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RESEARCH ARTICLE

Metropolitan Quantum-Drone Networking and Computing: A Software-Defined Perspective

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ABSTRACT Swarms of drones are utilized in a wide range of applications, considering that they can be deployed on-demand and are economically affordable. Furthermore, they can also have a significant role in the creation of future Quantum Networks (QNs). As a matter of fact, the use of drones allows deploying a non terrestrial Quantum Metropolitan Area Network (QMAN), overcoming Optical Fibers' (OFs) limits, due to the large percentage of photons that scatters before reaching the receiver. However, random fluctuations of drones' positions and atmospheric turbulence can affect the quality of the Free Space Optic (FSO) link with a significant impact on performance. Considering that Quantum Drone Networks (QDNs) require significant control, Software-Defined Networking (SDN) paradigm can play a key role in their provisioning. Specifically, an SDN Controller is responsible for managing the global strategies for the distribution of end-to-end (E2E) entangled pairs. Therefore, this paper provides the design of an SDN-based architecture for supporting high-performance Metropolitan Quantum Drone Networks (MQDNs) with a specific protocol for creating entanglement between two Ground Stations (GSs) through the swarm of drones. The proposed architecture can be employed for distributed quantum computing applications and entanglement-based Quantum Key Distribution (QKD) services. Moreover, a suited objective function to optimize the planning and operation of the swarm mission has been proposed. Finally, the paper provides a performance evaluation considering the most relevant metrics, such as fidelity, entanglement rate, and the overhead of the proposed protocol, pointing out that even higher performance than OFs is achievable.

INDEX TERMS Quantum cloud, quantum drone swarms, quantum internet, quantum key distribution, quantum software-defined networking.

I. INTRODUCTION

Swarm of drones are envisioned as a significant component for new generation networks. The deployment of multiple drones, indeed, allows delivering cellular and Internet services to remote regions or areas, where a massive number of users are temporarily gathered or where terrestrial infrastructure is unavailable or difficult to deploy. Furthermore, drones can be *on-demand* disposed above the desired area in order to assist communications at any given time and according to their dynamic requirements [1]. In the 5G and 6G networks, one of the main objectives is the creation of a fully integrated heterogeneous network [2], [3] following the Service-Oriented Architecture (SOA) paradigm [4]. SOA is an approach that addresses the requirements of loosely coupled, protocol-independent, and standards-based distributed computing. In SOAs, it is irrelevant whether services are local or remote, the interconnecting scheme or protocol used to perform the invocation, or which infrastructure components are required to establish the connection [5], [6].

Considering the technological advances in the realization of Quantum Devices (QDs), swarms of drones can also be used for the creation of non terrestrial Quantum Networks (QNs), that are based on the quantum entanglement and

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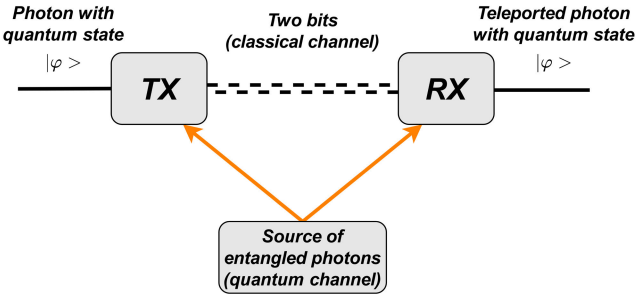

FIGURE 1. Quantum teleportation scheme: a qubit with a specific quantum state is teleported sending *two* bits on a classical channel.

quantum teleportation phenomena [7], [8], whose basic principle is expressed in Fig. 1. During the first phase of the quantum teleportation protocol, a Bell pair, which is a couple of qubits in a maximally entangled state [9], [10], is distributed: one member to the source and the other one to the destination [11]. A maximally entangled state is a quantum state with maximum von Neumann entropy and form an orthonormal basis of the Hilbert space of the two qubits [12], [13], [14]. In the second phase of the quantum teleportation protocol, a measure is taken on the qubit to be teleported and the source's Bell qubit together with its results are communicated to the destination through a classical channel. The receiver then performs specific operations to reconstruct the desired quantum state on the basis of the received classical bits [15].

As explained in [16], the Bell pairs can be generated onboard the intermediate drones that act as Quantum Repeaters (QRs). Differently from the repeaters used in classical communications, QRs can not clone quantum signals. This peculiarity depends on the *no-cloning theorem* and the *uncertainty principle*, both making quantum communications extremely secure [17], [18]. The QRs perform the *entanglement swapping* operation that allows entangling two particles originated from different sources and completely independent [19], [20]. However, many of the studies conducted so far only consider simplified scenarios consisting of a limited number of drones [21], [22] usually a single drone that connects two Ground Stations (GSs).

In order to reduce the impact of channel losses, several QRs have to be deployed and connected along the logical end-to-end (E2E) path [23] and the performance can be further improved with the use of the Free Space Optics (FSO) technology [24], [25]. As a matter of fact, some models show that in good meteorological conditions, attenuation values even lower than those ones achievable with Optical Fibers (OFs) can be obtained [26], [27]. This results in a significant reduction of losses, due to the scattering phenomenon and permits to reduce the number of required QRs [28].

However, the quality of the FSO link can be severely impacted by the change of drones' position and orientation due to their random fluctuations [29]. Specifically, pointing errors and atmospheric turbulence contribute to increased losses [30]. These effects are known as *beam wandering* and can significantly deteriorate the communications performance [31], which depends on the fraction of power that falls onto the photo-detector. Despite the circuitry onboard the drone could contribute to mitigating these effects [32], nevertheless, they cannot be completely neglected.

