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Towards Quantum Satellite Internetworking: a Software Defined Networking Perspective

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ABSTRACT Recently, quantum computing and communications rapidly developed to interconnect heterogeneous quantum devices. In particular, some researchers have been performed about terrestrial quantum communications over typical optical fiber links. However, this technology is affected by extremely high losses that can be faced only through the deployment of several repeaters, which in turn involve impractical costs for end-to-end (E2E) route management. Quantum Satellite Networks (QSNs) can overcome the limitations of terrestrial optical networks, such as a remarkable signal attenuation over long distances and difficulty of intercontinental communications. The recent studies on quantum satellite communications motivated our research towards a Low Earth Orbit (LEO) quantum satellite backbone for interconnecting quantum on Earth Servers in order to achieve an unprecedented computational capacity. Specifically, our paper proposes a near optimum E2E path evaluation procedure allowing an efficient switching in order to maximize the entanglement generation rate. Indeed, this is one of the main issues that involve the Data Link Layer and the Network Layer of the Quantum Internet (QI) protocol stack, which is in its early standardization phase. In particular, the design of our approach is based on the Software-Defined Networking (SDN) paradigm with the aim of minimizing the number of hops for E2E connection and maximizing network capacity. Therefore, we compare distributed and centralized approaches in order to achieve a trade-off between performance and cost.

INDEX TERMS Low Earth Satellite Constellations, Quantum Internet, Software-Defined Internetworking

I. INTRODUCTION

An impressive progress has been made recently in the making of Quantum Computing (QC), up to the realization of 53 qubit processing devices, as explained in [1]. It is therefore necessary to create networks that are able to interconnect these quantum servers with the aim of obtaining an extraordinary computational capacity. These networks are based on the phenomena of quantum entanglement and quantum teleportation, described in [2] and [3]. It is possible to make a comparison between classical and quantum networks considering that a network of quantum nodes which is linked by classical channels and comprises k nodes each with n quantum bits has a state space of dimension $k2^n$, whereas a fully quantum network has an exponentially larger state space, that is 2^{kn}. This implies that if we consider k remote quantum devices, by devoting at least one qubit at each device for the teleporting process, a virtual quantum device consisting of up to $kn - k$ qubits is obtained [4] [5]. As described in [6], the Quantum Internet (QI) will be merged into the classical Internet to form a new *hybrid* Internet which may either improve classical applications or enable new quantum applications. The physical connections among the various nodes in the QI are expected to be primarily fiber optics and free-space optics. Optical signals are particularly efficient because photons are very suitable for physically encoding qubits. As can be deduced from [7], single-photon signal transmitted over long-distance optical fiber suffers from depolarization and very high losses. In order to overcome such distance limit, *quantum repeater* (QRs) nodes between the sender and the receiver are needed to obtain high efficiency on the total distance. In contrast to classic repeaters, QRs can not clone quantum signals. This peculiarity depends on the no-cloning theorem and the uncertainty principle, which are the physical laws making quantum communications absolutely secure [8]. Specifically, these devices are equipped with quantum memories, which generate the entanglement between adjacent nodes via the transmission of photons entangled with their memories. The entanglement swapping is then performed, between adjacent nodes that acknowledge the existence of entanglement with other repeater nodes by receiving heralding signals from different repeater nodes at long distances [9]. Hence, could not be an effective solution to carry the keys using optical fiber over long distances, as confirmed in [10].

Moreover, free-space quantum links have been considered in recent years in order to address the limitation of optical fibers. Compared to optical fibers, the free-space photon will experience negligible loss in vacuum, making it feasible to distribute secret keys over thousands of kilometers [8] [11].

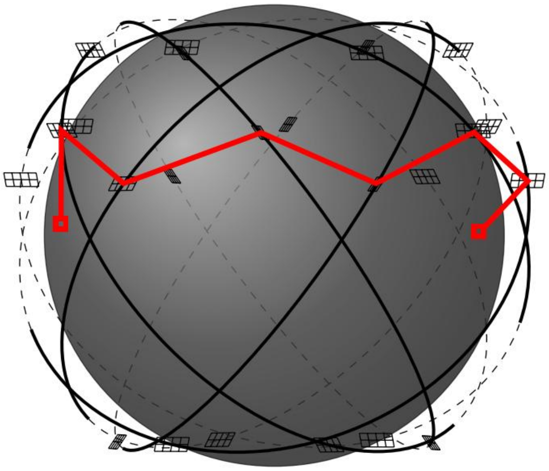

FIGURE 1: A possible connection between two ground stations (represented as squares) via multiple satellite links.

