Mobile Control Plane Design for Quantum Satellite Backbones

Francesco Chiti, Romano Fantacci, Roberto Picchi, and Laura Pierucci

Abstract

The interconnection of quantum computers through the so-called Quantum Internet is a very promising approach.

The most critical issues concern the physical layer, considering that the creation of entanglement over long distances is still problematic. Given the difficulty that usually arises from fiber optics due to exponential losses, the introduction of intermediate quantum repeaters (QRs) allows mitigating the problem. A quantum satellite network based on QRs on satellites deployed over low Earth orbit could make it possible to overcome the constraints of terrestrial optical networks. Hence, the recent technological developments in terms of quantum satellite communications motivated our investigation on an ad hoc quantum satellite backbone design based on the software defined networking paradigm with a control plane directly integrated into the constellation itself. Our aim is to outline some guidelines by comparing several options. Specifically, the focus is to analyze different architectural solutions making some considerations on their feasibility, possible benefits, and costs. Finally, we performed some simulations on the architectures we considered the most promising, concluding that the integration of the control plane in the constellation itself is the most appropriate solution.

Introduction

Recently, many efforts have been made to build increasingly high-performance quantum computers (QCs). But in order to complete the quantum revolution, quantum networks (QNs), which are able to connect distant QCs through remote quantum entanglement distribution, need to be addressed [1].

The framework of the future quantum Internet (QI) is modeled as an *entangled* network structure, in which the quantum nodes are connected by remote maximally entangled states otherwise known as *EPR pairs* [1, 2]. Maximal entanglement means that these states have the strongest correlations among all the possible states in which two qubits can be [3].

The QI could provide intrinsic benefits, starting from a near optimal network security; furthermore, the QI supports other important facilities like remote quantum computing in order to perform distributed quantum computing. It is possible to achieve this aim by interconnecting remote *small*-capacity QCs in order to make them work together in a coordinated manner so as to obtain a *single* quantum device with extremely higher performance [4]. The increase in the performance of distributed quantum algorithms is due to the possibility of creating EPR pairs, even between remote QCs [3]. However, despite the progress recently made in quantum technologies, an efficient entanglement distribution over long distance is still challenging because of the exponential decay of communication rate. In order to relieve the effects of attenuation, quantum repeaters (QRs) are the unique viable solution. These devices are equipped with quantum memories, which generate the entanglement between adjacent nodes via the transmission of photons entangled with their own memories. The entanglement swapping is then performed between adjacent nodes that acknowledge an already established entanglement with other QRs by receiving heralding signals from different QRs at long distances. Hence, this operation allows creating entanglement between two not directly connected QRs through optical Bell state measurement (BSM) of the two photons in possession of the QR that separates them [1]. In order to further address the limitation of optical fibers, free-space quantum links have been considered in recent years. As a matter of fact, the free-space photon will experience negligible loss in vacuum, making it feasible to create entanglement over thousands of kilometers [5].

Given the previous considerations, we propose a quantum network backbone composed by a low Earth orbit (LEO) satellite constellation, which would allow the interconnections of ground stations (GSs) located at long distances with a limited number of QRs with regard to a fiber optic-based solution. According to our approach, each satellite of the constellation is able to perform the swapping operations in order to create a path between two stations on the ground [5]. It should be noted that, as reported in [6], the overhead due to swapping operations has to be minimized, especially for distributed applications. Indeed, given a particular quantum circuit describing a quantum algorithm, the distributed quantum compiler must optimize the circuit so that the number of remote operations is minimized to limit the decoherence effects and to reduce the overhead arising with the swapping operations. In fact, when decoherence occurs, some qubits become entangled with the environment, and the entire computation of the QC — or a link in the case of quantum communication — is corrupted [7]. Considering this, it is necessary that these operations be completely *controlled* and the software defined networking (SDN) technology is appro-

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priate for this purpose. For this reason, we have studied different strategies of entanglement generation on single links [3], managed by the controller that also handles the swapping operations. In this article, we introduce a further improvement by assuming that some satellites within the constellation are enabled to work as SDN controllers. In addition, to increasing the robustness and flexibility, this scheme also contributes to improved performance, significantly reducing the traffic on critical routes with regard to an architecture with a single controller on the ground and, consequently, decreasing the latency required to establish an end-to-end (E2E) entanglement.

