the middle of the path section, as depicted in Figure 2, is fundamental to optimizing Bell pair propagation and minimizing packet delay to and from the Controller. Moreover, it is possible to avoid the satellite to ground link, which is critical. In the following section, we describe in detail the functioning of the protocol and the messages that are exchanged.

3.2. Protocol

The proposed protocol is designed for the architecture defined in Figure 2 and it is organized in two main phases:

1. Management of the connection request between GSs and the setup of the satellite path;
2. Generation of E2E entanglement using the configured satellite path.

In order to manage these operations properly, we have also defined a specific packet format, which is depicted in Figure 3. The fields that compose the defined packet are described as follows:

- `Type`: This field is composed of 4 bits and it defines the type of packet;
- `C`: This is a field composed of a single bit. It is useful in order to enable the controller's functionality for a specific satellite if the field `Type` is set to 3, or if the field `Type` is set

to 8, it is used in order to signal that the inter domain teleport between two border QSRs is completed;

- `Duration`: This field contains the lifetime of the path. It is important in order to program the opening and closing of the connections between the satellites that compose the path;
- `Source`: This field contains the address of the source of the message that could be the MCS or a satellite controller;
- `Destination`: This field contains the address of the destination of the message;
- `Previous`: Address of the previous satellite;
- `Next`: Address of the next satellite;
- `Teleportation Data`: This field contains the classic bits related to teleportation.

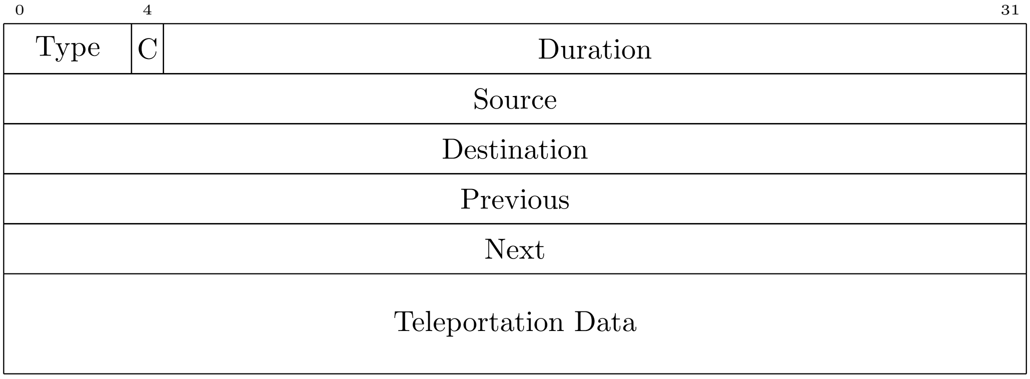

Figure 3. Packet format used by the protocol designed for the proposed architecture.

In the first phase, which is depicted in Figure 4, the MCS processes the connection request from one of the GSs located on the Earth's surface. In this case, the message received by the MCS consists of the `Type` field set to 0 and the `Previous` field that contains the IP address of the GS to which it wants to connect. Thus, the controller in the MCS calculates the best paths for all instants of time, creating a list with which it is able to obtain the duration of every best path.

At the same time, it sends the connection request to the selected QSRs and a message that has the `Type` as a field, which in this case is identified with 1 and the `Previous` field, which contains the address of the station that has generated the request.

When the station affirmatively acknowledges the request, the MCS begins to perform the setup of the satellite path by sending messages of `Type` 2 to each satellite that is part of the selected path, indicating which is the neighboring satellite to connect to. Furthermore, the satellite recovers the value of the field called `Duration`, in order to set a timer that closes the connection when the path is expired.

Once the controller has received notification from the satellites of the selected path that all the connections have been established, the second phase of the protocol begins. As shown in Figure 5, this involves the generation of entanglement on the selected satellite path and has a duration equal to the value specified in the field `Duration`, which corresponds to the duration of the satellite path.