Given all the previous considerations, the swarm of drones can be taken into account to create efficient ad hoc Metropolitan Quantum Drone Networks (MQDNs) for critical missions. Furthermore, considering that the Software-Defined Networking (SDN) is a suitable technology for the management of mobile QNs [19], [23], [33], [34], [35], this paper proposes an SDN oriented architecture that can be used to manage and control a MQDN and to adapt it to possible quantum applications. As a matter of fact, in a QN an SDN Controller would be responsible for managing the global strategies for the distribution of long-distance Bell pairs that are produced as a result of entanglement swaps between separate links. Specifically, in Quantum SDN (QSDN), the Control Plane (CP) usually performs path selection and signaling operations, and it is decoupled from the Data Plane (DP), which is dedicated to the creation of link-to-link (L2L) Bell pairs. The CP messages are exchanged over a classical channel, while DP traffic is sent over a specific quantum channel [23], [36]. Specifically, in a MQDN, the SDN Controller can set up the E2E drones' path by sending control messages on a particular classical control channel [10]. Furthermore, with the SDN technology, it is possible to further mitigate pointing errors by compensating the trim changes due to atmospheric agents [37].

This envisaged network could be devoted to distributed quantum computing, which allows creating *Quantum Cloud* with an unprecedented computational capacity [38], [39], [40], and quantum cryptography, that makes quantum communication extremely secure [41]. The most prominent quantum cryptography technique is the Quantum Key Distribution (QKD), which includes several protocols, partly implemented on scenarios consisting of drones [21]. However, many of the QKD protocols applied so far do not involve multiple drones as considered in this paper, and only a few studies concern the implementation of entanglement-based protocols [27], [42]. The proposed architecture allows to control the topology in order to create a chain of drones acting as QRs, which can share Bell pairs on a L2L basis. Through teleportation and entanglement swapping operations between the drones, our goal is to create E2E-based entangled states which can be used both for distributed quantum computing and as the basis for entangled-based QKD protocols such as E91. Specifically, in the distributed quantum computing case, the SDN controller through the Northbound APIs can interface with the higher-level applications explained in [39], which are the Virtual Quantum Processor (VQP), the Distributed Quantum Compiler (DQP), and the Distributed Quantum Algorithm (DQA).

Moreover, the proposed architecture provides accurate mission planning and control also allowing to reduce the effects due to quantum *decoherence* [43] that remarkably

affects both quantum communication and quantum computation. As a matter of fact, decoherence leads the qubits that compose the Bell pair to lose the entanglement as time passed [34]. Specifically, several parameters, e.g., temperature or magnetic fields, constitute an uncontrollable source of noise in the system, which influences the quality of the generated entangled state [10]. Nevertheless, as explained in [44], by positioning the QRs equidistant, it is possible to mitigate the effect of decoherence. Therefore, the drones that compose the swarm must be positioned as equidistant as possible. Through accurate positioning operations that can involve, e.g., the use of pseudospectral optimal control [45] for drone trajectory generation and the use of SDN technology, it is possible to approach such a configuration.

Despite the several efforts that have been dedicated to performing quantum communications through *couple* of drones, it is still unclear how the E2E paths between two GSs can be optimally configured. As a consequence, the aim of the paper is to provide some guidelines to dispose and manage a QDN optimally, to create an efficient ad hoc MQDN for specific missions, i.e., whenever a terrestrial connection is unavailable or difficult to set up or whether the performance achievable through OFs is not sufficient. The paper investigates the more relevant metrics, i.e., (i) the *fidelity* [10], [46], which indicates the quality of the generated entangled pairs, (ii) the *entanglement rate* [23] that is the number of generated entangled pairs per second, and (iii) the *overhead* of the proposed SDN-based protocol.

To the best of our knowledge, this paper is the first one to define a specific SDN architecture for the management of a QDN. Specifically, this paper provides some guidelines for the design of a MQDN relying on drones that act as QRs with the following contributions:

- Definition of an SDN-based architecture and control protocol for entanglement generation and swapping for MQDNs.
- Assessment of the most efficient FSO technology considering different wavelength values.
- Evaluation of the achievable E2E fidelity considering some realistic issues, as the beam wandering effects in different meteorological conditions and comparison with OF technology.
- Evaluation of the achievable E2E entanglement rate.
- Evaluation of the overhead provided by the control messages.
- Definition and evaluation of an objective function and its optimization.

This paper is organized as follows: Section II provides an overview of the related works. In Section III, the overall system model and the simulation framework are described. Section IV presents the results. Finally, Section V concludes the paper and outlines future perspectives.

II. RELATED WORKS

Considering that using OFs, a significant fraction of the photons scatters before reaching the receiver, it is necessary to consider different communication technologies [16], including drone networks [47] or even satellites controlled via SDN [36]. As a matter of fact, the SDN principle has already been considered for the design of QNs in both terrestrial and satellite scenarios [19], [23], [33], [34], [35]. In [23], an architecture with a single SDN Controller on the ground is presented, with a performance evaluation of different path selection algorithms. Furthermore, in [19], a similar architecture has been proposed, with a performance evaluation of several satellite constellations, demonstrating that Low Earth Orbit (LEO) guarantee better performances w.r.t. Medium Earth Orbit (MEO) constellations. However, these studies consider the use of a single Controller on the ground. A first investigation that considers multiple Controllers on a quantum satellite constellation is reported in [33]. Specifically, it presents an architecture composed of multiple Controllers also integrated into the constellation that operate in a hierarchical fashion with the related performance evaluation. Moreover, a mobile CP solution is explored in [34].

Even though some studies about the use of Quantum Drones (QDs) for the realization of mobile QNs have already been performed, the use of SDN technology has not been considered in this context. As a matter of fact, some of these studies are only aimed at testing the feasibility of some QKD protocols on individual drones without the aid of a properly designed CP. For instance, the BB84 QKD protocol [48] has been tested in [21] on a scenario composed of a single GS and a drone, measuring the Quantum Bit Error Rate (QBER) at different distances.

In particular, free-space quantum communication through drones equipped with quantum hardware has been proposed in [16]. A network constituted by QDs is an easily disposable on-demand solution to cover limited areas, where ad hoc quantum computation is expected. This solution also allows overcoming the static deployment typical of OFs.