Considering the satellites' kinematics, and that the connection between satellites may last for just a very short period, a *dynamic mobile* control plane (CP) can be a solution. As reported in [8], the controllers can be placed dynamically, based on real-time traffic conditions, hence, considering the origins of the flows and their number. Furthermore, the controller application can be installed on a virtual machine (VM) that can be directly migrated between servers.

Therefore, the article considers the deployment of a LEO constellation with a *dynamic mobile* CP integrated into the data plane (DP) consisting of satellites that include the functionality of QRs.

The most relevant aspect covered by this article is a set of guidelines for the design of a SDNbased quantum satellite backbone network with a specific focus on the CP, with the following contributions:

- A comparison between possible architectures with a qualitative analysis of their feasibility.
- The design of a SDN-based architectural scheme to control the quantum satellite backbone.
- The identification of management procedures for E2E entanglement generation.
- A comparison of the achievable performance between a single ground- and satellite-based controller architectures.

In particular, the performance is evaluated in terms of the overhead required to complete the E2E entanglement generation procedure and the overall delay to complete the entire process.

This article is organized as follows: First, several possible architectures are explored, showing both advantages and disadvantages. Following that, the overall system model is described, and the the results are provided. Finally, we conclude the article and outline future perspectives.

Control Plane Deployment Solutions Analysis

In the following, some of the possible SDN-based architectures are outlined, analyzing their characteristics with a specific focus on the advantages and disadvantages.

LEO Constellation With a Single Ground Controller

In [5] an architecture consisting of a single ground controller that manages the entire constellation has been preliminary introduced. The CP consists of a single controller deployed in a master control station, whereas the DP consists of quantum satellite repeaters (QSRs). The controller gathers the data required to build the entire satellite network state, querying a database that contains the constellation adjacency matrices. Whenever it is necessary to interconnect two GSs, the distributed application invokes the controller's best path evaluation module via the northbound application programming interface (API) and applies a centralized path selection algorithm. The QSRs generate and exchange entangled particles, based on information provided by the controller through the southbound API. The controller has complete control of the architecture managing the generation of link-to-link (L2L) entanglement and the swapping operations necessary to originate E2E entanglement. This architecture, consisting of a LEO constellation managed with SDN technology is certainly appropriate. However, further improvements can be introduced, taking into account that minimizing the swapping overhead is relevant for distributed operations and, therefore, it is important to properly design the topology [6].

Multi-Controller on GEO

Another solution is similar to the one described in [9], with a master controller that coordinates some domain controllers but deployed directly on geostationary Earth orbit (GEO) satellites. Since GEO communication satellites at latitudes above 81° are below the horizon, it would be very difficult to ensure complete coverage for the underlying LEO constellation. Furthermore, latency becomes significant, as it takes about 240 ms for a signal to pass from a GS on the equator to the satellite and back. In addition, the inter-satellite routes between GEO satellites could be longer than the satellite to ground links, introducing even greater latencies. Therefore, an architecture consisting of several controllers placed on GEO satellites may not be an adequate solution, since it is not possible to achieve complete coverage of the underlying LEO constellation; moreover, the high delays could severely limit the system response time. This makes the previous solution ineffective, especially for applications that require distributed quantum computing.

Coverage problems can be overcome by considering an Equatorial-Polar (EP) constellation as described in [10]. MEO polar orbit satellites could help ensure global coverage. Satellites that are part of the polar orbit segment could be enabled at the same time they pass over the polar areas, ensuring full control of the underlying LEO constellation. The satellite at sunset is deactivated and then reactivated when it passes over the opposite polar area. When it is in transit, it can retrieve the status of the underlying LEO network. Although this kind of constellation ensures complete global coverage, it does not solve the problem of reducing the latency. However, this type of architecture, even if not suitable for distributed quantum processing, can be used to resolve the routing and key allocation (RKA) problem as proposed in [11].