The geostationary earth orbit (GEO) satellites constellations are not suitable for quantum communications considering that their signal can suffer from high channel loss and limited key generation rate [8]. Given the previous considerations, in this paper we propose to realize a quantum network through a low orbit satellite network infrastructure. A Low Earth Orbit (LEO) quantum satellite backbone as represented in Fig. 1, would allow tackling the problem of distance by interconnecting ground stations located at long distances with a limited number of repeaters than a fiber optic connection. Each satellite of the constellation is a repeater node enabled to perform the swap operation in order to create a *circuit* between two stations on the ground. In addition to the search for a properly designed constellation, it is needed to find an efficient routing algorithm that takes the inter-distances into account. The issue concerns the Data Link Layer and the Network Layer of the quantum networks protocol stack, which is in an early standardization phase [12]. We have analyzed the problem from an end-to-end perspective, so as regards the choice of the *best* path, where it is necessary to compare *distributed* and *centralized* approaches to achieve the best performance. As reported here [13], the communication *rate* is a function of the maximum distance between two adjacent quantum repeaters instead of the overall length of the end-to-end path. Hence, the best routing approach applied on quantum networks has to maximize the entanglement generation rate minimizing the interdistances between the satellites of the end-to-end path. Quantum networks need a signaling function in order to establish the connection. In fact, once the path for a quantum virtual circuit has been evaluated, signaling is used to set up it along quantum routers on the path. The signaling may be distributed or centralized. A centralized routing algorithm can be implemented on a central controller following the Software-Defined Internetworking (SDNI) paradigm as defined in [14], which can include an interface between SDN Controllers belonging to neighbouring domains for coordinating traffic policies. Considering that quantum networks need an abstraction of the hardware for specifying the forwarding rules we can talk about Quantum SDN (QSDN). The Control Plane (CP) that concerns routing and signaling operations is decoupled from the Data Plane (DP) which is in charge of creation of Bell pairs. The CP traffic which is constituted by routing and signaling messages is exchanged over a classical channel, while DP traffic which is made up of Bell pairs is sent over a separate quantum channel [15].

The Data Link Layer model proposed in [13], is in charge of first creating a Bell pair at a node halfway between the source and destination, then propagates the member qubits toward the endpoints in a hop-by-hop teleported fashion. In order to do that, an application must requests that the node in the middle of the path creates the Bell pair and propagates it outward. Hence, the problem related to the identification of the central node can be easily solved using an SDN-based architecture.

In this paper we have analyzed and outlined the guidelines for a quantum satellite backbone network consisting of satellites that are quantum repeaters with the following contributions:

- the design of an SDN-based architectural scheme to control the quantum satellite backbone
- the optimization of the E2E best path analyzing distributed and centralized schemes and in particular evaluating the performance of two distributed algorithms such as Modified Random Walk and Ant Colony Optimization [16] and a centralized solution which uses Dijkstra's algorithm
- a feasibility study on a practical LEO constellation

The performance of the considered algorithms is evaluated in terms of the *entanglement rate* value, which is the rate for quantum communications measured as Bell pairs per seconds. This parameter is conditioned by the E2E path length, the maximum inter-satellite distance and the number of hops.

This paper is organized as follows: Section II provides an overview of the state of the art. In Section III we explain the satellite network architecture, while in Section III-A the problem statement is shown. Section III-B provides an overview of the proposed algorithms. In Section IV we describe the simulation framework, the system implementation and validation. Finally, Section V concludes the document and outlines future prospects.

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II. STATE-OF-ART

One of the prerogatives of QI is that of being able to interconnect multiple quantum devices in order to obtain an extremely high computational capacity. Considering the problem of distance, the physical interconnection infrastructure between a source node and a destination node can be realized following different approaches. Direct optical fiber links are likely to be the best choice only for distances of a few hundred kilometres. However, the use of LEO satellite links may be the optimum solution for longer distances of a few thousand kilometres to reduce the channel loss [17]. The future QI will be likely to integrate both the terrestrial and satellite network segments. This goal can be achieved with a Service-Oriented Architecture (SOA), which is an approach that addresses the requirements of loosely coupled, standards-based, and protocol-independent distributed computing. In this kind of architectures, it is irrelevant whether services are local or remote, the interconnect scheme or protocol to effect the invocation, or which infrastructure components are required to establish the connection [18] [19]. In Delay-Tolerant Networking Architecture (DTN), where communication links are not always available or reliable, the epidemic routing has been proposed [20] [21]. Moreover, architectures like DTN are particularly suited to cope with the challenges due to the space environment. Each node of the DTN architecture can store information for a long time before forwarding it. A suitable solution for routing on DTN space networks is represented by Contact Graph Routing (CGR), where each node on the path computes a route from itself to the bundle destination based on a computed graph [22].

Many studies consider that a quantum-capable satellite constellation can be used to realize a global quantum network. In particular, in [23] predicted that in the next few years, an increasing number of free-space quantum experiments will be performed all around the world, with a focus on how to share entangled quantum bits over a satellite channel and quantum key distribution. Some European Space Agency (ESA) funded studies are targeted to evaluate various methods to measure the gravitational decoherence effect [24]. Reducing the rate of environmental decoherence will improve the processing and communication of quantum information [25]. With lower satellite prices and the spread of quantum-based technologies, private companies could offer cryptographic services to their clients that are based on quantum satellite links.

As described in [26], a European research team built a single photon source that emits from a LEO satellite to a station on Earth demonstrating the feasibility of detecting individual photons from a source on a LEO satellite. Another contribution documented in [27] is about a microsatellite-based quantum-limited communication experiment in a LEO-to-ground link. The link consists of the microsatellite cubic in shape with a mass of 48 kg and a side length of 50 cm and an Optical Ground Station in Tokyo, Japan. Similar studies have followed over the years evaluating the entanglement generation rate on single links over time [28] [29]. The Micius satellite, which orbits at an altitude of about 500 km, was used as a trusted relay to distribute secure keys between multiple distant locations in China and Europe. Moreover, in this experiment some qubits were generated at a ground station and teleported to the satellite [30] [31].

As explained in [32], Free Space Optics (FSO) is a technology that has found application in several areas of the short and long-haul communications space, for instance on inter-satellite links. The performances of FSO systems are usually limited by atmospheric factors 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 [33]. This technology can also be applied to space communications on CubeSat satellites as explained in [34]. Moreover, the FSO technology has already been used in the realization of quantum communications on Earth, connecting via two free-space optical quantum and classical links, the two Canary Islands of La Palma and Tenerife [35].