In [32], there is an example of a quantum cryptographic network created using a couple of multi-copter drones. Specifically, it is focused on the development of an optical payload for QKD capable of maintaining pointing between two flying drones. Moreover, the air-to-air signal coupling between a couple of drones has been evaluated in [49].

The entangled photons can also be generated onboard QDs, as in [16], where a scenario consisting of a single drone that generates the entangled photons and relays them to a second drone for retransmission to the destination. Furthermore, the quality of the entanglement states generated by a single drone that connected two GSs has been verified in different daylight and weather conditions in [22].

Despite some papers discussing the use of drones for quantum communications, however, they are not related to entanglement-based quantum communications. As a matter of fact, they implement protocols such as BB84, which is consolidated and is not entanglement-based. Moreover, the papers in the literature employ only one drone, whereas in our case, a network of multiple QDs is analyzed. Therefore,

compared to state of the art, this paper provides essential architectural specifications for the design of a network of QDs, which can be managed via SDN technology, also defining a specific SDN-based protocol with the related performance evaluation. In particular, the topology can be optimized and controlled on the basis of an objective function related to specific QoS parameters. Moreover, the proposed architecture can be tailored to distributed quantum computing and entanglement-based QKD applications.

III. SYSTEM MODEL

This Section describes the proposed system model and the architectural criteria proposed to perform quantum communications and processing. Specifically, the considered scenario consists of two GSs interconnected through a swarm of drones equipped with quantum hardware. In order to organize the mission properly, the correct number of drones needs to be firstly selected and dynamically controlled during the mission.

One of the phenomena to be taken in consideration is the decoherence, which is orginated by the interaction between qubits and the surrounding environment. To prevent that a qubit becomes entangled with the environment, the system must be kept as possible isolated, otherwise, the processing and the communication process can result altered [34]. In the considered scenarios, we arranged the drones in an equidistant configuration, as shown in Fig. 5. This choice allows to minimize the coherence time required to successfully achieve entanglement [44], mitigating the negative effects due to decoherence not requiring higher-performance technologies with additional costs.

In order to achieve an E2E-based entanglement over a long distance, the involved QDs operate as QRs [16]. The quantum operations that a QR performs are *quantum teleportation* and *entanglement swapping*, which are explained in the following.

In quantum teleportation, the state of a qubit is destroyed in a location and recreated in another one [10]. The process of entanglement swapping uses teleportation *consuming* two Bell pairs covering adjacent short distances into one pair, which covers a corresponding longer distance [50]. The entanglement swapping procedure is depicted in Fig. 2 and works as follows: after preparing two independent entangled pairs α-β and δ-γ where - indicates the entanglement established, a Bell state measurement on β and δ projects α and γ onto an entangled state, even though these two particles have never shared any common past [19]. Therefore, the entanglement swapping procedure can also be defined as an extension of teleportation [51].

To reduce the impact of channel losses, several QRs have to be deployed along the E2E path [23], [52], [53] and the performance can be further improved with the use of FSO technology. However, despite the previously described phenomena limiting the performance of FSO significantly, as reported in [33], adequate performance can be achieved in clear air conditions using the 1550 *nm* wavelenght. In order

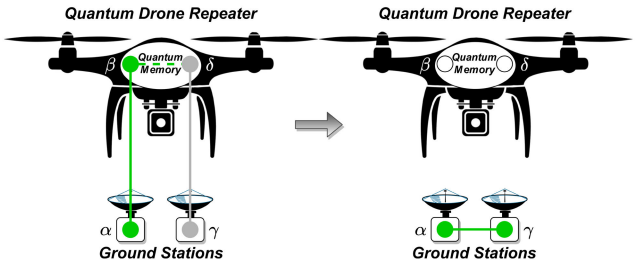

FIGURE 2. Operating principle of a drone acting as QR. Entanglement swapping is performed between two pairs of particles executing a Bell state measurement on the two of them.

to model the atmospheric links, several solutions [26], [54] predict the specific optical attenuation considering a wavelength-dependent relation that regards the *atmospheric visibility* and the *drop size distribution*. As a matter of fact, some models show that in favorable meteorological conditions, reduced attenuation values can be obtained, even lower than those obtainable with OFs [26], [54]. This results in a significant reduction of losses due to the scattering phenomenon and it allows to reduce the number of required QRs.

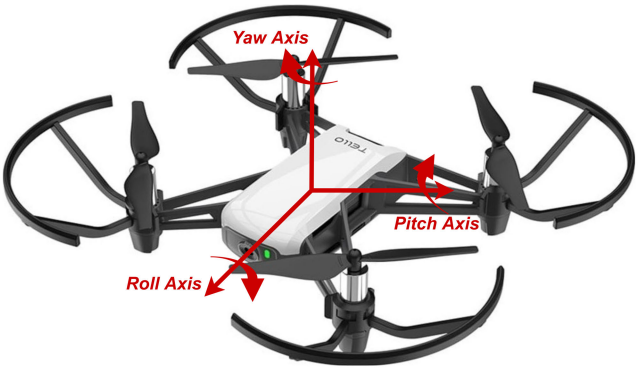

FIGURE 3. Oscillations that tipically affect a flying object. "DJI Tello Micro-Drone" by Dennis Sylvester Hurd https://www.flickr.com/photos/dennissylvesterhurd/49238096152 is licensed under CC BY 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by/2.0. The picture has been modified within the terms of the license by inserting the coordinate system.

Nevertheless, as explained in [31] the quality of the FSO link can be degraded, due to the random fluctuations of the drones w.r.t their position and orientation. As a matter of fact, aerial objects, including drones, are subject to phenomena such as pitch, roll, and yaw, which are variations in position with respect to all three axes [55], [56], as shown in Fig. 3. On a drone, these variations can be measured by an *Inertial Measurement Unit (IMU)* on board the drone itself [56], [57], [58], [59] and mitigated by the *Flight Controller*, which provides the following features:

- Kinesthetics of drone flight.
- Automatic thrust/angle control.
- Maintenance of position and orientation control [32].