Multi-Controller on MEO

To get more coverage on the Earth's surface and limit the latency problem, we could consider placing the controllers on a MEO constellation similar to GPS. The GPS constellation operates at an altitude of 20,200 [km], with each satellite providing high coverage. The lower the distance of the satellite toward GSs and between the LEO satellites and the respective MEO satellites has a beneficial affect on latency. However, considering the kinematics of both constellations, this kind of architecture could be very difficult to manage

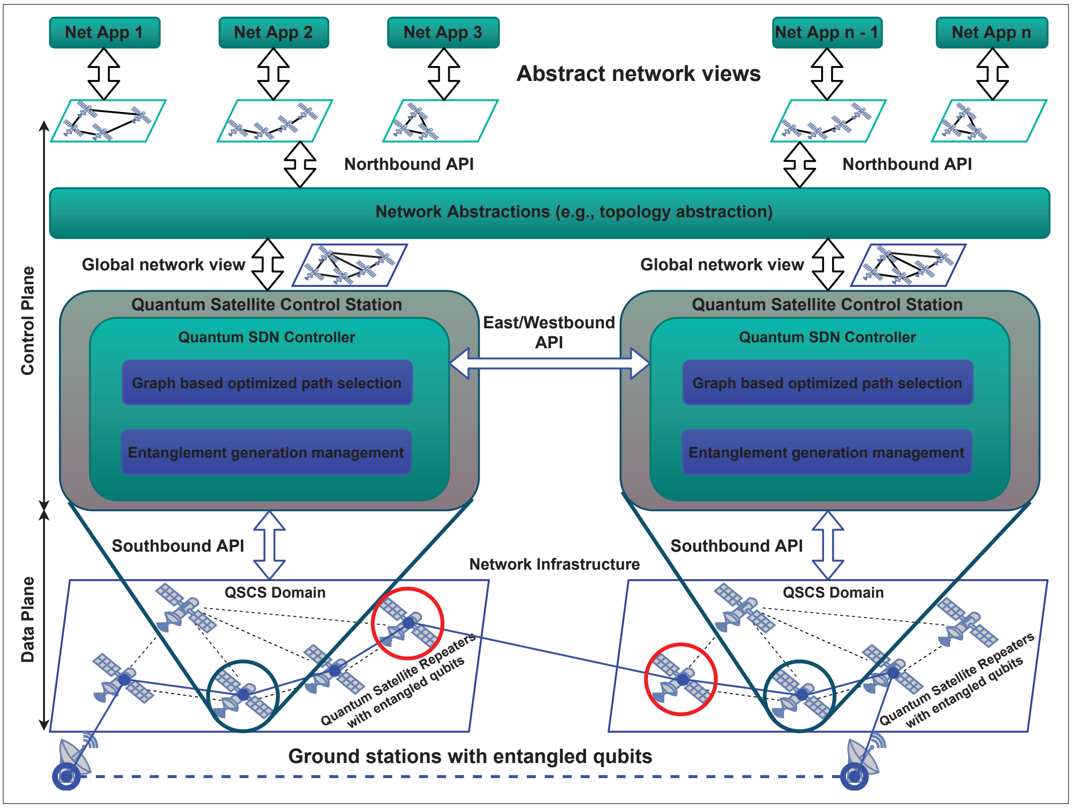

FIGURE 1. Quantum SDN backbone architecture. A Bell pair is generated between GSs through operations driven by the controllers embedded in the LEO constellation.

since it could require the design of appropriate *handover* procedures. In fact, a GS cannot be in line of sight (LoS) with respect to the same MEO satellite; the configuration of the LEO constellation also continuously changes for the MEO and the GSs. This architecture introduces considerable complications compared to the previous ones; it may not be suitable for distributed applications or for the resolution of the RKA problem.