The experiments carried out so far have concerned individual links between a ground station and a single satellite, that requires the realization of Data Link Layer protocols like in [36], but when the first constellations will be launched it will also be necessary to address efficient routing approaches.

Many studies have been carried out on routing for terrestrial quantum optical fiber networks, but the application of routing algorithms on quantum networks based on LEO satellites is a research direction worth exploring. The path selection problem we have faced in this paper is akin to the routing problem, therefore we compared distributed and centralized solutions also defining an SDN-based architecture.

III. SYSTEM MODEL

As explained in [8], the procedure of quantum satellite-to-ground communication consists of a quantum communication paired with a classical communication which usually uses different wavelengths multiplexed over the same laser link. The quantum satellites are able to conduct both quantum communication and classical communication using a unique integrated transponder. Typically, the quantum signal is transmitted on downlinks and the classical signal is transmitted on uplinks. The single polarized photons are sent through the quantum channel, while classical channel can be used for the measurement-basis signals and key-relay services, as well as for future data services. For the inter-satellite quantum channel, the FSO technology with a wavelength of 1550 [nm] is used due to its higher efficiency. To be compatible with classical communications, multi-beam system is used in inter-satellite communications. With the on-board multi-beam transponders, quantum signal and data signal can be carried on different laser beams, in the same optical link.

The satellite network is similar to a terrestrial fiber optic

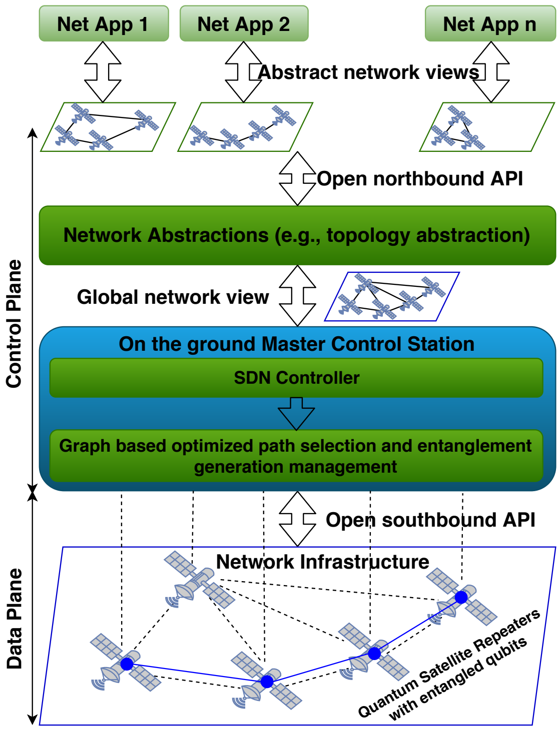

FIGURE 2: Quantum Software-Defined Internetworking architecture.

network, considering that the ground stations distributed across Earth and satellites are nodes equipped with quantum memories, as explained in [28]. In order to connect a source ground station and a target ground station, entanglement for quantum memories between adjacent quantum satellites is generated through the transmission of photons entangled with those memories.

A ground station may have characteristics similar to those of a typical radio telescope like the Italian Sardinia Radio Telescope, which as described in [37] has an elevation of between 5 and 90 degrees. LEO satellites, which orbit in a spherical region that extends from the Earth's surface up to an altitude of 2000 km [38], could be an excellent alternative to fiber optic communications. Because of their low altitude, the path length traversed via the satellites between points on earth is only slightly longer than the great circle distance between the points, hence they eliminate the long propagation delay encountered by Geostationary Earth Orbit (GEO) satellites [39]. New LEO satellite constellations like OneWeb, Telesat, and Starlink quoted in [40] are going to be launched in the near future, but the dataset we considered is the one related to the constellation IRIDIUM NEXT made up of 75 satellites, 66 cross-linked satellites and 9 in-orbit spares operating in a LEO, at an altitude of 800 km [41].

As explained in Section I, such a network could be controlled centrally following the SDN paradigm as shown in Fig. 2, of which we provide a brief description in the following. The entire constellation can then be controlled by one Master Control Station (MCS) on Earth like Global Positioning System (GPS), as explained in [42]. The Controller derives the data required to build the entire satellite network state. Then, a centralized routing algorithm that calculates the best path can be applied. Whenever it was necessary to interconnect two ground stations, the distributed application invokes the Controller best path evaluation via the northbound API. The quantum satellite repeaters which are the devices that make up the DP, generate and exchange entangled particles based on information provided by the controller through the southbound API. In order for the coupling procedures to take place quickly, it is necessary to carefully choose the satellite from which to start the propagation procedure of the Bell pairs. As in the model proposed in [13] the satellite in the middle is detected by the Controller which sends it the necessary instructions to start the propagation procedure. Then, the creation of the Bell Pairs starts from this satellite and propagates it towards both ground stations. The procedure of entanglement generation on the links that compose the path can be accomplished according to the schemes described in [15] that require a coordinated action between the nodes at the two ends of the inter-satellite link and between the ground stations and the connected satellite. When the entire E2E connection via Bell pairs has been established, the Controller will send the necessary messages to activate the swapping operations through the southbound API. When the Controller will be notified by the involved repeater that the swapping operations have been successfully performed and therefore the E2E entanglement has been created, it will send to the ground transmitting station an authorization notification to transmit the data packet containing the teleportation bits. The traffic needed for this process is all exchanged on the classic channel.