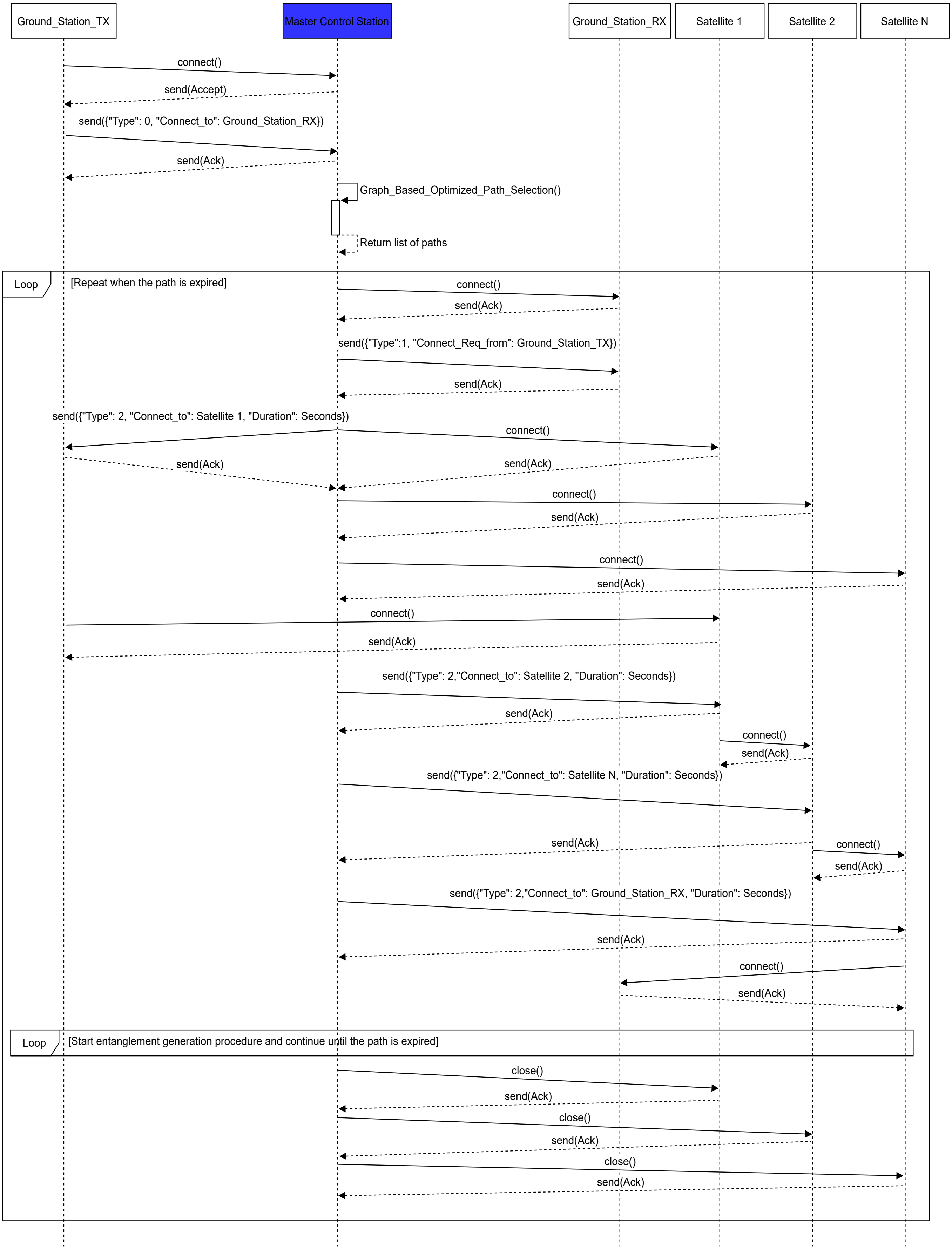

Figure 4. Sequence diagram of the first phase of the protocol. The MCS performs the setup operations on the selected path.