System Model

Before providing a description of the architecture that we have defined, it is important to describe some phenomenas that are necessary to consider to support efficient quantum communications and processing.

As explained in [1], the probability of successfully generating remote entanglement between two adjacent nodes is highly dependent on the distance and the characteristics of the propagation medium with an exponential decay. Compared to optical fibers, a free space photon experiences negligible loss in vacuum [5].

When decoherence occurs, some qubits of the computation become entangled with the environment, collapsing the state of the QC. Once a qubit has decohered, the entire computation of the QC is corrupted, and the result of the computation is no longer correct [7].

To obtain a long distance entanglement, QRs are necessary. These devices perform the entanglement swapping procedure, which works as follows: Considering two independent entangled pairs A-B and C-D, a BSM on B and D projects A and C onto an entangled state, although these two particles have never interacted [5].

Based on the previous considerations, in order to design an efficient satellite quantum network backbone, some basic requirements need to be addressed. It is clear that this system requires an extremely accurate control. Therefore, SDN technology could be proven to be fundamental for this type of network. Besides, an appropriate path selection algorithm could help to increase the rate on E2E routes by properly selecting QRs that compose the path. Furthermore, considering that the management of swapping procedures could increase the overhead, it is relevant to minimize it, especially for distributed operations [6]. These are the two main functions of the controller depicted in Fig. 1.

Based on previous considerations, we propose some guidelines through the design and dynamic placement of the CP within the constellation itself and some E2E entanglement generation strategies with the goal to identify the one that can provide the best performance for the derived architecture.

Proposed Reference Architecture

Considering that distance represents a serious impairment for QNs [1, 5], it may be preferable to consider a constellation consisting of a large number of satellites placed in a low orbit, such as LEO, as also recommended in [12].

The QSRs and the GSs — the elements that compose the DP — can operate in the same range of frequencies described in [5], which is also known as free space optics (FSO). FSO is a technology that has found application in several areas of the short- and long-haul space communications, such as on inter-satellite links. FSO has been used in the realization of quantum communications on Earth [13]. The performance of FSO systems are

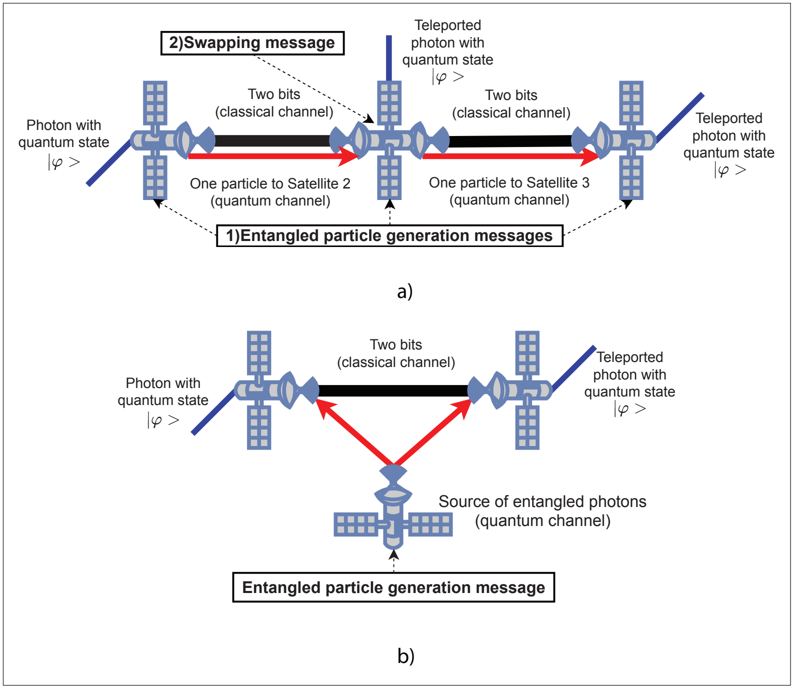

FIGURE 2. a) how the *at-source* strategy works; b) an example of the *at mid-point* strategy.