A. PROBLEM STATEMENT

A typical quantum network is based on the phenomenon of entanglement swapping which allows generating a pair of entangled particles at a long distance and quantum teleportation. In order to allow an exhaustive characterization of the model, we explain first the physical principles on which a quantum communication is based.

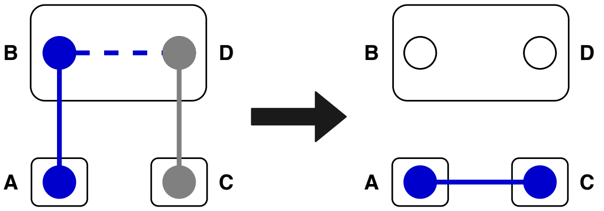

FIGURE 3: Operating principle of a repeater. Entanglement swapping is performed between two pairs of particles executing a Bell state measurement on two of them.

The entanglement swapping process can also be implemented in a satellite context, as it is proposed in [43].

As described in [44] and [45] the entanglement swapping procedure shown in Fig. 3 works as follows. Preparing two independent entangled pairs A–B and C–D, a joint Bell-state measurement on B and D has the effect of projecting A and C onto an entangled state, although these two particles have never interacted nor share any common past.

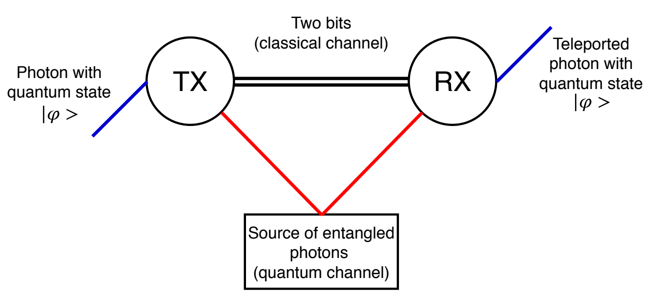

FIGURE 4: Scheme of a quantum communication based on teleportation. A particle with quantum state $|\psi\rangle$ is teleported sending two bits on the classical channel.

In quantum teleportation described in [46] and [47], the state of a qubit is destroyed in one location and recreated in another. Initially, a pair of particles indicated as a Bell pair is distributed, one member to the source, and the other to the destination. The qubit of the quantum memory that must be teleported is entangled with the source's member of the Bell pair. This is done performing a measure on the data qubit and source's Bell qubit. Each measurement that results in one classical bit destroys the quantum state of the qubit and these results are communicated to the destination using a classical channel. The recipient uses them to decide what quantum operations it has to perform on his Bell qubit in order to recreate the original state of the data qubit. In this manner, the *no-cloning principle* is observed and the *no faster than light communication principle* is not violated [48]. The quantum teleportation procedure has already been carried out in the satellite context, as described in [31]. As already specified in Section I, repeater nodes are required to implement this mechanism, therefore the satellites of the constellation can be considered as repeater nodes. For this reason, the model we have derived is similar to the one presented in [7], but with technological improvements in order to apply it to free space.

Specifically, it considers the *entanglement generation probability* (assumed the same for each node) as a product between the photons generation probability p_g, the heralding and entangling detector efficiency, respectively indicated with η_h and η_d:

$$p = p_g \eta_h \eta_d \tag{1}$$

A remote entanglement between two adjacent nodes is generated through the operation of *entanglement swapping* accomplished by carrying out an optical Bell-State Measurement (BSM) of the two photons. In details, an heralded local entanglement is generated on each node, they are sent to the BSM and then are measured. Hence, the link entanglement generation probability between the i-th and j-th nodes is defined as:

$$p_{i,j} = \frac{1}{2}\eta_0 p^2 e^{-\frac{d_{i,j}}{L_\alpha}} \tag{2}$$

where η_0 is the optical BSM efficiency, $d_{i,j}$ indicates the Euclidean distance between the two nodes involved and L_α is the electric field attenuation length. As defined in [49], α is the attenuation of optical wave amplitude, which is the wave energy losses

$$\alpha = \frac{\omega\sqrt{2\varepsilon}}{2}\left[\sqrt{1+(\frac{\sigma}{\omega\epsilon})}-1\right]^{\frac{1}{2}} \tag{3}$$

As described in [50], L_α is defined as:

$$L_\alpha = \frac{1}{\alpha} \tag{4}$$

In order to calculate the attenuation length, we considered ε_r that is the resistivity and σ which is the conductivity, respectively described in [51] and [52]. The values relating to these parameters are shown in Table 1 of Section IV in where the framework is described.

Moreover, respecting the specifications shown in the Section III, the wavelength that we have chosen is $\lambda =$ 1550 [nm]. In the proposed model, $T_{i,j}$ is the average time required to generate a remote entanglement between two adjacent nodes, that is equal to:

$$T_{i,j} = \frac{\bar{p}_{i,j}T^f_{i,j} + p_{i,j}T^s_{i,j}}{p_{i,j}} \tag{5}$$

where $T^f_{i,j}$ is the total average time required for the failed attempt and $T^s_{i,j}$ is the average time required for the successful attempt. As shown in [53], the quantum coherence is equivalent to quantum entanglement in the sense that coherence can be correctly described as entanglement, and conversely that each entanglement measure corresponds to a coherence measure. It therefore corresponds to time within which it is possible to keep the information in order to successfully teleport qubits [7]. As stated in these studies [54] [55], it is possible to achieve a coherence time greater than 39 minutes, therefore given the technological improvements, unlike what is expressed in the reference model, we do not take this parameter into consideration.