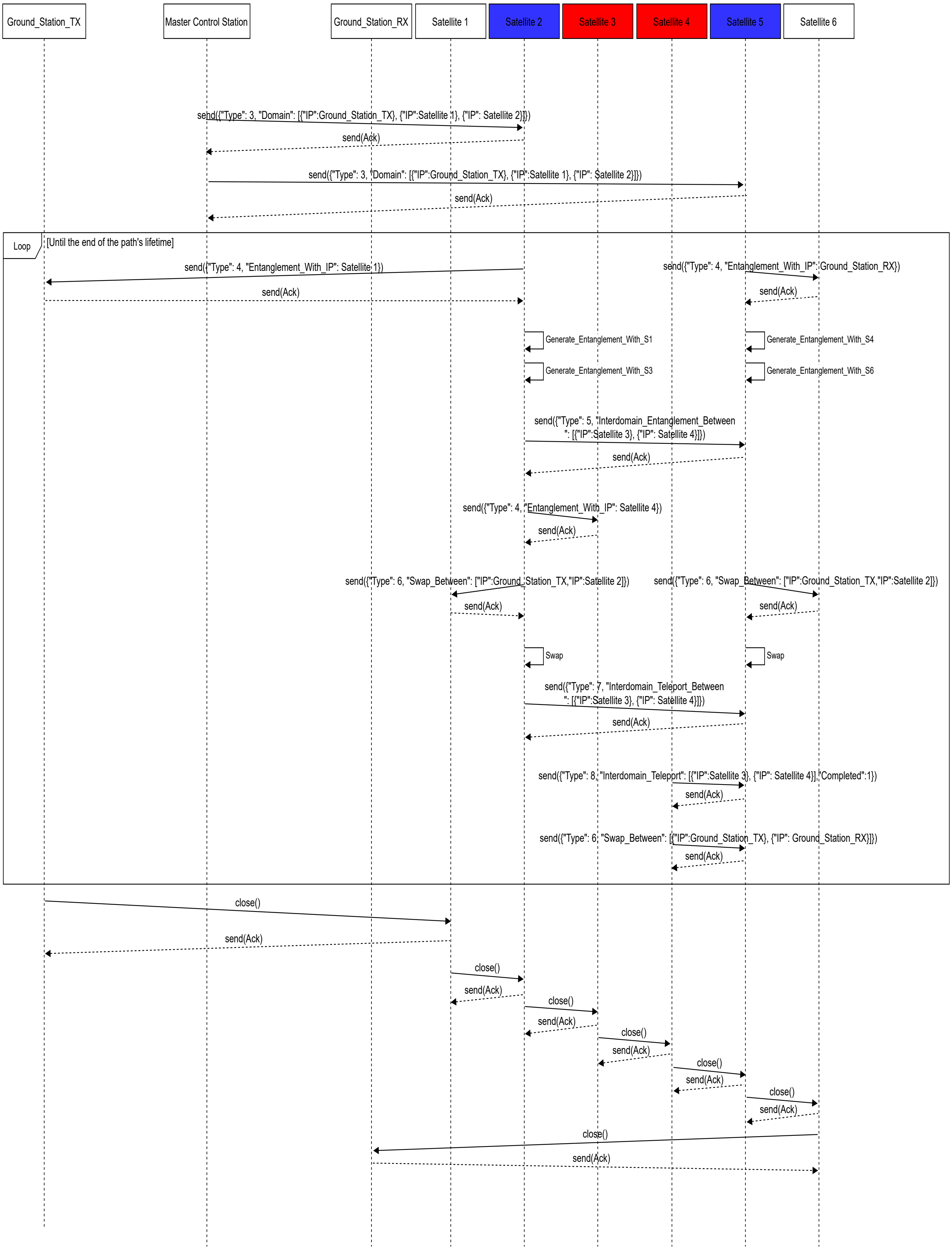

Figure 5. Sequence diagram related to the second phase of the protocol. The Controllers placed on the path manage the entanglement generation and swapping operations.

The MCS sends to the satellites chosen as controllers a message of `Type` 3 that indicates the ability to perform certain operations on a domain that is specified in the message itself in the fields `Previous` and `Next`.