usually limited by atmospheric factors and beam wandering [14], especially regarding Earth-satellite communication. But, considering a wavelength equal to 1550 [nm], the atmospheric absorption is negligible in clear air conditions, making it a favorable wavelength for FSO applications. Compared to optical fiber, the space vacuum has a much higher *attenuation length* [5] at the considered frequencies. For this reason, we have considered the realization of a satellite backbone with the controller embedded in the constellation in order to further reduce the delays between it and the satellites acting as QRs. Furthermore, the control virtual process migration is crucial in this architecture. It is always possible to deploy the control process on an appropriate satellite in the middle of the path [15] to reduce both the time required for the propagation of the L2L entanglement and the propagation delays of signaling packets.

This type of architecture provides notable advantages, considering that it allows for significantly reducing the losses related to the links between the GSs and the *first* satellite, which is the more problematic one, and considering that optical communications are subject to scattering phenomena due to the presence of water particles in the atmosphere that vary according to weather conditions. These problems are related both to the quantum link and to the classical link on which the control packets are transmitted. However, with the proposed architecture, only the packets exchanged between the GSs and the *quantum satellite control stations* (QSCSs) will have to pass through these links. Moreover, fiber optic terrestrial connections between the controller and GSs are also avoided, allowing losses to be neglected. Finally, since the distances are very high and the controller is in charge of managing the operations between the satellites, this helps to limit the propagation delays, given the very high distances are not negligible.

The proposed architecture is depicted in Fig. 1, wherein the domains that could consist of clusters of satellites of the same constellation in LoS of a QSCS are highlighted. The procedure that is performed in order to create an E2E entanglement operates as follows. Once the satellites that compose the E2E path have been selected, the controllers of the individual domains perform the operations needed to create an E2E entanglement between the GSs to which they are connected, and the *border QSRs* that are highlighted in red in Fig. 1. When the intra-domain E2E link has been established, the domain controller communicates this to the neighboring domain controller that has independently performed the same operations. The controller of the first domain sends the qubit to the edge satellite of the neighboring domain once the acknowledgment from the neighboring domain controller is received. The edge satellite receives the particle and performs a swapping operation in order to generate an E2E link between GSs belonging to the two distinct domains. At the end of the procedure, an E2E entanglement is created between the GSs.

Entanglement Generation Strategies

A QSCS, in addition to the northbound, southbound, east/westbound API typical of a SDN controller, also includes a module for the path selection and a module dedicated to the entanglement generation management, as depicted in Fig. 1. Whenever it is necessary to interconnect two GSs, the distributed application invokes the controller's best path evaluation module via the northbound API. The QSRs, which are the devices that make up the DP, generate and exchange entangled particles based on information provided by the SDN controller embedded in the QSCS through the southbound API. In order to speed up the E2E coupling procedure, it is necessary to carefully choose an appropriate scheme for generating the entanglement.

There are several basic schemes for generating entanglement on a link through the coordinated action of two end nodes. This article focuses on two of those methods:
- *At source:* In this scheme, one of the two end nodes sends a flying qubit that is entangled with one of its matter qubits. A transducer at the other end of the link transfers the entanglement from the flying qubit to one of its matter qubits.
- *At mid-point:* In this approach, an entangled photon pair positioned between the two nodes with matter qubits sends an entangled photon through a quantum channel to each of the nodes [3].

In the considered scenarios, the at-source strategy, which is depicted in Fig. 2a, works as described: The L2L Bell pairs are generated according to the policy applied by the controller, which sends a message to the GSs and all the satellites that are part of the path. Once the controller receives the feedback messages, it sends a message to a subset of the selected satellites in order to perform the swapping procedure. The controller continues sending the relative messages to the remaining satellites until the entangled E2E link is established.