As we specified in Section I, the communication rate is a function of the maximum distance between two adjacent quantum repeaters, instead of the entire length of the end-to-end link. Therefore, the time required to generate a remote entanglement on the route is defined as:

$$T_r = \frac{\max(T_{i,j}) + \tau_a + \max(T^c_{i,j})}{\eta_a} \tag{6}$$

where $T^c_{i,j}$ is the time required for ACK transmission over a classical communication link between two adjacent nodes marked with i and j, while τ_a and η_a are respectively the atomic BSM duration and efficiency. We considered η_a and η_0 values equal to 0.75 considering that in [56] are reported similar values. Finally, we define the *entanglement rate* on the same route as:

$$R \doteq \frac{1}{T_r} \tag{7}$$

The entanglement rate is also defined as a special kind of throughput [57] [58], or rather number of transmitted entangled states per second and is measured as Bell pairs per seconds. In [59] it is defined as the speed of variation of the relative entropy of entanglement.

B. PROPOSED FORWARDING STRATEGIES

Most traditional CP processes use a distributed architecture. For instance, each router runs its own Open Shortest Path First (OSPF) routing protocol process. Those distributed control plane processes use messages to communicate with each other, like OSPF protocol messages between routers. Therefore, traditional networks use a distributed CP [60]. A Delay-Tolerant Networking Architecture (DTN) does not expect that network links are always available or reliable [20]. In this scenario, epidemic routing could be an effective solution for an intermittently connected network. A generic node which applies the epidemic protocol works by transferring its data to each and every node it meets. As data is passed from node to node, it eventually reaches the target node. One of the advantages of an epidemic protocol is that by trying every path, it might be guaranteed to try the best path, while a disadvantage is the extensive use of resources with every node needing to carry every packet and the associated transmission costs [21].

On the other hand, a centralized CP has the logic in one place, running on a single device, or on an external server. Then the centralized procedure could have used protocol messages to learn information from the devices, but with all the processing of the information at a centralized location. A centralized application has all the data gathered into one place, hence it is easier to write than a distributed application. The SDN paradigm uses a centralized architecture, with a centralized control plane, with its foundations in a service called Controller [60]. In this paper, we have compared two distributed algorithms i.e. a Modified Random Walk (MRW) and an Ant Colony Optimization (ACO) with a centralized approach using the Dijkstra's algorithm that requires the integration into an SDN-based architecture like we have defined and that is depicted in Figure 2.

1) Modified Random Walk

We used as a benchmark a MRW procedure connecting satellites that are at minimum possible distance avoiding those ones that have been previously selected.

We can define as $\mathcal{G}$ the set of satellites that are part of the constellation. If we consider as $\mathcal{V}$ the set of visited nodes and with L_g the set of neighboring satellites of a satellite g, the algorithm proceeds only if

$$\forall g \in \mathcal{G} \; \exists \; l \in L_g \mid l \notin \mathcal{V} \tag{8}$$

Under the hypothesis of a perfect knowledge of the distances to neighboring satellites, a satellite routes a packet to the neighbor at minimum distance. If this satellite has already been visited previously, the next one in the sorted list of neighbours is selected and so on. The information about the previously visited satellites could be included in the data field of the packet and updated as it proceeds towards the destination node. If the packet reaches the destination node it means that the path has been identified and the quantum communication can be started.

This protocol has limited signaling traffic but may require the visit of a large number of nodes and may fail to establish the connection if all the nearby nodes have been previously visited.

Algorithm 1 Modified Random Walk

```
Initialize: $g$ as source, add $g$ to $\mathcal{V}$
while $g$ is not the destination do
    if $g$ is the destination then
        return Best path
    else
        for every node in $L_g$ do
            if all the nodes in $L_g$ are in $\mathcal{V}$ then
                Restart from source node
                  break
            else
                Consider nodes that are not in $\mathcal{V}$ and select
                  the closest one
                  Add the selected node to $\mathcal{V}$
        end for
end while
Output: Best path
```

2) Ant Colony Optimization

Adaptive routing is a process where a router can forward data via a different route or given destination based on the current conditions of the system. ACO, in which information gathered by simple autonomous mobile agents is shared and exploited for problem solving, has been applied to routing in telecommunications networks [61]. This algorithm is suitable for routing because it has characteristics like capability for self-organisation, self-healing, and local decision making [62]. As described in [63], social insect colonies like ants, bees, wasps or termites show sophisticated *collective* problem-solving in the face of variable constraints that emerges from relatively simple *individual* behaviors. Many of these processes are regulated by interactions between the individual agents within the colony, which will affect overall colony functioning. They use multiple modalities of communication, but the most commonly known are *pheromone* trails used to both recruit new workers to exploit the food source as well as guide these foragers to it. As shown in [16], an ant encountering a previously laid trail can detect it and decide with high probability to follow it, thus reinforcing the trail with its own pheromone. The obtained

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collective behavior is a form of *autocatalytic* behavior where the more the ants following a trail, the more attractive that trail becomes for being followed. Some definitions are given before describing the algorithm. The trail intensity is updated according to the following

$$\varphi_{ij}(t+n) = \varepsilon\varphi_{ij}(t) + \sum_{k=1}^{m} \Delta\varphi_{ij}^{k} \tag{9}$$

where ε is a decay factor of the trail on the edge and $\Delta\varphi_{ij}^{k}$ is the quantity per unit of length of trail substance laid on edge (i,j) by the k-th ant between time t and $t+n$. If the k-th ant does not use the edge in its tour the value is zero, otherwise it is equal to

$$\Delta\varphi_{ij}^{k} = \frac{Q}{\Lambda_k} \tag{10}$$

where Q is a constant that we set as 1 and Λ_k is the tour length of the k-th ant. The probability of going to the j-th node is:

$$p_{ij}^{k}(t) = \frac{|\varphi_{ij}(t)|^{\beta}|\frac{1}{d_{ij}}|^{\gamma}}{\sum_k |\varphi_{ik}(t)|^{\beta}|\frac{1}{d_{ik}}|^{\gamma}} \tag{11}$$