However, despite the Flight Controller onboard the drone could contribute to mitigating these effects [32], the consequences cannot be completely neglected. Specifically,

they consist in losses depending on whether the optical receiver can capture only the fraction of power that falls onto the photo-detector. Furthermore, pointing errors contribute to increased losses. These effects are known as *beam wandering*. Since that the beam may experience random displacements both along with the horizontal and vertical axis, the misalignment errors of the photo-detector are modeled as independent Gaussian random variables, expressed as follows [30], [31], [60]:

$$x \sim \mathcal{N}(\mu_x, \sigma_x^2) \tag{1}$$
$$y \sim \mathcal{N}(\mu_y, \sigma_y^2) \tag{2}$$

where μ_x and μ_y denote the averages and σ_x^2 and σ_y^2 the variances Moreover, as the number of drones increases, the error becomes progressively more significant, whereas every drone is affected by such phenomena [61].

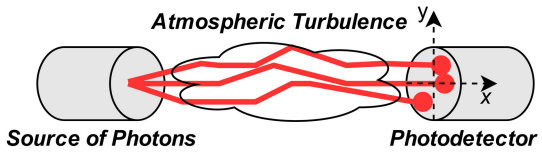

FIGURE 4. Representation of beam wandering due to atmospheric turbulence.

In the proposed architecture, depicted in Fig. 5, the mission is loaded by a classical server that optimizes and schedules the mission according to the user's request. Specifically, drones must be programmed by providing them the GPS coordinates calculated according to the optimization procedure, and a SDN Controller is installed on the drone close to the barycentre of the swarm. Therefore, the mission can start, and the drones position themselves at the specified coordinates. During the second phase, the SDN Controller starts managing the operations of entanglement generation and swapping to enhance the process. Furthermore, the Flight Controller mitigates pointing errors compensating the trim changes due to atmospheric agents relying on the position control given by the on-board GPS receiver and IMU [58]. If one or more drones deviate excessively from their position or in case of failure, the SDN Controller could reorganize the data flow on the path by reprogramming the devices that compose it via Southbound messages, in order to operate without the missing drones. According to the design specifications of QNs stated in [10], the Controller messages are sent over a dedicated classical control channel. The SDN-based protocol shown in Fig. 6 is structured in two phases described as follows:

1) The SDN Controller sends entanglement generation messages to the drones that compose the left and right sub-sets of the swarm to interconnect GSs and drones, including itself, on a L2L basis.
2) The SDN Controller sends messages to the drones to perform the entanglement swapping in order to create the E2E entanglement.

Naturally, considering that the SDN Controller is on board one of the drones, in order to perform the swapping operation on itself, no message has to be sent.

The proposed architecture can be used for distributed quantum computing and for entanglement-based QKD applications. As explained in [62] and [10], the entangled particles can be prepared by both the users sharing the key or by a third entity, and are distributed in a way that both the users have one photon of each pair. As depicted in Fig. 5, the SDN Controller positioned in the barycenter of the created E2E path is the entity that manages the E2E entanglement generation between the GSs properly, according to the protocol explained in Fig. 6. Therefore, the Controller allows the creation of remote entangled states between two Quantum Computers (QCs) if required by (i) a distributed quantum algorithm [34] operating in a Quantum Cloud context or (ii) to create the Bell pairs that compose the key in the case of communications performed using QKD entanglement-based protocols [62], [63].

Since drones operate in the lowest layers of the atmosphere, scattering of optical wavelenghts by aerosol particulates and fog have a significant impact on communication, and it is necessary to adopt specific models to simulate the links [64]. Moreover, considering that, as explained in [65], the effect of turbulence on quantum states is similar to the effect on classical vector modes, we have considered the Kruse model [66], which provides a wavelength-dependent relation between the *atmospheric visibility* V and the *extinction coefficient* ξ. In particular, it allows to calculate the specific optical attenuation as follows [26], [66]:

$$A = 10(\log_{10} e)\xi \tag{3}$$

where ξ is defined as:

$$\xi \doteq \frac{-\ln 0.02}{V}\left(\frac{\lambda}{550}\right)^{-\eta} \tag{4}$$

The term V present in (4) is defined as a distance where a 550 *nm* collimated light beam is attenuated to a fraction of 5% or 2% of original power, whereas λ is the wavelength of the signal. The η coefficient depends on experimental data about the drop size distribution [67] and is related to visibility:

$$\eta = \begin{cases} 0.585V^{\frac{1}{3}} & \text{if } V < 6\ km \\ 1.3 & \text{if } 6\ km < V < 50\ km \\ 1.6 & \text{if } V > 50\ km \end{cases} \tag{5}$$

To address the quality of the supported applications, several parameters can be considered, among which the fidelity that is a parameter that characterizes the quality of teleportation. Specifically, the fidelity between a pure state $|\psi\rangle$ and an arbitrary state ρ, is defined as follows [68], [69], [70]:

$$F(|\psi\rangle, \rho) \doteq \mathrm{Tr}\sqrt{\langle\psi|\rho|\psi\rangle\,|\psi\rangle\langle\psi|} = \sqrt{\langle\psi|\rho|\psi\rangle} \tag{6}$$

The fidelity values fall in the interval [0, 1], it is equal to 0 if and only if $|\psi\rangle$ and ρ have orthogonal support, and it is equal to 1 if and only if $|\psi\rangle = \rho$ [68]. Therefore, the fidelity is a