The at mid-point strategy considers some satellites of the path as *generators* of Bell pairs, which sends the particles to other satellites that in turn perform the swapping operation, as shown in Fig. 2b. Once the best path has been evaluated, QRs are assumed to have been properly selected by the controller. With the at mid-point procedure, it is possible to avoid some swapping operations, considering that some satellites are only generators of Bell pairs and are, therefore, not involved in the swapping process.

Performance Evaluation

We conducted a campaign of simulations with the objective of verifying the performance in terms of overhead and delay required to obtain an entanglement between two GSs using a quantum satellite backbone.

According to the considerations discussed in the previous section, a constellation such as Iridium NEXT, consisting of 75 satellites, has been considered in the simulated scenarios. As a first case, we considered a single controller located on a satellite in a continental scale scenario; we performed a simulation considering a reference time interval of 60 [min] and capturing a sample every second. The GSs have been located at a distance of 10,000 km from each other. We measured both the number of packets exchanged to generate a Bell pair between the GSs exploiting the satellite path and the latency required to achieve this E2E coupling. A comparison of the two strategies illustrated in the "Entanglement Generation Strategies" section was performed and the results show that the strategy named *at source* is the more appropriate one, as can be seen in Fig. 3. This is because the probability of success in generating an entangled particle pair with the at mid-point method is lower, considering that both particles have to pass through the free space. Hence, the total entanglement generation probability is given because of the likelihood of success on both the links.

Having identified the best strategy, we extended the scenario by placing the stations at the maximum distance possible at the Earth antipodes. We then compared two different architectures — a single controller positioned on the ground at 10,000 [km] from the GSs and one controlled by two controllers belonging to the constellation.

As seen in Fig. 4, the scenario with multiple mobile controllers allows achieving higher performance in terms of the overhead and the generation time of Bell pairs. The control protocol overhead is represented in Fig. 4a, where it is possible to notice that the distribution of operations between two domains requires fewer packets to perform the total amount of operations. The improvement, with regard to the architecture with a single controller on the ground, depends on the fact that part of the operations of entanglement generation and entanglement swapping are locally performed without the need to send additional control messages, considering that the CP is integrated into the DP. The number of packets exchanged also depends on the number of satellites that are part of the E2E path, which in the considered time interval varies between four and six.

In Fig. 4b, we considered a realistic packet loss probability for infrastructure with a single controller on the ground. Indeed, all the traffic from the controller to the satellites and the respective