The value of $\varphi_{ij}(t)$ gives information about how many ants in the past have chosen that same edge and $\frac{1}{d_{ij}}$ says that the closer a town the more desirable it is. The other parameters β and γ act as a weight on pheromone and distance respectively. In the context of networks, an ant is a routing packet emitted by a satellite node, interspersed with the normal traffic, with a randomly chosen destination node. Pheromones represent the quality of the traversed paths and a transition rule is used to define the probability that the ant chooses to move through the edge, as explained in [61] and [64]–[66]. The ACO algorithm proceeds as follows. Every ant moves from satellite i to satellite j choosing the satellite to move to with a probability described in (11). After n iterations all ants have completed a tour. At this point for each ant k the value of Λ_k is computed and the values $\Delta\varphi_{ij}^{k}$ are updated according to (10) and the shortest path found by the ants is saved. This process is iterated until the tour counter reaches the maximum (user-defined) number of cycles, or all ants make the same tour.

Algorithm 2 Ant Colony Optimization

```
Input: Number of ants, number of cycles
Initialize: Pheromone values
while number of cycles not completed do
    for each ant do
        Deposits a quantity of pheromones according to equation 10
        Ant makes a decision on what satellite to go according to the numerator of equation 11
    end for
    Multiply the pheromone matrix by decay factor
end while
Output: Best path
```

3) Dijkstra's Algorithm

The version of Dijkstra's algorithm that we used is described in [67] and [68].

Consider a directed graph G, one of whose vertices is distinguished as the source s, and each of whose edges (v,w) has a nonnegative length $l(v,w)$. The number of edges is denoted by m and the number of vertices by n. Furthermore, there is a path from s to any other vertex, therefore $m \geq n-1$. The algorithm solves the shortest path problem using a tentative distance function d from vertices to real numbers with the following properties:

- For any vertex v such that $d(v)$ is finite, there is a path from s to v of length $d(v)$
- when the algorithm terminates, $d(v)$ is the distance from s to v.

Initially $d(s) = 0$ and $d(v) = \infty$ for $v \neq s$; afterwards, each vertex can be in a state between unlabeled, labeled, or scanned. Initially, only the source node is labeled, while all other vertices are unlabeled. The algorithm proceeds scanning each vertex until there are no labeled vertices.

Using this version of Dijkstra's algorithm a total running time equal to $O(n\log n + m)$ is obtained. This algorithm requires a centralized routing CP that is a feasible concept and is capable of simplifying routing management. It requires SDN which separates the network control plane from the data plane and enables a Network Operating System (NOS) which interacts with packet forwarding elements [69].

Algorithm 3 Dijkstra

```
Input: Directed graph $G$
Initialize: A set $S$ to store finalized vertices and a distance matrix $d$, where $d[v]$ represents the length of the shortest path from $s$ to $v$. Let $d[s] = 0$ and $d[v] = \infty$ for $v$ not equal to $s$.
while every vertex is in $S$ do
    Delete the item of minimum key in heap $h$ and put it in $v$
    Declare $v$ scanned
    for each $arch(v,w)$ do
        if $d(w) = \infty$ and $d(w) = d(v) + c(v,w)$ then
            $d(w) = d(v) + c(v,w)$
            Insert x into heap
        else if $d(w) < \infty$ and $d(v) < d(v) + c(v,w)$ then
            $d(w) = d(v) + c(v,w)$
            Declare $w$ labeled
    end for
    Add $v$ to $S$
end while
Output: Best path
```

IV. SIMULATION RESULTS

In this Section, we firstly describe the framework and the adopted libraries to model and test the proposed approaches, whose results are then shown for different scenarios. All the trajectory data were obtained considering the Two-Line Element Set (TLEs), which is a data format encoding a list of orbital elements of Earth-orbiting objects for a given point in time, the epoch. They allow rapid, modestly accurate propagation of space object motion [70]. The satellite topology matrix is calculated when the satellite trajectory datas are obtained from these files. In particular, we used the `skyfield` Python package in order to operate on the file containing the TLE coordinates [71] to get the necessaries data and the `pygeodesy` package in order to work with the coordinates and the routing algorithms included in the `scipy` package. Many of the values are consistent with the reference model, but for p_g, η_h, η_d denoting the photons generation probability and the heralding and entangling detector efficiencies, respectively, we considered values reported in [72]–[74]. Other parameters considered in the model are the speed of light c, η_0 and η_a which denotes, respectively, the optical BSM efficiency and the atomic BSM efficiency, while with τ_0 and τ_a we denote the optical and atomic BMS duration.

Parameter	**Value**
c	$3 \times 10^8 [\frac{m}{s}]$
η_0, η_a	0.75
λ	$1550 \times 10^{-9} [m]$
L_α	$743704275.359 [m]$
η_h, η_d	0.95
τ_h	$10 \times 10^{-6} [s]$
τ_t	$20 \times 10^{-6} [s]$
τ_0, τ_a	$10 \times 10^{-6} [s]$
p_g	0.9
σ	$8 \times 10^{-15} [\frac{S}{m}]$
ε_r	$1.000536 [\frac{C^2}{Nm^2}]$

TABLE 1: Values of the parameters adopted in the experiment.