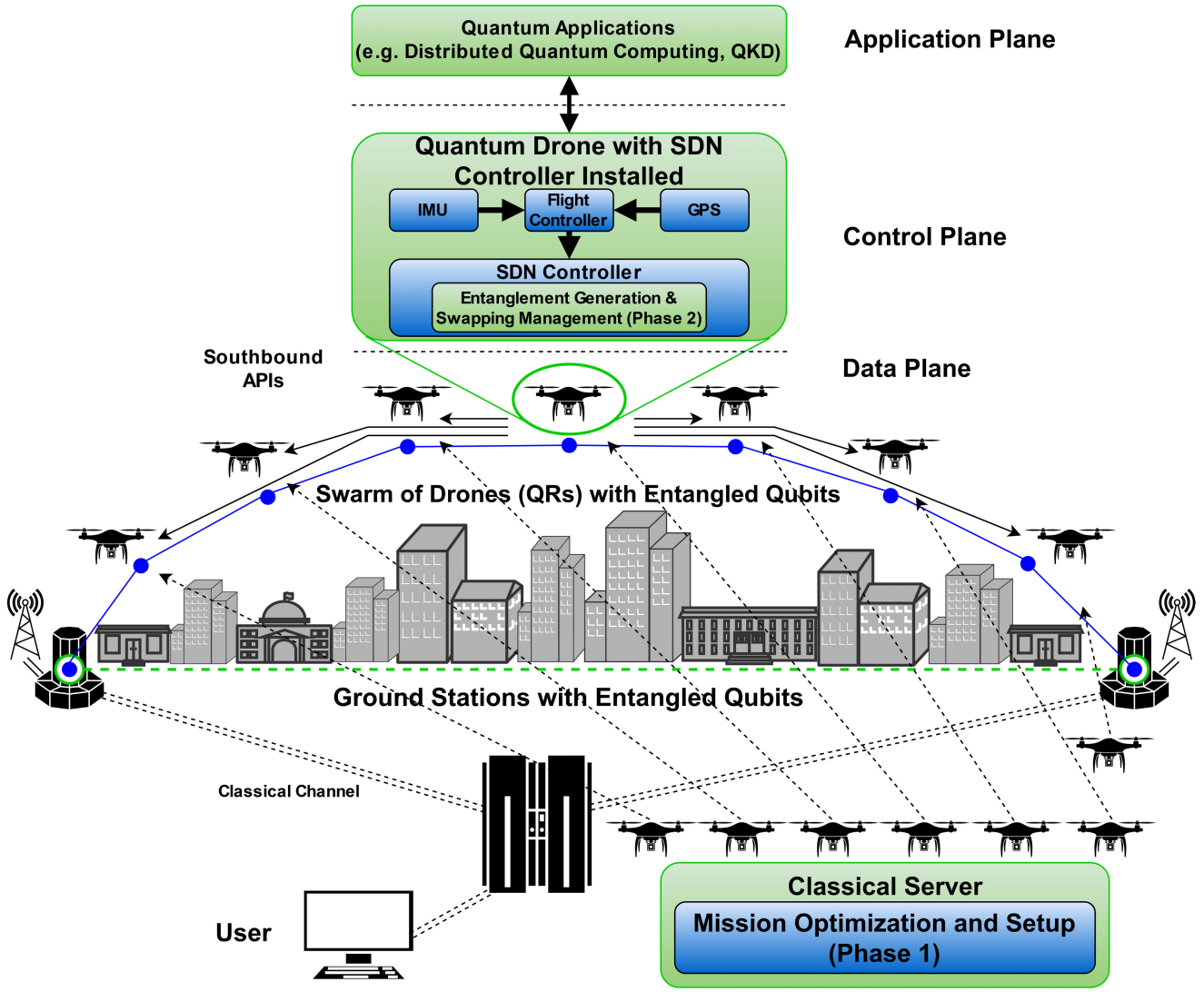

FIGURE 5. Quantum metropolitan SDN drone network. In phase 1, the mission is configured properly by calculating the coordinates of the drones according to the result of the optimization. During the second phase, the Bell pairs are generated between the GSs through operations driven by the Controller embedded in the swarm of drones.

probability that describes how *close* two quantum states are, and the closer it is to 1, the more the created state is similar to the desired one. It can be used to characterize drastic changes in quantum states in the presence of Quantum Phase Transitions (QPTs). If the fidelity value is below 0.5, the created state is unreliable, and it cannot be used for computing purposes [10]. However, the fidelity of a quantum state can be enhanced by the proper use of QRs [18], [71].

Moreover, we evaluated the entanglement rate R, which is defined as the number of created entangled states per second and is measured as Bell pairs per seconds [23], [72]. In QNs the entanglement rate is alternatively defined as throughput, or the speed of variation of the relative entropy of entanglement [73], [74]. Considering that the SDN Controller is centrally placed, the times required for the completion of operations on the left and right sides of the E2E path are respectively τ_l and τ_r. Furthermore, the time required to generate a L2L entanglement between drone i and drone $i+1$ can be defined as $\tau_{e_{i,i+1}}$ and the time required to perform the entanglement swapping operation on a specific drone j as τ_{s_j}. However, despite the swapping operations related to the drone on which the Controller is installed do not require messages to be sent, it is necessary to consider the time required for the state measurement to perform the swapping operation, which is then given as τs_0. For instance, if we consider the path as consisting of an odd number of drones equal to N the left and right sections consist of a number of drones equal to $\frac{N-1}{2}$, the times required to complete the operations on the left and right sides are:

$$\tau_l = \sum_{i=-(\frac{N+1}{2})}^{-1} \tau_{e_{i,i+1}} + \sum_{j=-(\frac{N-1}{2})}^{-1} \tau_{s_j} \tag{7}$$

$$\tau_r = \sum_{i=0}^{\frac{N-1}{2}} \tau_{e_{i,i+1}} + \sum_{j=1}^{\frac{N-1}{2}} \tau_{s_j} \tag{8}$$

Considering that the time required to complete operations on the entire path is determined by the longer time interval, the time required to obtain an E2E entanglement is equal to:

$$T = \max\{\tau_l, \tau_r\} + \tau s_0 \tag{9}$$

Therefore, the entanglement rate on the entire path can be effectively expressed as:

$$R \doteq \frac{1}{T} \tag{10}$$

where T is the time required to generate a remote entanglement over the entire E2E path [19], [23], [44].