The controller generates two pairs of particles to share with the two adjacent satellites in the path and sends a `Type` 4 message to the remaining satellites, specifying the satellite with which to perform the entanglement. In addition, the first controller on the path sends a `Type` 5 message to the second controller in order to negotiate the generation of entanglement between two satellites. In this type of message, the `Previous` and `Next` fields indicate the satellites to be interconnected. When the acknowledgment is received, the swapping procedure is started to generate the entanglement at level E2E.

A `Type` 6 message that contains the field is sent to the satellite that has to perform a swapping operation. In this type of message, the `Previous` and `Next` fields indicate the satellites that will be interconnected after the swap operation. The internal swapping operations of each domain are performed simultaneously by the controllers on their own domains. When a controller has completed its operations—i.e., the creation of the E2E entanglement between the ground station to which it is connected and the border QSR highlighted with a red circle in Figure 2—it sends a request to the other controller with the purpose of interconnecting the border satellites.

This is done with a `Type` 7 message and, in this case, the `Previous` and `Next` fields indicate the satellites between which to perform the teleportation operation.

When the teleportation process is completed, a `Type` 8 message is sent from the border satellite that received the particle to its controller with field C set to 1, indicating that the teleportation between the two border satellites has been completed. At this point, the controller sends a `Type` 6 message to its border satellite to perform the swapping operation. When this operation is completed, the entanglement E2E is established and the procedure can start again to perform the exchange of successive qubits.

When the path is no longer valid, a condition that can be detected by checking the list of paths calculated by the Graph-Based Optimized Path Selection process on the MCS, the satellites close the connections established with the others. Then, the controller processes are deallocated and the controller in the MCS closes the connections with the satellites involved up to that moment. Then, the procedure restarts until the end of the session.

4. Results

In order to investigate the performance of the architecture and the protocol that we propose, we have conducted a simulation in order to verify the time required to obtain an entanglement between two GSs using a quantum satellite backbone. In order to develop the software, we used the *skyfield* Python package to operate on the Two Line Elements set (TLE) [52,53] data in order to calculate the inter distance matrices, and the Dijkstra's algorithm included in the *scipy* package. In the scenario that we have simulated, we used the Iridium-NEXT constellation, composed of 75 satellites. We have considered the activation of two controllers on the path selected by the MCS, and we performed a simulation considering a reference time interval of 1 h, capturing a sample every second. The GSs were located at a distance of 20,000 km from each other. During the simulation, the number of satellites that composed the best path varied from 4 to 6; then, we derived a different distribution for each case. As can be seen from the graph depicted in Figure 6, with an increase in the number of satellites involved, the time required to generate a remote entanglement decreases.