In the following, the curves in red depict the performance obtained by the MRW algorithm, in blue the ones for ACO, while in green the results obtained by applying the Dijkstra's algorithm. The tests were carried out by connecting two terminal stations on the Earth's surface placed at the antipodes for a reference time interval of sixty minutes and capturing a sample every 500 ms.

First of all, we focus on the entanglement rate achieved over a single link, whose length has been varied between zero and 10000 [km]. As shown in Fig. 5, the entanglement rate value tends to decrease with a *super-exponential* trend. Considering that we have used in the model parameters that can be traced back to the best technologies currently available, the value of the entanglement rate is higher than other works in the literature, such as in [29], in which they claim to be able to reach an entanglement rate equal to 4 [Bell pairs / s] with LEO satellites. These considerations are fundamental, especially in the design of satellite backbones in even higher orbit as proposed in [75].

Moreover, we analyze the performance with respect to the length of the end-to-end path and the number of hops

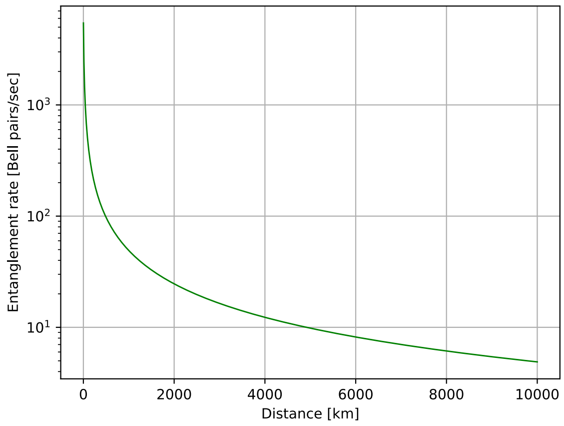

FIGURE 5: Entanglement rate for different L2L inter-distances.

for the three considered routing approaches. In particular, Fig. 6 shows the path length, while in Fig. 7 the maximum inter-satellite distances are shown. Furthermore, in Fig. 8 the number of hops are represented. Each Figure depicts the histograms of the Probability Density Functions (PDF) of the three algorithms for each considered parameter and their statistical fitting, where the value at the origin of the x-axis represents the failures, that only occurs when MRW fails in the generation of the E2E path.

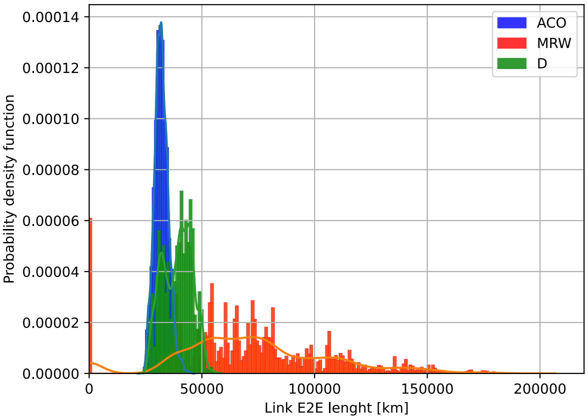

FIGURE 6: E2E path Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

As can be seen from Fig. 6 (summarized in Table 2 where the average values μ of the distributions and the relative standard deviations σ are presented), the length of the end-to-end paths achieved by the MRW protocol is greater than for the other two cases. As regards to the other two approaches, we can see that Dijkstra's algorithm creates routes that are shorter on average than MRW but longer than the ACO algorithm. Considering the results in Table 2, we

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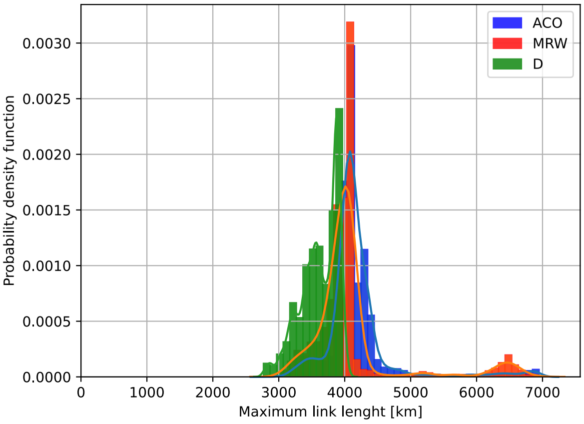

FIGURE 7: Maximum single link length Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

can see that using Dijkstra's algorithm we have longer routes with a greater number of hops.

Moreover, as can be seen from Fig. 7, the Dijkstra's algorithm is able to guarantee a maximum inter-satellite distance lower than the others, a factor that mostly affects the distribution of entanglement rate values. Fig. 9 shows the PDF of the entanglement rate which represents the objective function for all the investigated schemes.

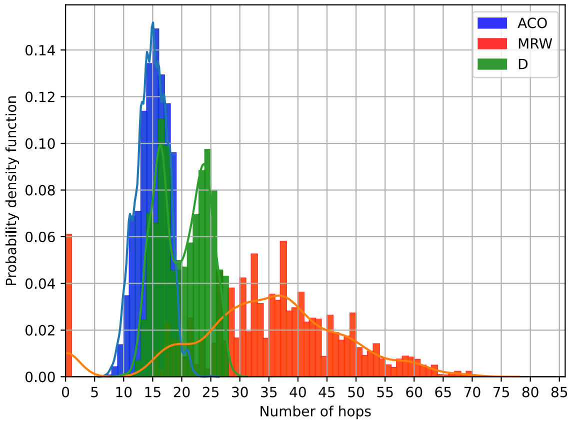

FIGURE 8: Number of hops Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

Finally, the distance between the two ground stations has been varied starting from a distance of 1000 [km] up to the antipodes with a step of 1000 [km]. As can be seen from Fig. 10, Dijkstra's algorithm provides better performance than the other ones. However, ACO has a similar trend managing to achieve similar performances.