In order to maximize the overall quantum processing capability, we introduce an objective function combining the two considered metrics. Since [10], quantum applications require that the fidelity is above some application-specific threshold F^*, the objective function can be consequently expressed as follows:

$$\begin{aligned} &\max_{N} \; R(V, d, \lambda, N) \\ &\text{s.t. } F > F^* \end{aligned} \tag{11}$$

The objective function expressed in (11) depends on the atmospheric visibility V, the distance d between the GSs, the wavelenght λ and the number of drones N. Specifically, the solution of this optimization problem yields the optimum number of QRs that provide the best performance in terms of R, while guaranteeing $F > F^*$. This optimization is calculated by mission control during Phase 1, which is shown in Fig. 5.

Finally, we evaluated the protocol overhead due to entanglement generation and swapping operations, which has to be minimized, especially for distributed quantum computing applications. Indeed, in this case, the distributed quantum compiler must optimize the E2E path so that the number of remote operations is minimized to limit the decoherence effects and to reduce the overhead arising with the swapping operations, as explained in [34]. In fact, when decoherence occurs, some qubits become entangled with the environment, and the entire computation of a single QC or a distributed computation performed by multiple QCs interconnected through QRs in a QN results corrupted [43], [75].

Specifically, the overhead minimization can be achieved by the efficient management of entanglement generation and swapping operations by the Controller. Furthermore, the integration of the CP into the drone swarm contributes to limiting overhead, since that some operations can be performed locally and do not require sending messages, as clarified in Fig. 6.

IV. SIMULATION RESULTS

The code developed in order to perform the simulations described in this Section was run on a machine with an Intel Core i7-10750H CPU at 2.6 GHz with 8192 MB of RAM and Ubuntu 20.04.4 installed. We developed the code on the `JetBrains PyCharm` environment, and we used

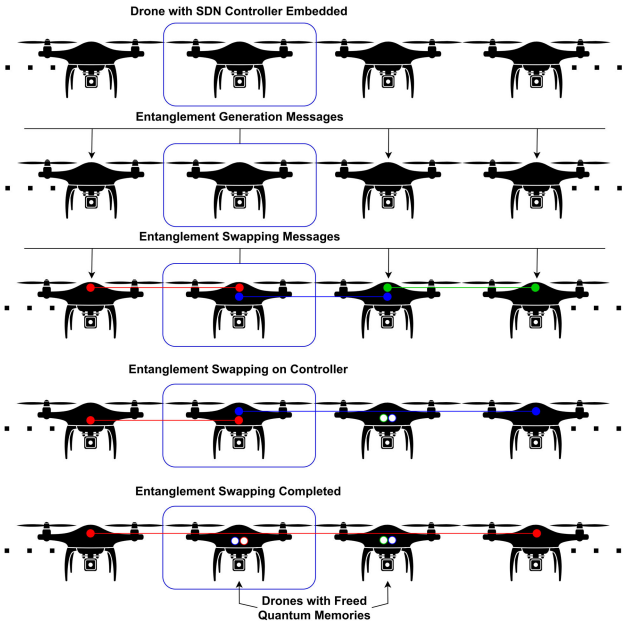

FIGURE 6. Entanglement generation and swapping protocol performed by the SDN Controller. Note that the swapping operation on the drone with the Controller embedded does not require the transmission of messages.

the `NetSquid` Python package [76] in order to model the hardware that composes a typical entangled-based QN.

Considering that different wavelengths are tipically used in communications using FSO technology [77], we evaluated the attenuation for several wavelengths by varying the meteorological conditions and using the Kruse model defined in (3). Moreover, we characterized the phenomenon of beam wandering by modeling the pointing error on the photo-detector as two independent Gaussian random variables. Specifically, with an aperture of radius 10 cm, as in [31], we assumed a pointing error with a standard deviation of $\sigma = 7.5$ cm with respect to both the x-axis and y-axis of the photodetector shown in Fig. 4. We supposed a significant value for the standard deviation considering that, although the effects of the beam wandering can be mitigated, it can be hard for drones to accurately maintain the position and, therefore, it is reasonable to assume that the impact of degradation cannot be neglected. The parameter values used in the following simulations are given in Table 1.

TABLE 1. Values of the parameters adopted in the simulations.

Parameter	Value
Aperture Radius	10 cm
σ	7.5 cm
FSO Wavelengths	650, 850 and 1550 nm
OF Attenuation	0.2 dB/km

As it can be seen from Fig. 7, in specific visibility conditions, the attenuation values are lower than those ones of the OF, which have been, indeed, considered only for comparison purposes. As a matter of fact, at 1550 nm, the OFs present an attenuation of 0.2 dB/km [78] depicted as a

dotted line in Fig. 7. Specifically, under the same visibility conditions, the use of this wavelength ensures the lowest attenuation w.r.t the other ones considered. Furthermore, Fig. 7 shows that if we consider as reference values the attenuation of 0.2 dB/km of OF, for the FSO case, this attenuation can be obtained at $\lambda = 1550$ nm with $V = 22.1$ km, i.e., in sub-optimal meteorological conditions. As a consequence, it is appropriate to endow the network of drones with 1550 nm communications technology.

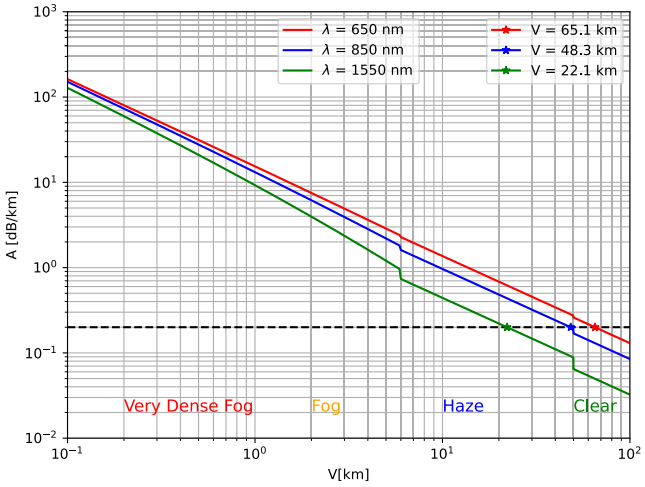

FIGURE 7. Attenuation for different wavelengths at varying meteorological conditions considering the Kruse model.