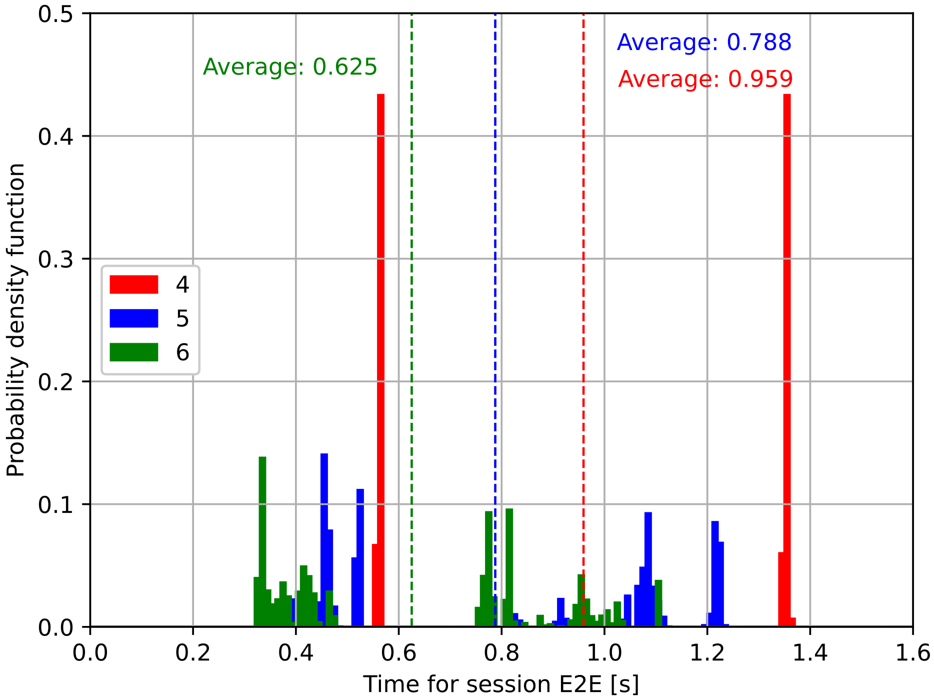

Figure 6. Time required to establish an entanglement E2E.

This fact confirms in part what has been claimed in [22,45]; i.e., that a larger constellation allows better results to be obtained in terms of the entanglement rate, defined as the number of transmitted entangled states per second, which is measured as Bell pairs per seconds [22].

From the graph in Figure 6, it appears that, considering the same number of controllers within the path, performance improves as the number of satellites increases. This is because, given the shorter distance, the probability of success in order to obtain an entanglement increases. Since the time needed to obtain the entanglement strongly depends on this probability, the time needed to obtain it decreases.

This provides a first indication that as the number of satellites that compose the path changes, the performance of the protocol is not degraded, but the beneficial effects of the distance between the satellites that compose the domains can be seen. Further studies on scalability could provide useful indications for the realization of an intelligent architecture in which the MCS allocates an appropriate number of controllers inside the path in order to achieve effective quantum communications.

5. Conclusions

In recent years, the development of quantum devices has been very significant. Considering this, it is also necessary to create a specific backbone based on quantum entanglement and teleportation in order to interconnect QCs on Earth reaching an extremely high computational capacity. With the deployment of a QSNs, it is possible to overcome the limitations of fiber optic networks, and the recent technological developments in terms of quantum satellite communications encouraged us to study an efficient management system for a LEO quantum satellite backbone. Given the difficulty in being able to create entanglement over long distances, SDN technology could be useful to control the operations necessary to create it. Specifically, we have designed a specific architecture consisting of SDN controllers positioned both on the ground and in the constellation itself with different roles, which is capable of controlling operations on the entire E2E path. Moreover, we have developed a specific communication protocol through which it is possible to obtain an E2E entanglement.

The performance of the protocol was evaluated considering the time required to establish an E2E entanglement as the conditions of the E2E path change. From the tests conducted, it is possible to deduce that as the number of satellites increases, the performance tends to improve, considering that the shorter distance increases the probability of success in order to obtain an entanglement. In fact, the time needed to obtain the entanglement strongly depends on this probability, and therefore the time needed to obtain it decreases.

Future development could consist of the integration within the MCS of a specific path selection algorithm designed for quantum networks, which would take into account the issues of quantum networks and contribute to further improve performance. In addition, more accurate analysis in terms of scalability could also provide additional elements in order to allocate controllers in the constellation even more efficiently.