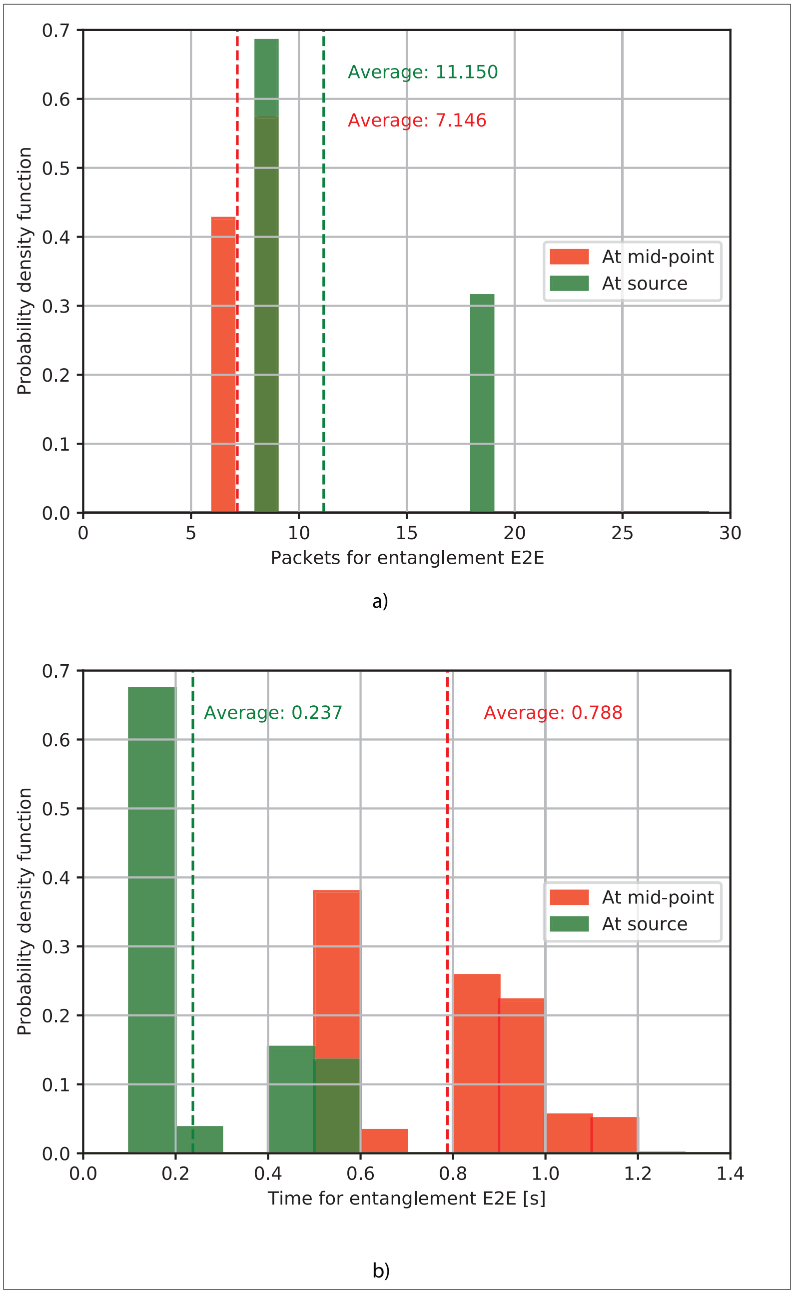

FIGURE 3. a) Packets exchanged for a single session using both strategies; b) The time required to establish an entanglement E2E.

acknowledgments use the link between the GSs and the directly connected satellite, which is the most critical link. In addition, traffic to and from the ground controller also uses a fiber optic link.

The packet flow between the GSs and the controllers was also considered in our architecture. But, deploying the controllers that manage the operations to be performed on the satellites of the selected path directly to the satellites mitigates the losses, which we considered negligible. The improvement in terms of latency required to establish an E2E entanglement compared to the case of a single controller on the ground depends on some entanglement generation and swapping operations that can be performed on the device with the controller process embedded, while avoiding sending some messages, thus saving time.