These considerations are confirmed from the simulation performed on a scenario that considers a swarm of drones used to connect two GSs located at a distance of 10 km typical of a metropolitan area. Table 2 shows the values used in the similations reported in Fig. 8, in which the achievable fidelity w.r.t. the number of involved drones for different wavelengths and considering atmospheric visibility of 30 km in free space has been evaluated and compared with OF. In Fig. 8 the maximum values of the obtained plots are also reported. In particular, it can be inferred that under specific meteorological conditions it is possible to achieve performance comparable to OFs with a reduced number of QRs.

TABLE 2. Attenuation values for the wavelengths employed in the simulations reported in Fig. 8.

λ [nm]	Atmospheric visibility [km]	Attenuation [dB/km]
650	30	0.456
850	30	0.322
1550	30	0.147

Furthermore, we have performed a simulation by varying the visibility conditions to verify the maximum fidelity values obtainable on the same scenario. Table 3 presents the parameters used in the similations reported in Fig. 9, which also shows the achieved maximum fidelity values. It is evident that in specific meteorological conditions, it is possible to obtain very high fidelity values, even with a limited number of drones.

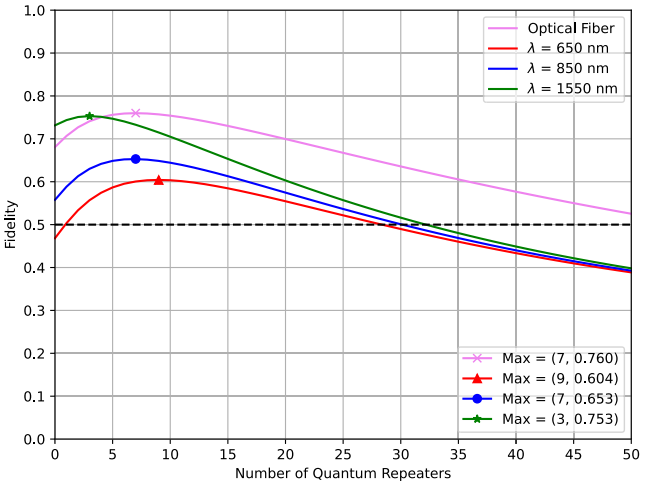

FIGURE 8. Fidelity for different wavelengths considering a visibility of 30 *km*.

TABLE 3. Parameters concerning the attenuation w.r.t. different atmospheric conditions considered in the simulations reported in Fig. 9.

λ [nm]	Atmospheric visibility [km]	Attenuation [dB/km]
1550	5 (Very Dense Fog)	1.205
1550	10 (Fog)	0.442
1550	25 (Haze)	0.177
1550	50 (Haze)	0.065
1550	75 (Clear)	0.043
1550	100 (Clear)	0.032

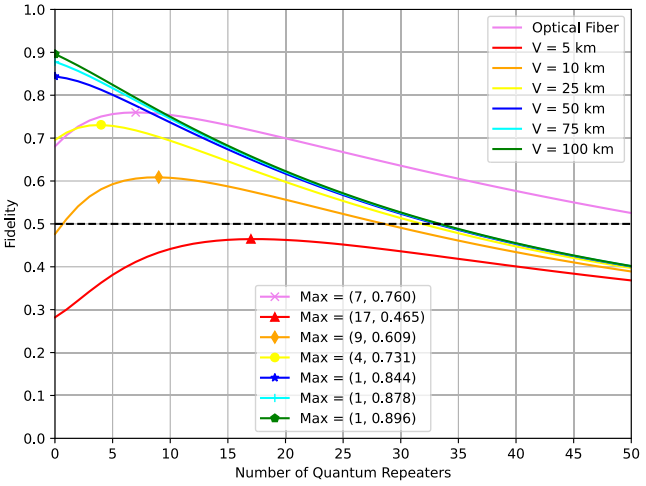

FIGURE 9. Fidelity at varying meteorological conditions at 1550 *nm* w.r.t. OF.

In addition, we investigate the fidelity by varying the distance between GSs as a function of the number of drones considering visibility of 50 km. The results are shown in Fig. 10, which points out that increasing the distance between the GSs, the value of fidelity significantly decreases.

Specifically, with a distance between the GSs above 40 *km*, the maximum fidelity value is below $F^* = 0.5$ for the considered meteorological conditions. It is clear from Fig.s 8, 9 and 10 that there is an achievable maximum; this allows obtaining significant information for the organization of the flight mission and the optimization of the E2E path.

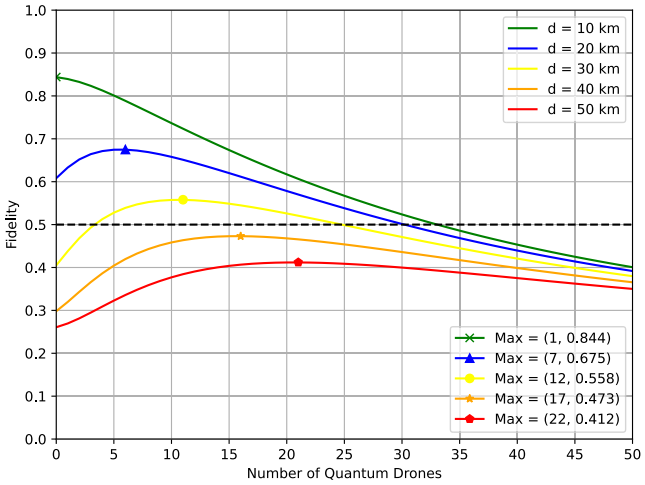

FIGURE 10. Fidelity at varying the distance between the GSs at 1550 *nm* considering visibility of 50 *km*.