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References

1. Wehner, S.; Elkouss, D.; Hanson, R. Quantum internet: A vision for the road ahead. *Science* **2018**, *362*, eaam9288. [CrossRef] [PubMed]
2. Caleffi, M. Optimal Routing for Quantum Networks. *IEEE Access* **2017**, *5*, 22299–22312. [CrossRef]
3. Horodecki, R.; Horodecki, P.; Horodecki, M.; Horodecki, K. Quantum entanglement. *Rev. Mod. Phys.* **2009**, *81*, 865–942. [CrossRef]
4. Franco, R.L.; Compagno, G. Indistinguishability of Elementary Systems as a Resource for Quantum Information Processing. *Phys. Rev. Lett.* **2018**, *120*, 240403. [CrossRef] [PubMed]
5. Bennett, C.H.; Brassard, G.; Crépeau, C.; Jozsa, R.; Peres, A.; Wootters, W.K. Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. *Phys. Rev. Lett.* **1993**, *70*, 1895–1899. [CrossRef] [PubMed]
6. Gyöngyösi, L.; Bacsardi, L.; Imre, S. A survey on quantum key distribution. *Infocommun. J.* **2019**, *11*, 14–21. [CrossRef]
7. Perseguers, S.; Lapeyre, G.J.; Cavalcanti, D.; Lewenstein, M.; Acín, A. Distribution of entanglement in large-scale quantum networks. *Rep. Prog. Phys.* **2013**, *76*, 096001. [CrossRef]
8. Ferrari, D.; Cacciapuoti, A.S.; Amoretti, M.; Caleffi, M. Compiler Design for Distributed Quantum Computing. *IEEE Trans. Quantum Eng.* **2021**, *2*, 1–20. [CrossRef]
9. Wang, C.; Rahman, A.; Li, R.; Aelmans, M. Applications and Use Cases for the Quantum Internet. Internet-Draft draft-irtf-qirg-quantum-internet-use-cases-04, Internet Engineering Task Force. Unpublished work. 2021.
10. Cuomo, D.; Caleffi, M.; Cacciapuoti, A.S. Towards a distributed quantum computing ecosystem. *IET Quantum Commun.* **2020**, *1*, 3–8. [CrossRef]
11. Jiang, L.; Taylor, J.M.; Nemoto, K.; Munro, W.J.; Van Meter, R.; Lukin, M.D. Quantum repeater with encoding. *Phys. Rev. A* **2009**, *79*, 032325. [CrossRef]
12. Collins, O.A.; Jenkins, S.D.; Kuzmich, A.; Kennedy, T.A.B. Multiplexed Memory-Insensitive Quantum Repeaters. *Phys. Rev. Lett.* **2007**, *98*, 060502. [CrossRef]
13. Munro, W.J.; Azuma, K.; Tamaki, K.; Nemoto, K. Inside Quantum Repeaters. *IEEE J. Sel. Top. Quantum Electron.* **2015**, *21*, 78–90. [CrossRef]
14. Ruihong, Q.; Ying, M. Research Progress Of Quantum Repeaters. *J. Phys. Conf. Ser.* **2019**, *1237*, 052032. [CrossRef]
15. Azuma, K.; Tamaki, K.; Lo, H.K. All-photonic quantum repeaters. *Nat. Commun.* **2015**, *6*, 1–7. [CrossRef]
16. Pan, J.W.; Bouwmeester, D.; Weinfurter, H.; Zeilinger, A. Experimental Entanglement Swapping: Entangling Photons That Never Interacted. *Phys. Rev. Lett.* **1998**, *80*, 3891–3894. [CrossRef]
17. Bose, S.; Vedral, V.; Knight, P.L. Purification via entanglement swapping and conserved entanglement. *Phys. Rev. A* **1999**, *60*, 194–197. [CrossRef]
18. Jin, R.B.; Takeoka, M.; Takagi, U.; Shimizu, R.; Sasaki, M. Highly efficient entanglement swapping and teleportation at telecom wavelength. *Sci. Rep.* **2015**, *5*, 9333. [CrossRef] [PubMed]
19. Bacsardi, L. On the way to quantum-based satellite communication. *IEEE Commun. Mag.* **2013**, *51*, 50–55. 6576338. [CrossRef]
20. Vasylyev, D.; Vogel, W.; Moll, F. Satellite-mediated quantum atmospheric links. *Phys. Rev. A* **2019**, *99*, 053830. [CrossRef]