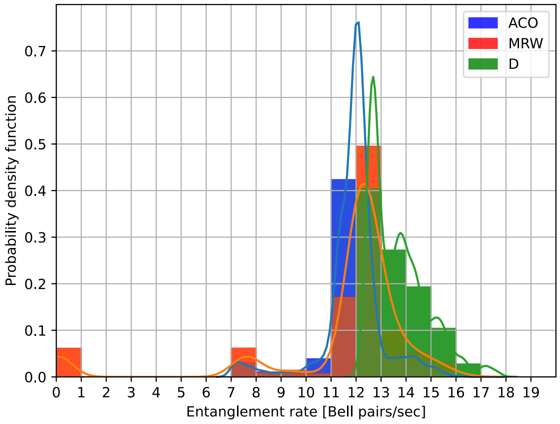

FIGURE 9: Entanglement rate Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

Algorithm	MRW		ACO		D	
Average and Standard deviation	μ	σ	μ	σ	μ	σ
End-to-end path length [km]	75610	34774	31897	2755	38965	6598
Maximum single link length [km]	4218	751	4229	564	3745	195
Number of hops	35	14	15	3	19	4
Entanglement rate [Bell pairs / s]	11.196	3.224	11.786	1.194	13.175	0.724

TABLE 2: Average and standard deviation of the evaluated parameters for the considered MRW, ACO and Dijkstra protocols.

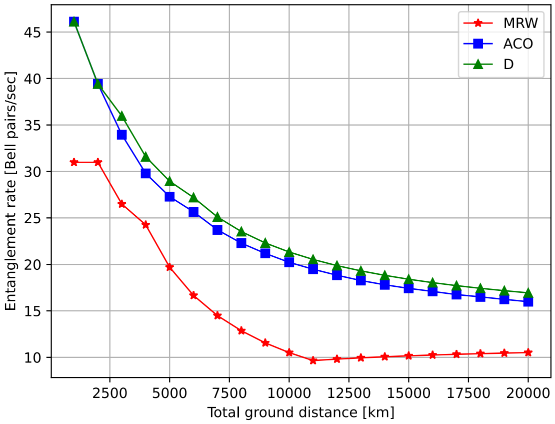

FIGURE 10: Entanglement rate as the distance between ground stations varies for the considered MRW, ACO and Dijkstra protocols.

As shown in the Figures and Table 2, the values achieved are not very high, due to the current technological limits of the devices. The results already allow us to understand which could be the best routing policies to be adopted on entanglement based networks. The centralized solution based on Dijkstra's algorithm allows reaching higher average entanglement rates this is because, although the end-to-end section is longer a greater number of nodes are also involved, which allows for shorter inter-node links. The fact of being able to obtain short inter distances increases the probability of success in the generation of Bell pairs.

Despite the application of ACO in network routing has many advantages, there are some unsolved problems when it is applied in satellite networks. The routing algorithm is limited by the mobility of satellite networks, and satellite handover could bring negative influence to the performance [76]. In particular, ACO's performances appear similar to that of Dijkstra's algorithm, but the speed of scenario variation due to the displacement of satellites in LEO orbit may require extremely high signal traffic for ACO. Moreover, as described in [77] [78], considering that the algorithm is computationally complex and has a slow converges speed, it could not be suitable for real-time business with a large volume. Therefore, an SDN-based architecture as well as higher values in terms of entanglement rate guarantees shorter convergence times in the calculation of the optimal solution and better strategies both in terms of entanglement propagation and swapping procedures management.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

Considering the progress that has been made recently in making quantum devices, it is necessary to create specific networks based on quantum physical principles in order to interconnect quantum on Earth servers reaching an unprecedented computational capacity.

Quantum Satellite Networks can overcome the limitations of terrestrial optical networks and the recent technological developments in terms of quantum satellite communications motivated our investigation on a LEO quantum satellite backbone. Specifically, our aim is to propose a near optimum E2E path evaluation procedure allowing an efficient switching in order to maximize the entanglement generation rate. We compared two distributed approaches MRW and ACO and one centralized using Dijkstra's algorithm in order to achieve a trade-off between performance and cost. We can note that the centralized strategy in addition to solving the problem of the propagation of Bell pairs, it allows reaching higher entanglement rate values by involving an acceptable number of intermediate nodes. Furthermore, the average entanglement rate value of the centralized approach relying on Dijkstra's algorithm is higher than the other ones. This is because Dijkstra's algorithm is able to select end-to-end links whose maximum inter-satellite distance is less than other algorithms.

New LEO satellite constellations are in the launch phase and arouse particular interest from many private companies and research centres, while a complete quantum LEO satellite constellation has not been designed yet. The problems that can emerge with networks of this type applied to the quantum world have to be explored. For instance, on the proposed architecture it is important to evaluate the necessary overhead traffic to perform the path selection and the swapping operations. In light of these considerations, our study opens a perspective on the design of an efficient SDN-based backbone control network that allows the application of appropriate routing strategies to maximize the entanglement rate on the future quantum constellations. Besides, we considered a LEO constellation to further limit the distance problem. This aspect should be taken into account for the design of constellations consisting of satellites with quantum repeater functionality.

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