Furthermore, for the sake of completeness we jointly evaluated the entanglement rate and the objective function in (11) by varying the number of drones on a 10 *km* path. The results shown in Fig. 11, point out that the number of drones employed has a significant impact on the maximum achievable entanglement rate, which rapidly decays as the number of drones increases. Moreover, in Fig. 11 the red curve denotes the values of entanglement rate achievable considering the objective function defined in (11), which limits the range of possible drones to a closed interval. It can be noticed that the optimum value is close to the lower boundary of the eligible range corresponding to the minimum fidelity threshold at 0.5, in the presence of a visibility of 10 *km*.

Finally, we evaluated the overhead of the proposed control protocol, which performance is depicted in Fig. 12. Considering the problems related to the maintenance of drones' positions and that the aerial link can be significantly perturbed, we have introduced a realistic packet loss probability, which is proportional to the number of involved drones. The results are reported in Fig. 12, in which it can be seen that the loss factor has more influence with a significant number of drones.

The evidence emerging from these simulations shows that the number of drones necessary to perform a quantum communication between two GSs depends both on the employed technology and meteorological conditions. Furthermore, we verified that the objective function has a unique maximum. Moreover, it is pointed out that the problems of beam wandering due to drones' random fluctuations and

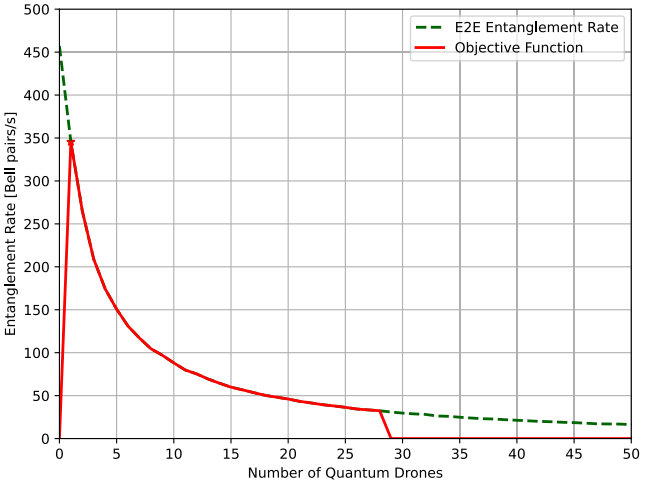

FIGURE 11. Entanglement rate at varying the number of QDs on a 10 *km* path. The red plot highlights the rate obtainable with fidelity greater than 0.5 with a visibility of 10 *km*.

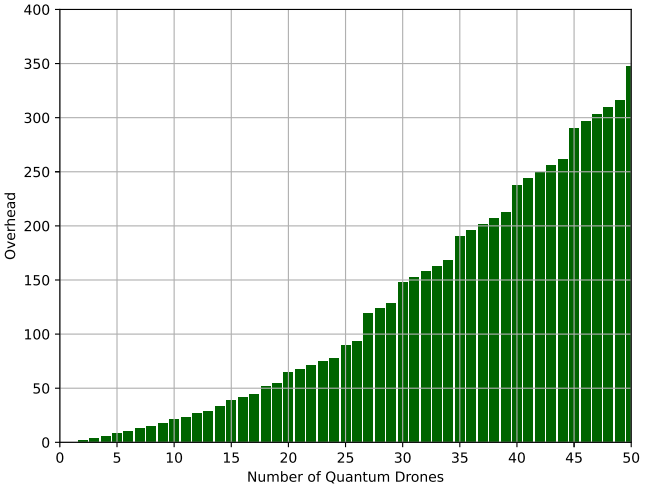

FIGURE 12. Overhead concerning the operations of entanglement generation and entanglement swapping for a single session.

atmospheric turbulence significantly degrades performance. As explained in [61], this issue is typical of communications among a large number of drones. In the quantum case, despite the use of multiple drones operating as QRs limits the performance degradation compared to a single link of equal length [52], [53], the effects of beam wandering become increasingly significant as the number of drones increases. Therefore, employing a limited number of drones contributes to maintaining adequate performance for all the evaluated parameters. The target is achieved considering specific objective functions aimed to balance the evaluated parameters in order to plan the mission properly and limit costs. In addition, through the SDN technology, it is possible to coordinate the operations of entanglement generation and swapping among the drones that compose the swarm. Finally, the integration of the CP into the swarm allows performing some of the operations locally, contributing to improving performance and limiting overhead and possible packet losses.

V. CONCLUSION AND FUTURE DEVELOPMENT

Swarms of drones are envisioned as a significant component of future QNs since these devices can be deployed on-demand in any place and time. Moreover, despite pointing errors due to random fluctuations w.r.t. drone positions, atmospheric links can provide lower attenuation values than OFs, guaranteeing even higher performance.

Therefore, our aim is to address the problem of designing an efficient QMAN composed of swarms of drones. Considering that SDN technology has been recognized as significant for the development of QNs that require intensive control, we propose an architecture that includes the SDN Controller directly embedded in the swarm of drones and enables support for applications such as distributed quantum computing and QKD. Furthermore, the paper proposes a specific objective function for calculating the optimal number of drones according to the meteorological conditions allowing for the proper trade-off between the performance expressed in terms of fidelity and entanglement rate.

The results show that, despite the atmospheric turbulence and beam wandering issues, planning the mission properly by optimizing specific objective functions, it is possible to reach reasonable fidelity values that also allow distributed quantum processing in a Quantum Cloud context. Employing a limited number of drones, it is possible to achieve significant performance in terms of entanglement rate while maintaining low overhead. Moreover, the integration of the CP into the swarm allows performing some of the operations directly on board the drone, without sending messages, limiting the overhead and packet losses.

Future developments should consider the evolution of the proposed protocol in order to consider multi-Controller segments and the interoperability among QMAN also through other kinds of aerial platforms or satellite segments. Furthermore, due to its configuration, the proposed architecture can also be used for applications of QKD and, specifically, to provide entanglement-based protocols.

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