21. Vallone, G.; Bacco, D.; Dequal, D.; Gaiarin, S.; Luceri, V.; Bianco, G.; Villoresi, P. Experimental Satellite Quantum Communications. *Phys. Rev. Lett.* **2015**, *115*, 040502. [CrossRef]
22. Picchi, R.; Chiti, F.; Fantacci, R.; Pierucci, L. Towards Quantum Satellite Internetworking: A Software-Defined Networking Perspective. *IEEE Access* **2020**, *8*, 210370–210381. [CrossRef]
23. Papazoglou, M.P.; Van Den Heuvel, W.J. Service oriented architectures: Approaches, technologies and research issues. *VLDB J.* **2007**, *16*, 389–415. [CrossRef]
24. Segura, R. Service-oriented architecture for coalition satellite communications. In Proceedings of the MILCOM 2008—2008 IEEE Military Communications Conference, San Diego, CA, USA, 16–19 November 2008; pp. 1–8.
25. Chiti, F.; Fantacci, R.; Pierucci, L. Energy Efficient Communications for Reliable IoT Multicast 5G/Satellite Services. *Future Internet* **2019**, *11*, 164. [CrossRef]
26. Pecorella, T.; Pierucci, L.; Nizzi, F. "Network Sentiment" Framework to Improve Security and Privacy for Smart Home. *Future Internet* **2018**, *10*, 125. [CrossRef]
27. O'Brien, L.; Merson, P.; Bass, L. Quality Attributes for Service-Oriented Architectures. In Proceedings of the International Workshop on Systems Development in SOA Environments (SDSOA'07: ICSE Workshops 2007), Minneapolis, MN, USA, 20–26 May 2007; p. 3. [CrossRef]
28. Kozlowski, W.; Wehner, S. Towards Large-Scale Quantum Networks. In Proceedings of the Sixth Annual ACM International Conference on Nanoscale Computing and Communication; Association for Computing Machinery, NANOCOM '19, Dublin, Ireland, 25–27 September 2019. [CrossRef]
29. Brask, J.B.; Rigas, I.; Polzik, E.S.; Andersen, U.L.; Sørensen, A.S. Hybrid Long-Distance Entanglement Distribution Protocol. *Phys. Rev. Lett.* **2010**, *105*, 160501. [CrossRef]
30. Shor, P.W. Scheme for reducing decoherence in quantum computer memory. *Phys. Rev. A* **1995**, *52*, R2493–R2496. [CrossRef]
31. Helm, J.; Strunz, W.T. Quantum decoherence of two qubits. *Phys. Rev. A* **2009**, *80*, 042108. [CrossRef]
32. Simon, C. Towards a global quantum network. *Nat. Photonics* **2017**, *11*, 678–680. [CrossRef]
33. Brito, S.; Canabarro, A.; Cavalcanti, D.; Chaves, R. Satellite-Based Photonic Quantum Networks Are Small-World. *PRX Quantum* **2021**, *2*, 010304. [CrossRef]
34. Liao, S.K.; Cai, W.Q.; Handsteiner, J.; Liu, B.; Yin, J.; Zhang, L.; Rauch, D.; Fink, M.; Ren, J.G.; Liu, W.Y.; et al. Satellite-Relayed Intercontinental Quantum Network. *Phys. Rev. Lett.* **2018**, *120*, 030501. [CrossRef]
35. Jianwei, P. Progress of the Quantum Experiment Science Satellite (QUESS) Micius Project. *Chin. J. Space Sci.* **2018**, *38*, 604. [CrossRef]
36. Bennett, C.H.; Brassard, G. Quantum cryptography: Public key distribution and coin tossing. *Theor. Comput. Sci.* **2014**, *560*, 7–11. [CrossRef]
37. Ma, X.S.; Herbst, T.; Scheidl, T.; Wang, D.; Kropatschek, S.; Naylor, W.; Wittmann, B.; Mech, A.; Kofler, J.; Anisimova, E. Quantum teleportation over 143 kilometres using active feed-forward. *Nature* **2012**, *489*, 269–273. [CrossRef]
38. Tom, G.; Joel, B.; George, L. *Analysis of Free Space Optics as a Transmission Technology*; US Army Information Systems Engineering Command: Fort Huachuca, AZ, USA, 2005; Volume 3.