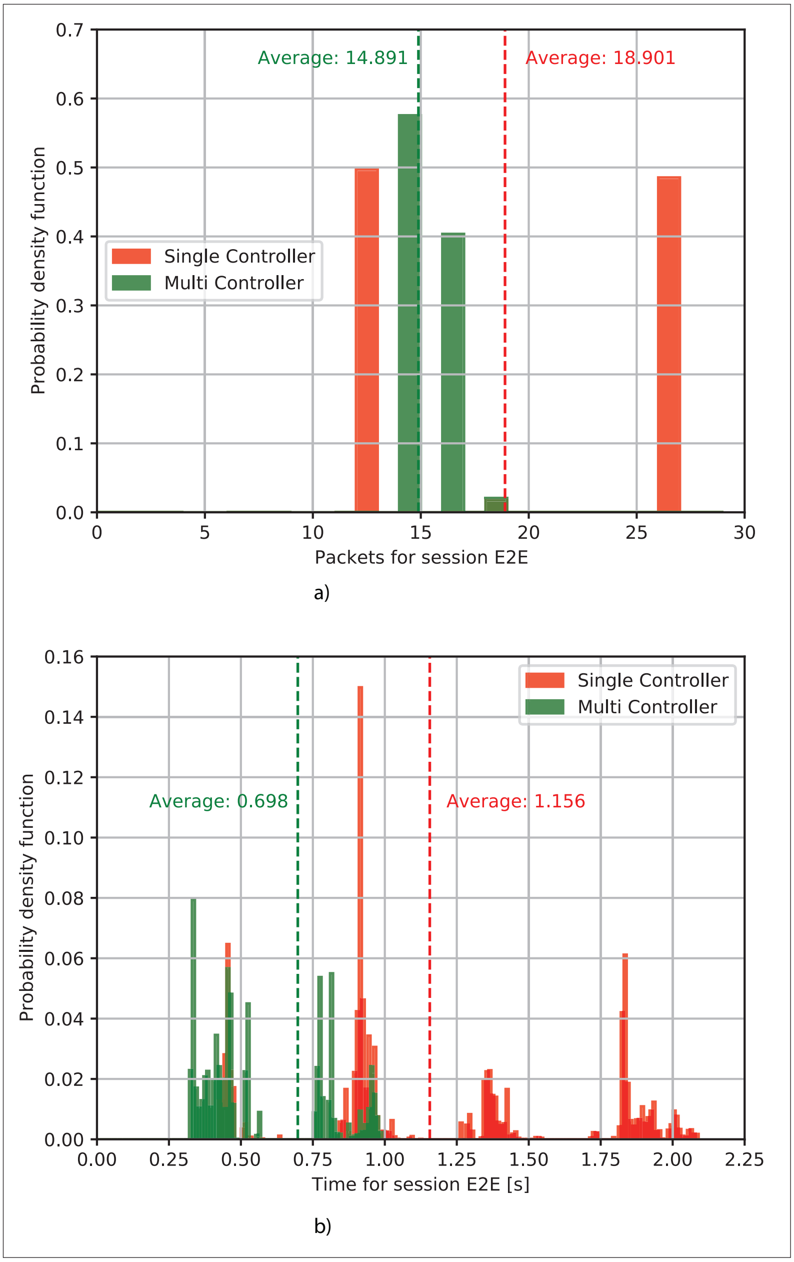

FIGURE 4. a) Packets exchanged during a single session using a single controller on the ground and the multi-controller architecture; b) the time required to establish an entanglement E2E.

Conclusions and Future Perspectives

Much progress has been made in the development of quantum devices. It is necessary to create specific networks based on quantum physical principles in order to interconnect quantum on Earth servers with the aim of obtaining an unprecedented computational capacity. Considering that satellite constellations can overcome the limitations of terrestrial QNs and the recent technological developments of quantum satellite communications, we have considered the option of creating a LEO quantum satellite backbone. Specifically, our investigation aims at deriving some guidelines for the design of an efficient quantum satellite backbone using SDN technology, with a focus on the CP procedures and interfaces. We compared two different procedures for the generation of E2E entanglement on a single controller scenario that is part of the constellation. In addition, we applied the most effective procedure to both scenarios — a single controller on the ground capable of managing the entire constellation and allocating multiple controllers within the constellation. Adopting an architecture comprised of multiple mobile controllers solves many issues and achieves better performance than a single controller on the ground. In addition to limiting the traffic on the satellite Earth routes, which are the most critical, it can help to reduce the overall delay, which is crucial in distributed quantum computing applications. The performance has been evaluated in terms of the overhead and latency required to establish an E2E entanglement. The proposed SDN backbone, based on the use of multiple mobile controllers deployed in the constellation, allows for achieving better performance for both the considered parameters with regard to the architecture with a single controller on the ground.

However, there are issues that need investigation. Notably, the integration of the quantum satellite segment with the terrestrial network — considering mixed and interoperable scenarios — will be an important step toward the creation of a global quantum network. The use of these technologies could bring considerable improvements in both security and information processing, allowing the interconnection between multiple clusters of QCs. A further step forward could be achieved with an architecture that includes a master controller able to allocate the controllers in the satellites that compose the entire path in an intelligent manner based on the results of an optimization algorithm studied for QNs to satisfy fidelity requirements. This article represents a first attempt to interconnect two QCs through a satellite backbone. However, considering that distributed quantum computing can rely on more complex communication patterns, that is involving more than two QCs, a generalized scenario will be addressed in future development by evaluating its E2E scalability and flexibility.

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