39. Hosseinidehaj, N.; Babar, Z.; Malaney, R.; Ng, S.X.; Hanzo, L. Satellite-Based Continuous-Variable Quantum Communications: State-of-the-Art and a Predictive Outlook. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 881–919. [CrossRef]
40. Horwath, J.; Knapek, M.; Epple, B.; Brechtelsbauer, M.; Wilkerson, B. Broadband backhaul communication for stratospheric platforms: The stratospheric optical payload experiment (STROPEX). In *Free-Space Laser Communications VI*; International Society for Optics and Photonics: San Diego, CA, USA, 2006; Volume 6304, p. 63041N.
41. Toyoshima, M.; Fuse, T.; Carrasco-Casado, A.; Kolev, D.R.; Takenaka, H.; Munemasa, Y.; Suzuki, K.; Koyama, Y.; Kubo-oka, T.; Kunimori, H. Research and development on a hybrid high throughput satellite with an optical feeder link Study of a link budget analysis. In Proceedings of the 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS), Naha, Japan, 14–16 November 2017; pp. 267–271. [CrossRef]
42. Bacsardi, L. Resources for Satellite-Based Quantum Communication Networks. In Proceedings of the 2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES), Las Palmas de Gran Canaria, Spain, 21–23 June 2018; pp. 000097–000102. [CrossRef]
43. Huang, D.; Zhao, Y.; Yang, T.; Rahman, S.; Yu, X.; He, X.; Zhang, J. Quantum Key Distribution Over Double-Layer Quantum Satellite Networks. *IEEE Access* **2020**, *8*, 16087–16098. [CrossRef]
44. Khatri, S.; Brady, A.J.; Desporte, R.A.; Bart, M.P.; Dowling, J.P. Spooky action at a global distance: Analysis of space-based entanglement distribution for the quantum internet. *Npj Quantum Inf.* **2021**, *7*, 1–15. [CrossRef]
45. Chiti, F.; Fantacci, R.; Picchi, R.; Pierucci, L. Quantum Satellite Backbone Networks Design and Performance Evaluation. In Proceedings of the IEEE International Conference on Communications, Montreal, QC, Canada, 14–23 June 2021.
46. Pirker, A.; Dür, W. A quantum network stack and protocols for reliable entanglement-based networks. *New J. Phys.* **2019**, *21*, 033003. [CrossRef]
47. Dahlberg, A.; Skrzypczyk, M.; Coopmans, T.; Wubben, L.; Rozpundefineddek, F.; Pompili, M.; Stolk, A.; Pawełczak, P.; Knegjens, R.; de Oliveira Filho, J.; et al. A Link Layer Protocol for Quantum Networks. In Proceedings of the ACM Special Interest Group on Data Communication SIGCOMM '19, New York, NY, USA, 9–24 August 2019. [CrossRef]
48. Meter, R.V.; Touch, J. Designing quantum repeater networks. *IEEE Commun. Mag.* **2013**, *51*, 64–71. [CrossRef]

49. Kozlowski, W.; Wehner, S.; Meter, R.V.; Rijsman, B.; Cacciapuoti, A.S.; Caleffi, M.; Nagayama, S. Architectural Principles for a Quantum Internet. Internet-Draft draft-irtf-qirg-principles-06, Internet Engineering Task Force. Unpublished work. 2021.
50. Munro, W.; Harrison, K.; Stephens, A.; Devitt, S.; Nemoto, K. From quantum multiplexing to high-performance quantum networking. *Nat. Photonics* **2010**, *4*, 792–796. [CrossRef]
51. Li, Y. Methods of Generating Entangled Photon Pairs. *J. Phys. Conf. Ser.* **2020**, *1634*, 012172. [CrossRef]
52. Norad Two-Line Element Sets Current Data. Available online: https://celestrak.com/NORAD/elements/ (accessed on 3 July 2021).
53. Vallado, D.A.; Cefola, P.J. Two-line element sets-practice and use. In Proceedings of the 63rd International Astronautical Congress, Naples, Italy, 1–5 October 2012.